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Ascorbic Acid, Tocopherol, and Arginine as Natural Biostimulants for Alleviating Salinity Stress in Maize: Roles in Antioxidant Defense, and Membrane Protection

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ABSTRACT

Salinity stress in maize causes disruption in antioxidant defense mechanisms and membrane stability as a result of the overproduction of reactive oxygen species. Thus, the current investigation designed to evaluate the role of ascorbic acid, tocopherol, and arginine at 1 g L^{-1}, when applied singly and in combination, as foliar spray in mitigating oxidative injury induced by salinity stress, with special emphasis on hydrogen peroxide (H_2O_2), superoxide radicals ($O_2{\bullet}^-$), membrane stability, total phenol content, and antioxidant enzyme activity. A field experiment was carried out in South Port Said, Port Said Governorate, Egypt, throughout growing seasons of 2023 and 2024. The investigation was structured according to a factorial completely randomized design. The findings indicated that all treatments were effective in reducing H_2O_2, $O_2{\bullet}^-$, and Malondialdehyde levels, and stimulating the activities of antioxidant enzymes particularly superoxide dismutase, catalase, peroxidase and ascorbate peroxidase, as well as the content of phenolic compounds. It was observed that a synergistic effect was pronounced when all three compounds were used, resulting in a more pronounced effect on the decrease in oxidative stress (OS) markers and improvement in antioxidant defense, membrane stability, and phenolic accumulation. While most studies have been implemented on the interaction of ascorbic acid and tocopherol, the addition of arginine provides a promising avenue to increase promote plant tolerance to abiotic stresses such as salinity.

Keywords: antioxidant enzymes, hydrogen peroxide, malondialdehyde, membranes stability index, superoxide radicals, total phenol content.

INTRODUCTION

Maize (*Zea mays* L.), classified within the Poaceae family, is one of the major cereal crops grown in Pakistan for its nutritional value and for its role in the national food system and development. Though it is an important crop, it is affected by soil salinity. Salinity affects plant growth and development through various morpho-physiological and biochemical changes in the plant, which ultimately results resulting in suppressed growth and poor plant establishment (Mohamed et al., 2009; Garcia et al., 2021; El-Beltagi et al., 2024).

Under saline conditions, plants exhibit increased production of reactive oxygen species (ROS), leading to oxidative stress that disrupts cellular homeostasis, damages essential biomolecules, and impairs growth. Elevated Na^+ and Cl^- concentrations disturb ionic balance, enhancing ROS generation in organelles such as chloroplasts, mitochondria, and peroxisomes. Salinity also induces osmotic stress, limiting water uptake and further intensifying oxidative damage. For example, exogenous pretreatment with salicylic acid significantly improved seedling growth and activated antioxidant enzymes such as SOD, CAT, and POD in sunflower

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and linseed under saline conditions, highlighting the importance of biochemical regulation in stress tolerance (Gürsoy, 2022). Consequently, key metabolic processes, including photosynthesis and respiration, become less efficient. Oxidative stress promotes lipid peroxidation, compromising membrane integrity, and protein oxidation, which disrupts metabolic functions. It may also damage DNA, leading to mutations and impaired cell division. Ultimately, excessive ROS reduce chlorophyll content, photosynthetic efficiency, and root and shoot growth, thereby decreasing overall plant productivity ((El-Beltagi and Mohamed, 2010; Tanveer and Ahmed, 2020; Hasanuzzaman et al., 2021; Majidian and Ghorbani, 2024).

Ascorbic acid (AsA) is a vital antioxidant that plays a crucial role in plant defense against OS by directly scavenging ROS *i.e.* superoxide radicals ($O_2^{\bullet -}$) and hydrogen peroxide (H_2O_2) and thus maintaining the redox balance in the cells and mitigating damage to cellular structures. Moreover, it increases the activity of the major antioxidant enzymes (AOE) such as superoxide dismutase (SOD), catalase (CAT) and ascorbate peroxidase (APX) that neutralize ROS and thus fortify the antioxidant defense system. It also increases the activity of ascorbate peroxidase and is involved in the ascorbate-glutathione cycle, a key process for the detoxification of H_2O_2 (Gill and Tuteja, 2010; El-Beltagi et al., 2024, 2026a, b). Furthermore, AsA plays central role in biosynthesis of phenolic derivatives like flavonoids and phenolic acids that act as secondary antioxidants to scavenge ROS and thus protect the cellular structure (Kanwal et al., 2024; El-Beltagi et al., 2023). Consequently, the reduction of ROS accumulation by AsA maintains cellular membrane integrity by preventing the leakage of ions such as Na^+ and K^+ and thus maintains the ion homeostasis (Hasanuzzaman et al., 2021). Furthermore, the use of AsA has been shown to greatly decrease the level of malondialdehyde (MDA) content in plants, thereby reducing lipid peroxidation and damage to the cellular structure, thus enhancing plant growth in crops including maize (Billah et al., 2017; Hasanuzzaman et al., 2021).

