***Systematic Review***

**Effects of Amino Acid Fertilizers on Plant Growth, Crop Productivity and Soil Health: A Systematic Review**

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ABSTRACT

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| Amino acid-based fertilizers represent a sustainable alternative to chemical fertilizers, offering benefits such as enhanced plant growth, improved nutrient uptake, and soil health. This review systematically synthesizes current research on their benefits and limitations, while identifying key factors that influence their effectiveness in sustainable agriculture. This systematic review, conducted following PRISMA 2020 guidelines, analyzed 19 peer-reviewed studies published from 2020 to 2025 to evaluate the effects of amino acid fertilizers on crop productivity and soil properties. Articles were selected through a screening process from Scopus and ScienceDirect databases, applying defined inclusion and exclusion criteria to ensure relevance. Fertilizers containing amino acids, whether derived from organic waste materials or formulated as commercial products, have shown significant potential to enhance plant nutrient uptake, vegetative growth, yield, and stress tolerance. Their effectiveness is influenced by application method, dosage, crop type, and environmental conditions. While generally promoting photosynthesis, phytohormone activity, and soil nutrient availability, excessive use may result in reduced efficiency or phytotoxic effects, emphasizing the need for optimized management strategies. Overall, amino acid-based fertilizers offer considerable promise for improving nutrient use efficiency and crop performance, though further research is required to support their broader implementation in sustainable agriculture. |

*Keywords: Foliar Application, Soil Amendments, Sustainable Agriculture, Systematic Literature Review, PRISMA*

1. INTRODUCTION

The global agricultural sector faces increasing challenges due to rapid population growth, urbanization, and industrialization, which have led to the decline of fertile agricultural lands (Kaya & Coşkun, 2020). As a result, optimizing crop productivity while maintaining soil health has become a critical issue. The excessive and prolonged use of synthetic fertilizers has contributed to soil degradation, groundwater contamination, and reduced soil microbial diversity, necessitating a shift toward more sustainable fertilization practices (Tripathi et al., 2020).

To address these challenges, various natural or synthetic substances, including amino acids, humic acids seaweed extracts, and chitin derivatives have been widely explored for their ability to promote plant growth and enhance resistance to environmental stress while enhancing the efficiency of fertilizers and pesticides (Xie et al., 2019). Among these substances, amino acid-based fertilizers have gained attention due to their dual function: providing essential nutrients and stimulating plant physiological processes (Xie et al., 2019). In addition, some amino acids function as chelating agents, protecting plants from heavy metal toxicity while improving micronutrient mobility and uptake (Patrick, 2015).

Amino acids are fundamental components of proteins and play crucial role in metabolic processes, nutrient transport, and stress tolerance in plants (Moormann et al., 2022). Their application has been shown to enhance plant growth and nutrient uptake by increasing fresh, dry weight, and nitrogen yield while reducing nitrate (NO3-) content by 24-38% (Liu et al., 2008). Additionally, amino acid fertilizers contribute to more efficient nitrogen utilization, minimizing nitrogen losses while supporting plant development. The exogenous application of certain amino acids has demonstrated significant benefits for plant growth and development, particularly in maize, with pronounced effects under stress conditions, especially when applied foliarly (Matysiak et al., 2020). Furthermore, amino acids serve as an efficient nitrogen (N) fertilizer in plant nutrition, helping to reduce the adverse effects associated with conventional N fertilizers like urea (Souri & Hatamian, 2019). Their addition can also enhance root development, leading to improved nitrogen fixation and increased root surface area for nutrient uptake (Khan et al., 2019), while accelerating the production cycle and enhancing dry matter accumulation (Wahba & Motawe, 2015). Therefore, the application of amino acids promotes plant growth and improves crop yield(Zhang et al., 2022).

Abiotic stresses such as drought, salinity, and extreme temperatures negatively impact plant growth and yield. Amino acids help mitigate these stresses by acting as osmoprotectants, maintaining cellular integrity under adverse conditions (Ali et al., 2024). In addition, amino acid fertilizers support soil health by improving soil physicochemical properties and microbial activity. Unlike synthetic fertilizers, which contribute to soil acidification and nutrient leaching, amino acids provide a more sustainable alternative by enhancing plant productivity and nutrient retention (Radkowski et al., 2021). Plants can directly absorb intact amino acids, bypassing microbial mineralization of organic nitrogen while competing with soil microorganisms for uptake as a carbon and nitrogen source, thereby improving nitrogen retention in the soil (Cao et al., 2015; Lu et al., 2018).

