



REVIEW ARTICLE

Mineral nutrient acquisition under abiotic stress conditions

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Abstract

Mineral nutrient acquisition is central to plant growth, productivity and resilience, particularly under abiotic stresses such as drought, salinity, alkalinity, waterlogging, extreme temperatures, acidity and metal toxicity. Among essential mineral nutrients, nitrogen (N), phosphorus (P), potassium (K) and micronutrients such as zinc (Zn) and iron (Fe) are most severely affected under stress conditions, with nutrient uptake reductions often ranging from 20–60 % depending on stress intensity and crop species. These environmental stresses interfere with nutrient availability, transport and assimilation by modifying root morphology, membrane transport activity and gene expression patterns. This review summarises existing knowledge on the response of plants to such challenges, including physiological adjustments, transcriptional regulation of nutrient transporters, hormonal signalling and symbiotic interactions. Special attention is given to the roles of aquaporins, ion channels and nutrient-specific transporters, including nitrate transporters (NRTs), phosphate transporters (PHTs), high-affinity potassium transporters (HKTs) and zinc/iron transporters (ZIP) family members, in maintaining nutrient homeostasis. Recent studies indicate that improved regulation of these transport systems can enhance nutrient use efficiency by 15–40 % under adverse environments. The review also examines emerging approaches involving microbial biostimulants, including plant growth-promoting rhizobacteria and fungal bioinoculants, as well as chemical elicitors such as salicylic acid, that enhance nutrient uptake under stress conditions. Insights into these integrated responses provide avenues for improving nutrient use efficiency and strengthening crop resilience in marginal environments.

Keywords: climate resilience; nutrient transporters; plant nutrition; rhizosphere

Introduction

In contemporary agricultural systems, climate change represents a major challenge for both scientific research and farming practices. A projected climate change impact study, using crop simulation models across various regions in India, indicates significant reductions in crop yields under future climate scenarios. Specifically, rainfed rice yields are estimated to decrease by 20 % in 2050 and 47 % in 2080, if no adaptation measures are adopted. For irrigated rice, yields are projected to decline by 3.5 % in 2050 and 5 % in 2080. Wheat yields are expected to decline by 19.3 % in 2050 and 40 % in 2080, with considerable spatial and temporal variations. Similarly, kharif maize yields are projected to decrease by 18 % in 2050 and 23 % in 2080 (1). These yield losses are accompanied by declines in nutritional quality, reflecting disruptions in mineral nutrient acquisition and allocation. A significant factor contributing to these adverse impacts is the abiotic stress induced by climate change. Abiotic stresses such as drought, salinity, alkalinity, waterlogging, extreme temperatures,

acidity and metal toxicity have gained considerable attention due to their profound effects on plant growth, nutrient uptake and overall productivity (Fig. 1). Under these stress conditions, the ability of plants to acquire essential mineral nutrients becomes severely compromised (2).

Plants have evolved complex regulatory mechanisms to cope with environmental challenges. Stress-responsive genes activate to produce protective proteins and metabolites. Phytohormones like abscisic acid play a crucial role in stress signalling, triggering stomatal closure during drought (3). Osmolyte accumulation maintains cellular osmotic balance under stress (4). Antioxidant systems combat oxidative damage, while plants modify their root architecture and leaf morphology to enhance resource acquisition (5). These responses involve signalling cascades and transcriptional reprogramming, allowing plants to adapt to adverse conditions. Mineral nutrient acquisition is crucial for plant growth, yet abiotic stress disrupts nutrient uptake and transport. Stresses impair root development, alter membrane

permeability and affect nutrient transporter genes, leading to nutrient imbalance (6, 7). Drought and salinity reduce nutrient transporter expression, while extreme temperatures impair nutrient translocation (8, 9). As a result, stressed plants frequently develop nutrient deficiencies that further increase vulnerability to climate-related impacts. A summary of abiotic stress effects on crop yields is presented in Table 1.

Although substantial progress has been made in understanding mineral nutrient acquisition under abiotic stress, responses often vary considerably across crop species, stress types and experimental conditions. Studies report both enhancement and suppression of nutrient transporter activity under similar stress environments, indicating context-dependent regulatory mechanisms rather than uniform stress responses. Comparative evaluation across species and stress scenarios, along with identification of conflicting evidence and unresolved questions, is therefore essential to advance a cohesive understanding of nutrient acquisition under abiotic stress. This review synthesises existing evidence to highlight conserved strategies, species-specific responses and key knowledge gaps that require further investigation.

Impact of abiotic stress on nutrient acquisition

Drought

Water is fundamental to plant physiological processes and governs the mobility of mineral nutrients in soil-plant systems. The movement of mineral nutrients in soil plays a significant role in their absorption by plants. For plants to take up nutrients, ions must move toward absorbing roots, or roots must reach areas with available nutrients. Two key theories, soil solution theory and contact exchange theory, explain nutrient availability to plants (21, 22). Under drought conditions, anionic nutrients such as Nitrate (NO_3^-), Dihydrogen phosphate (H_2PO_4^-), Hydrogen phosphate (HPO_4^{2-}) and Sulfate (SO_4^{2-}) become less available due to reduced mass flow and diffusion (23). Nutrient absorption occurs through active and passive mechanisms (24). During drought, plants close stomata to reduce water loss, limiting CO_2 uptake and photosynthetic efficiency (25). This adaptive response indirectly constrains water flow and limits nutrient uptake via reduced transpiration streams (26). Reduced transpiration diminishes nutrient uptake through passive absorption. Drought stress induces expression of genes involved in nutrient transport, including aquaporins, which facilitate water and nutrient transport

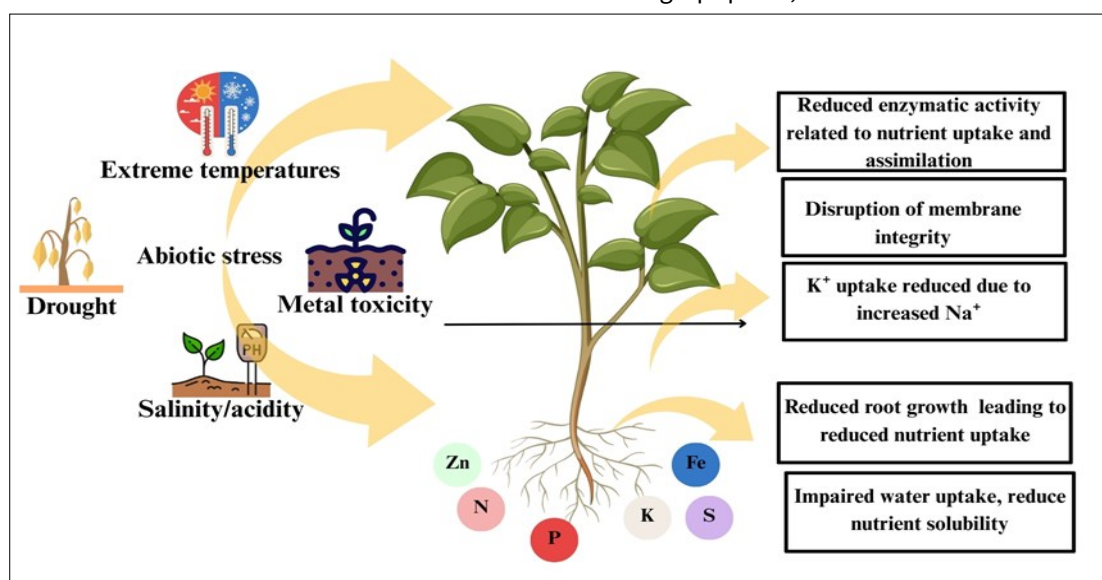


Fig. 1. A general representation on effect of abiotic stress on a plants nutrient uptake.