It has been found that the use of α-tocopherol (vitamin E) in leaves can successfully reduce negative impacts of salinity stress (SS) on plants by reinforcing cellular antioxidant defenses, ion homeostasis and physiological activities. Exogenous α-tocopherol can increase the activities of AOE (SOD, CAT, and POD), which are essential in controlling oxidative damage resulting from salt-induced ROS (Sadaf et al., 2025). In addition, α-tocopherol helps to enhance membrane stability through the protection of polyunsaturated fatty acids in cellular membranes owing to its lipid-soluble antioxidant properties. Thus, when α-tocopherol is used, MDA content is reduced, and membrane stability index (MSI) is increased, implying reduced lipid peroxidation and enhanced cellular integrity under saline conditions (Alnusairi, 2022). Moreover, foliar spraying of α-tocopherol helps to increase phenolic compound accumulation, which improves antioxidant system efficiency in plants, thus enhancing resistance to salinity stress. For example, 50-200 mg/L α-tocopherol spraying on soybeans was found to significantly increase phenolic compound accumulation, hence improving plant resistance to SS (Taie and Rady, 2024).

Exogenously applied arginine (Arg) in salinity stress conditions has been observed to increase tolerance in plants by improving antioxidant defense, membrane stability, and biosynthesis of protective compounds in plants. Arginine treatment of plants enhances activities of crucial AOE such as SOD, CAT and POD, which help in mitigating OS and protecting cellular metabolism from salt-induced ROS (Riaz et al., 2025). Arginine treatment also enhances membrane stability index (MSI) by limiting membrane damage caused by ROS, thereby improving ion transport and cellular integrity in saline conditions (Sadak et al., 2024). Exogenously applied Arg reduces MDA content, indicating lower lipid peroxidation and membrane-damaging potential (Ragaey et al., 2022). Arginine treatment also enhances biosynthesis of phenolic compounds, which strengthens the antioxidant defense and improves salinity tolerance in plants (Sadak et al., 2024).

Most studies have focused on the individual effects of ascorbic acid, tocopherol, and arginine, demonstrating their ability to enhance antioxidant enzyme activity, improve membrane stability, stimulate phenolic compound synthesis, and reduce malondialdehyde (MDA) under stress conditions. However, limited information is available on their combined application under salinity stress. Therefore, this study aimed to evaluate the effects of ascorbic acid, α-tocopherol, and arginine, applied individually and in combination, on oxidative stress mitigation and physiological in maize under saline conditions.

MATERIAL AND METHODS

The study was conducted in South Port Said, Egypt (31°08′20″ N, 32°17′29″ E) during two consecutive summer seasons: 2023 and 2024. During the study period, the average temperature was between 26°C and 27°C, with a corresponding range of 65% to 70% relative humidity. This region receives a large amount of solar radiation, averaging 11 to 12 hours of sunlight daily, which translates to an estimated 23 to 26 MJ m^{-2} day^{-1} of daily solar radiation. In addition, yellow maize hybrid (Single Hybrid SC 168) was used in the experiment. This was sourced from the Cereal Crops Department, Field Crops Institute, Agricultural Research Center, Giza, Egypt. During the two seasons, the previous crop was alfalfa (*Trifolium alexandrinum* L.). Before commencing experiment, surface soil was sampled from the upper 20 cm of soil. Chemical properties were determined following Dane and Topp (2020) and Sparks et al. (2020). The results were obtained as depicted in Table 1.

