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REVIEW ARTICLE

Amino acid-chelated micronutrients: A new frontier in crop nutrition and abiotic stress mitigation

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Abstract

Micronutrient deficiencies and abiotic stresses, such as drought, salinity and temperature fluctuations, significantly reduce global crop productivity, partly by limiting nutrient bioavailability. While micronutrients are essential for plant metabolism, their precise application is crucial to prevent heavy metal contamination and environmental degradation. Overuse or improper application of micronutrients can lead to toxicity, soil degradation and groundwater contamination. To address these challenges, chelating agents have been introduced into agricultural systems to enhance micronutrient availability and uptake by plants. Amino acid chelates, a class of 'smart fertilizers' that bind micronutrients to amino acids, offer an innovative solution to enhance nutrient efficiency and mitigate abiotic stress effects. By enhancing nutrient absorption, promoting antioxidant activity, regulating osmotic balance and supporting enzymatic functions, amino chelates contribute to improved crop health and resilience. This review explores the current challenges in agriculture related to micronutrient deficiencies and abiotic stress, focusing on amino chelates as an advanced solution for improving nutrient uptake and crop resilience. However, there remain uncertainties regarding their synthesis and properties, optimal application rates and interactions with other agricultural inputs. The aim is to provide a comprehensive understanding of amino chelates, their mechanisms and future potential for sustainable agriculture, while emphasizing the need for targeted research to optimize their use in addressing micronutrient deficiencies and abiotic stress.

Keywords: amino acids; crop yield; drought; nutrient availability; quality; salinity

Introduction

The Sustainable Development Goals (SDGs) 2.1 and 2.2, aimed ending hunger and malnutrition, are currently off track for achievement by 2030. Meeting these targets requires major shifts in agricultural systems to sustainably produce affordable, nutrient-dense food (1). Agriculture faces the dual challenge of ensuring food security for a growing global population while preserving natural resources. This challenge is further exacerbated by environmental stressors such as extreme temperatures, drought, salinity and nutrient deficiencies, all of which reduce crop yield and quality, thereby worsening food insecurity (2). Moreover, intensive farming practices have led to widespread micronutrient deficiencies in soils, negatively impacting crop productivity and human as well as animal health (3). To address these issues, urgent strategies are needed to replenish soil nutrients and biofortify crops with essential micronutrients, improving soil health and human nutrition.

Micronutrients, though required in trace amounts, are vital for balanced crop nutrition, supporting plant growth and development throughout their lifecycle (4). Applying micronutrient fertilizers enhances the stability and sustainability of food grain, pulse and oilseed production. Moreover, these fertilizers help mitigate stress by reducing reactive oxygen species (ROS) and participating in signal transduction pathways that regulate plant responses (5). Micronutrient fertilizers are generally classified into three main categories: inorganic sources, synthetic chelates like Ethylenediaminetetraacetic acid (EDTA), Ethylenediamine-N,N'-bis(o-hydroxyphenyl) acetic acid (EDDHA) and organic complexes such as phenolics, organic acids and amino acid-based compounds (6). Inorganic fertilizers, though widely used, often suffer from fixation issues, reducing their efficiency and necessitating supplementation with chelates or organic complexes to meet the nutritional requirements of crops. However, the extensive use of synthetic chelates raises concerns about sustainability and the potential for ecological contamination (7).

Considering these challenges, alternative forms of micronutrient fertilizers are essential to meet crop nutrient demands while supporting environmental sustainability. Amino acid chelates are smart fertilizer often get chelated with amino acids and micronutrients that offer a promising solution due to their improved safety profile compared to conventional inorganic and synthetic chelates (8). These chelates are coordination compounds in which a central metal ion (M^{n+}) is bonded to ligands containing amino groups ($-NH_2$, -NH-, or -N<) that donate electron pairs to form coordinate covalent bonds, resulting in cyclic chelate structures. These ligands are typically polydentate, meaning they can form multiple bonds with the same metal ion, creating a stable ring system for example the structural formula for metal glycinate is $M^{+}(H_2NCH_2COO)_2$. In some countries, natural chelates made from amino acids and micronutrient metals have rapidly gained popularity in the fertilizer market (8). These chelates demonstrate systemic behavior within plants, as amino acids are easily recognized and absorbed by plant tissues, facilitating effective nutrient uptake and utilization (9). This review provides a comprehensive analysis of amino chelates, including their chemistry, mechanisms of nutrient bioavailability and response of the crop to their application. It also examines, their role in mitigating stresses such as salt and drought. Despite their promise, significant gaps remain in understanding the synthesis, characterization and long-term impacts of amino chelates, highlighting the need for further research to optimize their use in sustainable agriculture.

Chemistry and properties of amino chelates

Natural amino acid chelates represent an effective strategy for delivering nutrients with improved bioavailability and safety, particularly in plant systems. These amino chelates are typically formed by reacting amino acids with metal salts in a 2:1 molar ratio (8). Unlike traditional nutrient bonding methods, these chelates utilize stable bi-, tri-, or polydentate groups that offer a stronger and more resilient bonds (10). As true chelates, they act as slow-release fertilizers, allowing nutrients to be gradually absorbed by plants. The chelating agents used are tolerably hard, enhancing their effectiveness as nutrient carriers. Upon application, these aminochelated micronutrients penetrate the plant promoting enhanced crop growth, while the residual amino acids serve as a water-soluble nitrogen source (11). Their multifunctionality extends to applications in fertilizers, biofuels and soil remediation.

Iron (Fe), a key micronutrient for processes like gene regulation, electron transfer and oxygen transport, often becomes unavailable in high-pH soils due to fixation. To overcome this, iron-chelated peptides have emerged as superior alternatives to iron salts, improving iron stability, absorption and bioavailability. For example, whey-derived peptide-Fe complexes (WPDP-Fe) are prepared by mixing WPDP with $FeSO_4$ at protein-to-iron ratios (40:0.5 to 40:2) at 40 °C for 2-4 hr (12). Such approaches ensure efficient chelation and absorption, particularly in alkaline soils.