Table 1. Impact of abiotic stresses on crop yield

Crop	Effect on yield	Reference
Water stress		
Mungbean	Decrease in 62.84 % seed yield plant ⁻¹ as compared to no water stress.	(10)
Rice	Decrease in 20.11 % grain yield hill ⁻¹ compared to no stress.	(11)
<i>Alyssum homolocarpum</i>	Decrease in 84.24 % seed yield pot ⁻¹ .	(12)
<i>Arachis hypogaea</i>	Moderate and severe water stress resulted in 7.35 % and 48.43 % decrease in yield compared to well-watered conditions.	(13)
Salinity		
Rice	Decrease in 37.72 % grain yield pot ⁻¹ under 6 dSm ⁻¹ over no stress.	(14)
Rice	Decrease in 15.9 % grain yield pot ⁻¹ with 34.2 mM NaCl compared to the control.	(15)
<i>Capsicum annuum</i>	A decrease in 10.43 % yield of plant ⁻¹ under 105 mM NaCl compared to the control.	(16)
Strawberry	75mM NaCl resulted in 34 % decrease in the yield of the strawberry over 0 mM NaCl.	(17)
Heat stress		
Spring wheat	Heat stress resulted in 10.43 % reduction in yield compared to the normal condition.	(18)
Maize	14.6–16.4 % yield reduction under heat stress compared to normal conditions.	(19)
Chilling stress		
Rice	Chilling treatment of 12 °C for 2 days resulted in 8.3 % decrease in grain yield plant ⁻¹ compared to 21 °C for 8 days treatment.	(20)

across cell membranes (27). Aquaporins are classified into plasma membrane intrinsic proteins (PIPs), tonoplast intrinsic proteins (TIPs), nodulin-26 intrinsic proteins (NIPs), small basic intrinsic proteins (SIPs) and X intrinsic proteins (XIPs), with PIPs and TIPs showing significant expression under drought stress (27). NH_4^+ enhances drought tolerance in rice by increasing aquaporin expression (28). Defective in urea uptake 3 (DUR3) and some aquaporins function as urea transporters (29), providing advantages when soil NO_3^- is reduced. However, some nutrient transporters, including nitrate transporters (NRTs) and phosphate transporters (PHTs), may be downregulated under drought conditions (30). Notably, reports on nutrient transporter regulation under drought stress are often contradictory. While several studies document downregulation of nitrate and phosphate transporters under prolonged or severe drought, others report transient upregulation during early stress phases or under moderate stress intensity. For instance, in *Brassica juncea* L., early induction of BjNRT1 family members followed by later repression of NRT2 transporters suggests a temporal shift in nitrogen acquisition strategy. Similar stress stage-dependent responses have been reported in rice and wheat, indicating that transporter regulation is influenced by stress duration, severity, tissue specificity and developmental stage. These contrasting findings highlight the need for time-resolved and tissue-specific analyses of nutrient transporter dynamics under drought stress. The NRT family includes NO_3^- transporters, classified as high-affinity (NRT2) and low-affinity (NRT1) transporters. Under drought stress, most genes encoding nitrate transporters and enzymes involved in NO_3^- assimilation and remobilisation are downregulated (30). In *Brassica juncea*, BjNRT1;1 and BjNRT1;5 expression were upregulated in response to abiotic stresses within the first hour, suggesting an early nitrogen (N) accumulation response. However, after 24 hr, N transporters, including BjNRT2;1, were downregulated (30). Water and potassium (K^+) share a close relationship under drought stress, as both are transported through channels and transporters regulated by similar mechanisms. In *Oryza sativa* L., water scarcity affects PIP aquaporins and K^+ channels/transporters, such as OsAKT1, OsHAK1 and OsHKT1, which influence hydraulic conductance (31).

Salinity

Salinity refers to the accumulation of major dissolved inorganic solutes in water and soil, including ions such as sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^+), chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), nitrate (NO_3^-), carbonate (CO_3^{2-}) (32). Soil salinity influences crop productivity, nutrient availability, uptake by plants and soil microorganism activity (33). Salinity stress affects plants through osmotic stress, reducing water availability (34) and ionic stress, which disrupts cellular ionic balance (35). This ionic imbalance leads to nutrient deficiencies and ion toxicities, thereby disrupting multiple physiological processes (36). Salinity induces nutrient imbalances by allowing Na^+ and Cl^- to compete with essential nutrients such as K^+ , Ca^{2+} and NO_3^- for uptake sites, resulting in extreme ionic ratios including $\text{Na}^+/\text{Ca}^{2+}$, Na^+/K^+ , $\text{Ca}^{2+}/\text{Mg}^{2+}$ and $\text{Cl}^-/\text{NO}_3^-$ (37, 38). Salinity stress affects nutrient uptake by impacting nutrient mobility or raising cellular nutrient demands (33). Potassium, crucial for water uptake regulation, is particularly affected by high salinity. High Na^+ in soil may reduce K^+ uptake through competitive inhibition, leading to downregulation of nutrient transporters. The high-affinity potassium transporter (HKT) family is often suppressed under

saline conditions (34). However, research has demonstrated that 40 % increase in K^+ concentration in cassava tubers when exposed to 40 mM NaCl was noticed (39). Comparative evidence across crop species reveals both conserved and divergent nutrient acquisition strategies under salinity stress. While Na^+ induced suppression of K^+ uptake is widely reported in cereals such as rice and wheat, certain species, including cassava and halophytes, exhibit enhanced K^+ accumulation or selective transporter activation under moderate salinity. These differences suggest that nutrient transporter regulation under salinity is highly species-specific and may reflect evolutionary adaptation to saline environments. However, the molecular basis underlying these contrasting responses remains poorly understood, particularly in non-model and oilseed crops. Many abiotic stresses do not act independently but converge on shared physiological and molecular pathways. Drought and salinity, for instance, both impose osmotic stress and activate overlapping signalling networks involving abscisic acid, calcium and reactive oxygen species. These shared signals often regulate common sets of transporters, including aquaporins, nitrate transporters and potassium channels, leading to similar nutrient acquisition constraints under different stress conditions. Recognising this overlap is essential for interpreting nutrient responses under field conditions, where multiple stresses frequently occur simultaneously.

