ANGIOTHERAPY REVIEW

Amino Acids and Polyamines in Foliar Spraying in Enhancing Medicinal Plant Resilience to Abiotic Stress – A Systematic Review

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Abstract

Background: Salinity and drought are significant environmental stresses that adversely affect the growth, metabolic processes, and yield quality of medicinal plants. These stresses lead to a decrease in photosynthetic pigments, plant morphology alterations, and an increase in reactive oxygen species, all of which negatively impact metabolite synthesis. This review explores the potential of amino acids and polyamines, applied through foliar spraying, to mitigate the detrimental effects of these stresses and enhance plant resilience. Methods: This review synthesizes current research on the role of amino acids and polyamines in alleviating the negative impacts of salinity and drought on medicinal plants. It examines how these compounds, when applied foliar, contribute to improved photosynthetic activity, growth, and essential oil production. The effects of specific amino acids such as L-phenylalanine, arginine, L-tryptophan, and glutamine, along with polyamines like putrescine and gamma-aminobutyric acid (GABA), were reviewed in relation to plant responses to environmental stress. Results: The findings suggest that foliar application of amino acids and polyamines significantly enhances plant stress tolerance. Amino acids contribute to the synthesis of proteins and nitrogenous compounds, while polyamines like putrescine regulate gene expression and cell functions, promoting better growth under stress conditions. Treatments with L-phenylalanine and arginine improved the morphological characteristics and essential oil yield of Salvia officinalis, while L-tryptophan and glutamine treatments enhanced rosemary plant growth. Polyamines, particularly putrescine, increased chlorophyll content and plant weight under drought conditions, and GABA improved growth in Lavandula dentate under salinity stress. Conclusion: Foliar spraying of amino acids and polyamines offers a promising strategy for enhancing the resilience of medicinal plants to salinity and drought stresses. Tailored treatments can improve photosynthetic pigment accumulation, reduce nitrate-nitrogen accumulation, and enhance yield quality by preventing leaf disorders. The review highlights the need for further research, particularly in vivo studies, to better understand the mechanisms through which these compounds enhance plant stress tolerance and optimize their application for medicinal plant cultivation under abiotic stress conditions.

Keywords: Amino acids, Polyamines, Foliar spraying, Drought stress, Salinity stress

Significance | This review discusses the potential of amino acids and polyamines in enhancing stress tolerance and improving medicinal plant resilience.

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Introduction

Medicinal plants, a diverse group of species, have been extensively

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utilized for their therapeutic properties in treating and preventing human diseases. Their role is rooted in traditional medicine systems across various cultures and remains integral to modern pharmaceutical advancements. The therapeutic efficacy of these plants arises from a synergy of bioactive compounds, including terpenoids, phenolic compounds, flavonoids, alkaloids, tannins, glycosides, and essential oils, which collectively contribute to their medicinal properties (Muhammadiyeva, 2024). These compounds exhibit diverse biological activities, such as anti-inflammatory, antioxidant, and antimicrobial effects (Kurkin et al., 2023; Singh, 2024), with structural diversity in terpenoids and flavonoids significantly enhancing their therapeutic potential.

Prominent families of medicinal plants, including Lamiaceae, Asteraceae, and Apiaceae, are renowned for their phytochemical richness and bioactive diversity. For instance, the Lamiaceae family, comprising aromatic species such as oregano (*Origanum vulgare* L.), mint (*Mentha* spp.), and rosemary (*Salvia officinalis* L.), produces essential oils rich in monoterpenes and sesquiterpenes, which are recognized for their antimicrobial, antioxidant, and anti-inflammatory properties (Isnaini et al., 2024). Similarly, the Asteraceae family, known for plants like chamomile (*Matricaria chamomilla*) and echinacea (*Echinacea purpurea*), offers a wealth of phenolic acids, flavonoids, and terpenoids with significant pharmacological applications (Mouffouk et al., 2023). The Apiaceae family, encompassing species like fennel (*Foeniculum vulgare*) and parsley (*Petroselinum crispum*), is celebrated for its antimicrobial and antitumor properties attributed to compounds such as furanocoumarins and flavonoids (Das et al., 2023).

The synthesis and regulation of these secondary metabolites are influenced by abiotic stressors such as salinity, drought, and thermal changes, which can enhance or suppress their production. Secondary metabolites play a pivotal role in plant adaptation, serving as defense mechanisms against environmental stresses and contributing to medicinal properties. For example, phenolic compounds and flavonoids are effective in scavenging reactive oxygen species (ROS), mitigating oxidative stress, and enhancing the plant's resilience under adverse conditions (Kumar et al., 2023). While abiotic stresses like drought and salinity may stimulate metabolite production, excessive stress often hampers plant growth and productivity, necessitating strategies to optimize secondary metabolite synthesis.

This review explores the critical roles of secondary metabolites in medicinal plants, emphasizing their biosynthetic pathways, environmental modulation, and therapeutic applications. It also highlights innovative strategies, including the use of elicitors like amino acids, polyamines, and plant extracts, to enhance the production of bioactive compounds under abiotic stress conditions. By integrating insights from recent studies, this review underscores the potential of secondary metabolites for sustainable medicinal plant production and their broader applications in healthcare and agriculture.

2. Methodology

This review incorporated multiple keywords, including amino acids, polyamines, algae extracts, yeast extracts, and plant extracts as elicitors. Abiotic stresses, particularly salinity and drought, were examined in relation to their effects on plant families such as Lamiaceae, Asteraceae, Apiaceae, and Solanaceae. The impact of elicitors on plant growth and secondary metabolite production was also analyzed.

