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Original Article

Mitigating Salt Toxicity in Tomato Plants via Foliar Silver Nanoparticle Application

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Abstract: Soil salinity severely reduces crop productivity by inducing osmotic and oxidative stresses. This study examines the potential of foliar silver nanoparticle (AgNP) application to mitigate salinity stress in tomato (*Solanum lycopersicum*) seedlings. Two local cultivars, Patatayi and Sewa, were exposed to 200 mM sodium chloride (NaCl) for 4 weeks, with or without 50 ppm AgNPs, to assess morphological, photosynthetic and biochemical responses. Under saline conditions, growth was severely compromised, with total plant height reduced by 24.98% and total chlorophyll levels decreased by 41% in Patatayi and by 50% in Sewa relative to control plants. However, exogenous AgNP application under saline conditions markedly alleviated these adverse effects. Compared with NaCl-stressed plants, co-application of NaCl and AgNPs increased overall plant height by 12.4%, total chlorophyll by 25.7%, free proline by 12.6% and catalase (CAT) activity by 53.6%. The ability of AgNPs to mitigate stress was strictly dependent on the cultivar, Patatayi showed strong recovery in vegetative growth (plant height +12.8%, leaf area +17.1%, and leaf number +21.3%) and good photochemical stability (Fv/Fm +18.9%, from 0.619 to 0.736), whereas Sewa mainly relied on enzymatic antioxidants such as CAT (+50%). Furthermore, Pearson correlation analysis confirmed strong positive associations between photosynthetic traits ($r = 0.72$, $p < 0.001$), which correlated negatively with malondialdehyde (MDA; $r = -0.78$, $p < 0.001$), whereas positive correlations between MDA, free proline ($r = 0.66$, $p < 0.001$), and CAT ($r = 0.41$, $p < 0.05$) underscored a proportional cytoprotective response to oxidative stress. In conclusion, foliar application of AgNPs is a practical, genotype-specific method for relieving salt toxicity in tomatoes by improving osmoprotection and scavenging reactive oxygen species.

1. Introduction

One of the major obstacles to increasing crop yields worldwide is soil salinity. In arid and semi-arid regions, high salt concentrations are believed to damage more than 800 million hectares of land, approximately 20% of the world's irrigated land [1]. Salinity can have disastrous effects on crop yields; for instance, a 50% reduction in wheat, rice and corn yields has been reported under salinity [2].

High salinity exposure causes osmotic and oxidative stress, which stunts plant development and reduces yield [3]. Osmotic stress is a condition in which plants find it difficult to absorb water from the soil because of the high concentration of dissolved salts in the soil solution. This water deficiency causes reduced turgor pressure, stomatal closure, cessation of photosynthesis and restricted cell growth and expansion [4]. Furthermore, the accumulation of excess sodium and chloride ions in plant tissues results

in ionic stress, which can weaken protein synthesis and enzyme activity and damage membrane integrity [5, 6].

The disruption of internal biochemical processes leads to the build-up of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide (H_2O_2) and hydroxyl radicals, which cause oxidative damage to plant cells [7]. Certain levels of accumulated ROS can be eliminated by the antioxidant defence mechanisms of plants; however, beyond a certain point, they oxidatively damage proteins, lipids and nucleic acids inside the plant cells, which can eventually result in cellular malfunction or even cell death [8].

Tomato plants (*Solanum lycopersicum*) are sensitive to salinity and tolerate it up to a soil electrical conductivity of 2.0–2.5 dS/m. Beyond this range, most tomato cultivars suffer significant physiological and morphological damage, leading to yield reductions [9]. A study conducted by Manan *et al*. [10] concluded that salinity affects several aspects of tomato plants, including plant height, leaf area, shoot and root biomass, fruit yield and quality. Another study exposed tomato plants to up to 200 mM salinity and observed a 29.6% reduction in plant height, along with a marked decrease in the number of leaves per plant and the overall leaf surface area [11]. Stomatal opening may also be limited by soil salinity, thereby reducing the photosynthetic capacity of tomato plants [12]. It is therefore important to understand and develop strategies that enhance salt tolerance in tomato crops.

