



REVIEW ARTICLE

Enhancing crop resilience and productivity through optimised nutrient management under abiotic and biotic stresses

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Abstract

Plants continuously encounter a wide range of biotic and abiotic stresses that adversely influence physiological, biochemical and metabolic processes, leading to substantial yield losses worldwide. Abiotic stresses such as drought, salinity, heat, waterlogging and heavy metal toxicity disrupt cellular homeostasis and photosynthetic efficiency, while biotic agents, including pathogens, pests, nematodes and weeds further compromise plant growth and productivity. Nutrient management plays a pivotal role in enhancing plant resilience to these stressors. Balanced application of macronutrients (sodium (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S)), micronutrients like zinc (Zn), iron (Fe), boron (B), copper (Cu)) and beneficial elements such as silicon not only sustains physiological functioning but also activates antioxidant defence systems, osmotic regulation and cellular detoxification mechanisms. Nutrient management, combining chemical fertilisers with organic amendments and microbial inoculants, strengthens root development, improves water and nutrient use efficiency and enhances stress tolerance through synergistic nutrient interactions. This review provides a comprehensive synthesis of current knowledge on the physiological roles of essential nutrients in mitigating plant stresses, evaluates their mechanisms of action and highlights sustainable management strategies that harmonise productivity with environmental stewardship. This review synthesises the integrative role of plant nutrients in reinforcing physiological and biochemical defence mechanisms and highlights future research priorities essential for developing climate-resilient crop production strategies.

Keywords: abiotic stress; biotic stress; crop productivity; nutrient management; plant physiology; stress tolerance

Introduction

Plant stress refers to any unfavourable condition or external factor that disrupts normal plant metabolism, growth and development, often resulting in reduced yield, structural damage, or even plant death under severe conditions. Such stresses are broadly categorised into abiotic and biotic types. Abiotic stresses are caused by non-living environmental factors such as drought, salinity,

extreme temperatures and pollutants including heavy metals, whereas biotic stresses arise from living organisms such as pathogens, parasites and pests (1). Biotic stresses occur due to biological interactions among organisms, whereas abiotic stresses result from interactions between plants and their physical environment.

Abiotic factors that negatively influence plants include water scarcity (drought), excess water (waterlogging), high or low

temperature extremes, soil salinity and mineral toxicity. These factors are major constraints affecting both the quality and quantity of agricultural production worldwide (2). Such stresses often occur simultaneously, leading to similar cellular injuries manifested as osmotic imbalance, ionic toxicity and disruption of cellular homeostasis. The molecular mechanisms underlying plant responses to abiotic stresses are highly complex and multi-layered. They involve stress perception, signal transduction, regulation of gene expression, protein synthesis and post-translational modifications, engaging numerous genes, signalling pathways and metabolic networks (3, 4). Although significant progress has been made in understanding the physiological and molecular responses of plants to individual stress factors, the specific interactions between nutrient dynamics and stress tolerance mechanisms remain insufficiently explored. The influence of essential macro and micronutrients on modulating stress-responsive pathways, enhancing osmotic balance and regulating antioxidant defence is still not clearly defined, particularly under combined or fluctuating stress environments. This knowledge gap limits the development of nutrient-based adaptive strategies and integrated management practices for improving plant resilience and sustaining crop productivity under stress-prone conditions.

Abiotic stress

Drought stress: When the lifeline dries up

Drought, often referred to as the “silent famine”, remains one of the most destructive abiotic stresses globally, driven by erratic rainfall and prolonged dry spells that are increasing under climate changes (5, 6). Across studies, drought consistently reduces crop productivity by impairing water balance, photosynthetic performance and reproductive success. Plants respond by closing stomata to limit transpiration and by modifying root architecture to explore deeper soil layers (7, 8). Additionally, osmo-protectants such as proline and soluble sugars accumulate to maintain cellular hydration and stabilise membranes (9). However, these protective mechanisms are often insufficient to prevent yield loss, as reduced carbon dioxide (CO₂) uptake and inhibited mesophyll conductance drastically lower photosynthetic efficiency (10, 11). Drought-induced yield reduction becomes particularly severe during reproductive stages, causing pollen sterility and floral abortion in cereals and legumes (12–15). Compared with other stresses such as heat and salinity, drought-induced photosynthetic limitations and reproductive impairments emerge as common bottlenecks that strongly determine final yield outcomes, regardless of species.

Salinity stress: The white menace of agriculture

Salinity, the “white plague” of agriculture, threatens nearly one-third of irrigated lands worldwide and is expanding by approximately 10 % annually (16, 17). Unlike drought, where water deficit is the primary constraint, salinity exerts a dual impact, causing both osmotic stress and ionic toxicity due to excessive sodium (Na⁺) and chlorine (Cl⁻) accumulation. These effects disrupt nutrient uptake, leading to deficiencies in essential minerals such as calcium (Ca), magnesium (Mg), zinc (Zn) and iron (Fe) and thereby impairing metabolic homeostasis (18, 19). Yield reductions under salinity vary widely across growth stages and crops; for instance, wheat grain yield declines by 39.1 % at anthesis compared to 13.4 % during mid-grain filling, whereas horticultural crops like cabbage may lose up to 62 % of yield at 8 dS m⁻¹ salinity (20, 21). Comparatively, both drought and salinity trigger osmotic stress and reactive oxygen species (ROS) accumulation, yet salinity uniquely introduces ion

Table 1. Impact of salinity stress on yield performance of different crops

Crops	Yield reduction (%)	References
Rice (<i>Oryza sativa</i>)	30–50	22
Wheat (<i>Triticum aestivum</i>)	10–50	23
Bajra (<i>Pennisetum glaucum</i>)	5–25	23
Maize (<i>Zea mays</i>)	50–60	24
Groundnut (<i>Arachis hypogaea</i>)	25–50	24
Cotton (<i>Gossypium</i> sp.)	10–20	24
Chickpea (<i>Cicer arietinum</i>)	10–30	25
Tomato (<i>Solanum lycopersicum</i>)	7.2–50	26
Potato (<i>Solanum tuberosum</i>)	~ 38.8	27
Iceberg lettuce (<i>Lactuca sativa</i>)	8.26–22.7	28

toxicity and nutrient imbalance, making its physiological consequences more complex and persistent. Table 1 summarises yield losses in key crops under salinity stress.

Heat stress: The rising threat in a warming world

With global temperatures projected to rise by 1.1–6.4 °C by 2100, heat stress represents an escalating threat to crop productivity (29). High temperatures compromise nearly every growth phase from seedling establishment to grain filling by damaging photosynthetic machinery, inhibiting chlorophyll synthesis and accelerating ROS formation (30, 31). Reproductive tissues are highly vulnerable, leading to spikelet sterility, poor pollination and reduced grain set (32). Each 1 °C increase above optimal levels can reduce rice yield by 3.2 % and other crop yields by 2.5–10 %, depending on genotype and environment (33–35). Unlike drought and salinity, where osmotic imbalance is central, heat stress primarily disrupts membrane stability and protein function, yet ROS accumulation emerges as a shared injury mechanism across

Table 2. Heat stress-induced yield reduction across key crop species

Crop	Stress	Yield loss (%)	Reference
Maize	Heat	45	36
Wheat	Heat	31	37
Rice	Heat	50	38
Sorghum	Heat	44	39
Soybean	Heat	46	40
Sunflower	Heat	10	41
Tomato	Heat	37–98	42
Bell pepper	Heat	30–50	43

stresses. Furthermore, heat stress intensifies drought effects through synergistic interactions, accelerating water loss and exacerbating cellular oxidative damage. Table 2 depicts yield losses in major crops due to heat stress.