Extreme temperatures

Extreme temperatures are significant abiotic stress factors limiting plant growth, development and distribution (40). With climate change, extreme temperatures increasingly disrupt agricultural production, leading to reduced crop yields in many regions (41, 42). Understanding the effect of temperature on nutrient and water transport is crucial for agricultural productivity. Extreme temperatures affect root architecture, influencing elongation, branching patterns and development. Root architecture determines nutrient acquisition, as root configuration regulates nutrient uptake efficiency (5). Root system size and branching determine soil exploration and nutrient absorption (43). Plants adapt their root architecture to nutrient availability, increasing branching in nutrient-rich areas. However, the relationship between root architecture and nutrient acquisition is complex. While several studies report improved nutrient uptake associated with specific root traits, others indicate limited or context-dependent effects (43). Nutrient uptake depends on root structure and soil nutrient availability (44). Root elongation rates vary with soil temperature, showing optimal growth within specific ranges. Soybean root elongation increases up to 30 °C but reduces with soil resistance (45). White oak root growth relates to soil temperature, while cold temperatures reduce root development in alpine plants (46, 47). Low temperatures induce smaller angles between primary and lateral roots (48). In maize, oligosaccharides mitigate cold stress effects on root elongation (49). Strigolactones promote root elongation under temperature stress in tall fescue (50). Low temperatures influence soil nitrogen forms, inactivating nitrifying bacteria and increasing the $\text{NH}_4^+/\text{NO}_3^-$ ratio (51). Low temperatures reduce NH_4^+ uptake via HATS (52, 53). In *Lens culinaris*, heat stress at 37 °C decreased zinc (Zn) and iron (Fe) concentrations (54). Low temperatures impair micronutrient uptake by reducing transporter expression, as shown in *Arabidopsis thaliana* L. through downregulation of AtNRAMP1 involved in manganese uptake (55).

Toxicity stress

Toxic stress arising from acidic soils and metal contamination poses a significant challenge to mineral nutrient acquisition by disrupting root function and nutrient homeostasis. Acidic conditions affect root development and disrupt nutrient homeostasis. In soybeans, low pH inhibits root elongation and alters essential mineral nutrient distribution across tissues. The concentrations of phosphorus (P), molybdenum (Mo), nitrogen (N), potassium (K) and magnesium (Mg) diminish, while calcium (Ca), sulfur (S) and iron (Fe) increase. These changes are accompanied by downregulation of mineral nutrient transport genes, indicating that acidity stress impedes nutrient uptake at biochemical and transcriptional levels (6). Aluminium (Al) toxicity, prevalent in acid soils, leads to reduced P and Mg concentrations in red clover, while K, Zn and Mn levels increase. The degree of nutrient imbalance correlates with Al resistance, as tolerant cultivars maintain stable nutrient profiles compared to sensitive genotypes, suggesting nutrient regulation as a potential Al tolerance mechanism (7). Heavy metals, including cadmium (Cd) and zinc (Zn), disrupt nutrient uptake and transport. In Scots pine seedlings, Zn toxicity impairs Fe translocation and induces Mn deficiency in roots (56). Cd exposure prevents key nutrient absorption and induces growth retardation and oxidative stress in most crops (9). These processes involve disruption of ion channels, competitive inhibition in transport sites and impairment of nutrient carriers (57). Fluoride and arsenic toxicity also affect nutrient acquisition. Fluoride replaces vital enzyme cofactors, including Ca^{2+} and Mg^{2+} , causing membrane malfunction and restricted nutrient transport. Arsenic interferes with phosphate ions due to structural similarity, blocking phosphorus absorption and reducing seedling growth and biomass retention (58). A summary of nutrient acquisition as affected by abiotic stress is presented in Table 2.

Adaptive mechanisms

Root architecture modification

Plants modify root architecture in response to abiotic stresses through coordinated interactions among phytohormones, soil microbes and environmental signals to optimise resource acquisition. Understanding these mechanisms is crucial for developing strategies to improve crop resilience under changing climatic conditions (59). Modification of root length represents a key adaptive mechanism that enhances nutrient acquisition under stress through interactions among genetic factors, environmental cues and hormonal regulation. Plant hormones, particularly auxin and cytokinin, regulate root growth under stress (60). Strigolactones (SLs) contribute to root architecture modification under nutrient-deficient conditions by promoting root development and facilitating

symbiosis with arbuscular mycorrhizal fungi (61). The interplay between these hormones and other phytohormones helps plants adapt to various abiotic stresses (61). Root cortical senescence (RCS) in Triticeae enhances plant growth under suboptimal nutrient conditions by reducing nutrient requirements, decreasing cortical respiration and increasing carbon reserves (62). Plants further adapt to abiotic stress by increasing root surface area through enhanced lateral branching, allowing exploration of new soil zones for nutrient acquisition (63).

Membrane transporters and channels

Membrane transporters and channels are crucial in plant responses to abiotic stress, particularly in mineral nutrient acquisition. These proteins maintain cellular homeostasis by regulating nutrient and water uptake across cellular membranes (64). Plants regulate transporter protein expression in response to abiotic stresses, including nutrient shortage, drought, salinity and low temperature. Macronutrient deficiency primarily activates plasma membrane transporters, whereas micronutrient deficiency often induces tonoplast transporter activity and is associated with reduced aquaporin expression (64). In stress-tolerant genotypes, low temperatures, salinity and drought are associated with increased expression of nutrient transporters and aquaporins (65). Plant ion transport regulation involves complex signalling pathways, including abscisic acid (ABA) and calcium (Ca^{2+}) signalling cascades. These pathways regulate protein kinases and phosphatases that guide ion transport activity in response to environmental stimuli (66). The calcineurin B-like (CBL) and CBL-interacting protein kinase (CIPK) signalling pathway is significant in fine-tuning plant responses to abiotic stresses by regulating ion channels and transporters (67). Understanding these transport systems and their signalling networks is crucial for developing strategies to improve crop tolerance to abiotic stresses and enhance sustainable agricultural production under unfavourable conditions (68).

Hormonal crosstalk

Hormonal crosstalk is vital in plant responses to abiotic stress and nutrient acquisition. Phytohormones interact in complex pathways to regulate growth, development and stress tolerance. Strigolactones (SLs), carotenoid-derived molecules, interact with auxin, abscisic acid, cytokinin and gibberellins to regulate stress adaptation. Under nutrient deficiency, plants increase SL production, modifying root architecture and enhancing symbiosis with arbuscular mycorrhizal fungi, improving nutrient uptake (61). External SL analogue GR24 may enhance abiotic stress tolerance. Nitrogen application mitigates salinity stress by stabilising membranes, improving plant water relations, enhancing leaf gas

Table 2. Effect of abiotic stresses on nutrient acquisition and uptake in plants

Nutrient	Abiotic stress	Acquisition constraint	Adaptive uptake response
Nitrogen(N)	Drought, Salinity	Reduced mass flow and root activity	Upregulation of NRTs and enhanced N remobilisation
Phosphorus (P)	Drought, Acidity	Reduced diffusion and P fixation	Altered root architecture, increased PHT expression
Potassium (K)	Salinity, Drought	Ionic competition (Na^+ vs K^+)	Selective K^+ uptake via HKTs
Calcium (Ca)	Salinity	Reduced Ca^{2+} availability in the rhizosphere	Enhanced Ca^{2+} transport and signalling
Magnesium (Mg)	Drought	Limited soil solution mobility	Improved root foraging efficiency
Zinc (Zn)	Drought, Salinity	Reduced solubility and diffusion	Increased ZIP transporter expression
Iron (Fe)	Alkalinity, Flooding	Reduced Fe^{3+} solubility	Activation of chelation and reduction strategies
Manganese (Mn)	Flooding	Redox imbalance affecting availability	Redox-regulated transporter activity
Boron (B)	Drought	Reduced transpiration-driven uptake	Aquaporin-mediated transport
Copper (Cu)	Metal stress	Competitive inhibition	Regulated ZIP/COPT transporters

exchange and reducing oxidative damage, thereby contributing to salt tolerance. Crosstalk between nitric oxide (NO) and salicylic acid (SA), involving signalling molecules and regulatory factors, modulates plant function during stress (69). Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with roots, enhancing phosphorus, water and mineral uptake (70). AMF colonisation also modulates antioxidant defence, osmotic adjustment and hormonal regulation, promoting plant performance under stress (70).