Plants have a sophisticated antioxidant defence mechanism. Superoxide dismutase (SOD), Catalase (CAT), ascorbate peroxidase, and glutathione reductase are the most important antioxidant enzymes in plant cells [3]. SOD catalyses the conversion of oxygen radicals into H_2O_2 and O_2, serving as the first line of defence against ROS [13], and CAT detoxifies the resulting H_2O_2 into water and oxygen [14]. Reducing H_2O_2 levels by increasing CAT activity might improve the tolerance of tomato plants to salinity. Plants often upregulate the expression and production of antioxidant enzymes, including CAT, during stress to counteract accumulated ROS [15]. Nevertheless, as this upregulation might not be sufficient, the application of exogenous chemicals has emerged as an effective strategy to enhance plant tolerance to stress [16].

Recent studies have reported that silver nanoparticles (AgNPs) have the potential to alleviate the negative effects of salinity on plants by modulating their antioxidant defence systems and inhibiting ROS [17]. The application of AgNPs increases the activity of antioxidant enzymes, including CAT, SOD and peroxidase (POD) [18]. These enzymes are essential for scavenging ROS produced under stress conditions [19, 20]. Moreover, individual studies have shown that plants' antioxidant capacity can be enhanced by applying AgNPs. For instance, Manaf *et al*. [20] found that the application of AgNPs and gold nanoparticles significantly increased ascorbate POD, CAT and guaiacol POD activity in wheat plants. Similarly, Danish *et al.* [21] observed upregulation of antioxidant enzyme activity in *Trachyspermum ammi* under biotic stress after treatment with biogenic AgNPs. AgNPs have also been documented to upregulate stress-responsive genes in fenugreek plants [22].

Although there is growing evidence of the beneficial effects of nanomaterials in mitigating salinity stress across global tomato cultivars, the effects of progressive salinity and exogenous AgNP application on local tomato cultivars remain unexplored. This study hypothesised that foliar AgNP application would alleviate the oxidative and osmotic phytotoxicity caused by sodium chloride (NaCl) by promoting osmoprotectant biosynthesis, maintaining photosynthetic efficiency and stimulating antioxidant enzyme activity. Therefore, this study aimed to investigate the potential of foliar AgNP application to improve tomato seedlings' tolerance to salinity by preserving vegetative growth, maintaining a vigorous photosynthetic apparatus, preventing lipid peroxidation and modulating antioxidant enzyme activity, with a particular focus on CAT activity. The findings are expected to enhance understanding and inform strategies to mitigate salinity impacts on tomato, particularly in salinity-affected regions.

2. Materials and Methods

2.1. Plant Materials and Treatment Conditions

This experiment was conducted using a factorial completely randomised design under controlled greenhouse conditions at the Department of Horticulture, College of Agricultural Engineering Sciences,

University of Raparin. Two local tomato cultivars (Patatayi and Sewa) were sown on September 3rd 2025 in 12 L pots (diameter 26 cm, width 25 cm) filled with a soil–sand–compost mixture in equal proportions (1:1:1, v/v/v). Tomato seeds were germinated in a soil–sand–compost (1:1:1, v/v/v) medium and grown under optimal greenhouse conditions, with daytime and nighttime temperatures of 20°C–30°C and 15°C–20°C, respectively. Relative humidity was maintained between 60% and 80%, and natural sunlight was provided. The plants were grown for 4 weeks without treatment. Subsequently, the plants of each cultivar were randomly assigned to four treatment groups, with five replicates per group and one plant per pot as the experimental unit (Table 1).

Table 1: The distribution of the treatment groups for each cultivar.