Another key benefit of amino acid is their ability to chelate heavy metals and reduce metal toxicity in plants, while also enhancing micronutrient mobility and uptake (Patrick, 2015). Studies have demonstrated that amino acids fertilizer can facilitate the uptake of heavy metals by hyperaccumulator plants, improving their efficiency in remediating polluted environments (He et al., 2019). Compared to chemical fertilizers, amino acid fertilizers offer multiple benefits, including enhanced soil fertility, increased nutrient use efficiency, and reduced pesticide dependency, which collectively contribute to sustainable agriculture and environmental conservation (Wang et al., 2014).

Amino acid fertilizers are highly versatile and compatible with modern agricultural practices. Commercially available amino acid enhance fertilizer absorption, optimize nutrient and water uptake, boost photosynthetic efficiency, and improve dry matter distribution, ultimately leading to increased crop yield (Shafeek et al., 2018). Their water-soluble products allow easy integration into irrigation system, foliar spray, fertigation, or applied into soil. Compared to traditional chemical fertilizers offer several advantages including faster absorption by plant roots and leaves (Liu et al., 2008), reduces nitrate accumulation in plant tissues, making crops safer for human consumption (Cao et al., 2015; Rosa et al., 2022). Recent advancements in amino acid-based fertilizers include their integration with humic acids, biofertilizers, and organic amendments to enhance soil fertility and crop resilience (Abdo et al., 2022; Disciglio et al., 2024; Thu et al., 2023; Wang et al., 2023). Additionally, amino acid fermentation byproducts, such as those derived from monosodium glutamate production, poultry waste, and keratin-rich sources (e.g., chicken feathers and pig hair), provide cost-effective alternatives for organic fertilization.

Despite the numerous reported benefits of amino acid fertilizers, inconsistencies exist in the literature regarding their precise mechanisms of action, effectiveness under different environmental conditions, and interactions with soil microbiota (Adamczyk et al., 2010). Some studies suggest that amino acids act as direct nitrogen sources, while others indicate that they primarily regulate nitrogen uptake and assimilation rather than serving as primary nitrogen providers (Cao et al., 2015; Souri, 2016). Moreover, the inconsistent effects observed across varying application methods, crop species, and soil conditions highlight the necessity for a comprehensive systematic review to: (1) Synthesize existing research findings on the effects of amino acid fertilizers on plant growth, crop productivity, and soil health, (2) Identify key factors influencing their efficacy, such as soil type, environmental conditions, and application strategies, (3) Highlight knowledge gaps and future research directions to optimize amino acid fertilizer use in sustainable agriculture. By consolidating evidence from previous studies, this systematic review aims to provide a clearer understanding of the potential benefits and limitations of amino acid fertilizers, ultimately guidingtheir effective application in modern agriculture.

2. material and methods

This systematic review, conducted in accordance with PRISMA 2020 guidelines (Page et al., 2021), analyzed articles on amino acid fertilizers in agriculture, focusing on their effects on crop productivity and soil properties. The review encompassed data sources, inclusion and exclusion criteria, the systematic review process, and data abstraction and analysis.

**2.1 Inclusion and Exclusion Criteria**

This systematic review examined studies evaluating the impact of amino acid fertilizers on soil fertility and crop performance. Article selection was conducted based on the inclusion and exclusion criteria outlined in Table 1 to categorize the search results. The inclusion and exclusion criteria were applied to determine the eligibility of a systematic review article for inclusion or exclusion.