Waterlogging: Drowning the roots

Waterlogging, caused by excessive rainfall or inadequate drainage, restricts gas diffusion and induces hypoxia in root zones (44). This contrasts with drought, where the challenge is insufficient water availability and with heat or salinity, where osmotic imbalance prevails. Under waterlogged conditions, stomatal closure, reduced chlorophyll content and impaired nutrient absorption (P, Ca, Mg, Fe, manganese (Mn), molybdenum (Mo)) drastically suppress photosynthesis (45, 46). Anaerobic respiration leads to energy deficiency and ROS proliferation, damaging cell structures and accelerating senescence. Yield loss depends on crop sensitivity and timing such as maize, which suffers sharp reductions after only 10 days of waterlogging, while cotton experiences poor boll development when exposed early in the season (47, 48). In comparison with other stresses, waterlogging uniquely affects root respiration and energy production, yet it shares ROS toxicity and nutrient disruption with drought, heat and salinity, emphasising oxidative stress as a universal response pathway across abiotic constraints.

Across all four stresses (drought, salinity, heat and waterlogging), ROS accumulation, impaired photosynthesis and reproductive vulnerability consistently determine yield outcomes, although the primary cause of stress differs (water deficit, ion toxicity, temperature excess, or oxygen deprivation). Contradictions across studies often stem from genotype-specific tolerance mechanisms, developmental stage at stress exposure and environment–nutrient interactions, highlighting the need for integrated stress-resilience strategies combining genetic improvement, optimised nutrient management and climate-smart agronomy.

Lodging: The physical barrier to productivity

Lodging, the bending or toppling of plants, is a physical yet devastating constraint in cereals and tall crops. It reduces yield, grain quality and harvest efficiency, often during the later growth stages (49). Major causes include wind, rain, dense planting, tall cultivars and excessive nitrogen application, which weakens stem structure.

There are two main types:

- **Stem lodging**, where the stalk bends or breaks near the ear-bearing node, disrupting nutrient transport (50).
- **Root lodging**, where plants tilt at $\geq 30^\circ$ from vertical, influenced by root number, diameter and brace root development (51).

Plants with deep, thick and vertical roots show greater anchorage and resistance (52).

Heavy metal stress: The hidden toxicity

Heavy metal contamination is an insidious threat to both crops and ecosystems. These elements, including lead (Pb), cadmium (Cd), nickel (Ni), cobalt (Co), chromium (Cr), arsenic (As), silver (Ag) and others, are characterised by a specific gravity five times greater than that of water (53). While some metals like Fe, copper (Cu) and Zn are essential micronutrients, excessive accumulation disrupts cellular homeostasis and growth (54). Soil contamination from industrial emissions, mining, smelting and agrochemicals elevates toxic metal levels beyond natural thresholds (55). This leads to oxidative stress, nutrient imbalance and morphological deformities in plants (56, 57). Even essential micronutrients like Ni and Cu can become toxic when accumulated in excess, while nonessential elements such as Pb and Cd induce severe chlorosis, membrane leakage and enzyme inhibition (58). Heavy metal toxicity also alters soil chemistry, reduces microbial activity and limits root growth, silently undermining plant health and productivity.

Biotic stress: Living challenges to crop productivity

Agriculture is constantly under siege, not just from the forces of nature, but from living organisms that compete, feed and proliferate at the expense of crops. Biotic stress, encompassing pests, pathogens, parasites and weeds, remains one of the most persistent threats to global food security and productivity. It contributes substantially to both pre- and post-harvest losses, directly reducing yield potential and crop quality.

Continuous exposure to biotic stress triggers metabolic disruptions and physiological damage in plants, leading to compromised productivity. Shifts in cropping systems, excessive pesticide reliance and the widespread cultivation of high-yielding varieties have unintentionally favoured the proliferation of pests and diseases. As a result, several once-minor pests have ascended to major status, while new, more aggressive species have emerged across

regions.

Pests and pathogens: The ever-evolving adversaries

The interplay between crops and their pests is continuously shaped by climate change, cropping intensity and global trade. Rising temperatures and erratic rainfall patterns weaken plant defence mechanisms, rendering crops more susceptible to attack. Moreover, international trade has accelerated the spread of invasive pest species, turning local outbreaks into global epidemics. It is estimated that insect and pathogen attacks cause 15–20 % yield losses in major food and cash crops worldwide (59). Studies conducted in India also reflect this global concern. In pigeon pea and cowpea ecosystems, *Maruca vitrata* (Geyer) has become a dominant pest, inflicting up to 42 % yield damage in Andhra Pradesh. Similarly, in coconut plantations of Thane, Maharashtra, the *Aceria guerreronis* mite infestation has reached alarming levels, causing 64.2–89.4 % nut damage. In cotton, *Phenacoccus solenopsis* (mealybug) outbreaks have resulted in 30–40 % yield reductions, while *Bemisia tabaci* (whitefly) devastated nearly two-thirds of Punjab's cotton crop during the 2015–16 epidemic (60, 61). Among millets, major pests such as stem borers, shoot flies, head feeders and grain feeders collectively account for 10–50 % yield losses, depending on infestation severity and crop stage (62). These figures highlight the growing urgency to strengthen integrated pest management (IPM) and adopt climate-resilient crop varieties.

Nematodes: The hidden soil invaders

While often overlooked, plant-parasitic nematodes represent one of the most destructive yet invisible biotic stresses in agriculture. Their infestation leads to root galling, nutrient deficiency and reduced water uptake, ultimately impairing plant vigour. Root-knot nematodes, in particular, affect a vast array of crops ranging from cereals and pulses to fruits, vegetables and ornamentals (63). In tropical and subtropical regions, nematode-induced yield losses account for 14.6 % of total crop loss, compared to 8.8 % in developed countries (64). These tiny but potent parasites underscore the importance of soil health management, crop rotation and biological control measures in sustainable agriculture.

Weeds: The silent competitors

Among all forms of biotic stress, weeds are often the most pervasive and costly. Competing relentlessly with crops for light, nutrients, water and space, they diminish yields, degrade product quality and complicate field operations (65). Weeds also act as alternate hosts for pests and pathogens, creating ecological niches that sustain harmful organisms throughout cropping cycles. Weed spread occurs through wind, water, animals, farm tools and human activity. Monocropping systems, in particular, exacerbate weed pressure and encourage the dominance of aggressive species. Climate change further worsens this issue by altering weed flora composition and promoting herbicide resistance (66).

