



Foliar titanium, Mn-graphene oxide, and molybdenum nanoparticles mitigate salt stress in *Pelargonium graveolens* L.

O.H.H. Hasan, L. Vojodi Mehrabani (*), K. Azizpour

Department of Agronomy and Plant Breeding, Faculty of Agriculture, Azarbaijan Shahid Madani University, Tabriz 5375171379, Iran.



(*) Corresponding author:
vojodilamia@gmail.com

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ORCID:

HOHH: 0009-0003-5639-8775
VML: 0000-0003-3213-759X
AK: 0000-0003-2955-7083

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Abstract: The present study aimed to evaluate the ameliorative effects of foliar-applied nanoparticles on growth, nutrient uptake, essential oil content, and physiological responses of *Pelargonium graveolens* under salt stress. A factorial experiment was conducted based on a completely randomized design with 3 replications. Plants were subjected to three salinity levels (0, 75, and 150 mM sodium chloride) and foliar spray of TiO₂ (2 mg L⁻¹), Mn oxide-graphene oxide (10 mg L⁻¹), molybdenum trioxide nanoparticles (0.5 μM), or no spray (control). Salt stress significantly reduced biomass, nutrient content (N, P, Ca), and adversely enhanced malondialdehyde content. The highest biomass and nutrients content were observed under no-saline conditions + all nanoparticle treatments, and under 75 mM NaCl + Mn oxide-GO and MoO₃ sprays. Essential oil content was the highest at 0 mM and 150 mM NaCl + MoO₃, and at 75 mM NaCl + all three foliar treatments. MDA levels peaked at 44 (75 mM NaCl) and 49 nmol g⁻¹ FW (150 mM NaCl) without foliar sprays. In conclusion, *P. graveolens* tolerated salinity of up to 75 mM NaCl when supplemented with foliar Mn oxide-GO and MoO₃ nanoparticles. These treatments mitigated salinity-induced oxidative damages, improved nutrient status and enhanced essential oil yield, highlighting their potential as stress-alleviating agents under saline conditions.

1. Introduction

Salt stress is a prevalent environmental challenge that impairs plant growth, reduces yield, and threatens the sustainability of agricultural systems in many regions. High salt concentrations in the root zone induce water stress due to osmotic imbalance and cause toxic ion accumulation, and disrupt ionic homeostasis, normal metabolism, lipid peroxidation, and photosynthesis (Parihar *et al.*, 2015; Deshmukh and Khare, 2017; Liu *et al.*, 2020; Liu *et al.*, 2024 a).

In *Pelargonium graveolens* (rose-scented geranium), an economically important aromatic-medicinal plant from the Geraniaceae family (Gevrenova *et al.*, 2024), salt stress reduced growth, biomass, chlorophyll

content, nutrient uptake, essential oil yield, and altered oil composition (Vojodi Mehrabani *et al.*, 2022). The essential oil of this plant is rich in citronellol, geraniol, linalool, isomenthone, geranyl acetate, and citronellyl acetate, and is widely used in pharmaceutical, perfumery, and food industries (Gevrenova *et al.*, 2024; Balabanova *et al.*, 2025). Iran hosts suitable microclimates for the cultivation of this valued crop, but salt stress owing to climate change in the arid and semi-arid areas severely limits the sustainable production of this plant (Akbari and Sayad, 2021; Vojodi Mehrabani *et al.*, 2022).

Plants counteract salinity damage through mechanisms such as osmotic adjustment, reactive oxygen species (ROS) scavenging, photosynthetic adaptation, hormonal regulation, ionic homeostasis, and activation of stress signaling pathways (e.g., CDPK cascades, SOS pathway, ABA signaling, and gene networks) (Refahi and Shahsavari, 2017; Li, 2024; Wang *et al.*, 2024 a).

Nanotechnology has emerged as a promising tool in agriculture over the past decade to mitigate abiotic stresses, including salinity. Nanoparticles (<100 nm) offer high surface area, reactivity, and unique properties, influencing plant morphology, physiology, and biochemistry in a concentration, size, type, application method, and species-dependent manners (Etesami *et al.*, 2021; Zulfiqar and Ashraf, 2021). At optimal levels, they enhance stress tolerance by modulating hormonal balance, antioxidant enzyme activity, ionic balance, gene expression, and other defense systems.

Titanium nanoparticles (metal oxide semiconductor nanocrystals) have wide applications in air purification, skin care products, and reduce the effects of environmental stresses in agriculture (Alabdallah *et al.*, 2024; Jadhav *et al.*, 2025). TiO₂ nanoparticles improve the growth and development of plants due to their chemical stability and non-toxic nature at low concentration (Nafchi *et al.*, 2024). Foliar spraying of titanium nanoparticles reduced malondialdehyde content and improved the growth and yield of chamomile (Ezzatmand *et al.*, 2024), Echinacea (Behnam *et al.*, 2021) and *Solidago canadensis* L. (Nafchi *et al.*, 2024) under salt stress.

Manganese is an essential micronutrient in plants, which is involved in the activity of photosynthetic enzymes, carbohydrate and nitrogen metabolism, fatty acid synthesis, and prevention of cell membrane damage (Ye *et al.*, 2020). The chemical properties of manganese nanoparticles are changing when

exposed to water or NaCl, which results in their affinity for proteins and variations in the N-H bond in several macromolecules (Ye *et al.*, 2020; Liu *et al.*, 2024 b). In pepper plants, salt stress inhibited root growth and caused changes in the pattern of proteins and lignins. Also, a decrease in the content of manganese, sodium, potassium, and calcium was observed in plants under salt stress. The application of MnSO₄ under such conditions improved the aforementioned traits in several plants and showed how nano-priming with manganese caused compositional changes and molecular interactions between key biomolecules (Ye *et al.*, 2020).

Graphene oxide (GO) is a biocompatible nanomaterial, promotes germinations, root development, photosynthesis, and antioxidant capacity in plants (Guo *et al.*, 2021; Zhang *et al.*, 2021; Yang *et al.*, 2022). Under salt stress (100 mM NaCl), foliar spraying of quantum dot-graphene oxide increased phenolic content, while combined application with titanium nanoparticles enhanced flavonoid accumulation in pepper (Hassanpouraghdam *et al.*, 2025).

Molybdenum is one of the essential microelements needed for plant growth (Haque, 1987). The different forms of molybdenum oxide have led to their widespread applications in various industries, making molybdenum a valuable metal for research and commercial applications (De Castro *et al.*, 2017). Molybdenum homeostasis helps the adaptation of plants to the extreme environments and increases plant tolerance to stress conditions (Kaiser *et al.*, 2005; Huang *et al.*, 2022).

The progressive salinity in Iran's arid and semi-arid regions exacerbates threats to food/feed security and even restricts crop production (Akbari and Sayad, 2021). There is a critical need to explore novel, nano-enabled approaches tailored to salt-sensitive essential oil crops like *P. graveolens*. The present study addresses this gap by evaluating the effects of TiO₂, Mn oxide-graphene oxide, and MoO₃ nanoparticles on biomass and key physiological traits of fragrant geranium under salt stress. These nanoparticles were selected for their reported abilities to enhance antioxidant defenses, maintain ionic balance, regulate ROS, and enhance essential oil content at appropriate concentrations. The findings are expected to provide practical insights for pioneer farmers and extension services in salinity-affected areas, potentially improving sustainable cultivation and economic viability of this high-demanded crop.