Reputable databases, including Web of Science, Scopus, ScienceDirect, PubMed, and Google Scholar, were used to gather data. Findings from these studies were systematically summarized and categorized into various sections of this review article, providing a comprehensive understanding of the strategies for mitigating abiotic stress effects in medicinal plants.

3. Common Medicinal Plant Families

Medicinal plants play an essential role in traditional and modern medicine, offering a plethora of therapeutic applications due to their diverse bioactive compounds. Certain plant families stand out for their rich phytochemical profiles, enabling their extensive use in treating various ailments. Among these, the families Lamiaceae, Asteraceae, and Apiaceae are particularly notable.

3.1 Lamiaceae (Mint Family)

Lamiaceae, commonly referred to as the mint family, comprises over 7,000 species across 236 genera, making it one of the most ecologically and economically significant plant families (Marzouk et al., 2018; Hamed et al., 2021). This family is renowned for its aromatic species, which produce essential oils rich in monoterpenes and sesquiterpenes, such as limonene and caryophyllene, known for their antimicrobial, anti-inflammatory, and antioxidant properties (Isnaini et al., 2024).

Historically, plants from the Lamiaceae family have served multiple purposes, including food flavoring, preservation, and medicinal applications (Nieto, 2017; El-Gharbaoui, 2017). Common representatives like oregano (*Origanum vulgare* L.), mint (*Mentha* spp.), culinary sage (*Salvia officinalis* L.), rosemary (*Lavandula* spp.), and thyme (*Thymus vulgaris* L.) are widely recognized for their extensive use as both culinary spices and herbal remedies (Ulewicz-Magulska & Wesolowski, 2023; Babotă et al., 2023). These plants contribute significantly to traditional medicine, addressing conditions ranging from digestive disorders to respiratory ailments.

3.2 Asteraceae (Sunflower Family)

The Asteraceae family, also known as the sunflower family, is among the largest plant families globally, encompassing between 1,600 to 1,911 genera and approximately 32,000 to 33,000 species

(Panda et al., 2019; Akhmetollayeva et al., 2024). Members of this family are rich in bioactive compounds such as phenolic acids, flavonoids, and terpenoids, which exhibit potent antioxidant, anti-inflammatory, and antibacterial activities (Mouffouk et al., 2023).

Traditional medicine has long utilized Asteraceae plants, with species like chamomile (*Matricaria chamomilla*), echinacea (*Echinacea purpurea*), and calendula (*Calendula officinalis*) gaining recognition for their therapeutic properties. These plants are employed to treat a variety of conditions, including inflammation, microbial infections, and oxidative stress-related disorders. Their pharmacological benefits have been increasingly validated by modern scientific research (Awuchi & Morya, 2023).

3.3 Apiaceae (Carrot Family)

The Apiaceae family, comprising approximately 434 genera and 3,700 species, is another significant group within the plant kingdom (Xu & Chang, 2017). This family is distinguished by its rich content of secondary metabolites and essential oils, which contribute to its antimicrobial, antifungal, and antitumor properties. Compounds such as flavonoids and furanocoumarins are particularly notable for their ability to induce apoptosis in cancer cells, highlighting their potential in oncology (Salehi et al., 2019; Das et al., 2023).

Representative species from the Apiaceae family, including fennel (*Foeniculum vulgare*), parsley (*Petroselinum crispum*), and coriander (*Coriandrum sativum*), are widely used in both culinary and medicinal contexts. These plants offer therapeutic benefits ranging from digestive support to immune modulation.

4. Secondary Metabolites and Abiotic Stress Mitigation

Secondary metabolites (SMs) are a diverse group of organic compounds synthesized by plants and certain microorganisms. Unlike primary metabolites, they are not directly involved in growth and development but play critical roles in stress response and survival (Omokhefe Bruce, 2022). These metabolites include phenolic compounds (e.g., flavonoids and phenylpropanoids), nitrogen-containing compounds (e.g., alkaloids and glucosinolates), and terpenoids (e.g., isoprenoids) (Jamwal et al., 2018; Sanchez & Demain, 2011).

Biosynthetic pathways for SMs include the malonic acid pathway, shikimic acid pathway, methylerythritol phosphate (MEP) pathway, and mevalonic acid pathway. These pathways facilitate the production of diverse metabolites that contribute to plant survival under various stress conditions, including thermal, osmotic, drought, and salinity stress (Figure 1).

4.1 Functions and Roles of Secondary Metabolites

Secondary metabolites serve multiple roles, such as defending plants against pathogens, attracting pollinators, and adapting to environmental stresses (Chen et al., 2022). They contribute to plant color, fragrance, and flavor, enhancing the plant's ability to thrive in challenging environments. For instance, phenolic compounds and flavonoids are highly effective in scavenging reactive oxygen species (ROS), thereby mitigating oxidative stress and preventing cellular damage (Kumar et al., 2023a; Ray et al., 2024).

Additionally, SMs such as phenolic compounds and glucosinolates have been linked to improved water uptake and transport, which are critical under drought and salinity stress conditions (Nicolas-Espinosa et al., 2023). However, the production of these metabolites is often stress-specific, posing challenges in maximizing their potential for agricultural applications. Crop domestication has, in some cases, reduced metabolite diversity, making plants more susceptible to environmental stresses (Pérez-Llorca et al., 2023).