Across Indian agro-ecological zones, the diversity of weed species ranges from 60–70 in humid regions to 30–40 in semi-arid areas (67). Major crops affected include rice, wheat, cotton and sugarcane (68–71). On average, weeds account for one-third of all pest-related yield losses, with reductions estimated at 5 % on commercial farms, 10 % on semi-commercial farms and up to 20 % on subsistence farms (72). In dryland systems, yield losses may reach a staggering 79 % while the combined effects of weed density and poor soil management can reduce productivity by as much as 65 %

(73, 74). Beyond yield suppression, weeds cause nutrient depletion, ecological imbalance, loss of biodiversity and lowered land value. Their dense growth also clogs irrigation channels, reducing water flow and availability in agricultural landscapes.

Plant nutrition

Plant nutrition, often referred to as mineral nutrition, is the fundamental component of healthy crop growth, metabolism and productivity. It involves the absorption, transport and utilisation of essential mineral nutrients from the soil through plant roots, enabling vital physiological and biochemical processes.

A total of 17 essential nutrients are indispensable for higher plants, each performing unique structural or metabolic roles. These nutrients are broadly categorised into three groups:

- **Basic nutrients:** carbon (C), hydrogen (H), oxygen (O).
- **Macronutrients:** nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S).
- **Micronutrients:** zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), boron (B), molybdenum (Mo), chlorine (Cl), nickel (Ni).

The nutrient requirement varies among crops, depending on their genetic makeup, soil environment and growth stage. When the supply of any nutrient drops below the optimum level, deficiency symptoms emerge; conversely, excessive accumulation can lead to toxicity (75). Adequate and balanced nutrient supply is critical for harnessing the potential of high-yielding crop varieties, especially under rainfed and dryland conditions. In such environments, nutrient limitations often arise due to low fertiliser application rates and poor soil organic matter. On the other hand, imbalanced fertiliser use can disturb soil fertility, leading to nutrient disorders and reduced crop performance (e.g., excess N causing Zn deficiency). In modern intensive farming systems, the challenge lies in maintaining equilibrium among nutrients. The availability of secondary nutrients (Ca, Mg and S) fluctuates widely due to disproportionate fertilisation, while micronutrient deficiencies, notably Zn and B, have become major yield-limiting factors in rainfed agriculture.

Sustainable soil fertility depends on maintaining a fine balance between nutrient input and output. Over time, disproportionate use of primary nutrients like N, P and K has disturbed the natural soil balance. This has led to secondary and micronutrient depletion, diminishing soil productivity.

To address these challenges, scientists and agronomists emphasise the concept of balanced nutrient management (BNM), guided by the internationally recognised 4R principles:

- **Right source:** Choose the appropriate fertiliser or organic input.
- **Right rate:** Apply nutrients in the correct quantity.
- **Right time:** Supply nutrients when crops need them most.
- **Right place:** Apply nutrients where plant roots can access them efficiently.

Adopting these principles enhances nutrient-use efficiency, maintains soil health and promotes eco-friendly farming by minimising nutrient losses through nitrate leaching and ammonia volatilisation (76).

Critical role of plant nutrients in managing plant stress

In the challenging landscapes of rainfed and dryland agriculture,

nutrient management is not just about feeding plants, but involves enhancing their capacity to withstand stress conditions. Every nutrient plays a strategic role in helping crops withstand harsh biotic and abiotic stresses (Fig. 1). A well-balanced nutrient regime acts as the plant's internal defence system, strengthening its capacity to thrive even under climatic uncertainty. Table 3 summarises the functional roles of essential plant nutrients in enhancing tolerance against major abiotic stresses through key physiological and biochemical mechanisms.

Primary nutrients

Nitrogen (N): The architect of growth and defence

Nitrogen is the critical determinant of plant growth, influencing everything from cell formation to stress resistance (77). It powers chlorophyll biosynthesis, drives photosynthesis and enhances photosynthetic efficiency. Under drought or low-water conditions, nitrogen fertilisation becomes a game changer as it aids carbon partitioning, carbohydrate accumulation and cell membrane stability, ensuring plants stay greener for longer periods (78). Even more fascinating, N enhances root elasticity, allowing plants to draw moisture efficiently and maintain hydration in dry soils (79). On a cellular level, N acts as a detoxifying agent. It reduces harmful reactive O species by enhancing the activities of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT) and ascorbate peroxidase (APX) and promotes the accumulation of proline, a natural stress protectant (80).

Phosphorus (P): The energy currency of stress tolerance

Phosphorus is often called the “key energy-related nutrient” and for good reason it fuels energy transfer, root expansion and cell resilience (81). Even in dry soils, P strengthens the root network, improving hydraulic conductance and nutrient uptake (82). Under stress, P acts as a metabolic stabiliser enhancing stomatal conductance, photosynthetic rate and leaf water potential, keeping plant cells hydrated and firm (83). Additionally, its influence extends even deeper. Phosphorus is vital for forming adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH), driving enzyme activities such as ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) and ATPase and regulating key hormones such as abscisic acid (ABA) and indole-3-acetic acid (IAA), which guide the plant's stress responses (84). Moreover, it shields cells from oxidative stress by neutralising ROS such as hydrogen peroxide and hydroxyl radicals while promoting the accumulation of osmolytes proline, sugars and proteins for cellular protection (85). However, abiotic stresses like drought, salinity and heat can restrict P uptake, slow enzyme activities and weakening the plant's overall defence machinery.

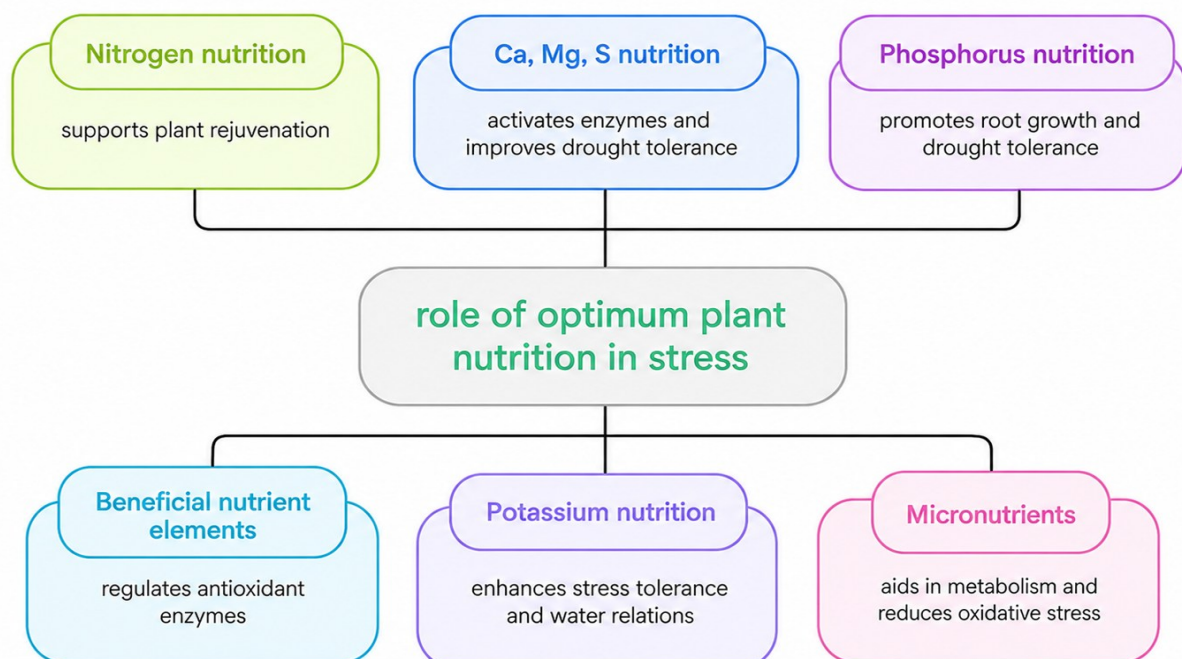
Potassium (K): The guardian of water and energy balance