2. Materials and Methods

To study the effects of NaCl salinity (0, 75, and 150 mM) and foliar spraying of titanium oxide (2 mg L⁻¹) (Ezzatmand *et al.*, 2024), Mn oxide-graphene oxide (Mn₂O₃: graphene oxide 1:1) (10 mg L⁻¹) (El-Beltagi *et al.*, 2024), and MoO₃ (0.5 µM) (Mabiya *et al.*, 2023) on *Pelargonium graveolens*, a factorial design was conducted based on CRD with three replications at the Research Greenhouse of Azarbaijan Shahid Madani University, Tabriz, Iran. All nanoparticles used in this experiment were supplied by the US-Nano Company (US Research Nano Materials, Texas, USA). The homogeneous (in size) *P. graveolens* seedlings (10-12 cm) were planted in 5-liter pots in soil (one plant per pot). Each pot was filled with approximately 4.8-5.0 kg of air-dried silty loam soil (pH: 7, EC 1.2 ds m⁻¹, total N content: 0.8%, available P content: 10.5 mg kg⁻¹ and K content 180 mg kg⁻¹). Light intensity was about 460 µmol m⁻² s⁻¹, and the temperature regime was 25°C and 19°C day and night. After transferring the plants to pots, they were irrigated with unsalted water for two weeks. Irrigation was performed manually by applying a fixed volume of 250 mL of the respective solution (unsalted water during the first two weeks, and thereafter the designated saline solution ± foliar treatments) to the soil surface of each pot using a graduated cylinder/measuring cup. When plants reached 6-7 leaflets, salinity treatment was applied [0 (2.1 mS cm⁻¹), 75 (9.0 mS cm⁻¹), and 150 mM (15 mS cm⁻¹)] for 9 weeks. Salt stress started from 25 mM and reached the final concentration by adding 25 mM to the salt concentration every three days over 15 days. One week after salinity treatment, plants were sprayed with distilled water (control), titanium oxide, manganese oxide-graphene oxide, and MoO₃. Two weeks later, the plants were resprayed with the same nanoparticles. To avoid salt deposition in the pot surfaces, the pots were regularly washed with tap water once every week. Seven weeks after the second foliar spraying, the plants were harvested for evaluation of physiological, biochemical and morphological traits. The pots were arranged as a factorial experiment based on CRD layout across the greenhouse benches, with spacing of 75 cm between rows and 40 cm within rows. The experiment consisted of 12 treatments with three replications, and each experimental unit had three pots (108 individual pots). Treatments were fully randomized to the

positions using random numbers to minimize any potential positional or environmental gradients.

Dry weight (Biomass)

At the end of the experiment, plants were harvested and separated into roots and aerial parts. Samples were oven-dried at 32°C until reaching the constant weight (approximately 72-96 h), and dry biomass of roots and aerial parts was measured using a digital analytical balance (BB141, Boeco, Germany; precision 0.001 g). Other growth parameters such as plant height, leaf length and width, and petioles length were measured prior to harvest using a ruler.

Essential oil extraction

Essential oil was extracted from 20 g of dried aerial parts (primarily leaves, stems and flowers) of *P. graveolens* using hydrodistillation during 4h by a Clevenger-type apparatus. The aerial parts, selected because they are the primary site of essential oil biosynthesis and accumulation in rose-scented geranium, yielding the highest concentrations of key volatile oil components (Al-Mijalli *et al.*, 2022).

Minerals analysis

Dry leaf samples (0.4 g) were acid-digested according to the methods described by AOAC (1990). The flame photometric method quantifies sodium and potassium content in the leaf tissue (Corning, 410, England), and the content of Ca and Mg was quantified using atomic absorption spectroscopy (Shimadzu, AA6300, Japan). Nitrogen content was measured by the Kjeldahl method, and phosphorus was determined with the vanadate molybdate method (Honarjoo *et al.*, 2013).

Chlorophyll index

Portable chlorophyll meter (SPAD 502 Plus Chlorophyll Meter, Japan) was used to determine chlorophyll index.

Total soluble solids (TSS) content

A hand refractometer (Erma, Tokyo, Japan) quantified TSS in *P. graveolens* leaves. The data were reported as °Brix.

Proline content

The amount of 0.3 g of fresh leaf tissue was homogenized in 5 mL of 3% sulfosalicylic acid. Then centrifuged for 7 min at 6000 rpm. One mL of supernatant was incubated with 1 mL acid ninhydrin

and 1 mL glacial acetic acid. Samples were incubated for 30 seconds at 100°C in a water bath and then in an ice bath for 30 min. The red phase formed above the sample was used for the determination of proline content at 520 nm (Fedina *et al.*, 2006).

Lipid peroxidation and hydrogen peroxide (H_2O_2) content

The amount of 0.3 g of *P. graveolens* leaf tissue was homogenized in 0.1% trichloroacetic acid. The extract was centrifuged for 15 min at 12000 × *g*. The reaction mixture of 0.5 mL of the extract and 1.5 mL of 0.5% thiobarbituric acid in 20% trichloroacetic acid was incubated at 95°C for 30 min. The samples were then cooled in an ice bath. The absorbance was determined at 520 nm and corrected for nonspecific absorbance at 600 nm. The malondialdehyde content was determined using the extinction coefficient of 155 mM cm⁻¹ (Sahu and Sabat, 2011).

The amount of 0.3 g of leaf tissue was rubbed off in liquid N₂. The samples were ground in 0.1% ice-cold trichloroacetic acid and centrifuged for 15 min at 12000 × *g*. 0.5 mL of the supernatant was mixed with 0.5 mL of potassium phosphate buffer (10 mM) at pH 7.5 and 1 mL of potassium iodide (1M). The H₂O₂ content was evaluated using standards of H₂O₂. The absorbance of samples was measured at 390 nm (Alexieva *et al.*, 2001).

Catalase activity

0.5 g of *P. graveolens* leaf samples were homogenized with 0.1 M cold potassium phosphate buffer with 0.5 mM EDTA. 0.05 mL of supernatant was added to 1.5 mL of 0.1 mM phosphate buffer with pH 7 and 1.45 mL of double-distilled water. The reaction was started by adding 0.5 mL of 75 mM hydrogen peroxide, and a decrease in absorption was recorded at 240 nm (1 min) (Luhova *et al.*, 2003).

Data analysis

A two way analysis of variance (ANOVA) ($Y = \mu + S_i + N_j + S*N_{ij} + \epsilon$) was performed by MSTATC ver 2.1 software, and the significant differences among the means were evaluated with the Least Significant Difference (LSD) test at $p \leq 0.05$.

3. Results

Growth traits

Root and aerial parts dry weight was influenced by the interaction effects of salinity + foliar spray. The top amounts of root and aerial parts dry weight were recorded in NaCl₀ × foliar spray + all three nanoparticles and NaCl_{75 mM} + foliar spray with Mn oxide-graphene oxide, and MoO₃ (Table 1). Independent effects of salinity and foliar spray

Table 1 - Mean comparison for the interaction effects of varying concentrations of sodium chloride stress and foliar spray (spray with distilled water, Mn oxide-graphene oxide, MoO₃ and TiO₂ nanoparticles) on biomass, essential oil content, and chlorophyll index of *P. graveolens*

NaCl (mM)	Nanoparticle foliar spray	Aerial part dry weight (g pot ⁻¹)	Root dry weight (g pot ⁻¹)	Chlorophyll index (Spad)	Essential oil content (%)
0	Without spray	14 e	4.6 b	29 b	0.11 f
0	Mn oxide-graphene oxide (10 mg L ⁻¹)	26 a	5.3 a	37 a	0.15 e
0	MoO ₃ (0.5 μM)	24 a	5.4 a	39 a	0.21 a
0	Titanium oxide (2 mg L ⁻¹)	21 ab	5.3 a	36 a	0.17 d
75	Without spray	13.5 f	4.4 b	21 d	0.19 c
75	Mn oxide-graphene oxide (10 mg L ⁻¹)	24.7 a	5.1 a	35 a	0.25 a
75	MoO ₃ (0.5 μM)	23.1 a	5.3 a	36 a	0.24 a
75	Titanium oxide (2 mg L ⁻¹)	19.6 b	4.8 b	31 ab	0.22 a
150	Without spray	11.1 f	2.9 d	19 e	0.18 c
150	Mn oxide-graphene oxide (10 mg L ⁻¹)	16.9 c	3.6 c	23 d	0.20 b
150	MoO ₃ (0.5 μM)	17.4 c	3.4 c	26 c	0.21 a
150	Titanium oxide (2 mg L ⁻¹)	15.3 d	3.7 c	24 c	0.19 c
Source of variance					
Salinity (S)		*	**	**	**
Foliar (F)		**	**	**	**
S × F		**	**	*	*
CV (%)		6.4	8.5	4.3	5.2

Means with different letters within the columns are statistically different according to the LSD test ($p \leq 0.05$). ns, non-significant, * significant difference at $P \leq 5\%$, and ** significant difference at $P \leq 1\%$. CV= Coefficient of variation.

influenced plant height, leaf length, leaf width, and petiole length of the plant. The highest values for plant height (41.0 g and 39.9 g), leaf width (4.9 cm and 4.7 cm), and leaf length (5.2 cm and 5.1 cm) were recorded in the non-saline (control) and the 75 mM NaCl treatment, respectively. By increasing the salt stress to 150 mM, petiole length of the plants decreased by 13% compared to the control. The highest petiole length was observed in no-saline conditions (Table 2). Foliar spray with Mn oxide-graphene oxide and MoO₃ NP significantly improved plant height, leaf length, leaf width, and petiole length (Table 3).