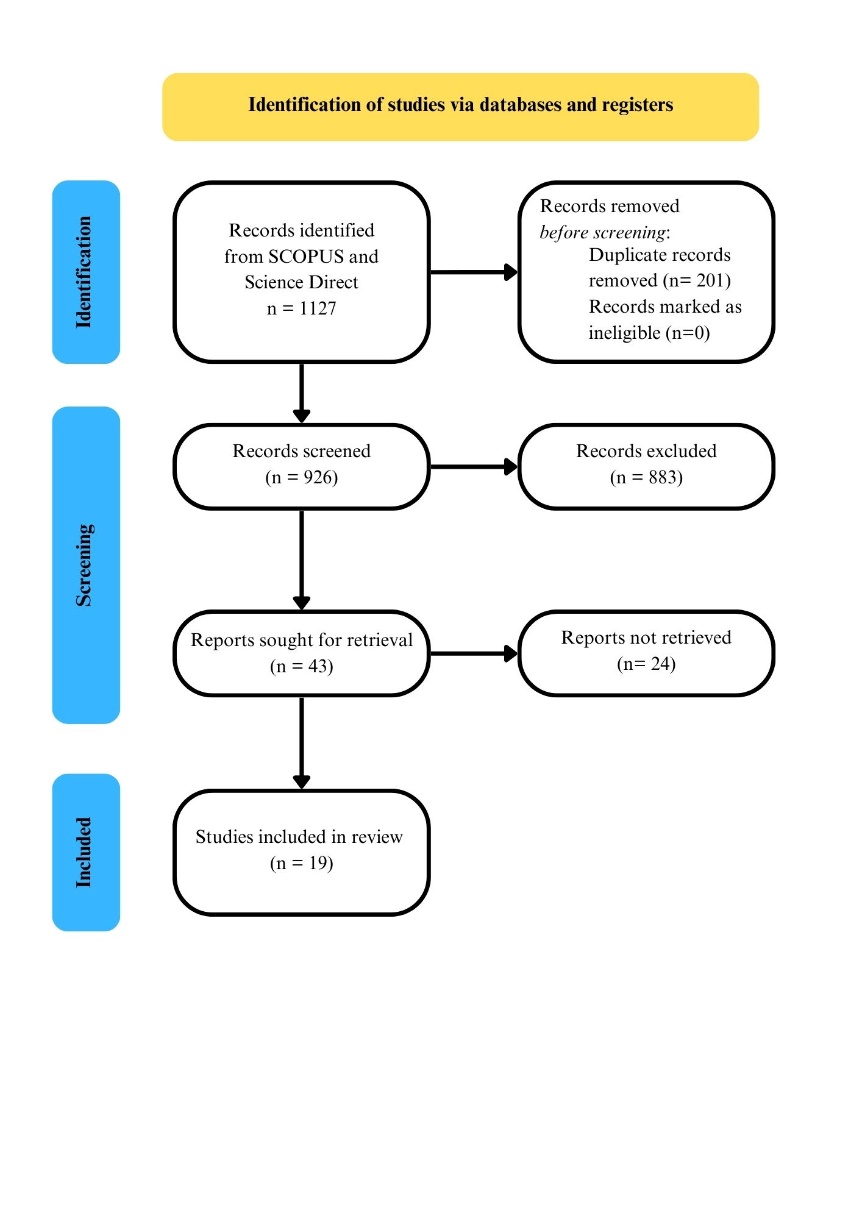
Table 1. Inclusion and exclusion criteria

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| **Criteria** | **Inclusion** | **Exclusion** |
| Period of publication | 2020-2025 | Articles prior 2020 |
| Language | Only article published in English | Articles in languages other than English |
| Publication Type | Research article | Conference Papers, Review Articles, Books/Books Chapters, Reports, Theses and Dissertations, Grey Literature |
| Accessibility | Open access | No open access |
| Databases | Scopus and ScienceDirect | Articles not indexed in Scopus or ScienceDirect |
| Research focus | 1. Studies assessing crop responses, such as growth parameters, nutrient uptake, photosynthesis, and yield.  2. Studies investigating the impact of amino acid fertilizers on soil properties, chemical composition, and nutrient dynamics. | 1. Studies that do not focus on non-agricultural applications of amino acids.  2. Research on biofertilizers, biostimulants, organic matter amendments, or other fertilizers without specific mention of amino acids. |
| Study Type | Experimental Study, Observational Study, Case Report | Review papers & Meta-Analysis, Unpublished studies, Conference Abstracts, and Opinion Papers |
| Subject Area | Agricultural and Biological Sciences, and Environmental Science | Other than Agricultural and Biological Sciences, and Environmental Science |

**2.2 Search Strategy and Database Selection**

The search strategy targeted manuscripts exploring the influence of amino acid fertilizers on key aspects, including plant development, yield, crop performance, soil characteristics and nutrient dynamics. Additionally, studies addressing environmental implications were included. Manuscripts not aligned with the review’s objectives were excluded. Searchers were performed in the Scopus and ScienceDirect database. Keywords for the database search were selected to ensure relevant studies were retrieved. The search results were obtained using a strategic combination of keywords, including: (“Amino acid fertilizers”) OR “Amino acid-based fertilizers” AND (“Soil fertility” OR “Soil health” OR “Soil amendments” OR “Organic Amendment”) AND (“Nutrient availability” OR “Soil chemical properties” OR “Soil organic matter”) AND (“Crop productivity” OR “Plant growth” OR “Yield”). The search was restricted to peer-reviewed journal articles and review papers published from 2020 to 2025, with studies written in English.