4.2 Environmental Influences on Secondary Metabolite Production

The synthesis and accumulation of secondary metabolites are significantly influenced by environmental conditions. Stress factors such as drought, salinity, and extreme temperatures can enhance or suppress metabolite production, affecting plant adaptation and resilience. For instance, environmental stressors often induce ROS formation, which triggers the production of antioxidant metabolites like phenolics and flavonoids (Aftab, 2019).

Over 200,000 bioactive phytochemicals derived from more than 391,000 identified plant species have been documented globally, highlighting the immense potential of secondary metabolites in plant physiology and human health (Yeshi et al., 2022). These compounds are invaluable for their roles in plant survival and as active ingredients in pharmaceuticals, nutraceuticals, and agrochemicals.

Medicinal plants from families such as Lamiaceae, Asteraceae, and Apiaceae offer immense therapeutic potential due to their rich phytochemical profiles. Their secondary metabolites play pivotal roles in mitigating abiotic stress and contributing to plant adaptation. By understanding the biosynthetic pathways and environmental influences on secondary metabolite production, researchers can harness their full potential for sustainable agriculture and pharmaceutical development.

4.3 Abiotic Stresses and Their Effects on Medicinal Plants

Abiotic stress conditions, such as drought, salinity, extreme temperatures, and nutrient deficiencies, significantly impact medicinal plants by triggering biochemical and physiological changes. These stresses often activate the shikimate pathway, which produces aromatic amino acids that serve as precursors for secondary metabolites (SMs) (Gupta et al., 2023). Abiotic stresses, including osmotic stress and ion toxicity from drought and salinity, disrupt water balance, nutrient assimilation, and photosynthetic efficiency in plants. Such disruptions affect chlorophyll metabolism, degrade plastids, and induce oxidative stress, ultimately reducing photosynthesis rates and plant productivity (Nazari et al., 2023; Rahman et al., 2023). These conditions alter the biosynthesis of SMs, leading to changes in their concentration and composition (Rahman et al., 2023; Jampílek & Kráľová, 2023). While mild stress can stimulate SM production, severe stress often hampers plant growth and reduces both the yield and quality of these bioactive compounds (Jampílek & Kráľová, 2023).

4.4 Plants' Responses to Environmental Stresses

Medicinal plants deploy multiple defense mechanisms to mitigate the detrimental effects of abiotic stresses. These include accumulating osmolytes, producing antioxidants, and enhancing SM production. Biostimulants and phytohormones have been shown to bolster stress tolerance by improving nutrient uptake, mitigating oxidative damage, and increasing chlorophyll content (Tadele & Zerssa, 2023; Nazari et al., 2023).

Genetic variability in plants plays a crucial role in determining their response to stress. Differences in metabolic pathways can lead to variations in the synthesis of bioactive compounds. For example, in Lonicera japonica, transcriptomic analyses have revealed genetic differences that influence the production of phenolic acids, flavonoids, and terpenoids, all vital for the plant's medicinal properties (Yuan et al., 2012). These genetic and environmental interactions are critical for understanding plants' adaptability to stressors, including climate change, pathogens, and herbivory (Yeshi et al., 2022).

Secondary metabolites serve essential roles in ecosystem functioning, defense, and communication, aiding plants in minimizing damage from environmental stresses. Abiotic stress impairs critical metabolic processes such as water uptake, photosynthesis, respiration, and protein synthesis. These effects are often mediated by the excessive accumulation of reactive oxygen species (ROS) (Alnusaire et al., 2022). Plants counteract these stresses through membrane stabilization, structural maintenance, and the production of antioxidants and SMs. Complex interactions between phytohormones and genetic regulation modulate these responses, enabling adaptive changes in metabolism and defense mechanisms (Lerner, 2018).

5. Elicitation and Its Mechanisms

Elicitation enhances Sexpression through transcription factors such as WRKY, MYB, and bHLH. These factors bind to promoter regions, activating defense-related genes and initiating secondary metabolite production in response to stress (Gupta et al., 2023). Signal perception and transduction are central to elicitor-induced responses, which play a pivotal role in increasing SM yields in plant cultures (Goel et al., 2011).

This cost-effective approach is particularly valuable for pharmaceutical applications. For example, elicitation strategies have significantly increased the production of tropane alkaloids, which are widely used in medicinal formulations (Wen et al., 2023).

5.1 Salinity Stress

Salinity refers to the concentration of dissolved salts in water, often expressed in practical salinity units (PSU), derived from the ratio of a seawater sample's conductivity to that of a standard potassium chloride solution (Barrientos et al., 2021). In freshwater systems, salinity is measured using total dissolved solids (TDS) or electrical conductivity (EC). TDS quantifies the solid residue after water evaporation, while EC assesses the ease with which water conducts electricity (Othata & Pochai, 2019).

Salinity is a major agricultural challenge, especially in arid and semi-arid regions. It disrupts osmotic balance, induces ion toxicity, and alters soil properties, such as pH and nutrient availability, leading to reduced crop yields and microbial diversity (Majeed & Muhammad, 2019; Rai et al., 2024).

Medicinal plants exposed to salinity stress often enhance their antioxidant defenses, increasing the activity of enzymes such as catalase, peroxidase, and superoxide dismutase (Tran et al., 2024; Bistgani et al., 2023). Secondary metabolites like phenolics, flavonoids, and essential oils are frequently produced in higher concentrations under moderate salinity conditions, contributing to the plant's medicinal value (Bistgani et al., 2023). Additionally, compounds like proline and other osmolytes play a vital role in osmotic adjustment and stress tolerance (Kumar et al., 2023b).