If N builds and P fuels, K protects. This essential macronutrient fine-tunes the plant's metabolic and physiological functions (86). It regulates photosynthesis, carbohydrate metabolism and stomatal movement, while maintaining osmotic balance and cell turgor. Potassium regulates stress responses under drought or salinity, it helps plants conserve water through stomatal regulation, enhances leaf area and improves root efficiency (87). It strengthens plant vigour by optimising nutrient uptake, water-use efficiency and aquaporin activity, which governs water flow in cells (88). Moreover, K acts as a biochemical shield activating antioxidant enzymes (superoxide dismutase (SOD), peroxidase (POD), ascorbate peroxidase (APX), catalase (CAT)) to neutralise reactive oxygen

Table 3. Role of plant nutrients in mitigating abiotic stresses (77–102)

Nutrient	Major functions in stress tolerance	Biochemical / physiological mechanisms	Associated molecules / enzymes	Improved plant response	Abiotic stress mitigated
Nitrogen (N)	Enhances growth, osmotic balance, antioxidant defence	Regulates chlorophyll synthesis, carbon partitioning, membrane stability	SOD, CAT, POD, APX, Proline	Increased water retention, delayed senescence, improved photosynthesis	Drought, heat, salinity
Phosphorus (P)	Improves energy metabolism and cellular hydration	ATP production, stomatal regulation, hormone modulation (ABA, IAA)	RuBisCo, ATPase, Osmolytes	Stronger root system, higher water potential, improved gas exchange	Drought, salinity, heat
Potassium (K)	Controls stomatal movement and ion balance	Osmoregulation, aquaporin regulation, ROS detoxification	SOD, APX, POD, Proline	Turgor maintenance, improved WUE, membrane stability	Drought, salinity, heat
Calcium (Ca)	Strengthens membranes and signalling pathways	Secondary messenger in stress signalling, Na ⁺ exclusion	Ca ²⁺ signalling proteins	Reduced membrane injury, ion homeostasis	Salinity, waterlogging, heat
Magnesium (Mg)	Maintains photosynthesis and enzyme activity	Chlorophyll formation, ribosomal stability, carbohydrate metabolism	ATPase, Kinases, Polymerases	Sustained energy production, reduced chlorosis	Drought, heat
Sulfur (S)	Enhances detoxification and antioxidant protection	S-containing compounds synthesis, redox regulation	GSH, H ₂ S, Met, Cys, Phytochelatins	ROS reduction, enhanced cellular defence	Heavy metals, drought, salinity
Boron (B)	Maintains cell wall structure and sugar transport	Membrane integrity, reproductive development regulation	Cell wall polysaccharides, sugar alcohols	Improved pollen viability & fruit set, ionic balance	Salinity, heat
Zinc (Zn)	Supports enzyme activity and membrane protection	Cofactor for multiple enzymes, antioxidant strengthening	Carbonic anhydrase, RNA polymerase, Cu-Zn SOD	Reduced electrolyte leakage, enhanced tolerance to chilling	Chilling, drought, salinity
Iron (Fe)	Enhances photosynthesis and redox balance	Electron transport in chloroplasts and mitochondria	Fe-S proteins, CAT, POD, APX	Improved chloroplast integrity, reduced oxidative damage	Drought, cold, nutrient deficiency
Copper (Cu)	Regulates redox reactions and photosynthetic integrity	Antioxidant enzyme activation, membrane protection	GSH, Cu-chl, PPO, POD	Improved water status, reduced lipid peroxidation	Drought, salinity

SOD: superoxide dismutase; APX: ascorbate peroxidase; POD: peroxidase; ROS: reactive oxygen species; ATP: adenosine triphosphate; GSH: glutathione; H₂S: hydrogen sulphide; Met: methionine; Cys: cysteine; CAT: catalase; chl: chlorine; PPO: polyphenol oxidase; RuBisCo: Ribulose-1,5-bisphosphate carboxylase/oxygenase.

**Fig. 1.** Role of optimum plant nutrition in stress. (Image source: created using Napkin.ai)

species. It also boosts proline accumulation, further elevating drought tolerance. Foliar sprays of K have been shown to enhance these adaptive responses, keeping crops green, firm and productive under stress.

Secondary nutrients: The silent strength behind plant resilience

Beyond the well-known primary nutrients N, P and K there exists another trio of unsung heroes: calcium (Ca), magnesium (Mg) and sulfur (S). These secondary nutrients may not always steal the spotlight, but they form the support of plant defence and recovery under stressful environments. From stabilising cells to energising enzymes, their roles are fundamental to a plant's survival strategy.

Calcium (Ca): The cellular guardian and signal messenger

Calcium is far more than just a nutrient it is a molecular communicator, guiding plants through stress and recovery. Acting as a secondary messenger in intracellular signalling pathways Ca helps plants interpret and respond to environmental stress cues swiftly and effectively (4).

It governs essential functions such as nutrient absorption, hormonal regulation and enzyme activation, all while reinforcing cell wall integrity and membrane stability key defences against abiotic stress. Under salt stress, calcium ions (Ca^{2+}) safeguard the cell by blocking Na^+ from occupying membrane-binding sites, thus minimising ion toxicity (89).

Innovative practices like seed pelleting with calcium oxide (CaO) have been shown to enhance seed germination and seedling vigour under waterlogged conditions, mainly through improved oxygen availability (90). Foliar Ca sprays can also increase leaf water retention, contributing to drought tolerance by strengthening plant tissues and maintaining hydration balance.