The production of amino acid chelates can be achieved through several methods, one of which is the hydrolysis of biomasses. This process converts proteins into amino acids or peptides through chemical or enzymatic treatments. Various steps used in the synthesis of these micronutrient chelates are illustrated in Fig. 1, providing detailed insights into their formation pathways (Table 1). The structural confirmation of amino chelates relies on a range of analytical techniques, with Raman spectroscopy being particularly effective. This method provides insights into molecular structures through vibrational spectra, making it especially useful for distinguishing between different forms of the same amino acids, such as L-methionine and L-methionium cation (13). The coordination bond formation between metal ions and amino acid ligands is typically identified through the characteristic spectra of carboxylic motion and metal-ligand vibrations. In a study using Raman spectroscopy, the molecular spectra of 18 amino acids and their aqueous solutions were analyzed. Complexation between Zn^{2+} and cysteine was observed in the Raman spectral bands within the 200-400 cm^{-1} range. This confirmed the coordination of Zn^{2+} with the cysteine ligand via Zn-S and Zn-N stretching, which resulted from the deprotonation of the SH and NH_3^+ groups (14). Additionally, the vibrational frequencies detected in the solid phase were consistent with those observed in the aqueous phase (15). UV-Vis spectroscopy further verified metal cation complexation with amino acids by revealing a shift in the inter-ligand band to higher energy levels in the visible and near-infrared regions, attributed to charge transfer and d-d transitions (16). Furthermore, copper amino acid complexes were synthesized using L1 (histidine), L2 (methionine) and L3 (threonine) as ligands and the coordination between the metal ion and the amino acids was confirmed by comparing specific bands in the ligands with those in the copper complexes. For example, the $n \rightarrow \pi^*$ band related to the C=O bond, initially observed with λ_{max} values of 275, 267 and 267.5 for L1, L2 and L3, respectively, shifted to longer wavelengths in the copper complexes (17). The strength and nature of coordination significantly influence vibrational frequency patterns in amino acid-metal complexes. For example, chelation of copper with alanine was identified by a notable shift in the asymmetric amine (NH_3^+) bands to higher wavelengths (18). This shift highlighted the coordination of carbonyl (C=O) and NH_3^- groups with $Zn^2{}_+$ ions, forming new complexes and displacing the groups from their native positions in free amino acids.

Fourier Transform Infrared Spectroscopy (FTIR) analysis was essential for confirming metal-ligand bond formation, quantifying metal chelates and free acids such as citric and malic acids and detecting significant changes in frequency intensity (19). FTIR analysis has demonstrated that zinc amino acid chelates possess superior surface characteristics and higher zinc concentrations compared to organic acids. In the solid state, amino acids typically adopt zwitterionic forms, characterized by specific vibrational modes such as ust($-NH_2$), ust(C=O), us($-COO^-$), ust(O-H) and ust(C-N) for free ligands (20). Amino acids often act as bidentate ligands, coordinating with metals through oxygen and nitrogen atoms, with the process largely influenced by pH (21). FTIR analysis of glycine (Gly), zinc-glycine (Zn-Gly) and selenium-glycine (Se-Gly) in the 400-4000 cm^{-1} range revealed NH_2-M and COO-M bonds, confirming cyclic

Table 1. Properties of amino acid based chelates

Name of the amino acid chelate	pH	Solubility	Hygroscopic nature	Colour	Concentration of metal (%)	References
Zinc glycinate	5.83	++	Hygroscopic	White	9.93	
Zinc proline	6.13	+	Hygroscopic	White	8.13	(46)
Zinc glutamic acid	3.46	+	Hygroscopic	White	6.51	
Zinc lysinate	7.5	++	Hygroscopic	White	20.6	(74)
Ferrous bisglycinate:Zinc methionate (25:17)	7.3	++	Slightly hygroscopic	Reddish brown	17	(38)
Ferrous bisglycinate:Zinc methionate (17:17)	7.3	++	Slightly hygroscopic	Light brown	17	
Fe-Glycine	5.35	++	Hygroscopic	Brown	15.2	
Fe-Arginine	9.01	++	Non-hygroscopic	Black	13.5	
Fe-Proline	5.64	+	Hygroscopic	Yellow	14.2	
Fe-Leucine	3.55	++	Non-hygroscopic	White	8.6	
Fe-Asparagine	5.95	+	Hygroscopic	Yellow	10.5	(75)
Fe-Cystine	5.29	++	Non-hygroscopic	White	11.6	
Fe-Valine	4.01	++	Non-hygroscopic	Brown	8.4	
Fe-Alanine	4.11	++	Non-hygroscopic	Black	10.1	
Fe-Histidine	6.78	++	Non-hygroscopic	Yellow	8.6	
Copper amino acid hydrolysate complex (L6H) CuO_n $(H_2O]\cdot nH_2O$	-		-	Green	-	
Zinc lysine complex $[(L_1H)\ Zn\ (OAC)_2(H_2O)_2]\cdot H_2O$	-	+	-	Yellow	21.60	
Cobalt lysine complex $[(L_1H)\ (Co)_2(OAc)_2(H_2O)_4]\cdot H_2O$	-	+	-	Violet	18.90	(20)
Manganese lysine complex $[(L_1H)\ Mn_2(OAc)_2(H_2O)_4]$	-	+	-	Yellow	16.80	
Copper cysteine complex (L_3H) Cu]	-	+	-	Green	34.1	
Cobalt cysteine complex $[(L_3H)\ Co\ (OAc)_2\ (H_2O)]\cdot 5H_2O$	-	+	-	Violet	13.3	

+: soluble; ++: highly soluble.