ROS and antioxidant systems

Reactive oxygen species (ROS) act as both toxic byproducts and signalling molecules in plants, including in abiotic stress responses (71). Under normal conditions, a balance exists between ROS generation and elimination. However, abiotic stresses can disrupt this balance, causing excessive ROS production and cellular damage (72). The antioxidant defence system comprises enzymatic and non-enzymatic components that scavenge ROS and mitigate their harmful effects (73). Key enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX) and glutathione reductase (GR), while non-enzymatic antioxidants include ascorbic acid, glutathione and carotenoids (72). The Ascorbate-Glutathione (AsA-GSH) pathway aids in ROS detoxification and interacts with other defence mechanisms to help plants resist abiotic stress damage (73). Increased ascorbate levels have been shown to alleviate various abiotic stresses in crop plants (74). In addition, cerium oxide nanoparticles have been reported to enhance plant growth and mitigate abiotic stress through modulation of stress signalling cascades and ROS scavenging (75). These findings suggest that increasing plant antioxidant capacity may improve mineral nutrient uptake by promoting plant health and stress tolerance.

Nutrient-specific adaptation strategies

Nitrogen

Plants have evolved sophisticated regulatory systems to cope with abiotic stress while maintaining nitrogen uptake, which is essential for growth and productivity. One mechanism involves fungal symbiosis, wherein endophytic fungi (EFs) enhance stress tolerance and nutrient uptake by modulating plant hormones, stimulating osmolyte synthesis and activating stress-related enzymes (76). Additionally, nitrate transporters, such as MdNRT1.1 in apple plants, are essential for nitrate uptake, although research indicates that overexpression may result in trade-offs, including reduced tolerance to abiotic stresses like drought and salinity (77). When analysing these transporters, it is necessary to consider autophagy in plants, especially regarding root development under N deficiency. Autophagy-related genes such as MdATG10 in apple plants promote root growth and nitrogen assimilation, mitigating nitrogen starvation (78). Ethylene has been identified as a modulator of root plasticity, critical for plants to adapt to environmental stress and enhance nitrogen uptake under adverse conditions (79). Brassinosteroids (BRs) regulate key stress-response pathways and have been shown to enhance nitrogen uptake and utilisation under abiotic stress conditions (80). In leguminous plants, symbiotic relationships with N-fixing bacteria are vital under salinity stress, facilitating N fixation, maintaining ion homeostasis and reducing oxidative stress (81). These adaptive strategies underscore plants' resilience, enabling them to optimise nitrogen uptake under challenging environmental conditions.

Phosphorus

Plants employ coordinated mechanisms of organic acid exudation, acid phosphatase activity and PHT transporter gene expression to enhance P acquisition under abiotic stress. These mechanisms mobilise P in the rhizosphere and facilitate uptake and translocation within the plant. Organic acid exudation, mainly citrate and malate, enhances inorganic P solubility in the rhizosphere for plant uptake (82). Under P deficiency, plants like white lupin increase the expression of genes involved in organic acid metabolism and exudation from proteoid roots (83). In elephantgrass, P deficiency induces pentanedioic acid exudation, which has high P-mobilising activity (84). Acid phosphatase activity helps plants utilise organic P from soil. Lupin roots secrete acid phosphatase, detected up to 2.5 mm from the root surface, leading to organic P depletion in the rhizosphere (85). The expression of acid phosphatase genes, such as LePS2, is induced under P starvation conditions (86). PHT transporter genes, particularly members of the PHT1 family, are crucial for high-affinity phosphate uptake and translocation. Under P deficiency and salinity stress, PHT gene expression is upregulated in roots (87). PHT1 family genes are important for high-affinity P uptake and activate rapidly to P availability changes (88). Silicon application enhances P uptake by upregulating PHT1 gene expression and stimulating organic acid exudation (82).

Potassium

The maintenance of the K^+/Na^+ ratio is crucial for plant salt tolerance under abiotic stress conditions. HKT and AKT transporters play key roles in potassium acquisition and sodium exclusion under such stresses. HKT transporters are involved in Na^+ and K^+ transport, with members showing varying selectivity. TsHKT1;2 from *Thellungiella salsuginea* exhibits strong K^+ transporter activity and selectivity for K^+ over Na^+ , contributing to salt tolerance (88). In barley, HvHKT1;5 is associated with higher K^+ and lower Na^+ concentrations in shoots under salt stress, improving Na^+ exclusion (89). Rice HKT transporters show diverse permeation modes, including Na^+-K^+ symport and Na^+ uniport, depending on external ion concentrations (90). AKT1, a Shaker-like potassium channel, is regulated by AtKC1 in Arabidopsis. AtKC1 negatively regulates AKT1-mediated K^+ uptake in roots under low K^+ stress conditions (91). The HAK/KUP/KT transporter family also plays crucial roles in high-affinity K^+ uptake and redistribution under abiotic stress conditions (92). Maintenance of an optimal K^+/Na^+ ratio depends on coordinated interactions among multiple transporter systems. HKT transporters contribute to Na^+ exclusion and K^+ uptake, while AKT and HAK/KUP/KT transporters focus on K^+ acquisition. These transporters' diverse functions highlight their importance in plant adaptation to abiotic stresses and crop improvement.

Iron

Iron acquisition strategies in plants can be classified into two main types: Strategy I and Strategy II. Strategy II, found in graminaceous monocotyledonous plants, involves the production of phytosiderophores called mugineic acids. These plants effectively regulate iron acquisition through biosynthesis, secretion, solubilization and uptake of mugineic acids (93). Strategy I, used by dicotyledonous and nongraminaceous monocotyledonous plants, relies on different mechanisms for iron uptake. Siderophores, including those produced by plants and microorganisms, play a crucial role in iron acquisition under abiotic stress conditions.

These low molecular mass organic compounds chelate ferric iron [Fe(III)] from various terrestrial and aquatic habitats, making it available for microbial and plant cells (94). Siderophores are particularly important in environments where iron availability is limited, such as calcareous soils with high pH and high concentrations of bicarbonate, Ca²⁺ and Mg²⁺ (93). By chelating ferric iron [Fe(III)], siderophores enhance iron bioavailability in high-pH and nutrient-deficient soils, as demonstrated by studies documenting improved iron nutrition through microbial siderophore activity under calcareous conditions (95).