The search was completed on 9 March, 2025, yielding 1127 manuscripts. The identification and selection of studies for this systematic review followed a rigorous screening process, as illustrated in Figure 1. Initially, a total of 1,127 records were retrieved from SCOPUS and ScienceDirect databases. Prior to screening, 201 duplicate records were removed, leaving 926 records eligible for initial assessment.



**Fig. 1. Flow chart Systematic Literature Review**

During the screening phase, the titles and abstracts of these 926 records were reviewed to determine their relevance to the research objectives. As a result, 883 records were excluded based on predefined eligibility criteria, leaving 43 reports for full-text retrieval. Among these 43 reports, 24 were not included in the final review because their full-text content did not align with the titles and abstracts. Consequently, 19 studies met the inclusion criteria and were incorporated into the final review. This stepwise selection process ensured that only high-quality and relevant studies were considered for further analysis.

3. results and discussion

3.1 Types of Amino Acid Fertilizer

Amino acid significantly influences nutrient concentrations in plants, with their effects varying depending on the specific type of amino acid used, and can also be influenced by plant species and cultivation methods, such as soilless or soil-based systems (Wang et al., 2007). Moreover, the absorption efficiency of amino acid-based fertilizers is affected by several factors, such as the type and concentration of the fertilizer, the nutrient status of both the plant and the growing medium, the developmental stage of the plant, and prevailing environmental conditions (Liu et al., 2021).

Amino acid fertilizers can be derived from various sources such as algae extracts, fermented animal and plant waste (Liu et al., 2021; Zhang et al., 2021), or hydrolyzed animal carcasses (Liu et al., 2016). Zhang et al. (2021), developed a liquid amino acid fertilizer using a bionic approach based on the amino acid composition of earthworm (*Eisenia fetida*) epidermal mucus. However, since amino acids contain less nitrogen than conventional fertilizers like urea, larger quantities are required to meet the plant’s nitrogen needs. Similarly, Hashem et al. (2024), produced amino acid-rich liquid fertilizers (LFs) from animal waste materials like pig hair, chicken feathers, and their faeces using a method called microwave-assisted acid hydrolysis, where sulfuric acid and microwave heat help break down the materials and extracted amino acids from the materials.

Beyond organic waste-derived fertilizers, a wide range of commercial amino acid-based products is now available. Some formulations are enriched with micronutrients such as iron, copper, manganese, zinc, and boron, or combined with macronutrients like nitrogen, phosphorus, and potassium (Abdo et al., 2022; Disciglio et al., 2024; Octavia et al., 2024; Thu et al., 2023; Zhang et al., 2022). There are also commercial protein hydrolysate solutions that serve as a concentrated source of amino acids (Tsouvaltzis et al., 2020). Furthermore, these fertilizers can contain a wide range of amino acids, including Aspartic acid, Alanine, Arginine, Cystine, Cysteine, Glutamic acid, Threonine, Tyrosine, Proline, Leucine, Serine, Lysine, Methionine, Valine, Isoleucine, Aspartine, Phenylanie, and others (Al-Tufaili et al., 2025; Bakpa et al., 2021; Hu et al., 2023; Rosa et al., 2022; Salmani & Rezaei, 2023; Tsouvaltzis et al., 2020).

3.2 Methods of Application

Amino acid fertilizers can be applied through various methods, including foliar application (leaf spraying), soil application, fertigation, or seed soaking. They are available in different forms, such as liquid, granulated, or chelated with micronutrients, allowing for flexible application based on plant needs and soil conditions. In foliar application, the fertilizer is sprayed directly onto plant leaves, while soil application involves either dissolving the fertilizer in water and applying it to the soil or directly applying it in solid or liquid form around the root zone of plants.

Octavia et al. (2024) compared foliar and soil application methods for shallots, finding that foliar spraying led to higher nitrogen accumulation in plant tissues and increased total chlorophyll content, suggesting greater photosynthetic efficiency. Although soil-applied amino acids can enrich soil microbiota, they are more susceptible to microbial decomposition, potentially reducing direct plant uptake. Similarly, Brankov et al. (2020), reported that foliar application of amino acid-based fertilizers increased fresh matter by 5.5% to 51.6%, positively impacting maize growth and suggesting its effectiveness in enhancing crop yields.