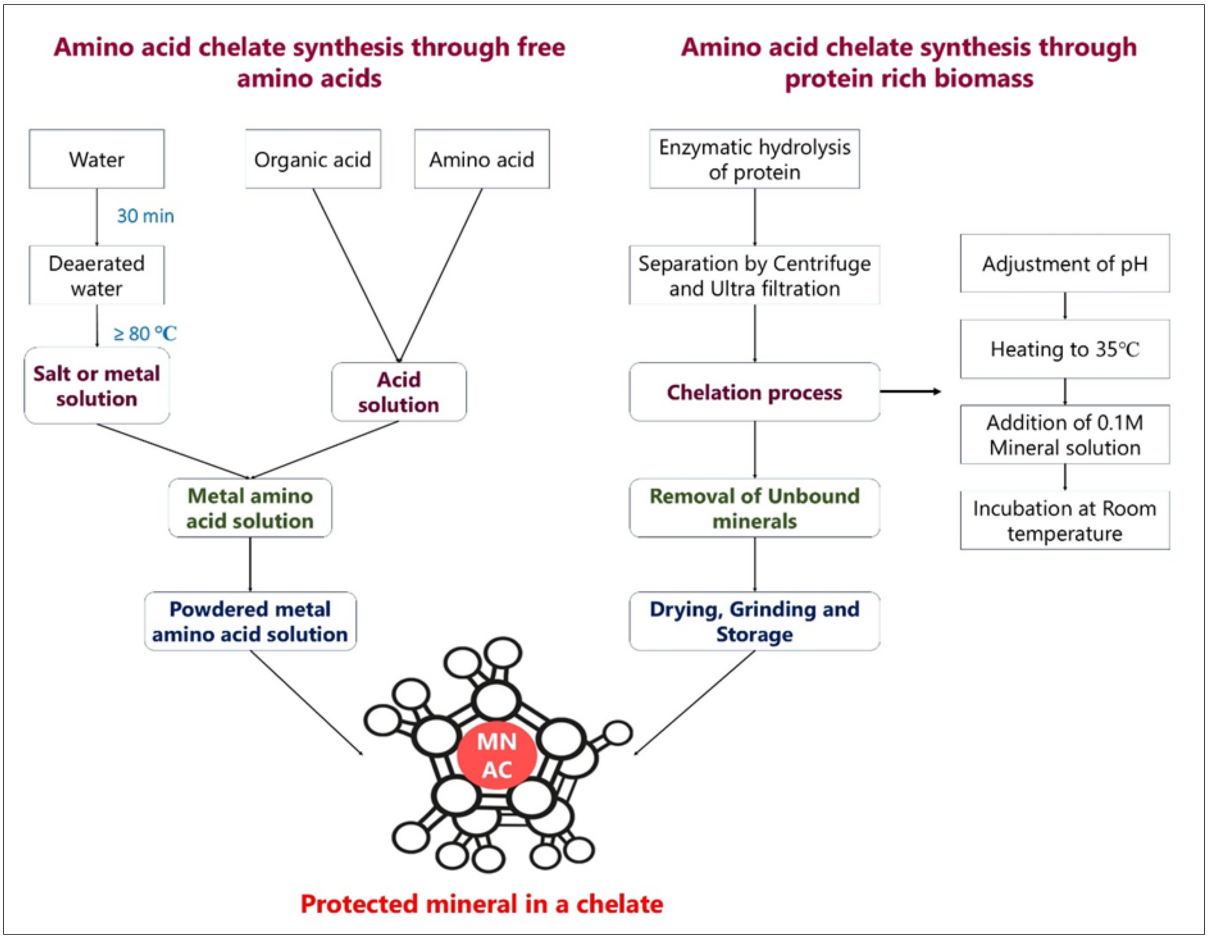

Fig. 1. Synthesis of amino acid-based micronutrient chelates (MNAC).

structure formation via glycinate chelation (22). Synthesizing copper complexes with histidine, methionine and threonine showed significant complexation, with shifts in vs(N-H) vibrations by 49, 83 and 35 cm^{-1}, respectively, indicating amine group involvement (23). Additional peaks in the 2500-3800 cm^{-1} range for zinc-glycine sulphate complexes further confirmed successful chelation (24).

Why Amino chelates are Preferred Over Synthetic Chelates?

Micronutrient bioavailability in soil is significantly influenced by factors such as soil pH and redox potential. Micronutrients generally thrive in acidic to neutral soils, with the notable exception of molybdenum (Mo). In calcareous soils, a large portion of essential nutrients like zinc (Zn) and iron (Fe) becomes immobilized as insoluble precipitates, such as zinc and iron hydroxides. This immobilization severely limits their availability, particularly in alkaline soils, thereby challenging optimal crop yields. To counteract this, chelating agents are employed to enhance the mobility and availability of micronutrients in soil environments. A chelate is created when a metal ion interacts with two or more electron-donating groups within a single molecule, forming a ring-like structure (25). This chelation process enhances nutrient uptake by facilitating the movement of metals from the soil to plant roots, thus improving bioavailability. The encapsulation of metals within chelate rings changes their cationic properties, reducing their susceptibility to precipitation under specific chemical conditions. Chelated forms of nutrients are widely used in agriculture as supplements in fertilizers, seed treatments, foliar sprays and hydroponic solutions (26-28). Despite these benefits, synthetic chelates have certain challenges such as higher costs and limited leaf penetration due to their larger molecular size. These limitations have led to growing interest in alternative, environmentally friendly chelating agents, particularly those based on organic or amino acid compounds. Recent advancements have highlighted the role of naturally produced chelators from roots or microorganisms in mitigating soil micronutrient deficiencies. Organic chelating agents can selectively capture metal ions such as Ca, Mg, Fe, Zn, Mn, Cu and Co, ensuring their gradual release and sustained availability to plants.

Among organic chelators, amino acid-based chelates are particularly attractive due to their high bioavailability, lower production costs and non-toxic nature. They maintain a neutral charge, which prevents attraction or repulsion by negatively charged leaf surfaces (29). Research suggests that organic-chelated zinc sources are often more effective than their inorganic counterparts. However, the efficiency of amino acid chelates can vary depending on the type of crop, soil and application method used. Amino acid based chelates offer several advantages, including reducing competition among cationic minerals, minimizing nutrient antagonism and significantly lowering nitrate losses and metal ion pollution, which ultimately promotes environmental sustainability. The key difference between synthetic and amino acid chelates is tabulated in Table 2. Furthermore, amino acids optimize plant growth by enhancing photosynthesis, boosting protein production and promoting mRNA transcription (30). However, more research is needed to validate the full extent of these effects across different plant systems.

Amino chelates and its Role in Crop Nutrition

Effect on growth attributes

Amino acids have gained prominence in plant nutrition due to their dual function as biostimulants and nutrient carriers, promoting overall plant development and improving nutrient uptake (31). These natural chelates are vital for enhancing chlorophyll production and minimizing its degradation in leaves, which is essential for maintaining plant vitality, particularly under challenging conditions. Amino acids directly impact nitrogen metabolism, leading to improved leaf colour, increased leaf area and enhanced growth attributes such as plant height, leaf area index and root and shoot development (32). For instance, a study on foliar application of amino acids like glycine and glutamine at concentrations of 250, 500 and 1000 ppm demonstrated that applying glycine and glutamine at the rate of 250 and 1000 ppm has significantly increased leaf chlorophyll levels compared to control plants (33).

A synergistic approach involving seed priming with zinc-tryptophan complexes and inoculation with zinc-solubilizing bacteria (ZSB) significantly improved leaf area,

Table 2. Difference between synthetic chelates and amino acid chelates

Property	Synthetic chelates	Amino acid chelates
Chemical structure	Synthetic organic ligands forming multiple coordination bonds	Metal ion bonded to one or more natural amino acids via the amino and carboxyl groups
Chelation sites	Tetra- to hexa-dentate	Bidentate
Molecular size	Larger, complex structures	Smaller, simpler molecular structures
Absorption mechanism	Passive uptake by plants	Active uptake by plants since it utilizes amino acid-based transport pathways
Target sites in plants	Non-specific; requires pH optimization for uptake	Recognized by plant amino acid transporters, enhancing efficiency
Systemic mobility in plants	Limited	Higher mobility due to mimicry of natural plant molecules
Stability in soil pH	Stability varies for different chelating agents, i.e. EDTA: stable up to pH 6.5; DTPA: up to 7.5; EDDHA: up to 10	Stable across a wide pH range varied by amino acid
Interaction with soil components	Can bind to heavy metals, altering bioavailability	Minimal interaction with soil nutrients
Effect on soil microbiome	May disrupt microbial balance with long-term use	Supports microbial activity and soil health and acts as food source for microorganisms
Biodegradability	Poor and persistent in soil and water	Highly biodegradable
Environmental impact	Potential accumulation and toxicity in ecosystems	Environmentally friendly
Economic feasibility	Generally low due to large scale production	Slightly higher due to difficult extraction and synthesis

likely due to increased tryptophan availability-a key precursor in auxin biosynthesis, which regulates leaf expansion (27). Additionally, amino acids such as alanine, serine, phenylalanine and tyrosine have been shown to increase leaf concentrations of essential nutrients like calcium, potassium, iron, copper and manganese. In paddy crops, the foliar application of amino acid-chelated zinc and iron were compared to synthetic chelates and sulphate fertilizers, led to superior growth improvements. Notably, iron glycinate applied at 5 kg ha^{-1} to the soil and 1 % as a foliar spray achieved the highest plant height and SPAD values. The soluble glycinate form of iron supports continuous chlorophyll synthesis and promotes the production of phenolic acids and vitamin C in pods (34).