The soil was tilled two weeks before planting and then leveled using laser technology. A completely randomized design was employed in experiment with five treatments and five replications for each growing season. Each experimental unit had 5 ridges, 3 m long, and spaced 70 cm apart, covering an area of 10.5 m^2. The experiment was conducted on May 25, 2023, and May 30, 2024. The planting was done by planting seeds in hills and spacing them 25 cm apart under high salinity conditions (Table 1). Seedling emergence was followed by thinning done 21 days after sowing to have one plant per hill. The experiment was harvested at the beginning of September in both seasons. Fertilizers were applied by applying 36 kg P_2O_5 per hectare as calcium superphosphate containing 15.5% P_2O_5 during soil preparation. In addition, 288 kg N per hectare as urea containing 46% N was divided into three equal doses and applied prior to irrigation. The rest of the practices were conducted following the standard procedures for the cultivation of maize.

Table 1. Mean values of selected chemical soil properties at the experimental site prior to planting during the two growing seasons

Seasons	EC	PH	Texture	Cations (ml equ/L)				Anions (ml equ/L)			
				Ca^{+2}	Mg^{+}	Na^{+}	K^{+}	CO_3^{-}	HCO_3^{-}	Cl^{-}	SO_4^{-}
2023	7.6	8.68	clayey	9.88	11.64	63.1	2.29	-	1.1	64.9	21.09
2024	7.2	8.94	clayey	10.12	12.03	64.1	2.41	-	1.03	65.21	22.42

Treatments

Foliar application of ascorbic acid (1 g L^{-1}), tocopherol (1 g L^{-1}), and arginine (1 g L^{-1}) was carried out individually and in combination on 25 and 40 days after sowing, and control plants were maintained without any treatment.

For this study, leaves from third leaf from the apex of 65 days post-sowing were collected.

Hydrogen peroxide and superoxide anion

The content of H_2O_2 was assessed according to procedure proposed by Sergiev et al. (1997). Plant material (about 0.5 g) was homogenized in 1% trichloroacetic acid and then centrifuged at 12,000 g for 20 min. The obtained supernatant was mixed with 0.7 cm^3 of 10 mM phosphate buffer at pH 7.0 and 1.4 cm^3 of 1 M potassium iodide. The reading was taken at a wavelength of 390 nm, and the

H_2O_2 content was measured by standard curve.

Superoxide radical formation was evaluated based on method of Achary et al. (2011). Fresh leaves were taken and incubated in 50 mM Tris HCl buffer at pH 6.4 containing 0.2 mM nitroblue tetrazolium, 0.2 mM NADH, and 250 mM sucrose. Samples were then infiltrated under reduced pressure for 10-15 min and then placed under light at an intensity of 200 µmol m^{-2} s^{-1} for 24 h. Reaction mixture was then measured at absorbance of 530 nm, and the superoxide radicals were quantified by extinction coefficient of 12.8 mM cm.

Malondialdehyde content (MDA)

Malondialdehyde content was assessed by a modified thiobarbituric acid assay based on Du and Bramlage (1992). Fresh leaves (0.4 g) were frozen in liquid nitrogen, homogenized in 80% ethanol, and centrifuged at 6,000 rpm for 5 min in 2 mL microcentrifuge tubes. An aliquot of 0.7 mL of supernatant was added to 0.7 mL of 0.65% TBA in 20% trichloroacetic acid (TCA) with 0.01% butylated hydroxytoluene (BHT). Another 0.7 mL of supernatant was added to 0.7 mL of 20% TCA with 0.01% BHT, which was used as control.

Both mixtures were incubated in boiling water for 25 minutes at 95°C, cooled immediately, and centrifuged again at 6,000 rpm for 5 minutes. Absorbance was measured at 440, 532, and 600 nm. Concentration of MDA was determined with an extinction coefficient of 157 mM^{-1} cm^{-1} and expressed in nM g^{-1} fresh weight.

Total phenols content

Total phenolic compounds were assessed according to method described by Bessada et al. (2016).

Preparation of Enzyme Extract

For the determination of AOE activities, the frozen maize leaf samples were first grounded to fine powder in liquid nitrogen. The powdered samples were then homogenized in ice-cold solution containing 0.1 M Tris-HCl buffer at pH 7.5, 5% sucrose, and 0.1% 2-mercaptoethanol at ratio of 3 parts buffer to 1 part tissue. Homogenate was then centrifuged at 10,000 x g for 20 min at 4°C. Supernatant obtained was then used for determination of enzyme activities. The entire process was carried out at 4°C to maintain enzyme activity.

Estimation of Enzymes Activity

The catalase (CAT, EC 1.11.1.6) activity was determined through measuring the decline H_2O_2 absorbance at 240 nm using the Aebi (1984) method. The peroxidase (POD, EC 1.11.1.7) activity was assayed utilizing method described by Polle et al. (1994).