Treatment Groups	Treatment conditions
G1: Control	Irrigated with 200 mL of deionised water twice a week.
G2: NaCl	The seedlings were subjected to a progressive increase in NaCl concentration over the 4 weeks; each plant was irrigated with 50 mM NaCl in the first week, 100 mM NaCl in the second week and 150 and 200 mM NaCl in the third and fourth weeks, respectively, to harden the seedlings. Each pot was irrigated with 200 mL twice a week.
G3: AgNPs	Irrigated with 200 mL of deionised water twice a week and foliar-sprayed with a 50 ppm AgNP solution 24 h after each irrigation. One millilitre of the AgNP solution was applied to each tomato leaf.
G4: NaCl + AgNPs	The seedlings were subjected to a progressive increase in NaCl concentration over the 4 weeks; each plant was irrigated with 50 mM NaCl in the first week, 100 mM NaCl in the second week and 150 and 200 mM NaCl in the third and fourth weeks, respectively, to harden the seedlings. Each pot was irrigated with 200 mL twice a week. Twenty-four hours after each irrigation, a 50 ppm AgNP solution was foliar-applied at a rate of 1 mL per seedling leaf.

2.2. Preparation of AgNP Solution

AgNPs of <50 nm (manufactured by US Research Nanomaterials, Inc. (CAS: 7440-22-4, USA)) were used. The AgNP stock solution was prepared according to standard procedures. A 50 ppm AgNP solution was selected based on the protocol described by Akhoundnejad *et al*. [23]. Briefly, 50 mg of AgNP powder was dissolved in 100 mL of absolute ethanol and then diluted to 1 L with deionised water to obtain a 50 ppm nanoparticle solution. The solution was placed in spray bottles, and foliar application of the AgNP solution was performed 24 h after salinity induction.

2.3. Measured Parameters

After 4 weeks of treatment, various growth parameters were determined. Plant height was measured from the surface of the growing medium to the highest shoot tip using a precise metric ruler; leaf area was measured using allometric methods as the mean across all true leaves on the same plant, and the number of leaves per plant was recorded as the total number of true leaves. Photosynthetic pigments, including total chlorophyll content, were extracted from leaf homogenates using 80% acetone and quantified spectrophotometrically according to Lichtenthaler [24]. Chlorophyll fluorescence (Fv/Fm) was measured on dark-adapted true leaves using a FluorPen fluorometer, with values averaged across all true leaves of the same plant following Maxwell and Johnson [25]. Biochemical and osmoprotective parameters were evaluated from cryogenically stored leaf samples. Free proline content was quantified using the classic protocol of Bates *et al.* [26]; CAT activity was determined spectrophotometrically by monitoring the disappearance of H_2O_2 as reported by Aebi [27]; and lipid peroxidation was assessed by measuring malondialdehyde (MDA) levels using the thiobarbituric acid reactive substances assay, as described by Hodges *et al*. [28].

2.4. Statistical Data Analysis

The Shapiro–Wilk test, normal Q–Q plots and tests for skewness and kurtosis were used to assess normality of the data prior to statistical analysis. A two-way analysis of variance (ANOVA) was conducted to evaluate the main effects of cultivars and treatments, as well as the cultivar × treatment interaction. Subsequently, Duncan's multiple range test ($p \leq 0.05$) was used as a post hoc test for

comparing means across treatment groups. Multivariate relationships and trait associations were assessed using principal component analysis (PCA) and a Pearson correlation matrix on standardised data. Statistical analyses were performed using SAS/STAT version 15.

3. Results

The ANOVA results in table 2 indicate that the main effect of the tomato cultivar was highly significant for plant height ($F = 210.35$, $p < 0.001$), the number of leaves ($F = 63.99$, $p < 0.001$), chlorophyll fluorescence (Fv/Fm) ($F = 18.09$, $p < 0.001$), CAT activity ($F = 935.42$, $p < 0.001$) and MDA content ($F = 6.18$, $p < 0.05$). By contrast, no significant differences were observed among the cultivars for leaf area ($F = 1.79$), total chlorophyll ($F = 3.47$) and free proline content ($F = 1.48$). The treatment effect was highly significant ($p < 0.001$) for all measured parameters, namely plant height ($F = 7.51$), leaf area ($F = 12.40$), total chlorophyll ($F = 22.23$), Fv/Fm ($F = 30.82$), free proline content ($F = 108.07$), CAT activity ($F = 84.42$) and MDA content ($F = 60.82$). It was also significant for the number of leaves ($F = 3.88$, $p < 0.05$).