Effect on crop yield and quality

The use of amino acid chelate fertilizers markedly enhances plant yield and quality by promoting better vegetative growth and increasing dry matter production. This improvement results in superior nutrient uptake and more efficient use of chelated micronutrients. Amino chelates positively influence various yield components, including the number of flowers and fruits, fruit set, fruit size, number of seeds and seed size, thereby showcasing their potential to optimize agricultural productivity and crop quality (35). Notably, Fe amino chelates are found to be more effective than Fe-EDTA in nutrient solutions and can serve as an alternative for iron supply (36). On the other hand, amino acids alone can significantly boost biological yield under challenging conditions. For example, applying glycine at 300 and 600 mg/kg to coriander (*Coriandrum sativum*) reduced the number of flowering plants but extended the growth period, resulting in improved yield and biomass production (37). When amino acids are chelated with micronutrients, the resulting fertilizers offer increased efficiency and greater productivity and quality improvements.

For instance, applications of Zn-Gly and Zn-Ala resulted in higher zinc concentrations in plant tissues and greater seed yields compared to $ZnSO_4$. In cherry tomato cultivation under high-pH soilless conditions (pH 8.0), Fe-biochelates were found to be more effective than Fe-EDDHA in improving both yield and iron nutrition, likely due to their enhanced penetration and controlled nutrient release (26). In another study, integrating RDF (250:75:75 NPK kg/ha) with foliar applications of 0.2 % Fe-glycinate and Zn-methionine (17:17) raised maize grain yield to 5932 kg/ha and dry matter accumulation to 14013 kg/ha, outperforming conventional foliar treatments (38). The superior yields observed from foliar-applied amino acids can be attributed to their efficient penetration into leaf tissues. These amino acids are essential for a range of biological processes, including cell division, growth, mRNA transcription, photosynthesis, seed development and the synthesis of internal regulators, sugars and proteins (39). The detailed effects of amino chelate applications on yield enhancement are summarized in Table 3.

Amino acid chelate fertilizers not only significantly impact various biochemical parameters but also improve the quality of post-harvest products by extending their shelf life. Iron chelates have been shown to maintain storage quality by increasing L-ascorbic acid content, total carbohydrates, pH stability, phenol levels, ripening index, total soluble solids (TSS), titratable acidity (TA) and fruit firmness (26, 40). In tomato cultivation, the application of amino chelates such as Fe-Arg2 and Fe-Gly2 has been shown to boost the activity of antioxidant enzymes, including catalase (CAT) and ascorbate peroxidase (APX) (35). This suggests that glycine-chelated Fe is an effective option for enhancing antioxidant defense mechanisms in plants. For instance, a 1 % application of ferrous glycinate increased iron content, active Fe levels, catalase and peroxidase activity in black gram grown in calcareous soil because the chelated form of iron protected the mineral from fixation and ensured a gradual release. Similarly, Zn-amino acid chelates chelated with lysine (Lys), methionine, or threonine were found to be more effective than $ZnSO_4$ in enhancing growth and yield in onion cultivars (41). Zn-Lys notably enhanced zinc concentrations in onion tissues and resulted in lower nitrate content and higher total soluble solids (TSS) in bulbs compared to controls and $ZnSO_4$ treatments. Collectively, these findings confirm the broad-spectrum benefits of amino acid chelates on crop nutrition, metabolic health and post-harvest quality.

Improved bioavailability and uptake of nutrients

Several agricultural conditions can lead to reduced nutrient utilization efficiency, which is crucial for optimal crop development. Factors such as the physicochemical properties of applied fertilizers, plant genotype and environmental conditions all influence nutrient absorption efficiency (42). Chemical fertilizers often contain two or three ionic forms that can undergo detrimental interactions in the soil solution, such as complex formation, fixation, precipitation and leaching, which diminish their efficacy. Amino chelates, whether used in soil or as foliar sprays, enhance plant bioavailability by mitigating these negative reactions (9). Amino-based chelated fertilizers are anticipated to boost nutrient uptake and consequently, crop yields. Commercially available liquid amino acid chelate fertilizers typically have a pH range of 6-7, which enhances their stability, storage and absorption effectiveness. Amino acids like glycine and glutamic acid significantly enhance the uptake of essential minerals including calcium, zinc, copper and iron, especially under alkaline soil conditions where micronutrient fixation is a major constraint (42).

Zinc deficiency is a widespread issue that significantly reduces crop productivity and quality when not adequately addressed through fertilization. Typically, zinc use efficiency in crops is low, often below 5 % and influenced by soil factors such as pH, organic carbon content, free lime levels and nutrient interactions (43). To combat this, synthesized zinc-amino acid complexes have been developed to enhance zinc bioavailability and improve uptake, particularly in calcareous soils. Complexes like zinc alanine, zinc glycine, zinc phenylalanine and zinc tryptophan have been tested in hydroponically grown bean plants and wheat cultivars, showing promising results (44). This improvement is attributed to enhanced plant physiological traits, such as nitrogen metabolism.