Magnesium (Mg): The heart of photosynthesis

Magnesium sits at the core of the chlorophyll molecule, making it indispensable for photosynthesis, the plant's energy engine. It also supports enzyme activation, protein synthesis and nucleic acid stability, acting as a cofactor for key metabolic enzymes like ATPase, kinases and polymerases. As a ribosomal structural element, Mg stabilises macromolecules such as nucleic acids, proteins and membranes, ensuring smooth cellular operations even under stress. It further assists in carbohydrate metabolism by activating phosphorylating enzymes, which help convert and transport sugars for energy and growth. However, environmental stressors like drought and heat can drastically reduce Mg bioavailability, leading to chlorosis, reduced photosynthetic activity and diminished energy production. Ensuring an adequate supply of Mg is therefore crucial for maintaining both yield and stress tolerance.

Sulfur (S): The catalyst of cellular defence

Sulfur, often referred to as the fourth major plant nutrient after N, P and K, holds a central role in stress physiology (91). It fuels the biosynthesis of a wide spectrum of S-containing compounds that are vital for stress adaptation, cellular detoxification and redox balance. Exogenous application of S enhances plant tolerance to abiotic stresses by stabilising metabolic functions and boosting antioxidant capacity. Within plant cells, S forms the backbone of several critical molecules such as glutathione (GSH), hydrogen sulphide (H_2S), methionine (Met), cysteine (Cys), phytochelators (PC) and protein thiols each playing unique roles in maintaining normal

physiological and biochemical functions. Among them, GSH stands out as one of the most powerful antioxidants and stress protectants, regulates stress signalling and enabling plants to recover from oxidative damage (92).

Micronutrients: The molecular architects of stress resilience

Though required only in trace amounts, micronutrients serve as the molecular architects of plant life. They orchestrate key biochemical and physiological processes acting as enzyme cofactors, redox regulators and protectors of cellular integrity. Their influence extends beyond nutrition, shaping how plants sense, resist and recover from environmental stressors such as salinity, drought, heat and chilling.

Boron (B): The structural balancer

Boron is an essential element intricately linked with carbohydrate metabolism, cell wall architecture and membrane stability (87). It acts as a nutrient harmoniser, enhancing nutrient uptake, transport and reproductive development while mitigating the adverse effects of abiotic stress. Under saline conditions, B preserves internal potassium (K^+) balance and cell wall elasticity, effectively restoring the ionic equilibrium disrupted by salt stress (93). In leguminous crops, B supplementation restores nutrient balance and enhances nitrogen fixation efficiency, improving tolerance to saline environments (94). Beyond salinity, boron's pivotal role in sugar transport and cell wall biosynthesis makes it vital for sustaining growth under high-temperature stress, ensuring proper pollen tube development and fruit set even in adverse conditions.

Zinc (Zn): The enzyme protector and stress moderator

Zinc is the guardian of enzymatic activity and membrane stability, essential for plant endurance under multiple abiotic stresses. It fortifies the plant's antioxidant machinery and supports a variety of critical enzymes such as carbonic anhydrase, alkaline phosphatase, alcohol dehydrogenase (ADH), RNA polymerase, Cu-Zn SOD and phospholipase (95). As a key component of DNA and RNA synthesis, Z ensures structural integrity of proteins, lipids and cellular constituents, while also facilitating efficient ion transport (96). Zinc's protective functions extend to chilling stress, where ZnO nanoparticles (ZnO NPs) have demonstrated the ability to reduce ion leakage, stabilise root membranes and enhance salt stress tolerance (97).

Iron (Fe): The catalyst of energy and redox balance

Iron is at the heart of photosynthetic and respiratory electron transport, serving as a cofactor in vital antioxidant enzymes like CAT, POD and APX (94). It is also indispensable for chlorophyll biosynthesis and the maintenance of chloroplast structure. The Fe-S cluster, a prosthetic group present in numerous proteins, regulates redox balance and shields cells from oxidative stress (98). Under drought, adequate Fe nutrition enhances assimilate formation and promotes tissue recovery, strengthening the plant's physiological resilience. Moreover, iron oxide nanoparticles help mitigate cold stress by minimising electrolyte leakage, stabilising membranes and upregulating chlorophyll and Rubisco-binding protein genes, thus maintaining photosynthetic efficiency in low-temperature environments (99).

Copper (Cu): The redox regulator

Copper is both a micronutrient and a redox-active metal, central to C and N metabolism, photosynthesis, respiration and oxidative stress

defence. It functions as an enzyme catalyst, essential for numerous biochemical pathways and its deficiency leads to protein synthesis disruption and accumulation of soluble nitrogenous compounds. Application of Cu-chlorophyllin (Cu-chl) has been shown to protect tomato plants under drought stress by enhancing leaf antioxidant enzyme activity and increasing GSH levels (100). Similarly, Cu supplementation alleviates salinity stress by protecting cellular membranes, reducing lipid peroxidation and improving relative water content (RWC) (101). Additionally, colloidal Zn-Cu nanoparticles have demonstrated synergistic effects, enhancing leaf chlorophyll and carotenoid content, thereby improving photosynthetic performance and drought acclimation (102).

Strategies for abiotic plant stress management with optimum nutrition

Sustainable crop production amidst climatic variability relies heavily on efficient nutrient management to mitigate abiotic stresses. Optimum nutrient availability supports essential physiological and biochemical processes, promoting robust root systems, osmotic regulation and enhanced metabolic resilience under environmental adversities. Major abiotic stresses include drought, salinity, temperature extremes, heavy metal toxicity and waterlogging, all of which can be mitigated through targeted nutrient management strategies (Fig. 2).

Nutrient interactions play a pivotal role in shaping plant responses to abiotic stress and must be considered alongside individual nutrient functions. Synergistic interactions such as N – K, improve photosynthetic efficiency, osmotic regulation and water-use efficiency under drought and salinity. Conversely, Ca – Na antagonism protects membranes by reducing Na⁺ toxicity and maintaining ion homeostasis in saline soils. The P – Z interactions influence uptake and transport; imbalance between them can induce mutual deficiency, reducing stress tolerance and yield. Therefore, balanced and integrated nutrient management is essential for maximising plant resilience under adverse environments.

Drought stress management

In dryland and rainfed systems, drought severely disrupts N metabolism, reducing growth and productivity. Plants often accumulate osmolytes such as proline to maintain osmotic balance and stabilise cellular structures during water deficit. Foliar nutrient application provides a rapid and effective approach to counteract drought stress. In *Brassica rapa* var. *toria*, foliar application of 2 % potassium chloride (KCl) at pre-flowering and silique formation

stages, combined with 100 % N and P and 75 % basal K, enhanced yield, rainwater use efficiency and benefit-cost ratio under arid conditions (103). Examples of exogenous foliar spray applications under drought stress across crops are summarised in Table 4.

Nitrogen (N)

Plays a central role in drought tolerance by influencing photosynthesis, enzyme activation and antioxidant defence. In rice, N promotes root proliferation and xylem transport efficiency (79), while in wheat, it enhances chlorophyll fluorescence, enzymatic activity and relative leaf water content and reduces lipid peroxidation via activation of SOD and POX (104). Adequate N supply in maize maintains stomatal conductance, delays senescence and supports leaf elongation under drought (105). In rapeseed, N improves proline accumulation and water relations and in pearl millet, it promotes branching and water use efficiency under moisture stress (106).