Moreover, the interaction between cultivar and treatment was highly significant for total chlorophyll ($F = 11.48$, $p < 0.001$), free proline content ($F = 58.18$, $p < 0.001$), CAT activity ($F = 60.77$, $p < 0.001$) and MDA content ($F = 30.55$, $p < 0.001$); significant for leaf area ($F = 6.28$, $p < 0.01$) and Fv/Fm ($F = 5.02$, $p < 0.01$); and also significant for plant height ($F = 3.98$, $p < 0.05$) and the number of leaves ($F = 2.44$, $p < 0.05$).

Table 2: F-values and significance levels for measured growth, physiological and biochemical traits in tomato cultivars.

Measured Parameter	Cultivar [DF = 1]	Treatment [DF = 3]	Interaction [DF = 3]
Plant Height	210.35 ***	7.51 ***	3.98 *
Leaf Area	1.79 ns	12.40 ***	6.28 **
Number of Leaves	63.99 ***	3.88 *	2.44 *
Total Chlorophyll	3.47 ns	22.23 ***	11.48 ***
Chlorophyll Fluorescence (F_v/F_m)	18.09 ***	30.82 ***	5.02 **
Free Proline Content	1.48 ns	108.07 ***	58.18 ***
Catalase Activity	935.42 ***	84.42 ***	60.77 ***
Malondialdehyde Content (MDA)	6.18 *	60.82 ***	30.55 ***

ns = non-significant at $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, DF = degrees of freedom.

For the main effects listed in table 3, the Patatay cultivar had significantly higher mean values for plant height (25.31 cm), number of leaves (40.00) and Fv/Fm (0.749) than the Sewa cultivar (13.09 cm, 24.35 and 0.692, respectively). By contrast, the Sewa cultivar exhibited significantly higher CAT activity (79.26 μmol H_2O_2/min/g) and MDA content (23.29 μmol/g FW) than Patatay (19.84 μmol H_2O_2/min/g and 20.81 μmol/g FW, respectively). There were no significant differences between the two cultivars in leaf area, total chlorophyll or free proline content.

Table 3: Main effects of cultivar selection on vegetative growth and on photosynthetic and biochemical traits in the two tomato cultivars.

Cultivar	Plant Height (cm)	Leaf Area (mm^2)	Number of Leaves	Total Chlorophyll (mg/g FW)	Fv/Fm	Free Proline (μmol/g FW)	CAT Activity (μmol H_2O_2/min/g)	MDA Content (μmol/g)
Patatayi	25.31 a	763.50 a	40.00 a	1.73 a	0.749 a	0.584 a	19.84 b	20.81 b
Sewa	13.09 b	731.25 a	24.35 b	1.56 a	0.692 b	0.597 a	79.26 a	23.29 a

Means within a column followed by the same letter are not significantly different according to Duncan's multiple range test ($\alpha = 0.05$).

Among the treatments, the control group had the highest mean values for plant height (21.94 cm), leaf area (860.50 mm^2), total chlorophyll (2.10 mg/g FW) and Fv/Fm (0.787). All of these were significantly reduced under NaCl stress (16.46 cm, 657.00 mm^2, 1.13 mg/g FW and 0.634, respectively) (Table 4). Under salinity stress, the application of AgNPs (NaCl + AgNP) significantly improved these parameters compared with NaCl alone. Free proline content, CAT activity and MDA content were all significantly increased under salinity stress, with the combined treatment (NaCl + AgNP) showing the highest

free proline content (0.717 µmol/g FW) and CAT activity (69.58 µmol H_2O_2/min/g). By comparison, the highest MDA content was observed in the NaCl and NaCl + AgNP groups (28.05 and 28.64 µmol/g, respectively) (Table 4).

Table 4: Main effects of the treatments on vegetative, photosynthetic and biochemical traits in the two tomato cultivars.

Treatment	Plant Height (cm)	Leaf Area (mm^2)	Number of Leaves	Total Chlorophyll (mg/g FW)	Fv/Fm	Free Proline (µmol/g FW)	CAT Activity (µmol H_2O_2/min/g)	MDA Content (µmol/g)
Control	21.94 a	860.50 a	33.90 a	2.10 a	0.787 a	0.548 c	27.30 d	12.41 c
AgNP	19.90 ab	721.50 bc	36.20 a	1.94 a	0.777 a	0.460 d	56.01 b	19.09 b
NaCl	16.46 c	657.00 c	27.20 b	1.13 c	0.634 c	0.637 b	45.30 c	28.05 a
NaCl + AgNP	18.50 bc	750.50 b	31.40 ab	1.42 b	0.682 b	0.717 a	69.58 a	28.64 a

Means within a column followed by the same letter are not significantly different according to Duncan's multiple range test ($p \leq 0.05$).