Salinity stress affects fundamental physiological processes, including photosynthesis, water uptake, and ion homeostasis. The degradation of chlorophyll and accumulation of ROS lead to reduced photosynthetic efficiency and oxidative damage. Furthermore, the osmotic stress and toxicity of ions such as Na+ and Cl– disrupt nutrient balance, severely impairing plant growth (Nazari et al., 2023; Haider et al., 2023).

Abiotic stresses significantly impact the growth, productivity, and medicinal properties of plants. These stressors induce complex biochemical and physiological responses, altering the biosynthesis and accumulation of secondary metabolites. Advances in understanding plant stress mechanisms, coupled with biotechnological interventions like elicitation and the application of biostimulants, can improve plant resilience and the quality of medicinal compounds. By leveraging genetic diversity and optimizing stress mitigation strategies, researchers and agriculturists can enhance the sustainable cultivation of medicinal plants under challenging environmental conditions.

5.2 Drought

Drought is a critical environmental stressor that negatively impacts crop production, soil moisture, and agricultural yields. It is closely linked to meteorological and hydrological factors, including reduced precipitation and increased evaporation due to rising temperatures (Walia et al., 2024). Climate change is predicted to intensify the frequency and severity of droughts globally, further exacerbating their effects (Salehi-Lisar & Bakhshayeshan-Agdam, 2016). Droughts contribute to soil degradation, reduced vegetation growth, and adverse impacts on wildlife and aquatic ecosystems. Alterations in hydrological regimes and water quality degradation are additional consequences (Merlo et al., 2023).

In medicinal plants, drought stress disrupts critical physiological processes such as photosynthesis and respiration, leading to reduced plant size, diminished leaf area, and overall lower biomass (Shil & Dewanjee, 2022; Bistgani et al., 2024). Key indicators, including relative water content (RWC) and water use efficiency (WUE), decline under drought conditions, affecting plant turgor and metabolic activities. Photosynthesis is among the earliest processes impacted, with chlorophyll metabolism disruption leading to decreased CO_2 uptake and diffusion (Khalid et al., 2023; Nazari et al., 2023; Tan & Gören, 2024).

Interestingly, drought can increase the concentration of certain secondary metabolites, such as alkaloids, tannins, and terpenoids, either through enhanced biosynthesis or reduced overall biomass production (Shil & Dewanjee, 2022). In some cases, this stress-induced accumulation of bioactive compounds enhances the medicinal properties of plants, improving their antioxidant, antidiabetic, and anticancer activities (Balamurugan et al., 2024).

Structural changes in plants, such as reduced leaf size and increased root-to-shoot ratio, are common adaptations to drought. These changes minimize water loss and improve water uptake efficiency (Bistgani et al., 2024). Additionally, plants increase the production of osmoprotectants and antioxidants to mitigate drought-induced oxidative stress. This includes the activation of enzymatic antioxidants and the accumulation of osmolytes like proline (Khalid et al., 2023; Tan & Gören, 2024). Drought-resistant genes and pathways, such as the abscisic acid (ABA) signaling pathway, are also activated to enhance plant resilience during water scarcity (Liao et al., 2023).

5.3 Strategies for Mitigating Salinity and Drought Effects

Enhancing the tolerance of medicinal plants to abiotic stresses, such as drought and salinity, involves several strategies. Seed priming, the application of exogenous compounds like amino acids and polyamines, and the use of beneficial soil microbes, including mycorrhizal fungi and plant growth-promoting rhizobacteria, have shown promise (Lamsaadi et al., 2024; Misra & Mall, 2024). Genetic and breeding approaches, along with the use of salt- and drought-tolerant rootstocks, are also being explored to improve plant resilience (Chaudhary et al., 2024).

Emerging technologies, such as nanoparticles and growth regulators, offer additional avenues for stress mitigation. However, the application of nanoparticles requires caution, as their effectiveness varies with plant species, nanoparticle type, and environmental conditions. Low concentrations of nanoparticles can be beneficial, but higher doses may induce phytotoxicity, exacerbating stress (Kwaslema & Michael, 2024; Soni et al., 2024).

This review focuses on the potential of amino acids and polyamines as effective tools for mitigating the adverse effects of abiotic stresses while promoting sustainable production of medicinal plants.

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6. Foliar Application of Amino Acids and Polyamines in Medicinal and Aromatic Plants under Stress Conditions

6.1 Echinacea purpurea*: Drought and Foliar Application Effects*

Drought stress had notable effects on *Echinacea purpurea*, significantly increasing proline content from 13.83 μmol g^{-1} under normal conditions to 37.11 μmol g^{-1} under drought conditions. The interaction between drought stress and foliar treatments was significant, with the highest proline concentration (57.83 μmol g^{-1}) observed in plants subjected to drought without foliar spraying. However, foliar application of proline did not significantly influence volatile oil content. Increased drought severity resulted in the highest volatile oil concentration (71 μL/100 g dry matter). The dominant volatile oil compounds included germacrene D (44–52%), *p*-cymene (8–9%), α-pinene (3–5%), β-caryophyllene (6–8%), and β-bisabolene (3–4.5%). Foliar proline significantly improved the concentrations of these compounds except for β-bisabolene (Danesh-Shahraki et al., 2023).

6.2 Lavandula dentata*: Salinity and Gamma-Aminobutyric Acid (GABA)*

Salinity stress negatively affected the vegetative growth of *Lavandula dentata*. The highest saline water concentrations reduced plant height, fresh weight, and dry weight. However, the foliar application of GABA mitigated these effects, with significant improvements in growth traits at 1000 and 2000 ppm GABA. Fresh and dry weights were maximized with 40 mM GABA, especially under 2000 ppm salinity conditions.