Chlorophyll index

The interaction effects of salinity and foliar treatments affected chlorophyll index. Chlorophyll index was increased for all foliar sprayings × NaCl_{0 and 75 mM}. The lowest data of chlorophyll index was observed in NaCl_{150 mM} × without foliar treatment (Table 1).

Essential oil content

The interaction effects of salt stress and foliar

treatments affected the essential oil content of plants. Based on the results, the highest essential oil content was observed under no salinity × MoO₃, NaCl_{75 mM} × all three nanoparticle foliar spray, and NaCl_{150 mM} × MoO₃ foliar spray (Table 1).

Malondialdehyde content

Malondialdehyde content was influenced by the interaction effects of experimental treatments (Table 4). The highest malondialdehyde content was observed in NaCl_{75 and 150 mM} × without foliar spray, which indicated an increase of 42% and 58% compared to the control, respectively. In all salinity levels, foliar spray with nanoparticles positively declined the malondialdehyde content of plants (Fig. 1).

Hydrogen peroxide content

H₂O₂ content was influenced by the independent effects of salt stress and foliar treatments (Table 4). The highest H₂O₂ content was observed in 75 (1.95 μmol g⁻¹ FW) and 150 mM (2.25 μmol g⁻¹ FW) salt stress. The lowest content of H₂O₂ was recorded under no salinity conditions (Fig. 2A). All three foliar

Table 2 - Mean comparison for the effects of salt stress on growth characteristics of *P. graveolens*

Salinity (mM)	Plant height (cm)	Leaf length (cm)	Leaf width (cm)	Petiole length (cm)
0	41 a	5.2 a	4.9 a	6.1 a
75	39.9 ab	5.1 a	4.7 a	5.5 b
150	26.4 b	4.2 b	3.8 b	5.3 b
Source of variance				
Salinity (S)	*	*	**	*
Foliar (F)	**	*	*	*
S × F	NS	NS	NS	NS
C.V. (%)	10	12.1	8.9	10.4

Means with different letters within the columns are statistically different according to the LSD test (p≤0.05). NS, non-significant, * significant difference at P≤5%, and ** significant difference at P≤1%. CV= Coefficient of variation.

Table 3 - Mean comparison for the effects of foliar spray (spray with distilled water, Mn oxide-graphene oxide, MoO₃ and TiO₂ nanoparticles) on growth traits of *P. graveolens*

Nanoparticle foliar spray	Plant height (cm)	Leaf length (cm)	Leaf width (cm)	Petiole length (cm)
Without spray	34 c	4.7 b	3.8 c	5.2 b
Mn oxide-graphene oxide (10 mg L ⁻¹)	39 a	5.4 a	4.3 a	5.9 b
MoO ₃ (0.5 μM)	37 ab	5.6 a	4.7 a	5.6 ab
Titanium oxide (2 mg L ⁻¹)	35.5 b	4.8 b	4.0 b	5.1 b

Means with different letters within the columns are statistically different according to the LSD test (p≤0.05).

Table 4 - ANOVA for the effect of salinity and foliar spraying (no foliar spray, Mn oxide-graphene oxide, MoO₃, titanium oxide NPs) on malondialdehyde, H₂O₂ content, and catalase activity of *P. graveolens*

Source of variance	df	Malondialdehyde content	H ₂ O ₂ content	Catalase activity
Salinity (S)	2	**	**	**
Foliar (F)	3	*	**	NS
S×F	6	*	NS	NS
CV (%)		8.7	10.1	9.1

ns, non-significant, * significant difference at P≤5%, and ** significant difference at P≤1%. CV= Coefficient of variation.

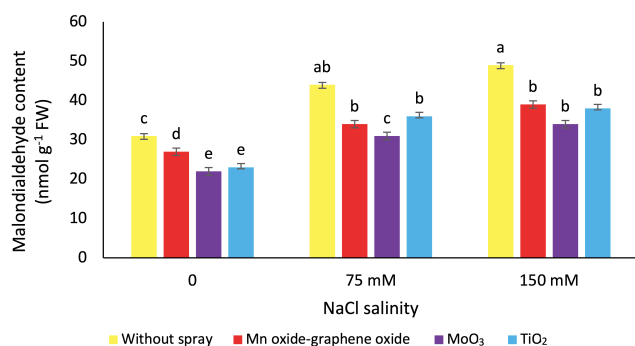


Fig. 1 - Mean comparison for the interaction effects of varying concentrations of sodium chloride stress and foliar spray on malondialdehyde content of *P. graveolens*. Means with different letters on bars are statistically different according to the LSD test (p≤0.05).

treatments reduced H₂O₂ content of the plant, but the lowest H₂O₂ content was recorded in Mn oxide-graphene oxide and MoO₃ foliar spraying (Fig. 2B).

Proline and soluble solids content

The variance analysis showed that the total soluble solids and proline content were affected by the interaction effects of experimental treatments. The top content of proline and total soluble solids was recorded under NaCl_{75 and 150 mM} × all three nanoparticles foliar spray (Table 5).

Catalase activity

The highest catalase activity was recorded under 75 (40.2 units mg⁻¹ protein) and 150 mM (42 units mg⁻¹ protein) salinity conditions, which showed a 21% and 26% enhancement compared to control (Fig. 3).

Nitrogen, phosphorus, and potassium content

The interaction effects of salinity and foliar treatments affected the nitrogen and phosphorus

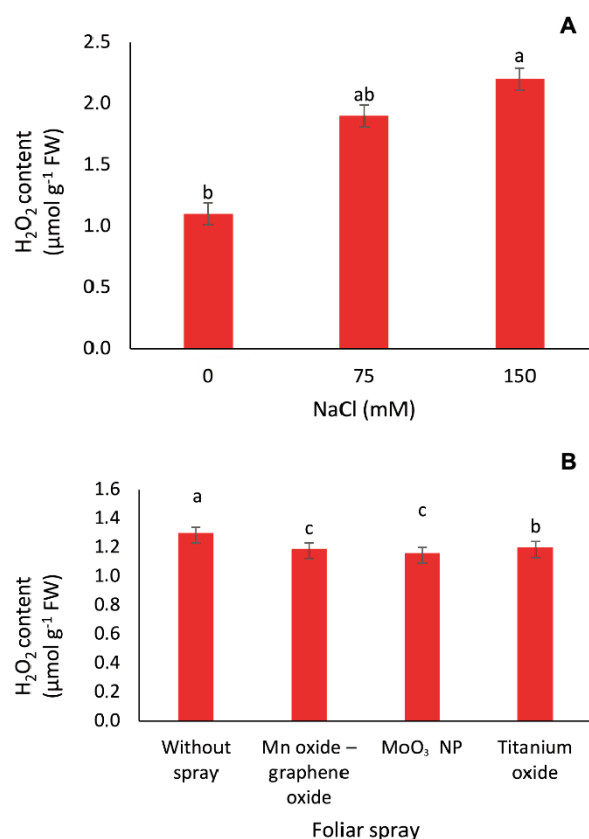


Fig. 2 - Means comparisons for the effect of NaCl salinity (A) and foliar spray (B) on H₂O₂ content of *P. graveolens*. Means with different letters on bars are statistically different according to the LSD test (p ≤ 0.05).

content of the plants. The highest phosphorus and nitrogen content was recorded in NaCl₀ × foliar spray with all three nanoparticles and NaCl_{75 mM} × foliar spray with Mn oxide-graphene oxide, and MoO₃ nanoparticles (Table 6). The potassium content was responsive to the independent effect of salinity and foliar spray (Table 7). Potassium content significantly decreased with enhancing salinity to 75 and 150 mM

Table 5 - Mean comparison for the interaction effects of varying concentrations of sodium chloride stress and foliar spray (spray with distilled water, Mn oxide-graphene oxide, MoO₃ and TiO₂ nanoparticles) on total soluble solids, and proline content of *P. graveolens*

NaCl (mM)	Nanoparticle foliar spray	Total soluble solids content	Proline content (µg g ⁻¹ FW)
0	Without spray	1.3 d	29 e
0	Mn oxide-graphene oxide (10 mg L ⁻¹)	1.5 d	31.2 d
0	MoO ₃ (0.5 µM)	2.1 bc	33 d
0	Titanium oxide (2 mg L ⁻¹)	1.7 c	32.8 d
75	Without spray	1.9 c	39 b
75	Mn oxide-graphene oxide (10 mg L ⁻¹)	2.5 ab	45 a
75	MoO ₃ (0.5 µM)	2.6 a	46.2 a
75	Titanium oxide (2 mg L ⁻¹)	2.5 ab	41.3 ab
150	Without spray	2.2 b	39 c
150	Mn oxide-graphene oxide (10 mg L ⁻¹)	2.6 a	41.2 ab
150	MoO ₃ (0.5 µM)	2.7 a	43.8 ab
150	Titanium oxide (2 mg L ⁻¹)	2.5 ab	43.2 ab
Source of variance			
Salinity (S)		**	NS
Foliar (F)		NS	**
S×F		*	*
CV (%)		11	7.9

Means with different letters within the columns are statistically different according to the LSD test ($p \leq 0.05$). NS, non-significant, * significant difference at $P \leq 5\%$, and ** significant difference at $P \leq 1\%$. CV= Coefficient of variation.