The interaction between cultivar and treatment produced distinct plant responses (Table 5). The greatest plant height (28.64 cm), leaf area (870.00 mm^2), total chlorophyll (2.22 mg/g FW) and Fv/Fm (0.820) were observed in the Patatayi cultivar under control conditions. By contrast, the smallest values for these traits were consistently recorded in the Sewa cultivar under NaCl stress (11.12 cm, 648.00 mm^2, 0.96 mg/g FW and 0.649, respectively). Under salinity stress (NaCl + AgNP), AgNPs mitigated adverse effects in both cultivars. However, Patatayi exhibited higher values for growth and photosynthetic traits than Sewa. Furthermore, the highest CAT activity (107.37 µmol H2O2/min/g) and the highest MDA content (29.83 µmol/g FW) were recorded in Sewa under NaCl + AgNP and NaCl treatments, respectively. The lowest values were documented in Patatayi under control conditions (10.72 µmol H_2O_2/min/g and 11.71 µmol/g FW). In both cultivars, the highest free proline levels were observed under the combined NaCl + AgNP treatment (0.708 µmol/g FW for Patatayi and 0.726 µmol/g FW for Sewa) (Table 5).

Table 5: Interaction effects of cultivar × treatment on growth and on photosynthetic and biochemical traits.

Cultivar × Treatment		Plant Height (cm)	Leaf Area (mm^2)	Number of Leaves	Total Chlorophyll mg/g FW	Fv/Fm	Free Proline (µmol/g FW)	CAT Activity (µmol H_2O_2/min/g)	MDA Content (µmol/g)
Patatayi	**Control**	28.64 a	870.00 a	41.00 ab	2.22 a	0.820 a	0.550 c	10.72 g	11.71 c
	AgNP	26.20 ab	738.00 abc	46.40 a	2.02 a	0.819 a	0.450 d	14.55 fg	17.52 b
	NaCl	21.80 c	666.00 c	32.80 bc	1.30 bc	0.619 c	0.628 b	22.28 f	26.28 a
	NaCl+AgNp	24.60 bc	780.00 ab	39.80 ab	1.40 b	0.736 b	0.708 a	31.79 e	27.74 a
Sewa	**Control**	15.24 d	851.00 a	26.80 cd	1.97 a	0.754 b	0.546 c	43.89 d	13.11 c
	AgNP	13.60 de	705.00 abc	26.00 cd	1.85 a	0.735 b	0.470 d	97.48 b	20.66 b
	NaCl	11.12 e	648.00 c	21.60 d	0.96 c	0.649 c	0.646 b	68.31 c	29.83 a
	NaCl+AgNp	12.40 de	721.00 abc	23.00 d	1.44 b	0.629 c	0.726 a	107.37 a	29.55 a

Means within a column followed by the same letter are not significantly different according to Duncan's multiple range test ($p \leq 0.05$).

To understand the global relationships among the morphological, photosynthetic and biochemical traits and to examine the phenotypic clustering of the different treatment groups, a PCA (Figure 1) and a Pearson correlation analysis (Figure 2) were conducted.

The first two principal components (PCs) accounted for 73.8% of the cumulative variance (PC1 = 54.1% and PC2 = 19.6%) (Figure 1). PC1 separated non-stressed from salt-stressed plants along the horizontal axis. Vegetative and photochemical traits (Fv/Fm, loading = 0.398; total chlorophyll loading = 0.385; number of leaves loading = 0.367; plant height loading = 0.352; and leaf area loading = 0.264) loaded positively on PC1. Stress-related biochemical measures loaded negatively on PC1: MDA content (−0.407), CAT activity (−0.342) and free proline (−0.288).