Salinity reduced chlorophyll *a* and *b* contents, but GABA application significantly enhanced photosynthetic pigments. The highest chlorophyll and carotenoid contents were observed in plants treated with GABA under moderate salinity conditions. Salinity increased relative water content and proline accumulation, with GABA-treated plants showing higher proline levels, especially under mixed irrigation water at 2000 and 3000 ppm.

Essential oil yield declined under elevated salinity levels but improved with GABA application, particularly in moderately stressed plants. Antioxidant enzyme activities, including SOD and APX, were elevated under moderate salinity but declined under severe stress. GABA significantly boosted enzyme activities under saline conditions. Overall, foliar application of 40 mM GABA improved growth, root characteristics, photosynthetic pigment retention, water content, proline accumulation, and antioxidant activity in *Lavandula dentata* (Shala et al., 2024).

6.3 Plectranthus amboinicus: *Salinity and Arginine*

Salinity stress adversely affected *Plectranthus amboinicus* morphological traits, including leaf area and shoot and root weights, particularly at 4 g/L salinity. However, arginine application mitigated these effects, with the highest morphological improvements observed in control plants treated with arginine. The combination of salinity and arginine increased essential oil percentages, with the highest accumulation at 4 g/L salinity and 300 mg/L arginine.

Salinity and arginine treatments enhanced the concentration of major essential oil constituents such as carvacrol, thymol, γ-terpinene, and limonene. Oxygenated monoterpenes were the dominant components under these treatments. Photosynthetic pigment contents (chlorophyll *a*, chlorophyll *b*, and carotenoids) were highest in unstressed plants treated with arginine but decreased with increasing salinity levels.

Proline accumulation peaked at 4 g/L salinity combined with 300 mg/L arginine, indicating enhanced osmotic adjustment. While salinity inhibited protein synthesis, the salinity-arginine interaction increased protein content. Nitrogen pyruvate (NPK) accumulation in leaves decreased with salinity but was restored by arginine. Salinity and arginine also significantly enhanced antioxidant enzyme activities, particularly SOD and APX, demonstrating their combined efficacy in alleviating salinity-induced oxidative stress (Ahmed et al., 2020).

6.4 Rosmarinus officinalis: *Soil Salinity and Amino Acids*

Soil salinity significantly reduced the dry weight of *Rosmarinus officinalis*. However, foliar application of amino acids such as L-tryptophan and glutamine at 100 and 200 ppm mitigated these effects. Rosemary plants treated with L-tryptophan + glutamine and exposed to salinity levels of 1.17 and 3.34 ds/m exhibited improved growth and dry weight. At higher salinity levels (9.68 ds/m), proline content in leaves increased significantly, particularly when L-tryptophan + glutamine was applied.

Salinity increased volatile oil content, with the highest percentages observed under L-tryptophan + glutamine treatments. Camphor content reached 40.21% at 9.68 ds/m salinity with combined amino acid application, while eucalyptol peaked at 12.47% under similar conditions with L-tryptophan alone. These findings suggest that foliar spraying of amino acids can enhance the tolerance and productivity of *Rosmarinus officinalis* under saline conditions (Al-Fraihat et al., 2023).

6.5 Salvia officinalis

Significant impacts ($p \leq 0.01$) were observed on essential oil content, oil yield, and dry matter yield of *Salvia officinalis* due to the main effects of year, drought, organic inputs, L-phenylalanine, and their interactions. The highest dry matter yield occurred in the second year when a combination of 50% L-phenylalanine × 100% field capacity (F.C.) × cow dung manure was applied with arbuscular mycorrhizal fungi (AMF). Conversely, the lowest yield was recorded in the first year under negative control conditions. Essential oil content peaked in the second year with the same treatment combination, while the lowest concentration was observed during the first year in a negative control setting with 50% F.C. The highest oil yield was recorded with 50% L-phenylalanine × 100% F.C., and the lowest yield occurred under negative control treatments.

Among volatile compounds, monoterpene hydrocarbons and oxygenated sesquiterpenes were highest under negative control conditions, whereas oxygenated monoterpenes increased with 50% L-phenylalanine application. Key essential oil constituents, such as 1,8-cineol, α-thujene, β-thujene, and camphor, demonstrated increased concentrations under optimal treatments, enhancing antibacterial properties. A positive correlation was identified between volatile oil content, yield, and dry matter yield across the two experimental years (Hasanabadi et al., 2024).

6.6 Thymus vulgaris

Foliar application of putrescine (butane-1,4-diamine) significantly improved the performance of *Thymus vulgaris* under drought stress. Chlorophyll concentration increased with putrescine application at 0.1 or 0.2 mM, although the Chl a/b ratio remained unchanged. Both concentrations of putrescine significantly enhanced shoot and root fresh and dry weights, with 0.2 mM producing the most significant improvements ($p \leq 0.05$).

Putrescine application elevated phenylalanine ammonia-lyase (PAL) activity and total soluble phenol concentrations, indicating enhanced phenolic metabolism. Additionally, polyphenol oxidase (PPO) activity increased, with 0.1 mM putrescine showing the highest activity. These metabolic changes reduced the adverse effects of drought stress, enabling plants to better adapt to water deficit conditions. Notably, 0.2 mM putrescine enhanced essential oil yield, promoting growth and productivity under drought stress (Abd Elbar et al., 2019).