Phosphorus (P)

Facilitates energy transfer, carbohydrate transport and root development, improving water uptake and root - shoot balance under adverse conditions.

Potassium (K)

Regulates osmotic adjustment, enzyme activation and stomatal function. In rice, K enhances shoot vigour and osmolyte synthesis (107); in wheat, it boosts antioxidant enzyme activities and protects chloroplast membranes (108); in oats, it improves N metabolism and antioxidative defence (109); and in Indian mustard, it enhances membrane stability and antioxidant enzyme activity including CAT, APX and SOD (110). In cotton, K supplementation increases photosynthetic efficiency and carbohydrate metabolism, reducing drought and heat stress effects (111).

Calcium (Ca) and magnesium (Mg) in stress amelioration

Calcium (Ca²⁺) plays a vital role in plant stress responses by contributing to structural integrity, stabilising cellular membranes and regulating ROS homeostasis. In addition, Ca²⁺ functions as an essential secondary messenger in stress signalling pathways, enabling plants to perceive environmental cues and activate appropriate defence responses. In rice, Ca improves germination, root and shoot growth, chlorophyll synthesis and proline accumulation while activating catalase and peroxidase to limit oxidative damage (112). In maize, it enhances osmotic adjustment and water retention while lowering H₂O₂ levels (113). In barley, Ca alleviates aluminium toxicity by reducing ROS generation and stimulating antioxidant enzymes (114).

Table 4. Exogenous foliar spray application under drought stress condition

Crop	Treatment / Foliar Spray	Beneficial effects	Reference
Cluster bean (<i>Cyamopsis tetragonoloba</i>)	Foliar spray of salicylic acid (SA) at 100–300 ppm and KCl at 0.5–1.5 % under drought stress (twice: at flowering and pod formation)	Increased relative leaf water content (RLWC), cell membrane stability (CMS), lower transpiration rate, improved plant height, branches/plant, pods/plant and grain yield (15.54 q ha ⁻¹) compared to control.	120
Rice (<i>Oryza sativa</i> L.)	Foliar spray of silica (potassium silicate) at 200 or 400 mg L ⁻¹ under well-watered (80 % WHC) and drought (40 % WHC) conditions	Improved photosynthetic pigments, proline accumulation, better water relations, reduced oxidative damage (lower lipid peroxidation), improved root structure under drought.	121
Wheat (<i>Triticum aestivum</i> L.)	Foliar spray of K (≈1 % K) at critical growth stages under drought	Improved physiological performance (leaf water potential, osmotic potential), higher uptake of N, P, K, Ca; reduced Na uptake; improved grain filling and yield under drought conditions.	122
Tomato (<i>Solanum lycopersicum</i> L.)	Foliar spray of KCl (3 and 6 mM) under moderate (75 % ET) and severe (50 % ET) drought stress	Foliar-applied KCl produced greater leaf area, stem diameter and length, higher yield per plant under drought compared to control; enhanced antioxidant enzyme activities (SOD, CAT, PPO) under drought.	123

KCl: potassium chloride; WHC: Water holding capacity; ET: Ethylene; SOD: superoxide dismutase; CAT: catalase; PPO: polyphenol oxidase.

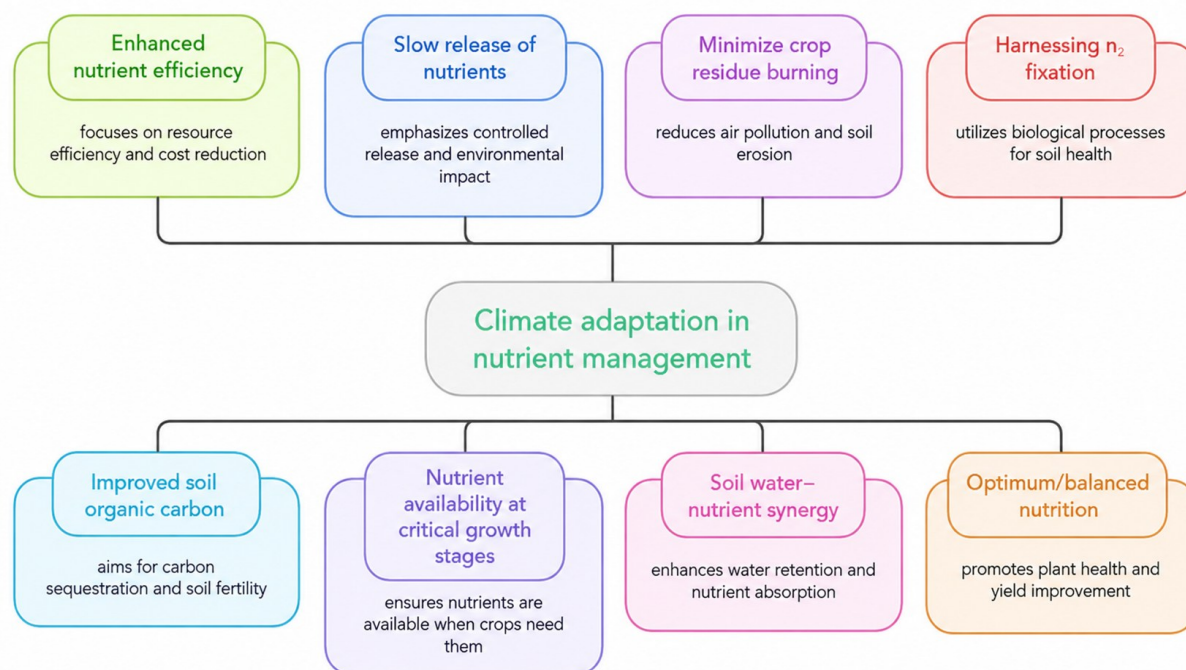


Fig. 2. Nutrient management strategies for abiotic stress.

Similarly, in sugar beet, Ca improves chlorophyll and carbohydrate accumulation while regulating polyamine and glutathione metabolism (115). In tobacco, Ca improves photosynthetic efficiency, stomatal conductance and the thermostability of photosystem II, enhancing heat tolerance (116).

Magnesium (Mg), the central atom in chlorophyll, supports ATP-related reactions, sugar transport and energy metabolism during stress. In rice, Mg improves carbohydrate partitioning and drought resilience while in wheat, it minimises ROS formation, prevents lipid peroxidation and activates antioxidant enzymes such as CAT and SOD (117–119).

Sulfur (S) and silicon (Si) in stress defence

Sulfur (S) is critical for redox homeostasis and ROS detoxification as a constituent of cysteine, methionine and glutathione. In rice, S mitigates arsenic stress by enhancing amino acid metabolism, proteome balance and thiol-based detoxification and reduces cadmium toxicity through Fe plaque formation and Cd chelation (124, 125). In barley, S limits salt accumulation by modulating nitric oxide signalling and counters aluminium toxicity via ATPase activation and oxidative stress suppression (126, 127).