PC2 separated the two tomato cultivars along the vertical axis (Figure 1). 'Patatayi' was in the upper quadrants (positive PC2) and was characterised by greater plant height (loading = 0.482) and leaf

number (0.415). 'Sewa' was in the lower quadrants (negative PC2) and was defined by significantly higher CAT activity (loading = −0.439). Under salinity stress, foliar co-application of AgNPs shifted the 'Patatayi' cluster to the right along PC1 towards the control, indicating recovery of vegetative and photochemical vigour.

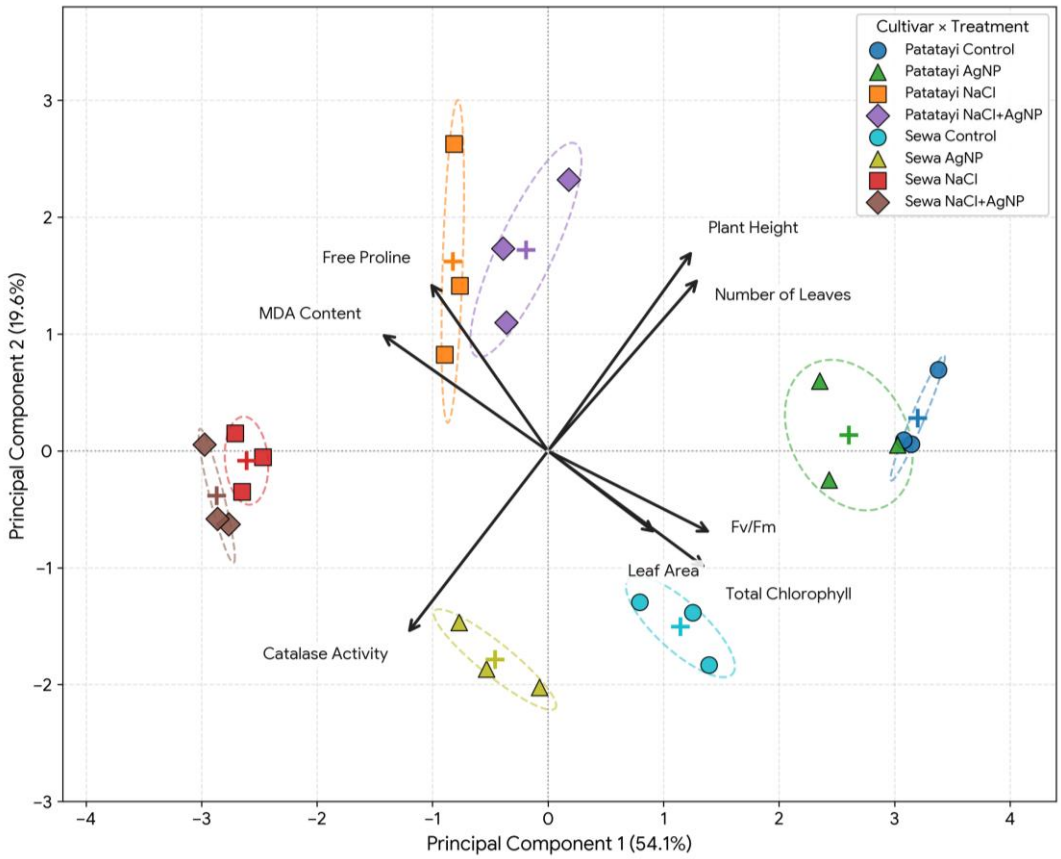


Figure 1: PCA biplot of the multivariate distribution of the two tomato cultivars (Patatayi and Sewa) under salinity stress and foliar AgNP application. Treatment groups are shown as score centroids (crosses) with 95% confidence ellipses, and measured traits are shown as directional loading vectors.