Several other studies have further supported the efficacy of foliar application. Rosa et al. (2022) found that L-glycine applied at 40–120 mg·L⁻¹ significantly increased lettuce leaf length. Thu et al. (2023) showed that combining amino acid foliar sprays with organic fertilizer enhanced bean yield compared to conventional NPK treatment. Hu et al. (2023) also reported that foliar application promoted the accumulation of glycine, methionine, and phenylalanine in tubers. In terms of nutrient use efficiency, Liu et al. (2021) emphasized that foliar nitrogen delivery was more effective than soil application for improving nitrogen uptake.

Meanwhile, soil application methods have also been explored. Wang et al. (2023) applied granular amino acids at a rate of 1500 kg ha⁻¹ before planting and found that the treatment increased yield by elevating soil organic matter and effective nitrogen content. Similarly, Bakpa et al. (2021) used a water-soluble fertilizer diluted in 50 liters of water and applied it along planting furrows, while Alowaiesh et al. (2023) applied an amino acid mixture at a 1.5% (v/v) concentration to the soil surrounding ‘Kalamata’ olive trees. These approaches demonstrate that amino acid fertilizers can be effectively utilized through various delivery techniques, each offering unique benefits depending on crop type, growth stage, and management practices.

3.3 Effect on Plant Vegetative Growth

Amino acid-based fertilizers have been shown to enhance plant growth by improving nutrient uptake, stimulating hormone activity, and boosting photosynthesis. These effects support vegetative development, including leaf formation, stem elongation, and biomass accumulation. However, responses vary by crop, dosage, and application method, with some studies reporting significant improvements, while others show no notable differences compared to other treatments or untreated controls.

3.3.1 Nutrient Uptake and Accumulation

The application of amino acid-based fertilizers has consistently shown to enhance plant nutrient uptake, particularly nitrogen (N), phosphorus (P), and potassium (K). For instance, Octavia et al. (2024) observed that application rates of 0.5–1 L/ha increased leaf N by 1.02%, P by 0.3%, and K by 3.5%. These nutrients play essential roles: N supports vegetative growth, P drives energy transfer and root development, and K regulates osmotic balance and enzyme activation. Similarly, Liu et al. (2021) reported that foliar application amino acid liquid fertilizers increased the total N concentration in mature leaves of Spring Tea by 0.7%. This enhancement may be attributed to the fact that plants can absorb amino acids more efficiently than urea, as they bypass the energy-intensive process of converting absorbed nitrogen into amino acids (Jones & Kielland, 2002). Abdo et al. (2022) found that amino acids, when combined with NPK fertilizers, enhanced N, P, and K uptake in maize, leading to higher leaf area indices (LAIs), improved photosynthesis, and increased grain yields (Canellas et al., 2019).

In soil systems rich in organic matter, amino acids not only stimulate plant uptake but also enhance microbial activity and nutrient mineralization (Zhang et al., 2021). Liquid fertilizers with amino acids significantly increased nitrogen availability (Alowaiesh et al., 2023), with bionic fertilizer treatments achieving over 140% nitrogen improvement compared to control.

3.3.2 Photosynthetic Pigments and Efficiency

Multiple studies have demonstrated that amino acid treatments elevate chlorophyll content, SPAD values, and photosynthetic efficiency (Abdo et al., 2022; Alowaiesh et al., 2023; Rosa et al., 2022). Zhang et al. (2022) found that amino acid foliar applications increased chlorophyll a and b by up to 49.71%, and carotenoid content by over 80%, thereby enhancing light absorption and energy conversion in *N. officinale*. These effects are likely linked to the ability of amino acids to stimulate hormone synthesis in plants, which not only boosts photosynthetic pigment formation but also improves nutrient absorption. Bakpa et al. (2021) supported this finding, where 1.8 kg of amino acid fertilizer produced the highest chlorophyll concentration in peppers. These results align with Octavia et al. (2024) and Zhang et al. (2021), who attributed the increase in chlorophyll to stimulated hormone and enzyme activity that enhances chloroplast development and N assimilation. Alowaiesh et al. (2023) highlighted that amino acid-based liquid fertilizers significantly improved (p < 0.05) the photosynthetic efficiency of maize, with effects visible as early as five days after transplanting. Notably, differences in photosynthetic efficiency became evident just five days after transplanting, and plants under high-concentration treatments consistently exhibited better photosynthetic performance throughout the growth cycle. These results demonstrate the close link between amino acid application, improved photosynthesis, and higher productivity in crops like maize