Superoxide dismutase (SOD, EC 1.15.1.1) activity was assessed using nitroblue tetrazolium (NBT) photoreduction method as detailed by Giannopolitis and Ries (1977). One unit of SOD activity was defined as amount of enzyme required to inhibit 50% of NBT photoreduction; the absorbance was measured at 560 nm. Activity of enzymes was expressed as units per milligram of protein. The total protein concentration was assessed using the Bradford (1976) method with bovine serum albumin (BSA) as the standard protein.

Peroxidase (POD; EC 1.11.1.7) activity was also determined according to Polle et al. (1994) and measured in units per milligram of protein, with one unit being the amount of enzyme that oxidizes 1 µmol of ascorbate per minute per mg of protein

Ascorbate peroxidase (APX; EC 1.11.1.11) activity was assayed as described by Nakano and Asada (1981), quantifying the decrease in A290 resulting from ascorbate oxidation with an extinction coefficient of 2.8 mM^{-1} cm^{-1}.

Statistical Analysis

Analysis of variance (ANOVA) was performed on the collected data and treatment effects were considered statistically significant at $p \leq 0.05$. All statistical analyses were performed utilizing the COSTAT statistical software package (CoHort Software, 1986). When significant differences were detected, treatment means were compared utilizing Duncan's multiple range test according to Duncan (1955).

RESULTS AND DISCUSSION

Hydrogen peroxide and superoxide anion

According to Fig. 1, H_2O_2 and $O_2^{\bullet-}$ levels varied between the two growing seasons, with slightly higher values in the second season. Foliar application of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg), either individually or in combination, significantly reduced the accumulation of both ROS compared with the control in both seasons. The combined treatment was the most effective, reducing H_2O_2 by 57.2% and 58.6% and $O_2^{\bullet-}$ by 55.4% and 56.8% across the two seasons, respectively. Among single applications, AsA showed the greatest reduction, followed by Arg, while Toc was comparatively less effective. These reductions indicate improved ROS detoxification and enhanced oxidative stress regulation under salinity conditions.

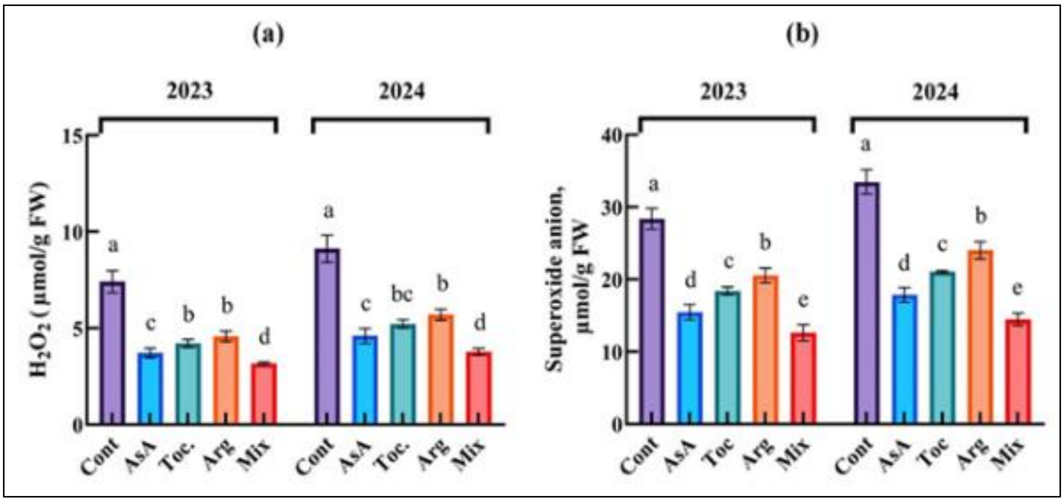

Figure 1. Influence of foliar spraying of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg) used individually or in combination (Mix) on hydrogen peroxide (a) and superoxide anion (b) accumulation in maize plants exposed to SS during the 2023 and 2024 growing seasons. Distinct letters assigned to the bars denote significant variations among treatments at $p \leq 0.05$ following Duncan's multiple range test.