Conclusion

The acquisition and management of mineral nutrients by plants is essential for growth, development and stress tolerance. Plants have developed sophisticated systems for detecting soil nutrient availability and modifying root growth patterns to optimise nutrient acquisition. Transporters in root cell membranes facilitate specific nutrient uptake and are tightly regulated by plant nutrient status. Nutrients are distributed via xylem and phloem transport systems, with signalling networks coordinating allocation. Under stress conditions like drought and salinity, plants employ adaptations to maintain nutrient homeostasis. The interplay between hormonal signalling pathways regulates plant growth and nutrient uptake. Recent advances in imaging and molecular techniques have enhanced nutrient acquisition research. High-throughput phenotyping enables the assessment of nutrient-related traits, while imaging methods visualise nutrient distribution. Integrated molecular-omics approaches provide detailed insights into nutrient sensing, signalling and utilisation pathways. By leveraging current mechanistic understanding and emerging technologies, it is possible to develop resilient crop varieties that support long-term food security. Continued interdisciplinary research will be critical for advancing knowledge and promoting sustainable agricultural practices under changing environmental conditions.

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Authors' contributions

NAB contributed to the drafting and writing of the manuscript, as well as a comprehensive literature review. DDB contributed to conceptualisation, drafting, supervision, manuscript editing and critical revision of content. RKS contributed to drafting the manuscript, provided critical revisions, final manuscript review and editing process. SJ contributed to revisions to the manuscript, refining the content for clarity. AS contributed to the organisation of the content and revision of the manuscript; CC contributed to the literature review and graphical abstract. MA contributed to the literature research and revised the manuscript as per the journal's style. SK contributed to manuscript review, ensuring technical accuracy and consistency across sections. AKP contributed to the literature review and revision of the manuscript. BKD contributed to the manuscript review and editing process. All authors read and approved the final manuscript.

Compliance with ethical standards

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References

1. Ministry of Agriculture & Farmers Welfare. Impact of climate change on agriculture. New Delhi: Press Information Bureau (PIB).
2. Wang L, Ju C, Han C, Yu Z, Bai MY, Wang C, et al. The interaction of nutrient uptake with biotic and abiotic stresses in plants. *J Integr Plant Biol.* 2025;67:455–87. <https://doi.org/10.1111/jipb.13827>
3. Daszkowska-Golec A, Szarejko I. Open or close the gate-stomata action under the control of phytohormones in drought stress conditions. *Front Plant Sci.* 2013;4:138. <https://doi.org/10.3389/fpls.2013.00138>
4. Nxele X, Klein A, Ndimba BK. Drought and salinity stress alters ROS accumulation, water retention and osmolyte content in sorghum plants. *S African J Bot.* 2017;108:261–6. <https://doi.org/10.1016/j.sajb.2016.11.003>
5. Wang Z, Guo D, Wang X, Gu J, Mei L. Fine root architecture, morphology and biomass of different branch orders of two Chinese temperate tree species. *Plant Soil.* 2006;288:155–71. <https://doi.org/10.1007/s11104-006-9101-8>
6. Chen Q, Zhao T, Liang C, Wu W, Tian J, Tan W. Complex gene regulation underlying mineral nutrient homeostasis in *Glycine max* root response to acidity stress. *Genes.* 2019;10:402. <https://doi.org/10.3390/genes10050402>
7. Yang Q, Lin Y, Liu Q, Ren X, Jin L, He C. Responses of mineral nutrient contents and transport in red clover under aluminum stress. *Legume Sci.* 2021;3:e94. <https://doi.org/10.1002/leg3.94>
8. Naik BV, Ahmad MA, Jangde S, Sanodiya P, Ray M, Reddy KM, et al. Effects of foliar application of salicylic acid on morphological, biochemical and yield attributes of maize (*Zea mays* L.) under rainfed condition. *Bangladesh J Bot.* 2024;53:273–8. <https://doi.org/10.3329/bjb.v53i2.74046>
9. Umair Hassan M, Yang B, Haider FU, Iqbal MM, Noor MA, Khan TA, et al. Application of zinc oxide nanoparticles to mitigate cadmium toxicity: mechanisms and future prospects. *Plants.* 2024;13:1706. <https://doi.org/10.3390/plants13121706>
10. Mahajan G, Wenham K, Chauhan BS. Mungbean (*Vigna radiata*) growth and yield response in relation to water stress and elevated day/night temperature conditions. *Agron.* 2023;13:2546. <https://doi.org/10.3390/agronomy13102546>
11. Chanu WS, Sarangthem K. Water stress response on morpho-physiology, biochemical parameters and yield of four different rice cultivars of Manipur. *Vegetos.* 2024;37:186–91. <https://doi.org/10.1007/s42535-023-00580-x>
12. Zaferanieh M, Mahdavi B. Effect of water stress on morphological traits, mucilage percentage and yield of *Alyssum homolocarpum*. *Desert.* 2021;26:99–113.
13. Zheng J, Wang S, Wang R, Chen Y, Siddique KH, Xia G, et al. Ameliorative roles of biochar-based fertilizer on morpho-physiological traits, nutrient uptake and yield in peanut (*Arachis*