Zinc use efficiency between Zn-EDTA and glycine-

Table 3. Impact of amino acid chelated micronutrients on crop yield

Crop type		Amino acids + micronutrients	Yield efficiency over control	Mechanism involved	References
Cereals	Rice	Fe glycine amino acid chelate	Fe-Gly increased the grain yield by 29.2 % over control	Improved rice yield, protein content and the levels of Zn and Fe in head rice	(76)
	Maize	Zinc-lysine chelate along with ZSB	Increased the cob diameter, cob length and 100 grain weight by 16.75 %, 42 % and 18.4 %, respectively	Application of Zn-Lys enhanced the biological yield due to expanded leaf area and greater plant height and dry matter production.	(48)
	Wheat	Zn-glutamine, Zn-glycine, Zn-arginine and Zn-histidine	46 % increase in yield compared to zinc sulphate alone	Zinc's role in auxin metabolism orchestrated the cell division, elongation and differentiation, root and stem tropisms and transition to flowering under stress condition	(77)
	Wheat	Zn glycine, Zn-Alanine	Increased the yield upto 4-4.5 times than $ZnSO_4$	Improved its bio accessibility by decreasing the phytic acid to Zn molar ratio	(78)
	Sorghum	Reasil micro-Amino Zn	The biomass productivity has been increased by 22.6-39.9 % over control	Amino acids like L-glycine, L-lysine and L-threonine acting as potent stimulants and complexing agents, ensuring trace elements are easily accessible to plants	(79)
	Sorghum	M(Gly)2] and [M(Met)]	Increase in grain yield of 33.3-36.4 % and 16.1-20.2 % as compared with control and non-chelated foliar application respectively	The foliar penetration of nutrients and amino acids through the cuticle is essential for cell growth, division, embryogenesis and seed development	(80)
Pulses	Soya Bean	Fe + Zn + Mn amino acid chelates	61.1 % increase in yield than control	Amino acid plays a crucial in mRNA transcription, cell division, somatic embryogenesis and photosynthesis	(30)
	Soya Bean	Fe + Zn + Mn amino acid chelates	61.1 % increase in yield than control	Amino acid plays a crucial in mRNA transcription, cell division, somatic embryogenesis and photosynthesis	(30)
	Black gram	Ferrous glycinate	Achieved maximum yield attributes, starch content and protein content of black gram in calcareous soil	The transport of nutrients and amino acids to developing structures enhanced the yield attributes	(75)
	Common bean	Zinc-histidine, zinc-methionine	21.6 % and 7.1 % increase in yield respectively compared to $ZnSO_4$	Zinc's role in tryptophan synthesis led to enhanced auxin biosynthesis that ultimately enhanced the growth attributes and flowering	(27)
	Peanut	Fe, Mn & Zn-amino acids	30.7 % increase in yield of peanut respectively over control	Higher absorption and targeted delivery of nutrients inside the plant tissues	(81)
Horticultural crops (Vegetables, fruits and spice crop)	Tomato	Fe-glutamate	Improved the fruit set and overall yield by 57 % and 44 % respectively over $FeSO_4$	Glutamate plays its direct role in seed germination, root architecture and pollen germination which all led to increase in yield attributes	(82)
	Tomato and cucumber	Amino acid chelates (2.0 % N-amino acid, 2.5 % Zn, 2.0 % Fe, 1.5 % Mn and 0.4 % Cu)	1500 g $plant^{-1}$ (cucumber), 770 g $plant^{-1}$ (tomato)	Quick nutrient absorption and distribution within the plant led to enhanced yield	(83)
	Date palm	Amino acid chelates (Mn-2 ppm, Cu-2 ppm)	42.2 % and 38.9 % yield increase over control (no amino acid chelates)	Amino chelated micronutrients boost antioxidant pathways, enhancing plant antioxidant capacity and fruit yield under stress.	(84)
	Apple	Zinc amino acid chelate and nano Zn-amino acid chelate	Fruit set has been increased by 60.2 %	Zinc played the crucial role in cell elongation; membrane function and protein synthesis enhanced the fruit set	(85)
	Cumin	Glycine and chelated zinc (@400 ppm + chelated-Zn @200 ppm)	30.6 % increase in no of umbel/plant over control	Stimulative effects of glycine and/or Zn-EDTA aided in promoting plant metabolism and activating the physiological processes of the crop	(86)
	Pistachio	Zinc methionine complex	Increased the nut yield by > 42 % in comparison with the control	Improved nut filling by promoting pollen tube growth, pollination and embryo development	(87)

chelated zinc was compared in maize, revealing that Zn-Gly significantly increased zinc concentrations in maize grains compared to Zn-EDTA. Moreover, a 0.4 % foliar spray of glycine-chelated zinc showed reduced phytotoxicity in maize leaves relative to $ZnSO_4$ (45). Research also indicates that amino acid-based chelates can outperform organic acid-based chelates in certain contexts. Hybrid tomatoes were found to absorb 30.4 % more zinc when treated with organo-zinc chelates, particularly zinc glycine and zinc glutamate, in comparison to zinc EDTA. Furthermore, combining zinc and magnesium chelated with glycine significantly increased crop biomass and seed yield of common beans by 55.3-80.6 % compared to controls (47). The application of 1.5 % Zn-lysine chelates with zinc-solubilizing bacteria (ZSB) further enhanced zinc content by 15.3 % in grains, 15.6 % in cob-pith, 49.1 % in stems and 33.0 % in roots compared to the control (48). The enhanced transportation and distribution of micronutrients and amino acids within plants due to amino acid chelate applications is illustrated in Fig. 2.

Iron deficiency is a common issue in crops, particularly due to its low solubility in calcareous soils. Advances in nanotechnology have led to the development of nanofertilizers coated with organic chelating agents, which enhance their solubility and bioavailability for plants (49). Consequently, organic coatings and chelated iron fertilizers are increasingly used as alternatives to traditional fertilizers. Despite their growing adoption, concerns about the action, dynamics, efficiency and safety of commercial chelate fertilizers persist. Amino acid-based chelates have shown potential in improving the efficiency of iron-based fertilizers. For instance, soybean seeds had the highest iron content with Fe glycine, followed by Fe glutamine, Fe lysine, Fe histidine and Fe arginine (36). Further studies reveal that foliar application of 1.5 kg ha^{-1} of Fe-glycine chelates increased iron content in head rice by about 32.6 %, which is due to glycine's role in enhancing chlorophyll synthesis, with iron being a key component of chlorophyll. Similarly, treatments with Fe glycine, Fe tyrosine and Fe chitosan at 20 mg Fe/kg enhanced both iron and nitrogen uptake in wheat, improving shoot iron concentration through more efficient transport mechanisms (50). However, caution is needed with higher doses of amino chelates, as they can cause phytotoxicity; for instance, applying EDDHA-Fe at 50 mg/kg to basil leaves initially increased iron content to 255 ± 1.50 mg/kg, but higher concentrations led to decreased iron content, indicating these fertilizers are beneficial primarily in iron-deficient soils (51).

In developing countries, shifting cropping patterns, such as the rice-wheat rotation, have led to increased iron (Fe) deficiency in rice, which subsequently causes manganese (Mn) deficiency in wheat (succeeding) crops. This situation has heightened the need for additional Mn supplementation. Research indicates that applying $MnSO_4$ alone in Mn-deficient soils effectively enhances Mn uptake in crops (2). However, studies have shown that Mn-chelates, when applied to hydroponically grown beans, do not improve yield, photosynthesis, or nutritional status compared to mineral forms. This may be due to impaired iron translocation to young leaves, potentially caused by the high stability of Mn in chelated forms, which disrupts nutrient balance (28).

Copper, an essential micronutrient, is found abundant in native soils hence it is often avoided in external applications due to risks of heavy metal pollution. Instead, copper is usually provided through nutrient solutions in hydroponic systems. For example, Cu-leucine chelate