Malondialdehyde content and membrane stability index

Figure 2a shows that foliar application of AsA, Toc and Arg, either individually or in combination, significantly reduced MDA content across both growing seasons. Among individual treatments, Toc was the most effective, lowering MDA by 30% and 29.2%, followed by AsA (20.2% and 19.3%) and Arg (13.8% and 14.3%) in 2023 and 2024, respectively, while the combined treatment achieved the greatest reduction (43.1% and 49.7%). In contrast, membrane stability index (MSI) increased significantly in all treated plants (Figure 2b). Tocopherol induced the highest improvement among single treatments (44.9% and 47.2%), followed by AsA and Arg. However, the combined application produced the highest enhancement in MSI (63% and 61.7%), indicating improved membrane integrity and reduced oxidative membrane damage under salinity stress.

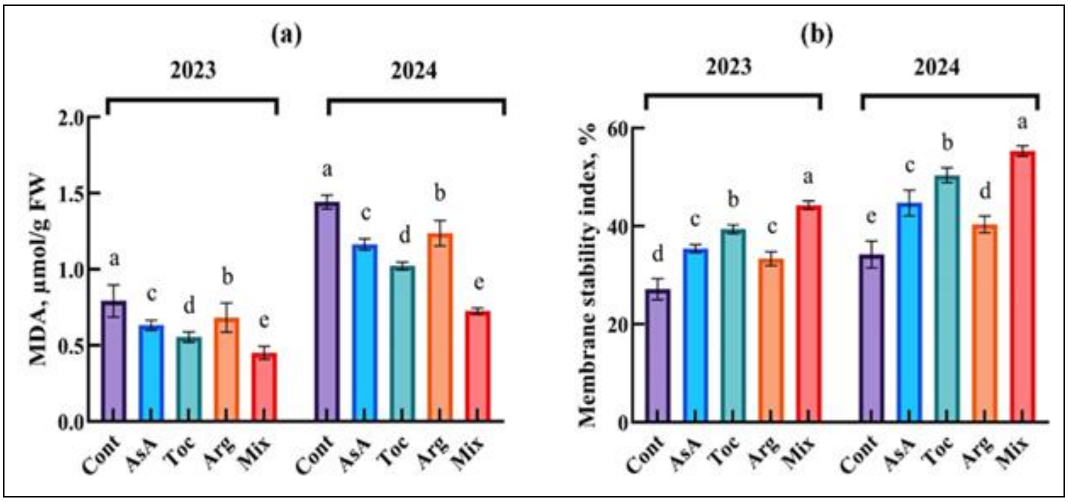

Figure 2. Influence of foliar use of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg) applied separately or in combination (Mix) on Malondialdehyde content (a) and membrane stability index (b) accumulation in maize exposed to SS during the 2023 and 2024 growing seasons. Bars labeled with different letters indicate statistically significant variations among treatments at $p \leq 0.05$ based on Duncan's multiple range test.

Antioxidant enzymes activity

The results presented in Figure 3 show that foliar application of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg), either individually or in combination, significantly enhanced the activities of antioxidant enzymes (SOD, CAT, POD, and APX) in both seasons. Among individual treatments, AsA was the most effective in stimulating enzymatic antioxidant activity, followed by Arg and Toc. For example, SOD activity increased by 50.1% and 48.4% with AsA, compared to 30.5% and 32% with Arg and 13.9% and 14.61% with Toc in 2023 and 2024, respectively, while the combined treatment showed the greatest increase (80.9% and 85%). A similar trend was observed for CAT, where AsA increased activity by 58.1%, compared to Toc (26.8% and 34.1%) and Arg (40.6% and 51%), whereas the combined treatment recorded the highest increase (85% and 104%). For POD, AsA increased activity by 39.9% and 36.2%, compared to Toc (19.9% and 17.3%) and Arg (30% and 28.3%), while the combined treatment achieved the maximum enhancement (82.6% and 80.3%). Likewise, APX activity followed the same pattern, with the combined treatment consistently showing the highest enzymatic activation across both seasons.