- hypogaea* L.) under water stress. *Agric Water Manag.* 2021;257:107129. <https://doi.org/10.1016/j.agwat.2021.107129>
14. Khan I, Muhammad A, Chattha MU, Skalicky M, Chattha MB, Ayub MA, et al. Mitigation of salinity-induced oxidative damage, growth and yield reduction in fine rice by sugarcane press mud application. *Front Plant Sci.* 2022;13:840900. <https://doi.org/10.3389/fpls.2022.840900>
 15. Zhang R, Wang Y, Hussain S, Yang S, Li R, Liu S, et al. Study on the effect of salt stress on yield and grain quality among different rice varieties. *Front Plant Sci.* 2022;13:918460. <https://doi.org/10.3389/fpls.2022.918460>
 16. El-Beltagi HS, Ahmad I, Basit A, Shehata WF, Hassan U, Shah ST, et al. Ascorbic acid enhances growth and yield of sweet peppers (*Capsicum annuum*) by mitigating salinity stress. *Gesunde Pflanzen.* 2022;74:423–33. <https://doi.org/10.1007/s10343-021-00619-6>
 17. Zahedi SM, Abdelrahman M, Hosseini MS, Hoveizeh NF, Tran LSP. Alleviation of the effect of salinity on growth and yield of strawberry by foliar spray of selenium-nanoparticles. *Environ Pollut.* 2019;253:246–58. <https://doi.org/10.1016/j.envpol.2019.04.078>
 18. Riaz MW, Yang L, Yousaf MI, Sami A, Mei XD, Shah L, et al. Effects of heat stress on growth, physiology of plants, yield and grain quality of different spring wheat (*Triticum aestivum* L.) genotypes. *Sustainability.* 2021;13:2972. <https://doi.org/10.3390/su13052972>
 19. Hussain HA, Men S, Hussain S, Chen Y, Ali S, Zhang S, et al. Interactive effects of drought and heat stresses on morpho-physiological attributes, yield, nutrient uptake and oxidative status in maize hybrids. *Sci Rep.* 2019;9:3890. <https://doi.org/10.1038/s41598-019-40362-7>
 20. Shi Y, Guo E, Cheng X, Wang L, Jiang S, Yang X, et al. Effects of chilling at different growth stages on rice photosynthesis, plant growth and yield. *Environ Exp Bot.* 2022;203:105045. <https://doi.org/10.1016/j.envexpbot.2022.105045>
 21. Barber SA. A diffusion and mass-flow concept of soil nutrient availability. *J Soil Sci.* 1962;93:39–49. <https://doi.org/10.1097/00010694-196201000-00007>
 22. Lagerwerff JV. The contact-exchange theory amended. *Plant Soil.* 1960;13:253–64. <https://doi.org/10.1007/BF01677506>
 23. Gloser V, Dvorackova M, Mota DH, Petrovic B, Gonzalez P, Geilfus CM. Early changes in nitrate uptake and assimilation under drought in relation to transpiration. *Front Plant Sci.* 2020;11:602065. <https://doi.org/10.3389/fpls.2020.602065>
 24. Tsukagoshi S, Shinohara Y. Nutrition and nutrient uptake in soilless culture systems. *Plant Fact.* 2020;221–9. <https://doi.org/10.1016/B978-0-12-816691-8.00014-5>
 25. Laxmi S, Chanu PH, Rani P, Rai S, Prasad SK, Singh RK. Effect of hydrogel on soil moisture stress. *J Pharmacogn Phytochem.* 2019;8:316–20.
 26. Pirasteh-Anosheh H, Saed-Moucheshi A, Pakniyat H, Pessarakli M. Stomatal responses to drought stress. In: Ahmad P, editor. *Water stress and crop plants: a sustainable approach.* New York: John Wiley & Sons; 2016. p. 24–40. <https://doi.org/10.1002/9781119054450.ch3>
 27. Shivaraj SM, Sharma Y, Chaudhary J, Rajora N, Sharma S, Thakral V, et al. Dynamic role of aquaporin transport system under drought stress in plants. *Environ Exp Bot.* 2021;184:104367. <https://doi.org/10.1016/j.envexpbot.2020.104367>
 28. Ding L, Gao C, Li Y, Li Y, Zhu Y, Xu G, et al. The enhanced drought tolerance of rice plants under ammonium is related to aquaporin (AQP). *Plant Sci.* 2015;234:14–21. <https://doi.org/10.1016/j.plantsci.2015.01.016>
 29. Wang WH, Köhler B, Cao FQ, Liu GW, Gong YY, Sheng S, et al. Rice DUR3 mediates high-affinity urea transport and plays an effective role in improvement of urea acquisition and utilization when expressed in *Arabidopsis*. *New Phytol.* 2012;193:432–44. <https://doi.org/10.1111/j.1469-8137.2011.03929.x>
 30. Goel P, Singh AK. Abiotic stresses downregulate key genes involved in nitrogen uptake and assimilation in *Brassica juncea* L. *PLoS One.* 2015;10:e0143645. <https://doi.org/10.1371/journal.pone.0143645>
 31. Liu HY, Sun WN, Su WA, Tang ZC. Co-regulation of water channels and potassium channels in rice. *Physiol Plant.* 2006;128:58–69. <https://doi.org/10.1111/j.1399-3054.2006.00709.x>
 32. Rhoades JD. Salinity: electrical conductivity and total dissolved solids. *SSSA Methods of Soil Analysis, Part 3 Chemical Methods.* 1996;5:417–35. <https://doi.org/10.2136/sssabookser5.3.c14>
 33. Ehtaiwesh AF. The effect of salinity on nutrient availability and uptake in crop plants. *Sci J Appl Sci Sabratha Univ.* 2022;55–73.
 34. Arif Y, Singh P, Siddiqui H, Bajguz A, Hayat S. Salinity induced physiological and biochemical changes in plants: an omic approach towards salt stress tolerance. *Plant Physiol Biochem.* 2020;156:64–77. <https://doi.org/10.1016/j.plaphy.2020.08.042>
 35. Singh A, Rajput VD, Sharma R, Ghazaryan K, Minkina T. Salinity stress and nanoparticles: insights into antioxidative enzymatic resistance, signaling and defense mechanisms. *Environ Res.* 2023;116585. <https://doi.org/10.1016/j.envres.2023.116585>
 36. Zhou H, Shi H, Yang Y, Feng X, Chen X, Xiao F, et al. Insights into plant salt stress signaling and tolerance. *J Genet Genomics.* 2023;51:16–34. <https://doi.org/10.1016/j.jgg.2023.08.007>
 37. Nouri H, Borujeni SC, Nirola R, Hassanli A, Beecham S, Alaghmand S, et al. Application of green remediation on soil salinity treatment: a review on halophytoremediation. *Process Saf Environ Prot.* 2017;107:94–107. <https://doi.org/10.1016/j.psep.2017.01.021>
 38. Yadav SP, Bharadwaj R, Nayak H, Mahto R, Singh RK, Prasad SK. Impact of salt stress on growth, productivity and physicochemical properties of plants: a review. *Int J Chem Stud.* 2019;7:1793–8.
 39. Gleadow R, Pegg A, Blomstedt CK. Resilience of cassava (*Manihot esculenta* Crantz) to salinity: implications for food security in low-lying regions. *J Exp Bot.* 2016;67:5403–13. <https://doi.org/10.1093/jxb/erw302>
 40. Hatfield JL, Prueger JH. Temperature extremes: effect on plant growth and development. *Weather Clim Extrem.* 2015;10:4–10. <https://doi.org/10.1016/j.wace.2015.08.001>
 41. Abbas S. Climate change and major crop production: evidence from Pakistan. *Environ Sci Pollut Res Int.* 2022;29:5406–14. <https://doi.org/10.1007/s11356-021-16041-4>
 42. Chaubey RK, Bhutia DD, Navathe S, Mishra VK, Singh AK, Chand R. Interrelationships among different grain characteristics of wheat grown under optimum and late sowing date conditions in the Eastern Indo-Gangetic plains of India. *Cereal Res Commun.* 2021;49:449–55. <https://doi.org/10.1007/s42976-020-00123-z>
 43. Bar-Tal A, Ganmore-Neumann R, Ben-Hayyim G. Root architecture effects on nutrient uptake. In: Altman A, Waisel Y, editors: *Biology of root formation and development.* Boston, MA: Springer US; 1997. p. 39–45. https://doi.org/10.1007/978-1-4615-5403-5_5
 44. Dunbabin V, Rengel Z, Diggle AJ. Simulating form and function of root systems: efficiency of nitrate uptake is dependent on root system architecture and the spatial and temporal variability of nitrate supply. *Funct Ecol.* 2004;18:204–11. <https://doi.org/10.1111/j.0269-8463.2004.00827.x>
 45. Moraes MTD, Gusmão AG. How do water, compaction and heat stresses affect soybean root elongation? A review. *Rhizosphere.* 2021;19:100403. <https://doi.org/10.1016/j.rhisph.2021.100403>
 46. Teskey RO, Hinckley TM. Influence of temperature and water potential on root growth of white oak. *Physiol Plant.* 1981;52:363–9. <https://doi.org/10.1111/j.1399-3054.1981.tb06055.x>
 47. Sebastian N, Christian K, Erika H. Critically low soil temperatures for root growth and root morphology in three alpine plant species. *Alp Bot.* 2015;126:11–21. <https://doi.org/10.1007/s00035-015-0153-3>
 48. Nagel KA, Kastenholz B, Jahnke S, Truhn D, Walter A, Van