**3.3.3 Phytohormone Synthesis and Vegetative Growth**

Amino acids have been closely linked to the upregulation of key phytohormones such as indole-3-acetic acid (IAA) and gibberellins, both of which are vital for regulating plant growth and development. Octavia et al. (2024) found that soil-applied amino acids at 2 L/ha yielded the highest IAA concentrations (5.81 mg/g), with foliar applications showing comparable results. These hormones stimulate cell elongation, leaf expansion, and root development, thereby enhancing vegetative biomass. Correspondingly, Jaff & Medan (2024) observed significant increases in stem and branch length, stem diameter, and leaf area in pomegranate trees treated with amino acids. Likewise, plant height, number of leaves, and number of branches were also enhanced significantly in multiple studies, further confirming the positive influence of amino acids on early plant development (Al-Tufaili et al., 2025; Rosa et al., 2022; Zhang et al., 2021). This can be attributed to the role of amino acids in enhancing characteristics of vegetative development by stimulating crucial activities, particularly the processes of cell division and elongation as well as boosting enzyme activity (Hildebrandt et al., 2015).

However, not all studies show consistently positive effects. Rosa et al. (2022) found that L-glycine foliar applications to lettuce increased leaf number and shoot traits, but had no significant effect on dry matter, protein, or sugar content. At high doses, reduced nitrogen in amino acids like glycine can even become toxic (Rosa et al., 2022). In the case of maize, Wang et al. (2023) reported that amino acid soil amendments had no significant effect on plant height or stalk diameter, indicating that while yield and grain quality may improve, structural vegetative traits might remain unaffected. Additionally, Bakpa et al. (2021) reported that although amino acid application increased root activity, this did not necessarily lead to improved plant growth or yield. This observation aligns with Thorup-Kristensen and Kirkegaard (2016), who argued that aboveground plant demand, rather than root system performance, often limits resource use efficiency under conditions of excessive fertilization, high rainfall, or suboptimal growth environments.

3.4 Crop Productivity, Yield, and Quality

Amino acid-based fertilizers have been widely explored for their potential to enhance crop productivity and improve yield quality across diverse agricultural systems. Numerous studies have demonstrated positive correlations between the application of amino acid fertilizers and improvements in grain yield, harvest index, fruit quality, and biochemical composition in various crops.

In maize, Brankov et al. (2020) observed an increase in grain yield upon the application of free amino acid (FAA) fertilizers, with the most pronounced increase at 32%. These improvements were attributed to enhanced nitrogen availability and rapid assimilation of amino acids, which are essential for protein synthesis and metabolic activity. Similarly, Abdo et al. (2022) reported that grain weight per ear had a direct and strong positive effect on grain yield in maize treated with amino acid-containing fertilizers, further supporting the argument that amino acids enhance nitrogen and phosphorus assimilation, leading to higher productivity. Amino acid application also positively influenced grain quality. Wang et al. (2023) reported that amino acid treatments to soil significantly enhanced maize crude protein content without altering sugar, fat, or starch levels. This improvement is likely due to amino acids’ dual function as nitrogen sources and protein precursors, as well as their role in stimulating microbial activity that enhances soil nutrient cycling (Wang et al., 2023).

Positive yield responses were also evident in vegetable crops. Bakpa et al. (2021) found that applying 1.8 kg of amino acid fertilizer to soil significantly improved pepper yield, capsaicin content, fruit firmness, and amino acid profiles. These benefits were likely due to the amino acid fertilizer serving as a readily available source of growth elements that support protein formation in plant tissues. While 2.7 kg improved fruit length, the 3.6 kg treatment led to a decrease in non-essential amino acids, suggesting that excessive application may be detrimental to fruit quality (Bakpa et al., 2021). This highlights the importance of dosage optimization to avoid diminishing returns and adverse effects on nutritional composition. Further supporting this, Disciglio et al. (2024) reported that soil application of amino acid-enriched fertilizer on tomato crops in low fertility soils significantly enhanced total and marketable yields, with increases up to 28.1%, highlighting their potential to compensate for poor soil conditions. The inclusion of micronutrients (Zn, Mg, Mn) likely worked synergistically with amino acids to support key physiological processes in fruit development.

In legumes, Thu et al. (2023) showed that foliar application of amino acid fertilizers led to considerable improvements in pod number, pod weight, and total yield in bush beans. These enhancements were attributed to the improved availability and uptake of organic nitrogen sources and essential micronutrients, which stimulated carbohydrate accumulation and improved flavor and sweetness (Hildebrandt et al., 2015; Sharma et al., 2012). Hu et al. (2023) expanded this perspective by linking amino acid fertilization with improved volatile flavor compound profiles in potatoes, noting increases in several key amino acids within the tubers that influence taste and aroma.