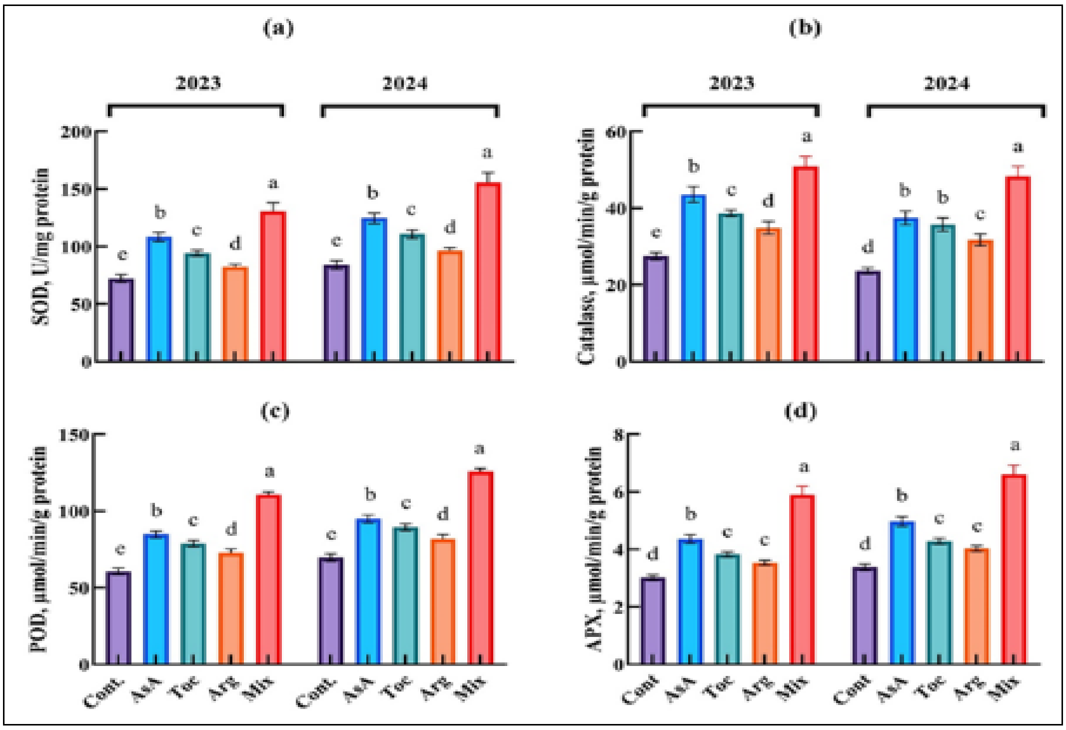

Figure 3. Influence of foliar use of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg) used either singly or in combination (Mix) on AOE activity: superoxide dismutase (a), catalase (b), peroxidase (c) and ascorbate peroxidase (d) in maize plants exposed to SS conditions during the 2023 and 2024 growing seasons. Distinct lettering on the bars denotes significant changes among treatments at $p \leq 0.05$ following Duncan's multiple range test.

Total phenol content

The results in Figure 4 indicate that foliar application of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg), either individually or in combination, significantly increased total phenol content (TPC) across both seasons. Among the individual treatments, AsA was the most effective, followed by Arg and Toc. AsA increased TPC by 38.4% in both seasons, while Toc enhanced it by 20.9% and 27.7%, and Arg by 27.4% and 44.9% in 2023 and 2024, respectively. The combined treatment showed the greatest effect, markedly increasing TPC by 88.9% and 121% in the two seasons.

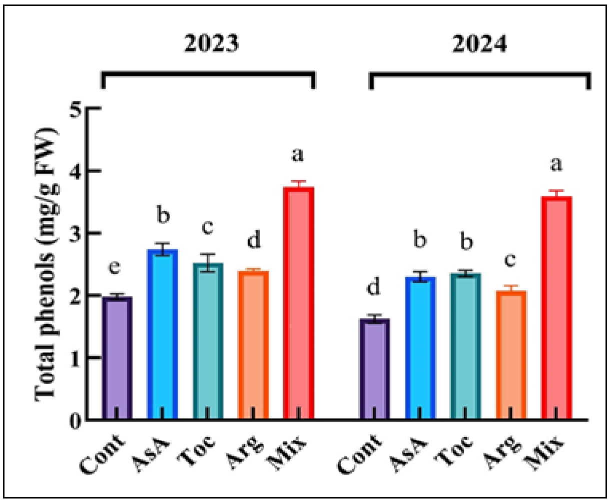

Figure 4. Impact of foliar spraying of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg) applied alone or together (Mix) on total phenol content in maize plants exposed to SS during the 2023 and 2024 growing seasons. Bars marked with different letters denote statistically significant variances among treatments at $p \leq 0.05$ according to Duncan's multiple range test.