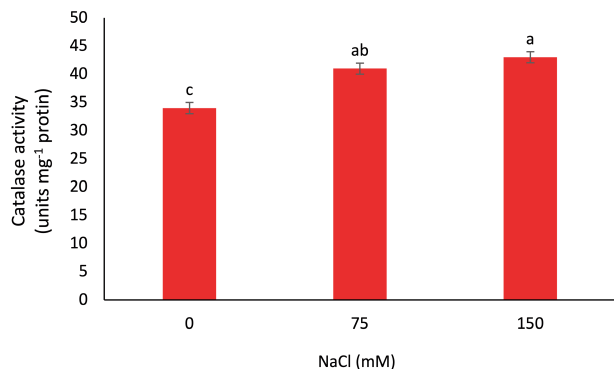


Fig. 3 - Means comparisons for the effect of NaCl salinity on the catalase activity of *P. graveolens*. Means with different letters on bars are statistically different according to the LSD test ($p \leq 0.05$).

compared to the control (Fig. 4A). Foliar spray with Mn oxide-graphene oxide, and MoO₃ nanoparticles enhanced potassium content compared to control and titanium oxide foliar spray (Fig. 4B).

Calcium and magnesium content

The magnesium and calcium content was affected by the interaction of salinity and foliar spray (Table 6). Based on the results, the highest content of calcium and magnesium was observed in NaCl₀ × all

three nanoparticle foliar sprays and NaCl_{75 mM} × Mn oxide-graphene oxide, MoO₃ nanoparticles treatment. With a salinity of 150 mM × without the foliar spray, the magnesium and calcium content decreased by 40% and 33% compared to the control. The results showed that NaCl_{150 mM} × foliar spray with all nanoparticles had positive effects on calcium and magnesium content compared to NaCl_{150 mM} × without foliar spray (Table 6).

Sodium content and sodium-to-potassium ratio

Sodium content was influenced by the interaction effects of salinity and foliar treatments (Table 6). The sodium-to-potassium ratio was responsive to the independent effects of salinity and foliar treatment (Table 7). Salt stress led to a significant increase in the Na⁺/K⁺ ratio, with the peak value at 150 mM NaCl, corresponding to 49% and 16% increase relative to the control and 75 mM NaCl, respectively (Fig. 4C). The least sodium-to-potassium content was recorded under the foliar spray with Mn oxide-graphene oxide, MoO₃ nanoparticles treatment which shows the positive effects of foliar spray on reducing the Na/K ratio (Fig 4D). Foliar treatment with nanoparticles reduced Na content in 75 and 150

Table 6 - Mean comparison for the interaction effects of varying concentrations of sodium chloride stress and foliar spray (spray with distilled water, Mn oxide-graphene oxide, MoO₃ and TiO₂ nanoparticles) on the elemental content of *P. graveolens*

NaCl (mM)	Foliar spray	Nitrogen content (g kg ⁻¹ DW)	Phosphorous content (g kg ⁻¹ DW)	Sodium content (g kg ⁻¹ DW)	Magnesium content (g kg ⁻¹ DW)	Ca content (g Kg ⁻¹ DW)
0	Without spray	8.1 e	2.2 d	1.9 e	1.0 b	2.7 b
0	Mn oxide-graphene oxide (10 mg L ⁻¹)	13.9 ab	3.4 a	1.5 f	1.5 a	3.2 a
0	MoO ₃ (0.5 µM)	15.1 a	3.6 a	1.2 g	1.4 a	3.6 a
0	Titanium oxide (2 mg L ⁻¹)	12.8 ab	3.5 a	1.1 g	1.4 a	3.3 a
75	Without spray	7.2 f	2.4 c	8.1 b	0.9 c	2.1 bc
75	Mn oxide-graphene oxide (10 mg L ⁻¹)	12.9 ab	3.1 ab	5.3 d	1.4 a	2.9 ab
75	MoO ₃ (0.5 µM)	12.6 ab	3.2 ab	5.1 d	1.2 ab	3.1 a
75	Titanium oxide (2 mg L ⁻¹)	11.2 b	2.9 b	5.6 d	1.1 b	2.8 b
150	Without spray	4.9 g	1.9 e	10.2 a	0.6 e	1.8 c
150	Mn oxide-graphene oxide (10 mg L ⁻¹)	8.9 e	2.3 c	8.6 b	0.7 d	2.2 bc
150	MoO ₃ (0.5 µM)	10.3 c	2.6 b	7.1 c	0.9 c	2.5 b
150	Titanium oxide (2 mg L ⁻¹)	9.8 d	2.1 d	7.4 c	0.6 e	2.4 b
Source of variance						
Salinity (S)		**	**	*	**	*
Foliar (F)		*	*	*	**	*
S × F		**	**	*	*	*
CV (%)		7.9	4.9	5.8	7.7	9.7

Means with different letters within the columns are statistically different according to the LSD test ($p \leq 0.05$). ns, non-significant, * significant difference at $P \leq 5\%$, and ** significant difference at $P \leq 1\%$. CV= Coefficient of variation.

Table 7 - ANOVA for the effect of varying concentration of sodium chloride and foliar spraying (no foliar spray, Mn oxide-graphene oxide, MoO₃, titanium oxide NPs) on the potassium content and sodium/ potassium ratio of *P. graveolens*

Source of variance	df	Potassium content	Sodium/ potassium ratio
Salinity (S)	2	**	**
Foliar (F)	3	*	*
S×F	6	NS	NS
CV (%)		12	10.1

ns, non-significant, * significant difference at $P \leq 5\%$, and ** significant difference at $P \leq 1\%$. CV= Coefficient of variation.

mM salt stress. The highest Na content was recorded in NaCl_{150 mM} × without foliar spray, which showed 81% increase compared to the control (Table 6).

4. Discussion and Conclusions

Salt stress is a major abiotic factor that disrupts plant nutrition and physiology, leading to toxic ions accumulation (e.g., Na⁺ and Cl⁻), reactive oxygen

species over-production, reduced photosynthesis, membrane peroxidation and osmolytes accumulation, as well as alterations in cell structures (Zeeshan *et al.*, 2020). In this study, the highest root and aerial parts dry weight were observed under no-saline conditions (NaCl 0 mM) + foliar spraying of all three nanoparticles, and under moderate salinity (NaCl 75 mM) + Mn oxide-graphene oxide and MoO₃ nanoparticles foliar use (Table 1). These findings indicate that foliar-applied nanoparticles, particularly Mn oxide-graphene oxide and MoO₃, effectively mitigated the adverse effects of moderate salinity on biomass accumulation, likely by enhancing nutrient availability, improving chlorophyll index, and reducing oxidative damage. High Na⁺ accumulation disrupts K⁺ uptake, leading to reduced cell division and expansion (Zeeshan *et al.*, 2020). In the present study, 150 mM NaCl severely reduced biomass and growth traits (plant height, leaf dimensions, petiole length), consistent with Na⁺ toxicity and altered Na⁺/K⁺ ratios, which impair metabolic processes.