6.7 *Trachyspermum ammi*

Drought stress significantly reduced leaf relative water content (RWC) in *Trachyspermum ammi*, with arginine (Arg) pretreatment mitigating these effects. The highest RWC values were recorded under control and -0.5 MPa treatments. Severe drought stress (-0.5 MPa) led to a 41.9% reduction in RWC compared to the control. Electrolyte leakage (EL) increased under drought stress, with the highest osmotic potential resulting in an 84.7% increase in EL compared to controls. However, Arg pretreatment reduced EL across all stress levels.

Soluble sugar content increased under drought, with the highest levels recorded at -0.5 MPa and Arg pretreatment (9.37). Chlorophyll a, b, total chlorophyll, and carotenoids decreased under drought conditions, with reductions of 24.7%, 33.33%, 27.5%, and 21.8%, respectively. Arg pretreatment effectively alleviated these reductions under severe drought.

Anthocyanin and flavonoid contents rose under drought stress, with anthocyanins increasing by 57.3% at -0.5 MPa. Spectrophotometric measurements revealed that Arg application further enhanced flavonoid levels under drought conditions. PAL and PPO activities also increased significantly under drought, with the highest PAL activity (15.9) recorded at -0.5 MPa. These findings indicate that Arg pretreatment enhances *Trachyspermum ammi* tolerance to drought by modulating osmotic potential, enzyme activity, and secondary metabolite accumulation (Kabiri et al., 2021).

7. Discussion

Our review demonstrates the versatility of amino acids and polyamines as foliar treatments, offering sustainable solutions for enhancing the resilience and productivity of medicinal and aromatic plants under adverse environmental conditions. Future studies should focus on optimizing dosages and exploring synergies between different amino acids and polyamines to maximize their benefits.

Amino acids and polyamines serve as effective foliar treatments for mitigating abiotic stresses in medicinal and aromatic plants. Their roles in osmotic adjustment, antioxidant defense, and metabolite regulation are critical for maintaining plant health under stress conditions.

Proline as a Foliar Spray:

In *Echinacea purpurea*, proline application enhanced drought tolerance by increasing proline content and improving essential oil composition (Danesh-Shahraki et al., 2023).

In *Lavandula dentata*, proline accumulation was linked to improved water retention and osmotic balance under saline conditions, with GABA also enhancing these effects (Shala et al., 2024).

Arginine for Salinity Stress:

Arginine application in *Plectranthus amboinicus* improved morphological traits, essential oil yield, and antioxidant activity, highlighting its potential as a salinity stress mitigator (Ahmed et al., 2020).

Amino Acid Combinations:

The combined application of L-tryptophan and glutamine in *Rosmarinus officinalis* boosted growth, volatile oil production, and tolerance to high salinity levels (Al-Fraihat et al., 2023).

7.1 Overview of Foliar Spraying with Amino Acids and Polyamines

This review examines the potential of foliar spraying with amino acids and polyamines to mitigate the effects of salinity and drought on medicinal plants. These environmental stresses adversely impact plant growth, morphology, and metabolite synthesis. Amino acids and polyamines are crucial in reducing these negative effects and improving plant resilience.

7.2 Impact of Drought and Salinity on Medicinal Plants

Drought stress significantly reduces plant growth parameters, photosynthetic pigment levels, and morphological features, including internode and shoot lengths. It also triggers reactive oxygen species (ROS) production and osmolyte accumulation while enhancing secondary metabolite concentrations such as rosmarinic acid and total phenolic content. These changes may increase the antioxidant capacity of plants.

In *Thymus vulgaris*, drought stress decreases chlorophyll content and total soluble protein levels while increasing carbohydrates, proline, and phenolics. Similarly, in *Dracocephalum moldavica*, drought raises sodium and chlorine content in leaves, leading to higher ion leakage and lipid peroxidation. Moderate drought stress alters essential oil composition, increasing compounds like geraniol and geranial while enhancing enzymatic antioxidant activities and proline content.

For *Rosmarinus officinalis*, drought stress boosts proline content in leaves, aiding osmotic adjustment and stress tolerance. In *Trachyspermum ammi*, drought stress reduces leaf relative water content (RWC), but arginine (Arg) treatment alleviates these effects. Salinity similarly impacts rosemary leaves, altering chlorophyll levels, brightness, and color values. High salinity reduces root and shoot growth, chlorophyll content, and zinc accumulation but can improve yield quality by reducing nitrate-nitrogen levels and preventing disorders like "blackheart" in young leaves.

7.3 Role of Amino Acids and Polyamines in Stress Mitigation

Amino acids, the building blocks of proteins and nitrogenous compounds like neurotransmitters, contain amino (-NH2) and carboxylic acid (-COOH) groups. Polyamines, characterized by two

Table 1: Different species affected by Amino Acids and Polyamines when grown under abiotic stress