The results summarized in Table 1 reveal that the experimental field is affected by high soil salinity. Under SS conditions, plants show excessive production of ROS, resulting in membrane damage and a rise in MDA content, which is a significant component of lipid peroxidation. This, in turn, reduces membrane stability, but tolerant genotypes show less membrane damage due to efficient antioxidant defense mechanisms (Hasanuzzaman et al., 2021; Majidian and Ghorbani, 2024). In saline environments, H_2O_2 and $O_2•^-$ are the primary ROS produced, contributing to oxidative damage in membrane and cellular protein components (AbdElgawad et al., 2016).

Ascorbic acid, Toc and Arg play key roles in alleviating oxidative stress (OS) in maize under salinity stress (SS) by limiting the accumulation of H_2O_2 and $O_2•^-$. AsA directly scavenges H_2O_2 via the ascorbate-glutathione cycle and enhances APX activity, reducing oxidative damage and improving membrane stability (Doğru and Torlak, 2021; El-Beltagi et al., 2026a, b). Toc, a lipid-soluble antioxidant, protects membranes from lipid peroxidation by scavenging ROS and preventing free radical chain reactions (AbdElgawad et al., 2016). Arg contributes to the biosynthesis of polyamines and nitric oxide, activating stress signaling pathways and increasing the activities of antioxidant enzymes such as SOD, POD, and APX, thereby decreasing ROS accumulation (Saravanan et al., 2026). Notably, the combined application of AsA, Toc, and Arg produces a synergistic effect, enhancing ROS detoxification, reducing OS markers such as MDA and electrolyte leakage, and further improving membrane stability under saline conditions.

With regard to maize plants under SS conditions, the decrease in the levels of H_2O_2, $O_2^{•-}$, and MDA content, along with the increase in the MSI, is related to the increased activity of AOE *i.e.* SOD, CAT, APX, and POD, and the buildup of phenolic compounds that act as non-enzymatic antioxidants. These AOE act together in a chain of antioxidant defense reactions that help in the scavenging of ROS such as $O_2^{•-}$ and the accumulation of H_2O_2, which is transformed into H_2O and O_2 by the enzyme CAT. APX is a key factor in conversion of H_2O_2 to water and oxygen and is particularly important in the chloroplast and mitochondria. Peroxidase plays a key role in neutralizing peroxides and the biosynthesis of lignin and plays a key part in antioxidant defense of plants against OS and damage of cellular structures such as lipids, proteins, and DNA (Rao et al., 2025).

Phenolics, including flavonoids, tannins and phenolic acids, are important non-enzymatic antioxidants that are capable of acting as efficient free radical scavengers by releasing hydrogen or electrons to react with ROS and also chelating metal ions that catalyze formation of ROS (Kanwal et al., 2024). Besides playing the role of antioxidants, phenolic compounds also contribute to structural defense by participating in lignin synthesis, thereby conferring strength to plant tissues. Phenolic compounds are important in promoting plant tolerance to OS by acting in conjunction with enzymatic antioxidant systems to provide long-term protection against ROS-induced injury in plant cells (Garcia-Caparros et al., 2021). In addition, in plant cells that are subjected to abiotic stress, there are reports indicating increased levels of genes encoding SOD, CAT, APX, and POD, as well as phenols. This shows that there are two lines of defense in plant cells subjected to abiotic stress (Mishra et al., 2023).

The present findings imply that AsA possesses a stronger antioxidant activity compared to Toc and Arg, particularly in neutralizing ROS and protecting against oxidative damage, owing to its ability to work more efficiently in aqueous environments. Indeed, AsA, being a water-soluble antioxidant, scavenges ROS in cellular compartments like the cytosol and apoplast, whereas Toc, a lipid-soluble antioxidant, primarily works to protect cellular membranes. As a result, AsA possesses a stronger antioxidant capacity compared to Toc in different biological systems (Miazek et al., 2022). Moreover, AsA has been found to increase the activities of some AOE i.e. SOD, CAT, and APX, which collectively form a synergistic antioxidant system. Alternatively, Toc primarily works to protect membranes but lacks consistent results, whereas Arg works indirectly by participating in metabolic pathways associated with stress responses (Das and Roychoudhury, 2014).

It has been found that a combination of ascorbic acid (AsA), tocopherol (Toc), and arginine (Arg) has a synergistic effect in alleviating oxidative stress. This combination has a more pronounced effect in reducing major OS markers *i.e.* H_2O_2, $O_2^{\bullet -}$ and MDA, along with increased antioxidant enzyme activities, MSI, and phenolic compound accumulation compared to the use of any one of these individually. This proves that a combination of antioxidants provides better protection against OS compared to the use of a single antioxidant.