Nanofertilizers are in common use to reduce the effects of environmental stresses on plants (Abou Seeda *et al.*, 2020). In our study, foliar spraying with

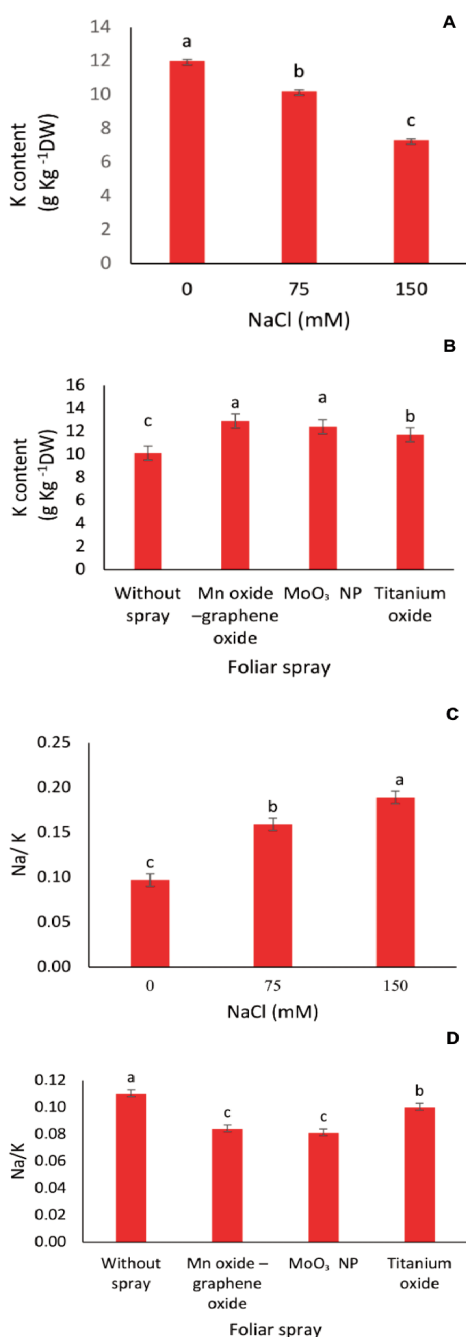


Fig. 4 - Means comparisons for the effect of NaCl salinity (A and C) and foliar spray (B and D) on K content and Na/K ratio of *P. graveolens*. Different letters on bars are statistically different according to the LSD test ($p \leq 0.05$).

Mn oxide-graphene oxide and MoO₃ nanoparticles significantly improved these growth parameters particularly under 0 and 75 mM NaCl (Table 4), suggesting that these treatments counteract salinity-induced inhibition of cell division and expansion, possibly through enhanced ionic homeostasis, elevated enzymatic activities, and promoted

carbohydrate metabolism. Moreover, this improvement may stem from Mn's role in carbohydrate metabolism, phenolics and lignin biosynthesis, cell wall strengthening, and activation of enzymes in the shikimic acid and phenylpropanoid pathways (Yano and Yachandra, 2014; Eskandari and Sharifnabi, 2020). Graphene oxide likely contributes by promoting cell division, stomatal conductance, photosynthesis, and nutrient uptake (Zhang *et al.*, 2021), as observed in related studies where graphene oxide mitigated salinity by enhancing photosynthetic efficiency and ion homeostasis in pepper plants (Hassanpouraghdam *et al.*, 2025). Treatment of wheatgrass (Babenko *et al.*, 2015) and Chinese cabbage (Zhang *et al.*, 2014) with molybdenum, and foliar spraying of mungbean with manganese (Shahi and Srivastava, 2016) improved plant yield and growth traits by reducing the effects of free radicals and increasing the activity of antioxidant enzymes under salt stress. MoO₃ nanoparticles positively influenced growth, potentially via improved nitrogen metabolism and nitrate assimilation, which support overall plant vigor under moderate stress (Kaiser *et al.*, 2005). The positive effect of nanoparticles on plant growth and physiological traits seems to be related to the polycationic nature of nanoparticles or the regulation of ionic metabolism in the plant, which enhance plant tolerance to stress conditions (Hnilickova *et al.*, 2021). The results of the present study also confirmed the above studies and indicated the effectiveness of the nanoparticles used in controlling salt stress.

Chlorophyll index was affected by the interaction of salinity $\times$ foliar spray (Table 1). The lowest chlorophyll index was recorded under 150 mM NaCl without foliar spray, while applications of all nanoparticles increased the pigments content under 0 and 75 mM NaCl. This suggests that nanoparticles protect photosynthetic pigments from salinity-induced degradation, possibly by reducing ROS-mediated damage to the oxygen-evolving complexes in PSII and via maintaining membrane stability (Lima Neto *et al.*, 2014; Zhang *et al.*, 2019; Nafchi *et al.*, 2024). Mn plays a crucial role in chlorophyll biosynthesis and electron transfer in photosynthesis (Eskandari and Sharifnabi, 2020), while graphene oxide enhances light energy conversion and PSII performance (Hassanpouraghdam *et al.*, 2022; Haydar *et al.*, 2023). These mechanisms likely explain

the sustained chlorophyll index up to 75 mM NaCl, supporting better carbon assimilation and biomass production under moderate stress environments. Under salt stress, foliar spraying of titanium to eggplant (Khalid *et al.*, 2024) and bean (Abdel Latef *et al.*, 2018), declined stress effects by reducing hydrogen peroxide content, improving photosynthesis, and increasing biomass. Foliar spraying of molybdenum under salt stress improved the chlorophyll content of sorghum (Mabiya *et al.*, 2023) and Chinese cabbage (Zhang *et al.*, 2014). At higher salinity (150 mM) levels, the protective effects on growth and chlorophyll index were less pronounced, indicating a threshold beyond which nanoparticle mitigation is limited, though they still conferred some tolerance.

Overall, foliar spraying with Mn oxide-graphene oxide and MoO₃ nanoparticles effectively ameliorated salt stress up to 75 mM NaCl by improving growth traits, biomass, and chlorophyll index. These benefits align with nanofertilizers' role in enhancing stress tolerance through improved nutrient delivery, antioxidant support, and photosynthetic protection, offering a promising strategy for crop production in saline environments (Eskandari and Sharifnabi, 2020; Mabiya *et al.*, 2023). Further studies with focusing on molecular mechanisms, such as gene expression and ionomics, could refine detailed application protocols.

Salt stress induces profound ultrastructural changes in plants, including thickening of cuticles and epidermis, as well as damage or disintegration of nuclei, chloroplasts, and mitochondria (Zeeshan *et al.*, 2020), which collectively impair primary metabolism and redirect resources toward secondary metabolites biosynthesis. In the present study, these stress-induced alterations likely contributed to variations in essential oil content, where moderate salinity (75 mM NaCl) combined with nanoparticle foliar sprays, and severe salinity (150 mM NaCl) + MoO₃, yielded the highest essential oil content compared to control (Table 1). This aligns with the established role of abiotic stress in modulating secondary metabolism, as evidenced by increased β -citronellol (24%) and citronellyl acetate (18.5%) in geranium under 50 mM NaCl + selenium foliar spraying (Vojodi Mehrabani *et al.*, 2022). The observed reductions in essential oil biosynthesis under unstressed or extreme stress conditions without adequate nanoparticle support may stem

from diminished cytokinin biosynthesis in roots and its translocation to shoots (Charles *et al.*, 1990), alongside ionic imbalances and disrupted enzymatic activities that curtail terpenoid metabolism (Deshmukh and Khare, 2017).

The intensity and duration of salt stress, coupled with plant species-specific responses, further dictate essential oil accumulation (Deshmukh and Khare, 2017), as seen in our results where nanoparticles use mitigated these effects. Specifically, the hydrophilic groups (-COOH and -OH) on nanoparticle surfaces, such as those in quantum dots, enhance water uptake and alleviate osmotic stress (Tounekti *et al.*, 2008), potentially explaining the elevated essential oil content under 75 mM NaCl with all nanoparticles and under 150 mM NaCl with MoO₃ (Table 1). This is corroborated by studies on basil, where glycine betaine-functionalized graphene oxide under salinity increased essential oil, photosynthetic pigments, proline, and phenols while reducing malondialdehyde and hydrogen peroxide (Ganjavi *et al.*, 2021). MoO₃ nanoparticles likely exert their beneficial effects through activation of key molybdenum-dependent enzymes, including nitrate reductase, aldehyde oxidase, xanthine dehydrogenase, and sulfite oxidase, which bolster metabolic and physiological resilience (Kaiser *et al.*, 2005). Overall, the synergy between salt stress and nanoparticle foliar spraying in this study particularly MoO₃ under non-saline and high-salinity conditions, and all nanoparticles at moderate salinity, appears to promote essential oil accumulation by improving nutrient uptake, lowering oxidative damage (reduced malondialdehyde content), and enhancing chlorophyll index (Table 1).