Contradictory findings also emerged, particularly in controlled or soilless systems. Tsouvaltzis et al. (2020) observed that intermediate concentrations (0.3%) of amino acid solutions did not significantly impact lettuce yield but did enhance quality parameters such as chlorophyll, Zn, and antioxidant content, while reducing nitrate accumulation. However, high concentrations (0.9%) inhibited root elongation and reduced biomass, suggesting osmotic stress due to increased electrical conductivity of the nutrient solution. Interestingly, despite the reduced biomass, the high concentration still led to elevated levels of proline and several mineral nutrients, indicating a complex stress response. This highlights a crucial caveat: amino acids at excessive concentrations can act as both biostimulants and stress inducers, especially in hydroponic environments. Bakpa et al. (2021)also showed that lower concentrations of soil application amino acid fertilizer (1.8 kg) outperformed higher ones (3.6 kg) in improving fruit diameter and weight in pepper, suggesting a risk of diminishing returns or toxicity at high application rates. Similarly, Rosa et al. (2022) found that L-glycine foliar applications to lettuce increased leaf number and shoot traits, but had no significant effect on dry matter, protein, or sugar content, reinforcing that not all studies show consistently positive effects.

Al-Tufaili et al. (2025) provided compelling evidence from field-grown tomato systems, showing a >160% increase in yield with the combined application of vermicompost and a commercial amino acid-based product compared to the control. The synergistic effect was attributed to enhanced physiological resilience, improved vegetative and root growth, and a more efficient recovery from abiotic stress. Overall, the existing body of research strongly supports the beneficial role of amino acid fertilizers in enhancing crop yield and quality. However, the magnitude of these effects is influenced by crop type, soil fertility, application method, and concentration. While moderate doses generally enhance productivity and quality traits, excessive application may reduce plant growth or nutrient balance, particularly in systems with high nutrient sensitivity.

3.5 Stress Tolerance

Amino acid-based treatments have demonstrated promising roles in enhancing plant tolerance to abiotic stress. Salmani & Rezaei (2023) reported that foliar application of amino acids significantly mitigated drought-induced yield losses in sweet pepper (*Capsicum annuum*), improving vegetative growth, fruit number, and overall yield. Under water stress conditions, the highest yield (2.93 kg/plant) was recorded with 300 mg/L amino acid treatment, compared to only 1.83 kg/plant in untreated stressed plants. This effect is hypothesized to stem from the role of amino acids in conserving energy and preventing protein degradation, although the precise physiological mechanisms remain unclear. Beyond drought resilience, amino acids have also been shown to bolster tolerance to heavy metal stress. Zhang et al. (2022) found that amino acid fertilizer enhanced the activity of antioxidant enzymes such as peroxidase (POD) and catalase (CAT) in *Nasturtium officinale*, thereby improving its resistance to cadmium (Cd) toxicity and promoting greater Cd uptake and accumulation—suggesting an enhanced phytoremediation potential.

3.6 Impact on Soil

3.6.1 Nutrient Availability

The application of amino acids (AA) and organic fertilizers has demonstrated a notable capacity to improve soil nutrient availability. Thu et al. (2023) reported that combining amino acids with organic fertilizers significantly increased the availability of nitrogen and phosphorus, while the presence of water-soluble phosphate helped suppress occluded phosphate formation, thereby enhancing phosphorus uptake and crop yield (Nardi et al., 2021). Similarly, Wang et al. (2023) observed substantial increases in soil nutrient levels, including organic carbon (23.36%–86.44%), alkali-hydrolyzable nitrogen (27.27%–41.80%), available phosphorus (20.77%–576.8%), and available potassium (13.14%–38.92%) under amino acid and humic acid treatments. These improvements are largely attributed to the high organic matter content in these amendments, which supports microbial mineralization during later stages of crop growth (Masunga et al., 2016; Siedt et al., 2021). Additionally, the use of organic amendments promotes the formation of stable aggregates that help sequester nutrients and prevent their microbial decomposition or leaching, thereby enhancing overall nutrient-use efficiency (Bailey et al., 2019; Bronick & Lal, 2005). Among organic-based soil amendments, amino acids enhance nutrient availability primarily through stimulating microbial activity and promoting organic matter decomposition, although their capacity for long-term nutrient retention and stabilization is relatively limited (Wang et al., 2023).