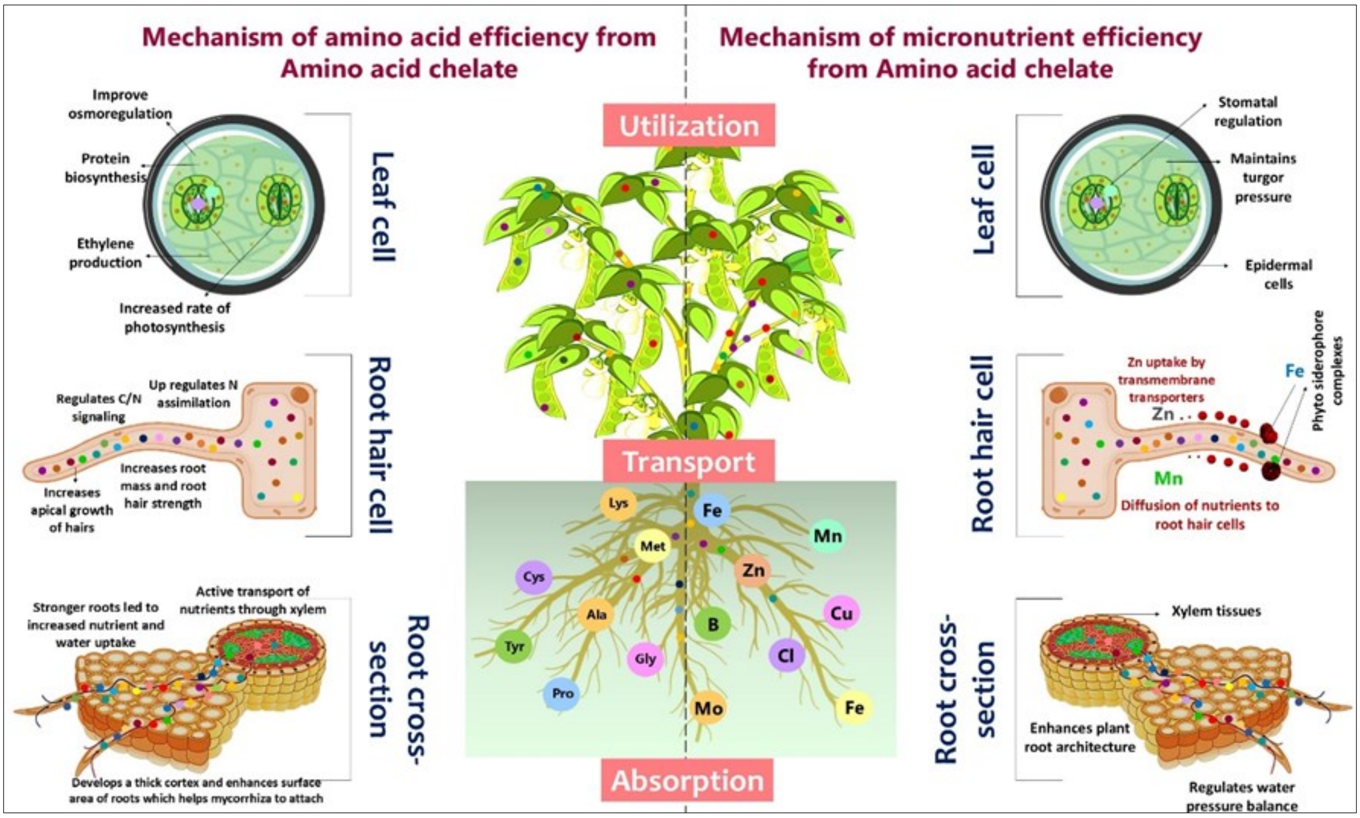

Fig. 2. Mechanism of amino acid chelates in plant system from plant cellular to root level.

application has been found to double copper content in hydroponically grown lettuce roots compared to $CuSO_4$. This increase is likely due to enhanced copper uptake facilitated by amino acids in nutrient solutions (52). These findings reinforce the potential of amino acid-based chelates to improve micronutrient absorption, contributing to better crop yield, quality and nutrient balance.

Effect of amino acid chelates on abiotic stress tolerance

Amino acids are increasingly recognized as vital biostimulants that enhance plant growth and yield while mitigating stress damage. Beyond their role as protein building blocks, they support various metabolic functions and strengthen plant resilience against abiotic and biotic stressors like UV radiation, drought, diseases and pests (53). For example, during drought stress in maize, proline levels increased fourfold, while asparagine rose 4.5 times and serine, glycine and aspartic acid levels increased by 2.2 and 1.5 times, respectively (54). These amino acids function as osmolytes, help maintain cellular pH, detoxify reactive oxygen species (ROS) and act as reserves for synthesizing enzymes and secondary metabolites, including flavonoids and lignin, which are crucial for stress recovery (35).

Amino acid chelated micronutrients have gained attention for their dual benefits, particularly in enhancing drought tolerance. These complexes significantly improve photosynthesis, both independently and under abiotic stress (42). The interaction between amino acids and minerals plays a key role in regulating cell organelles, facilitating micronutrient uptake and performing physiological functions, such as reducing ion toxicity, maintaining water balance, optimizing mineral absorption, regulating gas exchange and alleviating oxidative stress. As climate change intensifies, resulting in crop losses from frost and extreme temperatures, amino acid chelate fertilizers offer potential to mitigate environmental stresses like heat, cold, frost and biotic stressors (9). Salinity and drought, particularly harmful to crop productivity, disrupt physiological processes and restrict yields. Although data on the role of amino chelates in heat stress conditions remain scarce, further research is vital to fully harness their potential for improving crop resilience and sustainability.

Drought

In arid regions, water scarcity severely limits plant growth, with agriculture consuming 90-95 % of total water use. Drought stress worsens this by reducing nutrient transport from root to shoot due to lower transpiration and altered membrane transporter activity (55). Effective crop nutrition management is crucial for improving water use efficiency in agriculture. Nitrogen fertilization, including ammonium, amino acids and urea, can enhance plant water efficiency and optimize nitrogen use (56). Amino acids act as osmolytes, essential for ion transport, stomatal opening, protein synthesis, antioxidant enzyme activity and membrane integrity (57). Proline and glycine betaine are particularly effective in enhancing drought tolerance. Amino chelates, which deliver chelated macro- and micronutrients, boost tissue concentrations of key elements like potassium, calcium, zinc and boron, while simultaneously mitigating oxidative stress and reducing the toxic effects of sodium and chloride ions under drought conditions.

Micronutrients play a crucial role in activating essential physiological, biochemical and metabolic processes under drought stress. Their enhanced absorption through amino chelates is particularly significant (58). For instance, zinc application can alleviate drought stress by inhibiting membrane-bound NADPH oxidase, which reduces the generation of reactive oxygen species (ROS) and prevents photooxidative damage. Furthermore, zinc supplementation increases the activity of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), which are essential for ROS detoxification and enhancing plant resilience to drought (59). Zinc amino chelates, especially zinc tryptophan is effective in mitigating drought stress because tryptophan, a precursor of auxin synthesis, activates late embryogenesis abundant (LEA) genes through TLD1/OsGH3.13, thus bolstering drought resistance (60).

Soil water content fluctuations greatly influence plant iron absorption and availability, crucial for protecting plants from oxidative stress during drought. In moist soils, the Fe^{2+}:Fe^{3+} ratio rises, enhancing iron availability. Under drought, however, this ratio drops due to higher soil oxygen levels, limiting iron uptake (61). Foliar application of Fe-Lysine (Fe-Lys) has proven effective in mitigating drought stress in Nigella plants (62). Lysine, easily metabolized, serves as a precursor for proline, an osmoprotectant that reduces oxidative stress by enhancing antioxidant enzymes like peroxidase (POD), ascorbate peroxidase (APX) and Cu, Zn-superoxide dismutase (Cu, Zn-SOD) (63). Foliar iron aspartate also improves drought tolerance in sunflower, outperforming $FeSO_4$ due to aspartate's role in osmotic regulation and amino acid accumulation (64).

Salinity

Salinity stress significantly threatens sustainable crop production, potentially reducing yields by 20-50 % in various crops (65). It affects germination, growth and causes ionic toxicity, osmotic stress and nutrient imbalances. In saline conditions, micronutrient deficiencies occur due to reduced ion solubility, limiting plant uptake. Foliar nutrient application has been effective in mitigating these effects (66). Amino acid chelate fertilizers, whether applied via soil or foliage, offer minimal disturbance to soil salinity and nutrient balance. Numerous studies have demonstrated their effectiveness in enhancing salt stress tolerance in crops such as tomato, faba bean and wheat (67-69). Amino acid-based chelates improve stomatal conductivity, transpiration and photosynthesis, proving effective in reducing salt stress. For instance, zinc glycinate applied in saline hydroponics enhanced zinc uptake in lettuce, reduced lipid peroxidation and improved salt stress tolerance (37). The specific effects of amino acid chelate under different abiotic stress conditions are clearly illustrated in Fig 3. A detailed summary of these effects is also provided in Table 4 for better comparison and understanding.