The Pearson correlation matrix showed significant correlations among the measured parameters (Figure 2). Total chlorophyll was strongly positively correlated with Fv/Fm ($r = 0.72$, $p < 0.001$) and strongly negatively correlated with MDA ($r = -0.78$, $p < 0.001$) and free proline ($r = -0.56$, $p < 0.01$). Fv/Fm was likewise negatively correlated with MDA ($r = -0.70$, $p < 0.001$) and free proline ($r = -0.54$, $p < 0.01$). MDA was positively correlated with free proline ($r = 0.66$, $p < 0.001$) and with CAT activity ($r = 0.41$, $p < 0.05$). Plant height was negatively correlated with CAT activity ($r = -0.79$, $p < 0.001$) and positively correlated with leaf number ($r = 0.85$, $p < 0.001$), thereby confirming the contrasting morpho-physiological and enzymatic antioxidant profiles of the two cultivars.

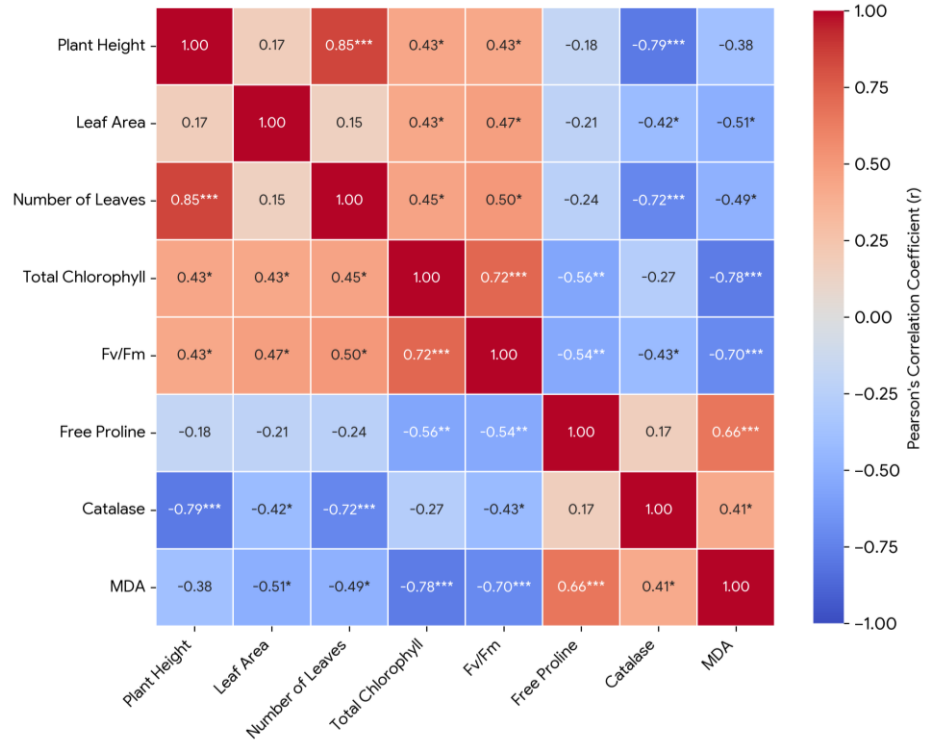


Figure 2: Pearson correlation heatmap among the morpho-physiological and biochemical traits. Asterisks denote significance levels: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

4. Discussion

This study investigated the morphological, physiological and biochemical responses of two tomato cultivars, Patatayi and Sewa, to progressive salinity stress and examined the potential of foliar AgNP application to alleviate salinity phytotoxicity. The results of ANOVA (Table 2) and the main effects (Tables 3 and 4) indicate that the morphological and biochemical responses of tomato plants to salinity stress are strongly genotype-dependent. The Patatayi cultivar exhibited an inherent morphological advantage over Sewa, with significantly greater mean plant height, more leaves and higher chlorophyll fluorescence (Fv/Fm). The difference in salinity tolerance between the two cultivars is due to distinct genetic, anatomical and physiological mechanisms. Genetically, tolerant cultivars have upregulated ion transporters that enable them to exclude sodium or sequester it in the vacuoles, thereby preventing the accumulation of toxic ions in the cytoplasm. Anatomically, differences in suberisation of the root endodermis and in the diameter of the xylem vessels between the cultivars may hinder salt transport from root to shoot. Physiologically, 'Sewa' showed greater dependence on its enzymatic antioxidant defence systems and had significantly higher total CAT activity than Patatayi, which aligns with the findings of Ergun [29] and Patanè *et al*. [30]. Salinity severely inhibited vegetative growth in both cultivars, leading to marked reductions in plant height, leaf area and leaf number (Table 3). This observed growth inhibition is in line with Yilmaz [6] and Majeed *et al*. [31], which state that the main causes are loss of cellular turgor and osmotic disruption.