Plants have evolved multifaceted adaptive mechanisms to counteract salt stress, encompassing osmotic adjustment, reactive oxygen species (ROS) scavenging, photosynthetic modulation, phytohormone signaling, and ion homeostasis regulation (Liu *et al.*, 2020; Wang *et al.*, 2024 b). Salinity elevates cellular osmotic pressure through excessive Na⁺ and Cl⁻ uptake and promotes osmotic regulation via biosynthesis of compatible solutes to maintain cytosolic homeostasis (Munns, 2002). Both enzymatic and non-enzymatic antioxidants mitigate ROS-induced damage under such conditions. Stress signaling activates the related gene expression for antioxidant enzymes biosynthesis (Ye *et al.*, 2020), while non-enzymatic antioxidants, including soluble amino acids (proline) and sugars, scavenge hydroxyl

and peroxy radicals, stabilize membranes, and reduce redox imbalances (Deshmukh and Khare, 2017). Proline, in particular, scavenges free radicals, lowers redox potential, preserves cellular water status, and stabilizes macromolecules. Otherwise, its rapid catabolism under stress promotes ATP production and mitochondrial repair (Lehmann *et al.*, 2010; Parihar *et al.*, 2015). In the present study, salt stress markedly upregulated catalase activity at both 75 mM and 150 mM NaCl (Fig. 3), consistent with the role of CAT as a pivotal enzyme in decomposing hydrogen peroxide (H_2O_2) into water and molecular oxygen, thereby mitigating oxidative damage to cellular components. This response aligns with observations in various species where moderate to high salinity induces CAT activity as part of the enzymatic antioxidant defense (e.g., in *Brassica oleracea* with Mn foliar spraying under 150-300 mM NaCl) (Altıntaş *et al.*, 2024). The observed improvements (21-26%) likely reflect an adaptive acclimation to elevated H_2O_2 generation from salinity-induced ionic and osmotic perturbations.

Foliar nanoparticle applications, including MoO_3 , further potentiated this antioxidant response, as evidenced by reduced H_2O_2 and malondialdehyde contents in treated plants. MoO_3 nanoparticles likely contribute via activation of molybdenum-dependent enzymes (e.g., nitrate reductase, aldehyde oxidase) that support metabolic resilience and indirectly bolster antioxidant systems (Kaiser *et al.*, 2005). Molybdenum enhances antioxidant defense under abiotic stresses, as seen in sorghum where Mo application improved proline content and salt tolerance (Mabiya *et al.*, 2023). Analogous effects occur with other nanoparticles; for instance, graphene oxide spraying elevated CAT activity in basil under salt stress (Vojodi Mehrabani *et al.*, 2023).

The synergy between salt stress and nanoparticle treatments in this experiment empowered enzymatic (including CAT) and non-enzymatic antioxidant biosynthesis, leading to decreased H_2O_2 and MDA content. This is congruent with broader evidence that nanoparticles act as stress ameliorants by scavenging ROS directly or modulating gene expression and enzyme activities, thereby enhancing physiological tolerance in medicinal and crop plants.

Plant tolerance to salt stress is largely determined by the ability to maintain ion homeostasis, particularly by restricting toxic Na^+ accumulation while preserving essential nutrient uptake such as N,

P, K, Ca, and Mg (Karimi and Hasanpour, 2014; Kumari *et al.*, 2022). In the present study, salinity levels of 75 and 150 mM NaCl, significantly disrupted nutrient uptake in the absence of foliar treatments, leading to reduced N, P, K, Ca, and Mg content, elevated Na^+ content, and a marked increase in Na^+/K^+ ratio (Tables 6, Fig. 4). These changes align with well-documented salinity-induced ionic imbalances, where excess Na^+ competes with K^+ and Ca^{2+} uptake, disrupts membrane stability, and impairs metabolic processes (Liu *et al.*, 2024 b; Wang *et al.*, 2024 a).

Foliar spraying of nanoparticles (NPs) particularly Mn oxide-graphene oxide and MoO_3 effectively mitigated these adverse effects, with the most pronounced benefits observed at 75 mM NaCl and, to a lesser extent, at 150 mM NaCl. The interaction between salinity and foliar treatments significantly influenced N, P, Ca, and Mg content (Table 6), while K content responded to both main effects (Table 7). The highest N and P levels were recorded under control (0 mM NaCl) with all three NPs and under 75 mM NaCl + Mn oxide-graphene oxide or MoO_3 (Table 6). Similarly, Ca and Mg contents were maximized in non-stressed conditions + NPs and at 75 mM NaCl + Mn oxide-graphene oxide and MoO_3 (Table 6). These improvements suggest that foliar NPs enhance nutrient acquisition and translocation under moderate salinity, possibly by improving root uptake efficiency, membrane integrity, or promoted translocation pathways.

Potassium content decreased progressively with enhancing salinity (Fig. 4A), consistent with sodium-induced K^+ efflux and competition at uptake sites (Guo *et al.*, 2015). However, foliar sprays with Mn oxide-graphene oxide and MoO_3 significantly elevated K content compared to the unsprayed control and TiO_2 treatment (Fig. 4B). This selective enhancement likely contributed to the reduced Na^+/K^+ ratio observed under these treatments (Fig. 4D), as the lowest ratios occurred with Mn oxide-graphene oxide and MoO_3 applications. The Na^+ content itself was lowered by all NPs at 75 and 150 mM NaCl. In contrast, the highest Na^+ accumulation was recorded in unsprayed plants exposed to 150 mM NaCl (81% increase compared to control) (Table 6). These findings indicate that NPs promote ion exclusion or compartmentalization, helping maintain cytosolic K^+ homeostasis essential for enzyme activation, osmotic adjustment, and stomatal

regulation under stress (Cavusoglu *et al.*, 2018; Liu *et al.*, 2024 a).

The superior performance of Mn oxide-graphene oxide and MoO₃ NPs, especially at 75 mM NaCl, over TiO₂ may stem from their specific elemental roles. Mn is critical for nitrogen metabolism and antioxidant enzyme activity, potentially aiding nitrogen uptake and reducing oxidative disruption to nutrient transporters (Pradhan *et al.*, 2014; Ye *et al.*, 2019). In contrast, graphene oxide likely improves water retention and nutrient delivery via its high surface area and hydration properties, facilitating better ionic balance under stress (Lian *et al.*, 2018; Vojodi Mehrabani *et al.*, 2023). MoO₃ NPs, provide molybdenum, support nitrate reduction and N assimilation, which in turn promote proline synthesis and further enhance K⁺, Ca²⁺, and P uptake (El-sayed *et al.*, 2017; Divyanshu *et al.*, 2019). At higher salinity (150 mM), NPs still conferred benefits over unsprayed plants (e.g., higher Ca and Mg), though less effectively, suggesting a threshold where severe ionic toxicity limits mitigation.

Calcium, a vital element for membrane stability and stress signaling (Chen *et al.*, 2015), increased under NP treatments up to 75 mM NaCl, potentially explaining improved tolerance by preserving membrane function and reducing Na⁺ influx. Overall, foliar NPs appear to counteract salinity by enhancing essential nutrient status, reducing Na⁺ accumulation, and optimizing Na⁺/K⁺ ratios, with Mn oxide-graphene oxide and MoO₃ showing particular promise for moderate stress levels.

These results explain previous findings on NP-mediated salinity alleviation by demonstrating differential efficacy among NPs and salinity × treatment interactions specific to nutrient dynamics. Future studies could explore underlying molecular mechanisms, such as expression of ion transporters (e.g., HKT, NHX, SOS1) or antioxidant genes, to confirm direct causation (Tester and Davenport, 2003; Yin *et al.*, 2019; Wang *et al.*, 2024 a). Limitations include the lack of mechanistic data beyond ion contents; however, the observed patterns strongly support a role for these NPs in improving ion homeostasis and nutrient efficiency under salinity.