Application Methods

Despite their agronomic and environmental advantages,

Table 4. Impact of amino acid chelates on mitigating abiotic stress

Abiotic stress	Amino acid chelates micronutrient	Crop	Concentration	Abiotic stress mitigation responses	References
Drought	Zinc lysine	Wheat	0.5 %	Zn-lysine played a key role in maintaining the plant's oxidative balance by facilitating the detoxification of reactive oxygen species (ROS), which can otherwise cause significant damage to cellular membranes	(88)
	Zinc and micronutrients	Maize	2.5 kg ha^{-1} and amino acids @ 200 mL L^{-1}	Proline accumulation was more strongly linked to alleviate the harmful effects of ROS and enhanced plant growth conditions	(89)
	Micronutrients + amino acids	Soyabean	0.5 kg ha^{-1}	Enhanced the activity of antioxidant enzymes, including superoxide dismutase, catalase and ascorbate peroxidase that alleviated the water stress	(90)
	Zn-Lys	Maize	25 mM	Effectively reduced cellular damage by limiting the excessive accumulation of hydrogen peroxide (H_2O_2) and malondialdehyde (MDA)	(91)
	Fe-amino acid chelates	Soyabean	nr	Fe functions as an activator for key enzymes such as catalase, cytochrome c oxidase and peroxidases. These enzymes play a crucial role in the biosynthesis of secondary metabolites, plant hormones and other biomolecules involved in signalling pathways	(36)
Heavy metal stress	Zn and Fe-Lys	Rapeseed	nr	Enhanced plant growth by reducing ROS levels and chromium concentration	(92)
Tannery wastewater -Cr toxicity	Zn-Lys	Maize	12.5 mM	Enhanced chlorophyll content and improved the photosynthetic system in maize crop grown in soil with toxic levels of Cr	(91)
Heavy metal stress (Cd stress)	Zn-Lys	Rice	Foliar - 0, 12.5 & 25 mM	Lysine had a direct impact on decreasing the electrolyte leakage (EL), malondialdehyde (MDA) and hydrogen peroxide (H_2O_2), while enhancing SOD, CAT and AP activity	(35)
Heavy metal stress (Cd stress)	Fe-Lys	Wheat	6 mg L^{-1}	Improves crop growth, enhances photosynthetic efficiency and boosts plant nutrient absorption in under cadmium contaminated soil	(93)
Salinity	Zn tryptophan (Zn-Trp)	Paddy	12 mg kg^{-1}	Tryptophan is a significant precursor of auxin which is a growth-promoting plant hormone thereby increased the transpiration rate, stomatal conductance and sub-stomatal carbon dioxide levels under salt conditions	(60)
	Micro nutrient amino acid chelated compound	Barley	nr	Boosts salt tolerance by reprogramming antioxidant defences and enhancing methylglyoxal detoxification, stabilizing the cell membrane	(94)
	Zinc foliar spray + amino acid	Rice	15 ppm	Application of amino acids led to increased protein biosynthesis and higher cell membranes integrity that can helped plants to maintain the hormonal balance of plant tissues under salinity stress	(95)
	Micronutrients + amino acids	Faba bean	nr	The presence of amino acids can influence the intracellular distribution of Na^+ and Cl^- ions, helping to mitigate their toxic effects on plant metabolic processes	(68)
	Iron (II) amino acid	Tomato	100 μM	Improved nutrient uptake as well as elevated activity of CAT and APX	(67)
High temperature	Free amino acids	Maize	6 mM and 3 mM	Seeds pre-treated with L-Arg and Gly, the amino acids, increased both the length of radicles and the number of lateral roots under high temperatures	(96)

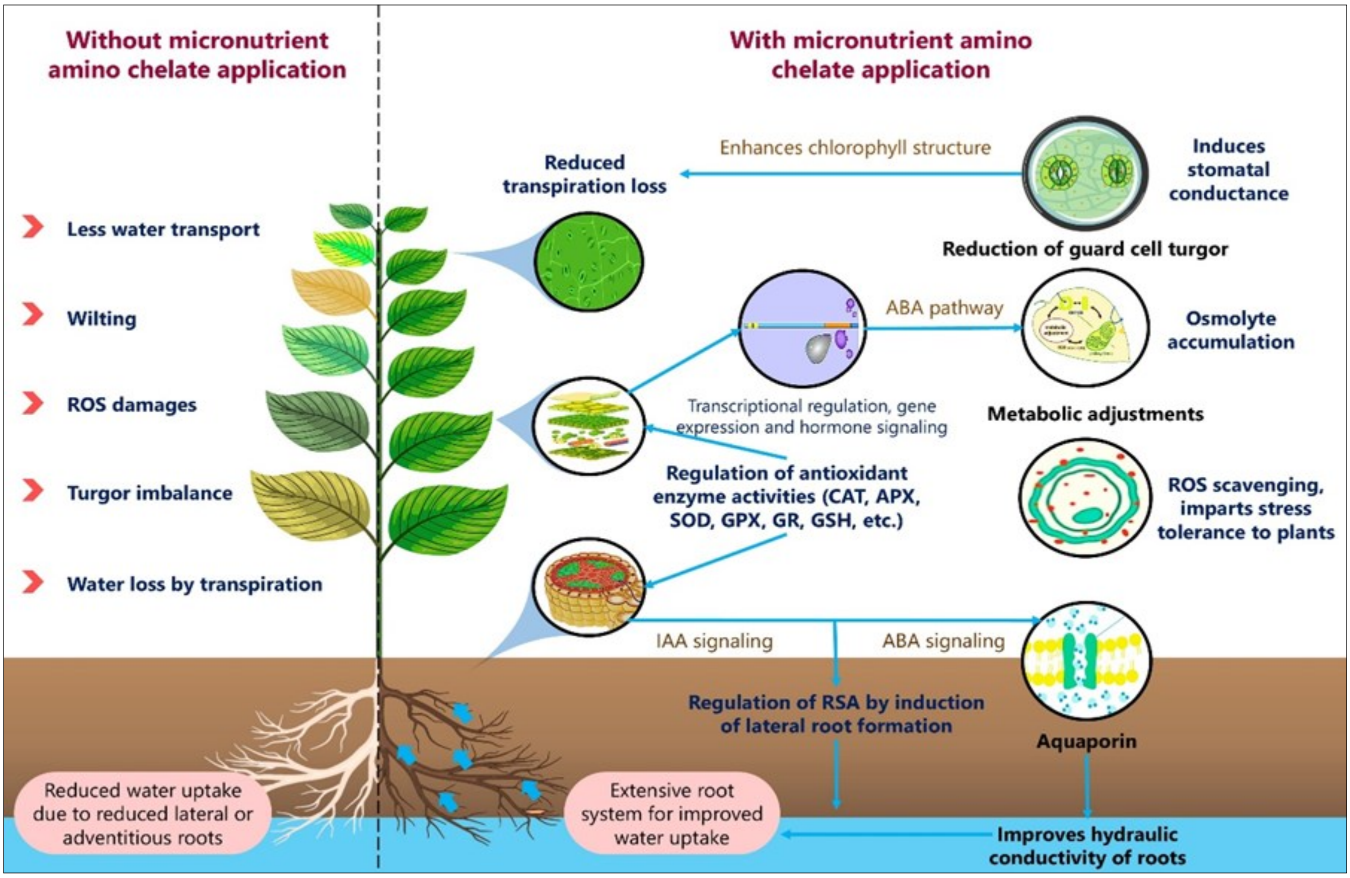

Fig. 3. Direct impact of amino acid chelates in plants under abiotic stress.