3.6.2 Soil Chemical Properties

The chemical properties of soil, particularly pH and salinity, are influenced by the application of amino acid-based fertilizers. According to Zhang et al. (2022) the use of amino acid fertilizers at 900–1500-fold dilutions resulted in a decrease in soil pH, which in turn increased the bioavailability of cadmium (Cd). This effect was likely due to the stimulation of organic acid exudation by plant roots in response to amino acid application, which enhanced the mobility of Cd in the soil (Montiel-Rozas et al., 2016). Wang et al. (2023) also reported that amino acid treatments reduced electrical conductivity (ECe) in the 0–50 cm soil layer and decreased soil pH in the 0–60 cm layer compared to control plots. Furthermore, salinity levels in the 0–40 cm soil layer were significantly lowered under amino acid treatments, with reductions ranging from 7.22% to 28.30%. These effects may be attributed to the presence of low-pH organic acids in the amino acid fertilizer, which can neutralize free hydroxide ions and improve the overall soil microenvironment (Wang et al., 2023). While amino acids contribute to chemical improvements in the soil, their impact is primarily through biochemical interactions rather than structural changes.

3.6.3 Soil Physical Properties

Soil physical properties such as moisture content and aggregation play a vital role in sustaining long-term soil fertility, and amino acid-based fertilizers have shown potential in enhancing these attributes. According to Wang et al. (2023), the application of amino acid fertilizer increased soil moisture content compared to untreated control (CK) plots, particularly in both the 0–40 cm and 40–100 cm soil layers, although to a lesser extent than other amendments. The treatment also contributed to an increase in the proportion of soil macro-aggregates in the 0–20 cm layer, suggesting improved soil structure. These effects are likely mediated through the stimulation of microbial activity and the decomposition of organic matter, which promote the formation of soil aggregates. However, the water retention capability of amino acids is relatively modest, as they do not possess strong water-absorbing properties. While amino acid treatments can support physical soil improvement through biological pathways, they do not directly enhance crop water use efficiency, since they do not influence plant water uptake mechanisms (Wang et al., 2023).

3.6 Challenges and Future Prospects

Despite growing evidence on the beneficial effects of amino acid-based fertilizers, current research still faces several limitations. Many studies are conducted under controlled conditions, which may not accurately reflect complex field environments. Variability in experimental designs, crop species, soil types, and application methods also leads to inconsistent results, making it difficult to draw generalized conclusions. Furthermore, limited understanding of the specific mechanisms by which different amino acids interact with plant physiological processes and soil microbial communities hinders the optimization of their use in diverse agroecosystems. In terms of future directions, research should prioritize long-term, field-based experiments that assess the cumulative effects of amino acid fertilizers under varying environmental and management conditions. There is also a need for molecular-level studies to elucidate the signaling pathways and metabolic responses triggered by amino acid treatments. In addition, developing standardized application protocols and evaluating their compatibility with other sustainable agricultural inputs could enhance their practical relevance. Integrating omics approaches and soil-plant-microbe interaction studies will be key to unlocking the full potential of amino acids as reliable biostimulants in resilient and sustainable cropping systems.

4. Conclusion

Fertilizers containing amino acids have demonstrated considerable potential to enhance plant productivity, improve nutrient use efficiency, and support long-term soil sustainability, positioning them as a viable alternative to conventional chemical fertilizers. Nonetheless, additional research is required to elucidate their mechanisms of action and to optimize their application under diverse environmental and soil conditions. Current evidence suggests that amino acid fertilizers contribute significantly to improved nutrient uptake, vegetative growth, and crop yield and quality. Their effectiveness is influenced by multiple factors, including the type and concentration of amino acids, the method of application, plant species, and surrounding environmental conditions. Foliar application often leads to more efficient nutrient absorption and increased photosynthetic activity, whereas soil application can enhance soil properties and microbial activity, although it may be more susceptible to microbial degradation.

Furthermore, amino acids are known to stimulate the synthesis of plant hormones, thereby promoting growth and developmental processes. However, their effects are not universally consistent, as plant responses may vary depending on dosage, crop species, and cultivation systems. In some cases, excessive application may cause nutrient imbalances, growth inhibition, or stress responses, particularly in highly controlled environments such as hydroponic systems. Therefore, careful adjustment of application rates and the integration of amino acid fertilizers with other nutrient sources, such as vermicompost or micronutrient-enriched amendments, is essential to achieve optimal agronomic outcomes. Overall, amino acid fertilizers represent a promising approach within sustainable agricultural practices, offering both productivity and environmental advantages when applied appropriately.

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