The interaction effects (Table 5) reveal biochemical and photosynthetic adaptations following foliar application of exogenous AgNPs. Under salinity stress, the photosynthetic apparatus was severely damaged, leading to a substantial decline in total chlorophyll in both cultivars. This decline is likely due to ROS accumulation and peroxidation of thylakoid membrane lipids [32]. Notably, under salinity stress, the combined application of AgNPs led to a specific recovery of total chlorophyll content in the Sewa cultivar, whereas no such recovery was observed in the Patatayi cultivar. Exogenous AgNPs help preserve chloroplast structure and light-harvesting pigments under abiotic stress [33-35] by assisting in ROS detoxification, which in turn prevents early leaf abscission, maintains cellular hydraulic conductivity and reduces lipid peroxidation. Moreover, salinity, a key osmoregulatory mechanism,

significantly increased the accumulation of compatible solutes, with the highest levels of free proline observed in the NaCl + AgNP treatment across both cultivars. The synergistic effect of AgNPs under salt stress aligns with Almutairi [33], who reported that AgNP application leads to upregulation of *P5CS*, a key gene in proline biosynthesis.

Under oxidative stress, the highest CAT activity was observed when AgNPs were applied together with salt stress (NaCl + AgNP) in both cultivars, confirming an increased capacity to detoxify ROS [23, 36]. However, MDA levels did not decrease significantly in the NaCl + AgNP treatments compared with the salt-only treatment. The persistence of elevated MDA suggests that interactions between membranes and nanoparticles may inherently lead to secondary oxidative stress, even in the presence of improved ROS scavenging and greater accumulation of compatible solutes [37, 38].

The multivariate results from the PCA (Figure 1) and the Pearson correlation matrix (Figure 2) further highlight the distinct adaptive strategies employed by the two cultivars under salinity. The strong negative correlation between the photochemical parameters (Fv/Fm and total chlorophyll) and membrane lipid peroxidation confirms that salt-induced oxidative stress directly compromised thylakoid membrane integrity [7, 32, 39]. The clear separation of the two cultivars along PC2 indicates that 'Patatayi' has evolved to prioritise morphological vigour and the maintenance of photochemical parameters, whereas 'Sewa' relies on inducing the enzymatic antioxidant defence to cope with hyperosmotic stress, consistent with the previous findings of Ergun [29] and Patanè *et al*. [30]. The positive correlation between MDA and proline ($r = 0.66$, $p < 0.001$) also suggests that the hyperaccumulation of proline observed in the NaCl + AgNP treatment was directly proportional to the level of oxidative and osmotic stress, thereby playing a crucial cytoprotective role [4, 8, 33].

5. Conclusions

Foliar application of AgNPs is a useful, though genotype-dependent, means of mitigating the adverse effects of salinity in tomato plants. The findings of this study show that salinity markedly impairs vegetative growth, particularly plant height, leaf area and leaf number, and reduces total chlorophyll content while increasing the levels of oxidative stress markers. The application of exogenous AgNPs offsets these negative effects by improving osmotic protection via increased biosynthesis of free proline, which in turn helps to maintain leaf hydraulic conductivity and turgor pressure.

Moreover, the AgNPs enhance the tomato plant's ability to scavenge ROS by increasing CAT activity to detoxify H_2O_2 produced as a result of salinity. Nevertheless, the ways in which these protective measures act vary considerably between the cultivars examined; the Patatayi cultivar mainly maintained its morphological growth and chlorophyll fluorescence (Fv/Fm) under stressful conditions, whereas the Sewa cultivar showed considerable restoration of total chlorophyll and relied strongly on its elevated enzymatic antioxidants. The persistence of high MDA levels in AgNP-treated plants under salinity indicates mild secondary oxidative stress, highlighting the need to consider not only the specific surface properties and dosages of the nanoparticles but also the genetic characteristics of the cultivars being treated.

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Conflicts of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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