Silicon (Si) enhances tolerance to drought, salinity and nutrient stress by reinforcing antioxidant systems and improving root architecture. In black gram, Si application improved growth, photosynthesis and osmolyte accumulation under drought (128). In wheat (*Triticum aestivum* L.), exogenous Si enhanced chlorophyll content, relative water content and antioxidant enzyme activity (129). Moreover, Si improved nutrient uptake efficiency, photosynthetic C assimilation and C:N:P balance, reducing oxidative stress (130).

Biological aids and precision nutrient management

Arbuscular mycorrhizal (AM) fungi offer a biological solution for abiotic stress mitigation. They enhance P uptake and improve drought tolerance in rainfed crops. In pea plants, AM inoculation significantly improved P acquisition and water stress adaptation (131).

Precision nutrient management using soil-test crop

response (STCR) methodologies ensures site-specific fertiliser recommendations, enhancing nutrient use efficiency and resilience under stress conditions. This approach is particularly effective for legumes and dryland crops, where it minimises costs while improving yield stability (132).

Nutrient roles in heat and temperature stress

Potassium also contributes significantly to temperature stress tolerance. Adequate K supply improves tissue water potential and enhances resilience to both heat and cold. In maize, pre-sowing seed treatment with KCl increased antioxidant enzyme activity and reduced oxidative damage under chilling stress (133, 134). During freezing, sufficient K maintains osmotic balance and prevents dehydration caused by apoplastic ice formation. Field studies confirm that balanced NPK nutrition reduces frost injury across multiple crops (135).

Salinity stress and ionic imbalance

Salinity stress causes osmotic imbalance and ion toxicity, often reducing uptake and translocation of essential nutrients such as K⁺. Sodium (Na⁺) competes with K⁺ for binding sites in enzymes and membranes. Maintaining a high K⁺ concentration and a low Na⁺/K⁺ ratio is vital for salt tolerance. Supplementing K enhances K⁺ retention, reduces Na⁺ accumulation and stabilises osmotic potential, thereby maintaining photosynthesis, respiration and nutrient homeostasis.

Heavy metal and waterlogging stress management

Heavy metal toxicity poses severe challenges to crop productivity, often resulting in physiological disorders such as chlorosis, necrosis, reduced chlorophyll synthesis, impaired nutrient uptake and inhibition of root growth. Potassium and Si act synergistically to enhance enzymatic activity, maintain ion homeostasis and strengthen antioxidant defence under such conditions. Potassium maintains osmotic equilibrium and reduces oxidative damage, while Si fortifies cell walls and restricts metal uptake by forming complexes with toxic ions.

Under waterlogging, oxygen deprivation disrupts root respiration and energy metabolism. Potassium alleviates these

effects by enhancing chlorophyll content, photosynthetic efficiency and plant vigour. In rice, K fertilisation under waterlogged conditions significantly increased plant height and photosynthetic activity compared to controls, demonstrating its vital role in sustaining metabolic stability under hypoxic stress (136).

Examples include K reducing Cd toxicity in tomato, Si lowering Cd accumulation and oxidative stress in strawberry and balanced K fertilisation improving bell pepper yield under protected cultivation (137–139). Effect of potassium (K) application on heavy metal stress tolerance in plants are depicted in Table 5.

Integrated nutrient approach for resilient cropping systems

Overall, balanced fertilisation with macronutrients (N, P, K, Ca, Mg, S, Si) and supporting biological inoculants like AM fungi enhances water relations, enzymatic activity and cellular protection mechanisms. These integrated strategies collectively strengthen plant resilience against drought, salinity, temperature extremes, heavy metal contamination and waterlogging, ensuring sustainable crop productivity under abiotic stress conditions.

Strategies for biotic plant stress management with optimum nutrition

Nutrient management plays a vital role in determining plant susceptibility or resistance to pests and diseases. Poor crop management, particularly the use of unbalanced fertilisers, often leads to pest outbreaks such as mites and other sucking insects. Hence, the application of balanced and optimum nutrition is essential for achieving high crop yields while minimising pest and disease incidence (Table 6).

Role of organic amendments in disease suppression

The incorporation of organic manures and soil amendments has been shown to significantly reduce the occurrence of several soil-borne diseases. The application of farmyard manure (FYM), groundnut cake and mustard cake in soils has been reported to reduce the incidence of chickpea wilt effectively. Organic matter improves soil structure, enhances microbial activity and promotes antagonistic organisms that suppress pathogens (9).

Nutrient imbalance and disease incidence

Nutrient imbalance can either enhance or suppress disease severity depending on the element and pathogen involved. For instance, excessive nitrogen fertilisation increases the severity of rice blast (*Magnaporthe grisea*) and scald (*Rhynchosporium oryzae*), while it reduces maize head smut (*Sporisorium reilianum*) infection (9). Similarly, phosphate fertilisation enhances cucumber mosaic virus (CMV) incidence in spinach but decreases potato scab (*Streptomyces scabies*).

Role of potassium and calcium in plant defence

Potassium plays a crucial role in improving plant defence mechanisms against a wide range of pathogens and pests. Adequate K nutrition has been associated with reduced infection by nematodes, bacteria such as *Corynebacterium nodosum* and *Xanthomonas* sp., fungi such as *Fusarium oxysporum* f. sp. *vasinfectum* and several viruses (143). Calcium, on the other hand, enhances cell wall integrity, thereby strengthening mechanical barriers against facultative pathogens such as *Rhizoctonia*, *Sclerotium*, *Botrytis* and *Fusarium*. However, excessive calcium may favour certain diseases, for example, black shank of tobacco caused by *Phytophthora nicotianae* (144).

Silicon as a bioprotective nutrient

Silicon (Si) is globally recognised for enhancing plant resistance against a broad spectrum of biotic and abiotic stresses. Species of the Poaceae family have the highest capacity for Si accumulation, followed by Cucurbitaceae and some Solanaceae (145). Silicon fortification in crops has been found to mitigate several plant diseases and pest attacks, including root rot of cucumber and tomato, powdery mildew of cucumber, anthracnose of chilli and various insect pests such as brown planthopper, leaf folder and stem borer. Additionally, Si improves plant resistance against pathogens causing rice blast, tomato wilt and sugarcane stalk borer (146).

Organic manures and biotic stress suppression

The addition of organic materials such as sawdust, straw and oil

Table 5. Effect of potassium (K) application on heavy metal stress tolerance in plants

Crop	Heavy metal treatment	Potassium (K) treatment	Protective effects	Reference
<i>Vicia faba</i>	200 μ M Cd	6 mM K	• Increased shoot and root length • Enhanced chlorophyll and protein content	140
<i>Prunus persica</i>	6 mM ZnCl ₂	10 mM KCl	• Improved photosynthetic efficiency • Increased shoot and root growth and dry biomass	141
<i>Gladiolus grandiflora</i>	50 mg kg ⁻¹ CdSO ₄ ·8H ₂ O	200 mg L ⁻¹ K + 200 mg L ⁻¹ Si	• Enhanced chlorophyll content	142

Cd: cadmium; ZnCl₂: zinc chloride; CdSO₄·8H₂O: Cadmium sulphate octahydrate; KCl: potassium chloride.