- Dusschoten D, et al. Temperature responses of roots: impact on growth, root system architecture and implications for phenotyping. *Funct Plant Biol.* 2009;36:947. <https://doi.org/10.1071/FP09184>
49. Kollárová K, Kamenická V, Vatehová Z, Lišková D. Impact of galactoglucomannan oligosaccharides and Cd stress on maize root growth parameters, morphology and structure. *J Plant Physiol.* 2018;222:59–66. <https://doi.org/10.1016/j.jplph.2017.12.017>
 50. Hu Q, Zhang S, Huang B. Strigolactones and interaction with auxin regulating root elongation in tall fescue under different temperature regimes. *Plant Sci.* 2018;271:34–9. <https://doi.org/10.1016/j.plantsci.2018.03.008>
 51. Yuan J, Dong W, Sun F, Zhao K. Low temperature effects on nitrification and nitrifier community structure in V-ASP for decentralized wastewater treatment and its improvement by bio-augmentation. *Environ Sci Pollut Res.* 2018;25:6584–95. <https://doi.org/10.1007/s11356-017-0927-9>
 52. Wang MY, Siddiqi MY, Ruth TJ, Glass AD. Ammonium uptake by rice roots (II. Kinetics of $^{13}\text{NH}_4^+$ influx across the plasmalemma). *Plant Physiol.* 1993;103:1259–67. <https://doi.org/10.1104/pp.103.4.1259>
 53. Warren CR. Why does temperature affect relative uptake rates of nitrate, ammonium and glycine: a test with *Eucalyptus pauciflora*. *Soil Biol Biochem.* 2009;41:778–84. <https://doi.org/10.1016/j.soilbio.2009.01.012>
 54. El Haddad N, Sanchez-Garcia M, Visioni A, Jilal A, El Amil R, Sall AT, et al. Crop wild relatives crosses: multi-location assessment in durum wheat, barley and lentil. *Agron J.* 2021;11:2283. <https://doi.org/10.3390/agronomy11112283>
 55. Ichnatowicz A, Siwinska J, Meharg AA, Carey M, Koornneef M, Reymond M. Conserved histidine of metal transporter AtNRAMP1 is crucial for optimal plant growth under manganese deficiency at chilling temperatures. *New Phytol.* 2014;202:1173–83. <https://doi.org/10.1111/nph.12737>
 56. Ivanov YV, Kuznetsov VV, Kartashov AV, Ivanov AI. Phytotoxicity of short-term exposure to excess zinc or copper in Scots pine seedlings in relation to growth, water status, nutrient balance and antioxidative activity. *Environ Sci Pollut Res Int.* 2020;28:14828–43. <https://doi.org/10.1007/s11356-020-11723-x>
 57. Siecińska J, Nosalewicz A. Aluminium toxicity to plants as influenced by the properties of the root growth environment affected by other co-stressors: a review. *Rev Environ Contam Toxicol.* 2016;243:1–26. https://doi.org/10.1007/398_2016_15
 58. Choudhary S, Rani M, Devika OS, Patra A, Singh RK, Prasad SK. Impact of fluoride on agriculture: a review on its sources, toxicity in plants and mitigation strategies. *Int J Chem Stud.* 2019;7:1675–80.
 59. Ye JY, Tian WH, Jin CW. Nitrogen in plants: from nutrition to the modulation of abiotic stress adaptation. *Stress Biol.* 2022;2. <https://doi.org/10.1007/s44154-021-00030-1>
 60. Meng F, Zhu J, Mao C, Xiang D, Li Y. Molecular mechanisms of root development in rice. *Rice.* 2019;12:1. <https://doi.org/10.1186/s12284-018-0262-x>
 61. Bhoi A, Yadu B, Chandra J, Keshavkant S. Contribution of strigolactone in plant physiology, hormonal interaction and abiotic stresses. *Planta.* 2021;254:1. <https://doi.org/10.1007/s00425-021-03678-1>
 62. Schneider HM, Postma JA, Kuppe C, Wojciechowski T, Lynch JP. Root cortical senescence improves growth under suboptimal availability of N, P and K. *Plant Physiol.* 2017;174:2333–47. <https://doi.org/10.1104/pp.17.00648>
 63. Nibau C, Coates JC, Gibbs DJ. Branching out in new directions: the control of root architecture by lateral root formation. *New Phytol.* 2008;179:595–614. <https://doi.org/10.1111/j.1469-8137.2008.02472.x>
 64. Barzana G, Rios JJ, Lopez-Zaplana A, Nicolas-Espinosa J, Yepes-Molina L, Garcia-Ibañez P, Carvajal M. Interrelations of nutrient and water transporters in plants under abiotic stress. *Physiol Plant.* 2020;171:595–619. <https://doi.org/10.1111/ppl.13206>
 65. Vishwakarma K, Mishra M, Patil G, Mulkey S, Ramawat N, Pratap Singh V, et al. Avenues of the membrane transport system in adaptation of plants to abiotic stresses. *Crit Rev Biotech.* 2019;39:861–83. <https://doi.org/10.1080/07388551.2019.1616669>
 66. Liu J, Niu Y, Zhou Y, Zhang J, Ma Z, Huang X. Ca^{2+} channels and Ca^{2+} signals involved in abiotic stress responses in plant cells: recent advances. *PCTOC.* 2017;132:413–24. <https://doi.org/10.1007/s11240-017-1350-0>
 67. Manik SN, Shi S, Mao J, Dong L, Su Y, Wang Q, et al. The calcium sensor CBL-CIPK is involved in plants' response to abiotic stresses. *Int J Genomics.* 2015;8:1–10. <https://doi.org/10.1155/2015/493191>
 68. Gong Z, Qin F, Xiong L, Yang Y, Guo Y, Xu G, et al. Plant abiotic stress response and nutrient use efficiency. *Sci China Life Sci.* 2020;63:635–74. <https://doi.org/10.1007/s11427-020-1683-x>
 69. Prakash V, Singh VP, Tripathi DK, Sharma S, Corpas FJ. Nitric oxide (NO) and salicylic acid (SA): A framework for their relationship in plant development under abiotic stress. *Plant Biol.* 2021;23:39–49. <https://doi.org/10.1111/plb.13246>
 70. Wahab A, Muhammad M, Ayaz A, Zaman W, Khizar C, Reddy SP, et al. Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity and potentially influencing ecosystems under abiotic and biotic stresses. *Plants.* 2023;12:3102. <https://doi.org/10.3390/plants12173102>
 71. Mansoor S, Ahmad P, Ali Wani O, Lone JK, Ahmad A, Alam P, et al. Reactive oxygen species in plants: from source to sink. *Antioxidants.* 2022;11:225. <https://doi.org/10.3390/antiox11020225>
 72. Garcia-Caparrós P, De Filippis L, Gul A, Hasanuzzaman M, Ozturk M, Altay V, et al. Oxidative stress and antioxidant metabolism under adverse environmental conditions: a review. *Bot Rev.* 2020;87:421–66. <https://doi.org/10.1007/s12229-020-09231-1>
 73. Hasanuzzaman M, Bhuyan MB, Anee TI, Parvin K, Nahar K, Mahmud JA, et al. Regulation of ascorbate-glutathione pathway in mitigating oxidative damage in plants under abiotic stress. *Antioxidants.* 2019;8:384. <https://doi.org/10.3390/antiox8090384>
 74. Venkatesh J, Park SW. Role of L-ascorbate in alleviating abiotic stresses in crop plants. *Bot Stud.* 2014;55:38. <https://doi.org/10.1186/1999-3110-55-38>
 75. Preetha JSY, Sriram D, Premasudha P, Pudake RN, Arun M. Cerium oxide as a nanozyme for plant abiotic stress tolerance: an overview of the mechanisms. *Plant Nano Biol.* 2023;6:100049. <https://doi.org/10.1016/j.plana.2023.100049>
 76. Morales-Vargas AT, López-Ramírez V, Álvarez-Mejía C, Vázquez-Martínez J. Endophytic fungi for crops adaptation to abiotic stresses. *Microorganisms.* 2024;12:1357. <https://doi.org/10.3390/microorganisms12071357>
 77. Liu G, Rui L, Yang Y, Liu R, Li H, Ye F, et al. Identification and functional characterization of MdNRT1.1 in nitrogen utilization and abiotic stress tolerance in *Malus domestica*. *Int J Mol Sci.* 2023;24:9291. <https://doi.org/10.3390/ijms24119291>
 78. Huo L, Guo Z, Wang Q, Cheng L, Jia X, Wang P, et al. Enhanced autophagic activity improved the root growth and nitrogen utilization ability of apple plants under nitrogen starvation. *Int J Mol Sci.* 2021;22:8085. <https://doi.org/10.3390/ijms22158085>
 79. Qin H, Huang R, Xiao M, Li Y. Ethylene modulates rice root plasticity under abiotic stresses. *Plants.* 2024;13:432. <https://doi.org/10.3390/plants13030432>
 80. Miao R, Li C, Liu Z, Zhou X, Chen S, Zhang D, et al. The role of endogenous brassinosteroids in the mechanisms regulating plant reactions to various abiotic stresses. *Agron.* 2024;14:356. <https://doi.org/10.3390/agronomy14020356>
 81. Wang Y, Wu Y, Hu T, Zhang P, Zhou Y, Yang P. A proteomic approach to understand the impact of nodulation on salinity