amino acid-based chelates present certain limitations. One key drawback is their relatively higher production cost compared to synthetic chelates, largely due to the use of purified amino acids and more complex manufacturing processes (70). Though amino acid chelates are safer than synthetic alternatives, overdosage can exhibit phytotoxic effects especially in foliar applications leading to symptoms such as leaf burn or growth inhibition (42). Furthermore, the overdosage might led to decrease the uptake of other nutrients. These risks highlight the importance of precise formulation and application practices to avoid adverse effects on plant health. Effective management of micronutrient deficiencies through targeted and cost-efficient interventions is crucial, as neglecting these deficiencies can lead to substantial yield losses, poor fertilizer efficiency and adverse environmental impacts. To mitigate these issues, amino chelates are applied through various methods: soil applications, foliar treatments and seed treatments. Soil applications are generally more efficient and economical compared to foliar treatments. However, foliar applications become a practical solution when deficiencies arise after crop emergence. Banding tends to be more effective than broadcasting, as broadcasting can sometimes fail to deliver micronutrients adequately due to low application rates, though it remains necessary in certain systems (71). Compared to non-chelated forms, chelated fertilizers, particularly amino chelates, exhibit superior mobility and nutrient availability within the soil.

Combining foliar feeding with amino chelates significantly enhances nutrient concentrations in plant tissues and reduces deficiencies, while also boosting plant resistance to both biotic and abiotic stresses (8). Natural chelators such as amino acids, due to their moderate molecular weight and extended organic chains, can readily penetrate the leaf cuticle and diffuse into the cytoplasm. However, in tender vegetable crops like cucumber and garden cress, foliar sprays may cause phytotoxicity, making soil application the preferred method (72). Soil application causes root cells to open channels or activate certain transporters, boosting nutrient uptake more efficiently. This method ensures that nutrients are directly utilized in plant metabolism with minimal loss, underscoring the effectiveness of natural chelates in optimizing nutrient uptake. Amino chelates can be applied through deep placement, banded application, or incorporated into fertilizer-irrigation systems. Deep placement enhances soil biological activity, as soil microbes utilize reduced nitrogen forms, such as amino acids and ammonium, more efficiently than nitrate (32). Amino acid chelates positively influence beneficial soil microbes by serving as biodegradable sources of carbon and nitrogen, promoting microbial activity and diversity. Unlike synthetic chelates such as EDTA, which may persist in soil and disrupt microbial communities, amino acid chelates decompose into nutrients and amino acids that stimulate the growth of beneficial taxa like *Pseudomonas* and *Bacillus*. They also enhance enzyme activity and microbial respiration without mobilizing harmful heavy metals. Additionally, application of amino acid chelates support rhizosphere interactions, improving colonization by symbiotic fungi such as arbuscular mycorrhizae (73), ultimately contributing to improved nutrient cycling and long-term soil health.

Long term application of amino acid chelate fertilizers can markedly improve nutrient absorption in saline and alkaline soils, comparable to the advantages offered by organic matter and humic acids. In calcareous soils, amino chelates applied through foliar sprays, soil treatments, or seed coatings effectively meet plant nutrient needs, making them popular among farmers in these regions (42). Another effective method is seed treatment or priming with amino acid-based chelated micronutrients. Coating seeds with micronutrients helps improve resilience against abiotic stresses, with amino acids like proline acting as osmoprotectants to maintain cell turgor and enzyme activity (42). Seed priming proves particularly effective due to the early provision of Zn during the plant's initial growth stage. For instance, a study comparing seed priming with zinc-amino acid chelates-zinc-histidine [Zn $(His)_2$] and zinc-methionine [Zn $(Met)_2$]-to zinc sulphate ($ZnSO_4$) in common bean cultivars revealed that the highest grain Zn concentrations were achieved with [Zn $(Met)_2$] in 'Sadri' and [Zn $(His)_2$] in 'Talash', respectively, compared to foliar application (27).

Future Thrust & Conclusion

For decades, traditional fertilization with low-efficiency chemical fertilizers has degraded soil fertility and quality which necessitated the need for more efficient and environmentally sustainable alternatives. Amino chelates offer a promising solution for improving micronutrient efficiency and mitigating abiotic stresses like drought, salinity and extreme temperatures. By chelating essential micronutrients such as iron, zinc, copper and manganese with amino acids, they can enhance nutrient uptake, translocation and utilization in plants. On the other hand, combining multiple micronutrients in a single chelate could further enhance crop nutrition and stress tolerance. This leads to improved crop performance, higher yields and better quality, particularly in nutrient-deficient or stress-affected soils. Amino chelates help maintain a steady nutrient supply, boost antioxidant activity and reduce oxidative stress, thereby enhancing plant resilience and enabling crops to withstand stress with minimal yield loss.

While current research highlights the numerous benefits of amino chelates, further investigation is needed to integrate advanced technologies, sustainable production practices and tailored nutrient solutions to address the evolving needs of modern agriculture. The application of nanotechnology in developing amino acid chelated micronutrients is a significant avenue, as nanoparticles can facilitate more efficient nutrient delivery and uptake in plants, potentially reducing the required fertilizer amounts and minimizing environmental impact. Additionally, utilizing biomass sources, such as agricultural and animal waste, for producing amino acids used in chelation can make the production of these fertilizers more sustainable and cost-effective. This approach not only reduces waste but also provides a renewable source of essential nutrients. It is also important to focus the ongoing research to evaluate the long-term environmental effects of amino acid chelated micronutrient use, including their interactions with soil microbiota and potential accumulation in ecosystems. Also, field trials are needed across different crops, regions and conditions to optimize application rates and timing for various climates, soil types and management practices to ensure their effectiveness in diverse agricultural framework. Cost-effectiveness remains a challenge due to higher production costs, potentially limiting widespread use. Incentives or subsidies may be needed to support farmers, especially in resource-limited regions, in adopting amino chelates. Overall, when applied in optimized dosages, amino chelates offer a sustainable solution to improve nutrient efficiency and enhance crop resilience to abiotic stresses.

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Authors' contributions

PN carried out conceptualization and writing - original draft. PPM helped in conceptualization, supervision, writing - review and editing. AG participated in writing - original draft, methodology and validation. JP supported in writing - original draft & editing. MP, KC and MY helped in writing - review and editing.

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