Table 6. Application of optimum nutrition for minimising biotic stress in crops

Crop	Nutrient applied	Pest/disease controlled	Major beneficial effects	References
Wheat (<i>Triticum aestivum</i> L.)	Potassium (K)	Leaf rust (<i>Puccinia triticina</i>)	Increased disease resistance through enhanced photosynthesis and enzyme activity	151
Rice (<i>Oryza sativa</i> L.)	Nitrogen (N) and Silicon (Si)	Rice blast (<i>Magnaporthe oryzae</i>)	Reduced disease incidence and increased cell wall strength and silica deposition	152
Maize (<i>Zea mays</i> L.)	Balanced NPK + Zinc (Z)	Downy mildew (<i>Peronosclerospora sorghi</i>)	Improved plant vigour, reduced disease incidence and enhanced chlorophyll content	153
Tomato (<i>Solanum lycopersicum</i> L.)	Calcium (Ca) and Silicon (Si)	Blossom-end rot and bacterial wilt (<i>Ralstonia solanacearum</i>)	Improved cell wall strength, reduced oxidative stress and disease suppression	154
Cucumber (<i>Cucumis sativus</i> L.)	Silicon (Si)	Powdery mildew (<i>Podosphaera xanthii</i>)	Enhanced resistance through activation of defence enzymes and lignin deposition	155
Chilli (<i>Capsicum annum</i> L.)	Potassium (K) and Organic manure	Anthracnose (<i>Colletotrichum capsici</i>)	Improved fruit firmness, higher phenolic content and reduced disease severity	156

cakes has been effective in controlling soil-borne pathogens including *Pythium*, *Phytophthora*, *Verticillium*, *Macrophomina*, *Phymatotrichum* and *Aphanomyces* (147). Neem, karanj and mahua cakes contain bioactive compounds such as azadirachtin, salannin, nimbin (from neem), karanjin and pongamol (from karanj) and saponins (from mahua), which effectively inhibit soil-borne pathogens and suppress pest populations. In organic farming systems, manure application plays a dual role by enhancing soil fertility and strengthening the soil's biological health. However, improper handling can introduce pathogens, insects, or viable weed seeds (148). Therefore, pre-treatment and controlled decomposition of raw materials are crucial to prevent disease transmission and weed proliferation.

Nutrient management and weed interaction

Nutrient management influences weed dynamics in cropping systems. High nutrient availability, particularly from organic sources, may promote weed growth by supporting their nutrient uptake. Studies have shown increased weed density and dry biomass under manure-enriched soils (149). Nevertheless, proper incorporation of manure into soil has been found to suppress certain weeds like spotted spurge (*Euphorbia maculata*) and giant crabgrass (*Digitaria sanguinalis*), likely due to allelopathic or microbial-mediated effects (150).

Overall, integrated nutrient management that combines organic and inorganic sources, balanced fertilisation and silicon supplementation contributes significantly to biotic stress management by enhancing plant defence responses, improving soil microbial activity and reducing pathogen virulence.

Critical limitations

Despite significant progress in understanding nutrient-mediated stress tolerance, major knowledge gaps persist. Most existing studies are conducted under controlled environments with limited field validation, restricting scalability to real cropping systems. Additionally, limited research examines nutrient interactions under combined or sequential stresses, which are more realistic under climate change scenarios. Variability in experimental conditions, crop genotypes and geographic environments often leads to inconsistent results, making comparison difficult. A lack of long-term, multi-location trials further constrains the development of universal nutrient management strategies.

Future prospects

Future research should focus on integrated nutrient interaction studies, particularly under multiple concurrent stresses such as drought-heat or salinity-heat combinations. Advancements in omics technologies, nanonutrients and precision agriculture offer new opportunities to unravel nutrient-stress signalling networks and improve real-time diagnosis of nutrient deficiencies. Developing stress-resilient crop varieties with enhanced nutrient-use efficiency will be crucial for climate-resilient agriculture. Expanding field-based multi-location validation and decision-support tools will enable adoption of nutrient-smart management strategies for sustainable crop productivity.

Conclusion

Abiotic and biotic stresses continue to threaten global agricultural sustainability, necessitating integrated strategies that fortify plant

resilience while maintaining productivity. Nutrient management stands as a cornerstone of such strategies, offering a multifaceted approach to enhancing stress tolerance. Balanced fertilisation guided by the 4R principles (right source, rate, time and place) together with organic amendments, biofertilisers and silicon supplementation, significantly improves plant physiological performance, enzymatic activity and antioxidant capacity. Macronutrients such as nitrogen, phosphorus and potassium drive growth and osmotic regulation, while secondary and micronutrients, including calcium, magnesium, sulfur, zinc and boron, act as biochemical stabilisers under stress conditions. Together, these elements enable plants to maintain photosynthesis, protect cellular integrity and adapt to fluctuating environments. Future agricultural systems should integrate nutrient optimisation with precision technologies and climate-resilient crop varieties to ensure sustainable yield stability. A holistic understanding of nutrient stress interactions will be central to developing resilient cropping systems that balance productivity, resource efficiency and ecological health. Overall, while the role of individual nutrients is increasingly understood, substantial gaps remain regarding multidimensional nutrient interactions and their behaviour under real-world stress combinations. Prioritising integrated, field-based and mechanism-driven research will be essential to translate nutrient-based stress tolerance strategies into scalable climate-smart solutions.

Authors' contributions

PA conceptualised the review theme, organised the overall framework and contributed to writing and critical revision of the manuscript. PT coordinated the study, supervised content organisation and served as the corresponding author. KS contributed to the literature compilation and preparation of the section on nutrient interactions influencing stress physiology. DKN assisted in collecting and analysing research data related to abiotic stress responses. SS contributed to sections dealing with biotic stress management and plant defence mechanisms. ND supported the compilation of recent findings on micronutrient management and participated in manuscript editing. P prepared the section on farmer-oriented nutrient management strategies and extension perspectives. PD contributed to sections on nutrient signalling pathways and stress-responsive gene regulation. RA worked on the economic and policy aspects of nutrient management for sustainable agriculture. KCS contributed to the soil chemistry and nutrient dynamics component of the manuscript. RRT contributed to the synthesis of literature on nutrient management approaches, provided critical inputs on crop resilience mechanisms under stress conditions and participated in manuscript editing and review. All authors read and approved the final manuscript.

Compliance with ethical standards

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Declaration of AI-assisted technologies in the writing process

During the preparation of this manuscript, AI-assisted technologies, specifically tools such as Paperpal, SciSpace, TrinkAI and Zotero, were used to assist with language refinement, literature review, reference management and overall manuscript organisation. These tools were used as supportive aids to enhance clarity, consistency and efficiency. However, all conceptualisations, analyses, interpretations and final content remain the original work of the authors, who take full responsibility for the integrity and accuracy of the manuscript.

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