Species	Stress	Elicitor	Physiological & biochemical characters	Secondary metabolites	Reference
Apium graveliens L.	Salinity stress	Silicon and Aspartic Acid	Growth parameters: Fresh weight and shoot length, tap root length, leaf length and width, whole dry weight, and stem diameter. Net photosynthesis. Transpiration rates. Stomatal conductance. Soluble Sugar, Starch, Soluble Protein, and Carotenoids. Electrolyte concentrations (Na, K, Ca, and Mg Concentration). Antioxidant Enzymes (SOD, CAT, POD, and APX) Activities. Oxidative Damage.	Not measured.	Song et al., (2024)
Calendula officinalis L	Drought stress: normal irrigation, 25, 50 and 75% field capacity.	proline (0, 50 and 100 mg L^{-1})	Growth characters: (Fresh weight of the aerial and root organs, Dry weight of the aerial and root organs, Plant height and root length, Number of flowers, Longevity of the flower on the plant, total chlorophyll, Carotenoid, and Total antioxidants (DPPH)). Protein percentage. SOD activity. Total phenols. Total flavonoid. Carbohydrates. Vitamin C.	proline	Soroori, Sophia, et al., (2021).
Echinacea purpurea (L.) Moench	Drought stress: 75–80% and 40-45% F.C.	salicylic acid and proline	Growth characters (plant height, fresh and dry weights).	volatile oils and proline content.	Danesh-Shahraki et al., (2023).
Lavandula dentata L	Salinity stress: 0, 1000, 2000, and 3000 ppm	Gamma Aminobutyric Acid	Growth characters: Photosynthetic Pigments (chlorophyll and carotenoids). Relative Water Content. Proline Content. Antioxidant Enzyme Activities (Catalase, Polyphenol oxidase)	Essential Oil and their components	Shala et al., (2024).
Plectranthus amboinicus lour	Saline stress: NaCl (0, 2 and 4 g/L)	arginine (0, 150 and 300 mg/L)	Growth characters (leaf area, fresh and dry weights of shoots and roots) Photosynthetic pigments, proline, soluble sugars, crude protein, nutrients (NPK), antioxidant enzymes activities and protein banding patterns of Indian borage	Essential oils and composition, proline and soluble sugars	Ahmed et al., (2020)

Table 1. Continuous

Rosmarinus officinalis	soil salinity levels (1.17, 3.34, 6.51, and 9.68 ds/m)	amino acid (control, L-tryptophan acid at 100 ppm, glutamine acid at 200 ppm, and L-tryptophan acid + glutamine acid)	Growth (Plant height (cm), dry weight of herb/plant (g), Salt Resistance Index Percentage, Total Chlorophyll Content, Proline Content (mg/g as Dry Weight).	Volatile Oil Percentage and oil compositions.	Al-Fraihat et al., (2023)
Salvia officinalis L.	Drought stress (50% and 100% F.C.)	25 and 50% L-phenylalanine	The leaves, stem.	Essential oils	Hasanabadi et al., (2024)
Thymus vulgaris	Drought at levels 70–80% and 30–40% of water holding capacity	Putrescine (butane-1,4-diamine) at 0, 0.1 and 0.2 mM	Chlorophylls (Chl a, Chl b) and Chl a/b ratio, shoot, root fresh and dry weights, total soluble phenols, Phenylalanine ammonia-lyase (PAL), polyphenol oxidase (PPO) activity	Essential oil (%) and total flavonoid contents and their compositions	Abd Elbar et al., (2019)
Trachyspermum ammi	Drought stress (osmotic stress levels of -0.3 and - 0.5 MPa): induced by polyethylene glycol 6000	Arginine (0, 10 and 20 µmol)	Leaf Relative Water Content (RWC). Electrolyte Leakage. Soluble Sugar Content. Chlorophyll Content and Carotenoids Content. Anthocyanin Content. Flavonoids Content. Polyphenol Contents. Soluble proteins. Phenylalanine Ammonia-lyase (PAL) Activity. Polyphenol Oxidase (PPO) Activity.	Not measured.	Kabiri et al., (2021)

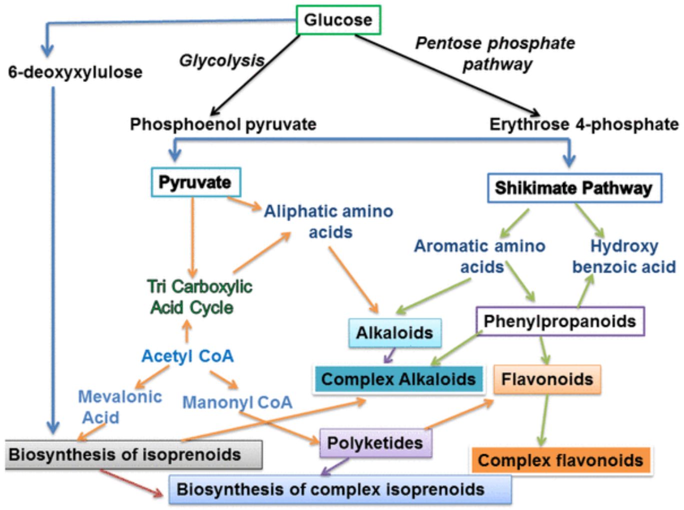

Figure 1. Biosynthesis pathway of secondary metabolites in plant (Isah., 2018).

or more amino groups, are essential for various cellular functions. Common polyamines include spermidine, spermine, and putrescine, which play vital roles in growth and development.

7.3.1. Amino Acids

Amino acids promote photosynthetic pigment accumulation, even under stress conditions like high salinity, enhancing photosynthesis and overall plant health. They also influence proline accumulation, an essential osmoprotectant that maintains cellular osmotic balance and shields plants from stress-induced damage. For instance, foliar application of L-phenylalanine and organic inputs significantly increased essential oil yield in *Salvia officinalis*. Similarly, aspartic acid supplementation promoted growth in celery plants under NaCl stress, while proline improved growth and chlorophyll content in *Calendula officinalis* under drought conditions.

L-tryptophan and glutamine applications at 100–200 ppm have shown promising results in enhancing growth and salinity tolerance in rosemary plants, improving the productivity of medicinal and aromatic species.