In particular, the joint use of AsA and Toc was found to significantly enhance antioxidant defense mechanisms in barley plants when subjected to SS by elevating AOE activity like SOD, CAT and POD, which resulted in reduced oxidative damages, hence improved physiological activities, implying a strong synergistic effect between the two antioxidants (Sadaf et al., 2025). Moreover, past literature reviews have highlighted that antioxidant defense mechanisms, particularly when a combination of AsA and Toc are employed, can elevate antioxidant enzyme activities as well as non-enzyme-based antioxidant mechanisms in plants, which may result in improved adaptability to abiotic stresses, including salinity (El-Bassiouny and Sadak, 2015). While most literature studies have centered on the combination of AsA and Toc, the addition of Arg appears to be a promising approach, which may further enhance plant resilience to salinity stress.

As demonstrated in Figure 5, the effect of the application of ascorbic acid, tocopherol, and arginine (1 g/L) alone and in combination on the levels of H_2O_2 and $O_2^{\bullet -}$, MDA content, MSI, phenolic content, and antioxidant enzyme activities under SS conditions was clear. The combined application was more effective than the single applications.

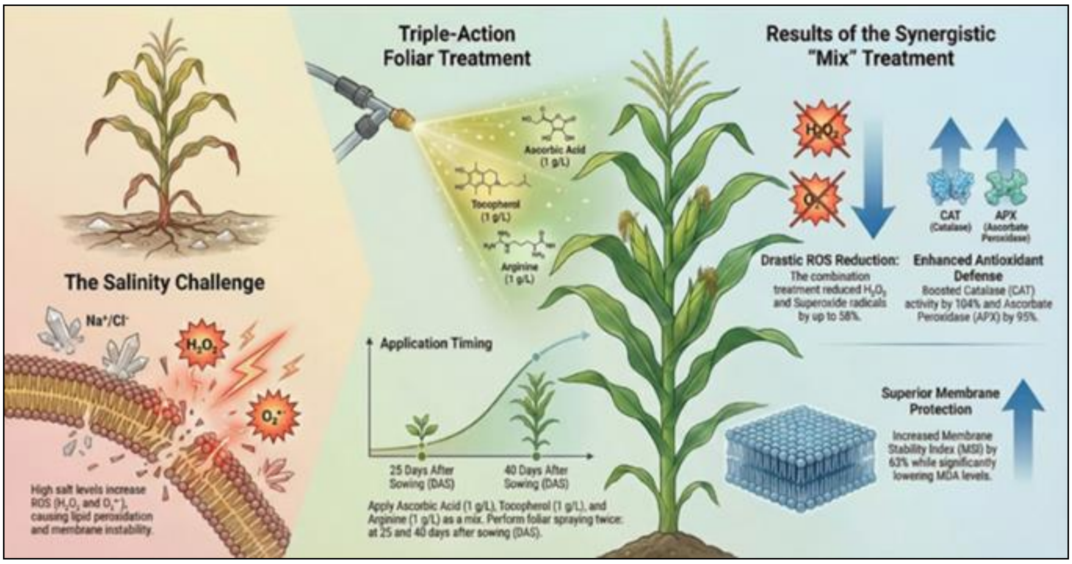

Figure 5. Graphical abstract illustrating the positive impact of foliar spraying of ascorbic acid, tocopherol, and arginine (1 g L^{-1}), used singly or in combination, on ROS (hydrogen peroxide and superoxide radicals), malondialdehyde (MDA), membrane stability index, total phenolic content, and AOE activity in maize cultivated under saline soil conditions.

CONCLUSIONS

The results demonstrated that the combined application of ascorbic acid, tocopherol, and arginine in maize exhibited a synergistic effect in enhancingantioxidant defense capacity. This combined treatment was more effective than individual applications in reducing oxidative stress and improving plant tolerance under salinity conditions. Although most plant studies on antioxidant interactions have focused on the combination of ascorbic acid and tocopherol, the addition of arginine to the combination may be an exciting breakthrough in enhancing plant tolerance, especially to salinity stress. These findings suggest that integrated antioxidant-based strategies may provide a useful tool for enhancing stress tolerance in maize under adverse environmental conditions.

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