- stress response in alfalfa (*Medicago sativa* L.). *Plant Biol.* 2021;24:323–32. <https://doi.org/10.1111/plb.13369>
82. Kostic L, Nikolic M, Samardzic J, Nikolic N, Bosnic D. Silicon increases phosphorus (P) uptake by wheat under low P acid soil conditions. *Plant Soil.* 2017;419:447–55. <https://doi.org/10.1007/s11104-017-3364-0>
 83. Uhde-Stone C, Gilbert G, Johnson JM, Litjens R, Zinn KE, Temple SJ, et al. Acclimation of white lupin to phosphorus deficiency involves enhanced expression of genes related to organic acid metabolism. *Plant Soil.* 2003;248:99–116. <https://doi.org/10.1023/A:1022335519879>
 84. Shen H, Wang X, Shi W, Cao Z, Yan X. Isolation and identification of specific root exudates in elephant grass in response to mobilization of iron- and aluminum-phosphates. *J Plant Nutr.* 2001;24:1117–30. <https://doi.org/10.1081/PLN-100103807>
 85. Li M, Shinano T, Tadano T. Distribution of exudates of lupin roots in the rhizosphere under phosphorus deficient conditions. *J Soil Sci Plant Nutr.* 1997;43:237–45. <https://doi.org/10.1080/00380768.1997.10414731>
 86. Varadarajan DK, Karthikeyan AS, Raghothama KG, Matilda PD. Phosphite, an analog of phosphate, suppresses the coordinated expression of genes under phosphate starvation. *Plant Physiol.* 2002;129:1232–40. <https://doi.org/10.1104/pp.010835>
 87. Murugan N, Palanisamy V, Channappa M, Ramanathan V, Ramaswamy M, Govindakurup H, et al. Genome-wide *in silico* identification, structural analysis, promoter analysis and expression profiling of PHT gene family in sugarcane root under salinity stress. *Sustainability.* 2022;14:15893. <https://doi.org/10.3390/su142315893>
 88. Ali A, Raddatz N, Pardo JM, Yun D. HKT sodium and potassium transporters in *Arabidopsis thaliana* L. and related halophyte species. *Physiol Plant.* 2021;171:546–58. <https://doi.org/10.1111/ppl.13166>
 89. Van Bezouw RF, Janssen EM, Ashrafuzzaman M, Ghahramanzadeh R, Kilian B, Graner A, et al. Shoot sodium exclusion in salt stressed barley (*Hordeum vulgare* L.) is determined by allele specific increased expression of HKT1;5. *J Plant Physiol.* 2019;241:153029. <https://doi.org/10.1016/j.jplph.2019.153029>
 90. Jabnourne M, Espeout S, Mieulet D, Fizames C, Verdeil JL, Conéjéro G, et al. Diversity in expression patterns and functional properties in the rice HKT transporter family. *Plant Physiol.* 2009;150:1955–71. <https://doi.org/10.1104/pp.109.138008>
 91. Wang Y, Wu WH, Xu J, Li HD, He L. Potassium channel α -subunit AtKC1 negatively regulates AKT1-mediated K⁺ uptake in *Arabidopsis* roots under low-K⁺ stress. *Cell Res.* 2010;20:826–37. <https://doi.org/10.1038/cr.2010.74>
 92. Cai XT, Xu P, Zhao PX, Liu R, Yu LH, Xiang CB. *Arabidopsis* ERF109 mediates cross-talk between jasmonic acid and auxin biosynthesis during lateral root formation. *Nat Commun.* 2014;5:5833. <https://doi.org/10.1038/ncomms6833>
 93. Ma JF, Nomoto K. Effective regulation of iron acquisition in graminaceous plants: the role of mugineic acids as phytosiderophores. *Physiol Plant.* 1996;97:609–17. <https://doi.org/10.1111/j.1399-3054.1996.tb00522.x>
 94. Ahmed E, Holmström SJM. Siderophores in environmental research: roles and applications. *Microb Biotech.* 2014;7:196–208. <https://doi.org/10.1111/1751-7915.12117>
 95. Ansari M, Devi BM, Sarkar A, Chattopadhyay A, Satnami L, Balu P, et al. Microbial exudates as biostimulants: role in plant growth promotion and stress mitigation. *J Xenobiot.* 2023;13:572–603. <https://doi.org/10.3390/jox13040037>

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