Manganese is an essential micronutrient for plants that plays an important role in the growth, phytochemical, and metabolic activities of the plant. The use of manganese nanoparticles improves

nitrogen metabolism in plants by increasing the activity of enzymes involved in nitrogen metabolism (Pradhan *et al.*, 2014). The application of manganese under salt stress reduces the content of free radicals by decreasing the sodium ions availability in the cell, regulating osmotic pressure, and improving water status of the plant (Ye *et al.*, 2019). Foliar spraying of manganese under salt stress conditions reduced the root sodium content, sodium to potassium and sodium to calcium ratios in *Brassica oleracea* L., which was due to the downstream regulation of the mTERFs gene (Altıntaş *et al.*, 2024). Foliar spraying of graphene oxide elevated the calcium and magnesium content in basil (Vojodi Mehrabani *et al.*, 2023). One of the reasons for the increased nutrient uptake under graphene oxide application treatment may be related to the ability of graphene oxide nanoparticles to absorb and release water (Lian *et al.*, 2018), which maintains water relations under stress conditions and creates ionic triazones in plants (Zarifi *et al.*, 2025). Considering the above and the role of the elements used in foliar spraying in plant metabolic and enzymatic activities, it can be concluded that in the present study, nanoparticles, by improving the physiological activities of several elements, have helped the plant to absorb other nutrients under stress conditions.

In this study, *P. graveolens* plants exhibited moderate tolerance to salt stress by maintaining acceptable growth, physiological performance, and essential oil production up to 75 mM NaCl. At this salinity level, key growth traits including root and shoot dry weights, plant height, leaf length and width, petiole length, and chlorophyll index remained comparable to the non-saline control or showed only minor reductions. Essential oil content was preserved or slightly increased, particularly under nanoparticle foliar treatments. Nutrient homeostasis (N, P, K, Ca, and Mg) was effectively maintained, with the highest concentrations recorded under no-saline conditions and 75 mM NaCl when supplemented with nanoparticles. By contrast, severe salinity (150 mM NaCl) caused substantial negative effects, including marked reductions in root and shoot dry weight, petiole length, chlorophyll index, and nutrient uptake. These impairments were accompanied by severe ionic imbalance, as evidenced by elevated Na⁺ content and a substantially higher Na⁺/K⁺ ratio. Oxidative damage was intensified by the fact that malondialdehyde content increased by 42% and 58%

at 75 and 150 mM NaCl without foliar spraying, respectively. Foliar spraying of Mn oxide-graphene oxide and MoO₃ effectively alleviated salinity-induced damage across all stress levels. These treatments improved physiological and biochemical traits, elemental content and Na⁺/K⁺ ratio. Notably, essential oil content was maintained or even increased under 150 mM NaCl, especially with MoO₃. Overall, *P. graveolens* can be cultivated under moderate salinity (≤75 mM NaCl) with minimal yield penalty, while foliar spraying of Mn oxide-graphene oxide and MoO₃ nanoparticles offers an effective and sustainable strategy to mitigate severe salt stress via enhancing physiological resilience, improving nutrient efficiency, and maintaining or even increasing essential oil yield in this high-valued medicinal crop.

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References

- ABDEL LATEF A.A.H., SRIVASTAVA A.K., EL-SADEK M.S.A., KORDROSTAMI M., TRAN, L.S.P., 2018 - *Titanium dioxide nanoparticles improve growth and enhance tolerance of broad bean plants under saline soil conditions*. - Land Degrad. Dev., 29: 1065-1073.
- ABOU SEEDA M.A., YASSEN A.A., ABOU EL-NOUR E.A., ZAGHLOU S.M., 2020 - *Importance of molybdenum and its diverse role in plant physiology: A review*. - Middle East J. Appl. Sci., 10: 228-249.
- AKBARY M., SAYAD V., 2021 - *Analysis of climate change studies in Iran*. - Physical Geography Res., 53(1): 37-74. In Persian.
- ALABDALLAH N.M., ALLUQMANI S.M., ALMARRI H.M., AL-ZAHRANI A.A., 2024 - *Physical, chemical, and biological routes of synthetic titanium dioxide nanoparticles and their crucial role in temperature stress tolerance in plants*. - Heliyon., 10(4): 1-10.
- ALEXIEVA V., SERGIEV I., MAPELLI S., KARANOV, E., 2001 - *The effect of drought and ultraviolet radiation on growth and stress markers in pea and wheat*. - Plant Cell Environ., 24(12): 1337-1344.
- AL-MIJALLI SH., MRABTI H.N., ASSAGGAF H., ATTAR A.A., HAMED M., EL BAABOUA A., EL OMARI N., EL MENYIY N., HAZZOUMI Z., SHEIKH R.A., ZENGİN G., SUT S., DALL'ACQUA S., BOUYAHYA A., 2022 - *Chemical profiling and biological activities of Pelargonium graveolens essential oils at three different phenological stages*. - Plants, 11(17): 2226.
- ALTINTAŞ S., YASEMIN S., ÇATKIN S., İNAL, B., 2024 - *Effectiveness of manganese foliar spraying to mitigate salt stress in ornamental cabbage: Insights into morphological, physiological biochemical adaptations and mTERF gene responses*. - J. South Afr. Bot., 168: 462-475.
- AOAC, 1990 - *Official methods of analysis. 15th Edition* - Association of Official Agricultural Chemists, Washington, DC, USA, pp. 1298.
- BABENKO O.N., BRYCHKOVA G., SAGI M., ALIKULOV Z.A., 2015 - *Molybdenum application enhances adaptation of crested wheatgrass to salinity stress*. - Acta Physiol. Plant., 37: 1-3.
- BALABANOVA V., ZHELEVA-DIMITROVA D., GEVRENOVA R., 2025 - *Recent studies on Pelargonium graveolens L'Hér.: A review on chemical composition and biological activity*. - Pharmacia, 72: 1-2.
- BEHNAM H., FEIZI H., ALIPANAH M., 2021 - *Alleviation the effects of salinity stress using titanium dioxide nano and bulk particles in Echinacea seeds and seedlings*. - Adv. Hort. Sci., 35(4): 351-360.
- CAVUSOĞLU K., KILIC S., KABAR K., 2018 - *Effects of pretreatments of some growth regulators on the stomata movements of barley seedlings grown under saline (NaCl) conditions*. - Plant Soil Environ., 53: 524-528.
- CHARLES D.J., JOLY R.J., SIMON J.E., 1990 - *Effect of osmotic stress on the essential oil content and composition of peppermint*. - Phytochemistry, 29: 2837-2840.
- CHEN H.T., CHEN X., WU B.Y., YUAN X.X., ZHANG H.M., CUI X.Y., LIU X.Q., 2015 - *Whole-genome identification and expression analysis of K⁺ efflux antiporter (KEA) and Na⁺/H⁺ antiporter (NHX) families under abiotic stress in soybean*. - J. Integrative Agric., 14: 1171-1183.
- DE CASTRO I.A., DATTA R.S., OU J.Z., CASTELLANOS-GOMEZ A., SRIRAM S., DAENEKE T., KALANTAR-ZADEH K., 2017 - *Molybdenum oxides-from fundamentals to functionality*. - Adv. Mater., 29(40): 1701619.
- DESHMUKH Y., KHARE P., 2017 - *Effect of salinity stress on growth parameters and metabolites of medicinal plants: A review*, pp. 160-197. - In: GUPTA S.K., and M.R. GOYAL (eds.) *Soil salinity management in agriculture. Technological advances and applications*. Apple Academic Press, Boca Raton, FL, USA, pp. 454.
- DIVYANSHU K., KUMAR M.M.S., KUMAR S., SWAPNIL P., ZEHR A., SHUKLA V., YADAV M., UPADHYAY R.S., 2019 - *Regulation of L-proline biosynthesis, signal transduction, transport, accumulation and its vital role in plants during variable environmental conditions*. -