7.3.2 Polyamines

Polyamines influence physiological processes such as stress responses, organogenesis, and cell membrane stability. Foliar application of putrescine at 0.1–0.2 mM improved chlorophyll content and increased fresh and dry weights of shoots and roots in *Thymus vulgaris* under drought stress. These concentrations also elevated phenylalanine ammonia-lyase (PAL) activity and total soluble phenol levels, improving drought tolerance.

Gamma-aminobutyric acid (GABA), another polyamine, demonstrated significant benefits for *Lavandula dentata* under salinity stress. GABA application at 1000–2000 ppm enhanced antioxidant enzyme activity, plant height, and branch number, mitigating growth reduction caused by salinity. In *Plectranthus amboinicus*, arginine application under saline conditions improved morphological traits and essential oil production.

7.4 Mechanisms Underlying Stress Tolerance

Amino acids and polyamines contribute to stress tolerance through various mechanisms:

Nitrogen Metabolism: Amino acids play critical roles in nitrogen assimilation pathways, acting as substrates for protein synthesis and signaling molecules to regulate growth and stress responses (Song et al., 2012).

Osmotic Adjustment: Proline accumulation under drought acts as an osmolyte, stabilizing proteins and cellular structures (Ingrisano et al., 2023).

Ion Homeostasis: Amino acid treatments reduce ion toxicity and improve the uptake of essential ions like potassium under stress conditions (Abdelkader et al., 2023).

Cellular Integrity: Polyamines stabilize cellular membranes and regulate water transport by influencing xylem cell differentiation, crucial for stress resilience (Blázquez, 2024).

7.5 Enhancing Plant Productivity with Amino Compounds

Exogenous application of amino acids and polyamines improves photosynthetic efficiency and secondary metabolite production, enhancing plant growth and quality. For example, L-phenylalanine application increased key essential oil components in *Salvia officinalis*, while glutamine enhanced antioxidant capacity in rosemary. Polyamines such as putrescine and spermidine also stimulated phenolic biosynthesis, which strengthens plant defenses against abiotic stresses.

8. Perspective

This review highlights the potential of foliar spraying with amino acids and polyamines to mitigate the effects of salinity and drought stress in medicinal plant families. Drought stress significantly impairs plant growth parameters, reduces leaf photosynthetic pigments, and alters morphology, resulting in shorter internodes and shoots. It also triggers the accumulation of reactive oxygen species (ROS) and osmolytes, which can cause oxidative damage. At the same time, drought stress enhances the concentration of secondary metabolites such as rosmarinic acid and total phenolic content, potentially increasing the plant's antioxidant capacity. For example, in rosemary (*Rosmarinus officinalis*), drought stress induces proline accumulation, which aids in osmotic adjustment and stress tolerance.

Salinity stress affects plant growth and development by altering chlorophyll levels, leaf brightness, and color values. High salinity significantly reduces root and shoot growth, chlorophyll content, and zinc accumulation. However, salinity can improve yield quality in certain cases by reducing nitrate-nitrogen accumulation and mitigating physiological disorders such as "blackheart" in young leaves.

The foliar application of amino acids and polyamines can alleviate these stress effects by improving photosynthetic pigment accumulation, enhancing photosynthesis, and boosting overall plant health. Treatments such as gamma-aminobutyric acid (GABA) have demonstrated the potential to improve growth parameters in *Lavandula dentata* under saline conditions, while arginine application has been shown to enhance the morphological characteristics of *Plectranthus amboinicus*. These findings emphasize the role of amino acids and polyamines in improving plant resilience and productivity under various environmental stresses.

Despite these promising outcomes, challenges remain. The response of plants to amino acid and polyamine treatments varies widely depending on species, environmental conditions, and application methods. This underscores the need for tailored approaches to maximize the effectiveness of these treatments. Additionally, there is a significant gap in research regarding the in vivo pharmacological effects of medicinal plants treated with amino acids and polyamines. This limits the understanding of their broader implications for human health and medicinal use.

Furthermore, while the physiological and biochemical mechanisms underlying stress tolerance are partially understood, many remain unclear. Research on the role of amino acids and polyamines in regulating stress responses in medicinal plants is still limited, particularly under abiotic stress conditions such as drought and salinity. Future studies should focus on elucidating these mechanisms and exploring the long-term impacts of amino acid and polyamine applications on plant growth, metabolite profiles, and medicinal properties.

The foliar application of amino acids and polyamines is a promising strategy to enhance the growth and resilience of medicinal plants under salinity and drought stress. By improving physiological and biochemical processes, these compounds support stress adaptation and productivity. Their roles in nitrogen metabolism, osmotic adjustment, and cellular stability underline their potential for broader agricultural applications.

Future research should focus on optimizing concentrations and combinations of amino acids and polyamines for various plant species and stress conditions. Additionally, integrating these treatments with sustainable farming practices could further enhance crop performance and resilience in the face of changing climatic conditions.

9. Conclusion

In conclusion, foliar spraying with amino acids and polyamines offers a promising avenue for enhancing the resilience of medicinal plants to salinity and drought stress. Addressing the current research gaps through comprehensive studies and developing species-specific, environmentally optimized strategies will be critical for realizing the full potential of this approach in sustainable agriculture and medicinal plant cultivation.

Author contributions

I.M.A.M.S. and A.M.A.-M. contributed equally to the conceptualization and design of the study. S.Y.S.E. and A.T.A. were responsible for data collection and initial analysis. M.A.A. and S.A.E. performed the statistical analyses and contributed to the interpretation of results. A.M.A. supervised the project, provided critical revisions, and finalized the manuscript. All authors contributed to drafting the manuscript, reviewed the final version, and approved it for submission.

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Competing financial interests

The authors have no conflict of interest.

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