- Heliyon, 5(12): e02952.
- EL-BELTAGI H.S., EL-NADY M.F., AL-DAEI M.I., EL-NAQMQ K.A., REZK A.A., EL-AFRY M.M., SHEHATA W.F., ISMAIL A.M., ELTONOBYC W.F., METWALY M.M.S., 2024 - *Exogenous application of manganese and arginine alleviates the adverse effects of salinity stress on pea (Pisum sativum L.)*. - Cogent Food Agric., 10(1): 1-21.
- EL-SAYED N.S., NASSEEM M.G., HUSSEIN, M.A., 2017 - *Effect of molybdenum, phosphorus and sulfur on yield and elements content in leaves of wheat grown in saline soil*. - J. Adv. Agric. Res., 22(2): 326-342.
- ESKANDARI S., SHARIFNABI B., 2020 - *Foliar spray time affects the efficacy of applied manganese on enhancing cucumber resistance to Podosphaera fuliginea*. - Sci. Hortic., 261: 108780.
- ETESAMI H., FATEMI H., RIZWAN, M., 2021 - *Interactions of nanoparticles and salinity stress at physiological, biochemical and molecular levels in plants: A review*. - Ecotoxicol. Environ. Saf., 225: 112769.
- EZZATMAND I., VOJODI MEHRABANI L., ABDOLZADEHFARD A., 2024 - *Nano-titanium oxide and nano zinc oxide foliar application ameliorates the salinity stress effects on Matricaria chamomilla*. - Appl. Biol., 36(3): 86-101.
- FEDINA I., GEORGIEVA K., VELITCHKOVA M., GRIGOROVA, I., 2006 - *Effect of pretreatment of barley seedlings with different salts on the level of UV-B induced and UV-B absorbing compounds*. - Environm. Exp. Bot., 56(3): 225-230.
- GANJAVI A.S., ORAEI M., GOHARI G., AKBARI A., FARAMARZI A., 2021 - *Glycine betaine functionalized graphene oxide as a new engineering nanoparticle lessens salt stress impacts in sweet basil (Ocimum basilicum L.)*. - Plant Physiol. Biochem., 162: 14-26.
- GEVRENOVA R., ZENGİN G., BALABANOVA V., SZAKIEL A., ZHELEVA-DIMITROVA D., 2024 - *Pelargonium graveolens: Towards in-depth metabolite profiling, antioxidant and enzyme-inhibitory potential*. - Plants, 13: 2612.
- GUO R., YANG Z., LI F., YAN C., ZHONG X., LIU Q., XIA X., LI H., ZHAO L., 2015 - *Comparative metabolic responses and adaptive strategies of wheat (Triticum aestivum) to salt and alkali stress*. - BMC Plant Biol., 15: 1-12.
- GUO X., ZHAO J., WANG R., ZHANG H., WU, J., 2021 - *Effects of graphene oxide on tomato growth in different stages*. - Plant Physiol. Biochem., 162: 447-455.
- HAQUE I., 1987 - *Molybdenum in soils, plants, and its potential importance to livestock Nutrition, with special reference to sub-Saharan Africa*. - ILCA Bull., 26: 20-28.
- HASSANPOURAGHDAM M.B., VOJODI MEHRABANI L., KHEIROLLAHI N., SOLTANBEIGI A., KHOSHMMARAM L., 2022 - *Foliar application of graphene oxide, Fe, and Zn on Artemisia dracunculus L. under salinity*. - Sci. Agric., 80: e20210202.
- HASSANPOURAGHDAM M.B., VOJODI MEHRABANI L., KHOSHMMARAM, L., RASOULI F., 2025 - *Amelioration of the growth and physiological responses of Capsicum annum L. via quantum dot-graphene oxide, cerium oxide, and titanium oxide nanoparticles foliar application under salinity stress*. - Sci. Rep., 15(1): 467.
- HAYDAR M.S., ALI S., MANDAL P., ROY D., KUNDU S., KUNDU S., CHOUDHURI C., 2023 - *Fe-Mn nanocomposites doped graphene quantum dots alleviate salt stress of Triticum aestivum through osmolyte accumulation and antioxidant defense*. - Sci. Rep., 13: 11040.
- HNILICKOVA H., KRAUS K., VACHOVA P., HNILICKA F., 2021 - *Salinity stress affects photosynthesis, malondialdehyde formation, and proline content in Portulaca oleracea L.* - Plants, 10(5): 845.
- HONARJOO N., HAJRASULIHA S.H., AMINI H., 2013 - *Comparing three plants in absorption of ions from different natural saline and sodic soils*. - Inter. J. Agric. Crop Sci., 6(14): 988-993.
- HUANG X.Y., HU D.W., ZHAO F.J., 2022 - *Molybdenum: More than an essential element*. - J. Exp. Bot., 73(6): 1766-1774.
- JADHAV A.J., GOSWAMI A.D., TRIVEDI D.H., CHAVAN P.V., JADHAV N.L., PINJARI D.V., 2025 - *A comprehensive review on pure and doped titanium oxide nanoparticles for photocatalytic applications*. - Inorg. Chem. Commun., 181: 115206.
- KAISER B.N., GRIDLEY K.L., NGAIRE BRADY J., PHILLIPS T., TYERMAN S.D., 2005 - *The role of molybdenum in agricultural plant production*. - Ann. Bot., 96(5): 745-754.
- KARIMI H.R., HASANPOUR Z., 2014 - *Effects of salinity and water stress on growth and macro nutrients concentration of pomegranate (Punica granatum L.)*. - J. Plant Nutr., 37: 1937-1951.
- KHALID M.F., JAWAID M.Z., NAWAZ M., SHAKOOR R.A., AHMED T., 2024 - *Employing titanium dioxide nanoparticles as biostimulant against salinity: improving antioxidative defense and reactive oxygen species balancing in eggplant seedlings*. - Antioxidants, 13: 1209.
- KUMARI V.V., BANERJEE P., VERMA V.C., SUKUMARAN S., CHANDRAN M.A.S., GOPINATH K.A., VENKATESH G., YADAV S.K., SINGH V.K., AWASTHI N., 2022 - *Plant nutrition: An effective way to alleviate abiotic stress in agricultural crops*. - Int. J. Mol. Sci., 23: 8519.
- LEHMANN S., FUNCK D., SZABADOS L., RENTSCH D., 2010 - *Proline metabolism and transport in plant development*. - Amino Acids, 39: 949-962.
- LI Q., 2024 - *The metabolism, detrimental effects, and signal transduction mechanism of reactive oxygen species in plants under abiotic stress*. - J. Biobased Mater. Bioenergy, 18: 359-376.
- LIAN B., DE LUCA S., YOU Y., ALWARAPPAN S., YOSHIMURA M., SAHAJWALLA V., SMITH S.C., LESLIE G., JOSHI R.K., 2018 - *Extraordinary water adsorption characteristics*

- of graphene oxide. - Chem. Sci., 9(22): 5106-5111.
- LIMA NETO M.C., LOBO A.K.M., MARTINS M.O., FONTENELE A.V., SILVEIRA J.A.G., 2014 - *Dissipation of excess photosynthetic energy contributes to salinity tolerance: A comparative study of salt-tolerant Ricinus communis and salt-sensitive Jatropha curcas*. - J. Plant Physiol., 171: 23-30.
- LIU C., JIANG X., YUAN Z., 2024 a - *Plant responses and adaptations to salt stress: A review*. - Horticulturae, 10(11): 1221.
- LIU C.Y., YAN M., HUANG X.B., YUAN Z.H., 2020 - *Effects of NaCl stress on growth and ion homeostasis in pomegranate tissues*. - Eur. J. Hortic. Sci., 85: 42-50.
- LIU Y., LIU D., HAN X., CHEN Z., LI M., JIANG L., ZENG J., 2024 b - *Magnesium-doped carbon quantum dot nanomaterials alleviate salt stress in rice by scavenging reactive oxygen species to increase photosynthesis*. - ACS Nano, 18(45): 31188-31203.
- LUHOVA L., LEBEDA A., HEDERORVA D., PEE P., 2003 - *Activities of amino oxidase, peroxidase and catalase in seedlings of Pisum sativum L. under different light conditions*. - Plant Soil Environ., 49: 151-157.
- MABIYA T.C., HENDRICKS K., NKUNA M., FARO A., DOUMBIA I.Z., AJAYI R.F., IWUOHA E., NDIRIMBA B.K., MULAUDZI T., 2023 - *Molybdenum improves Sorghum bicolor tolerance to salt stress by regulating the antioxidant system and the heat shock protein 70 expression*. - Int. J. Phytol. Res., 3(1): 30-40.
- MUNNS R., 2002 - *Comparative physiology of salt and water stress*. - Plant Cell Environ., 25(2): 239-250.
- NAFCHI M.A., KACHOIE M.A., GHODRATI L., 2024 - *Co-application of titanium dioxide and hydroxyapatite nanoparticles modulated chromium and salinity stress via modifying physio-biochemical attributes in Solidago canadensis L.* - Environ. Sci. Pollut. Res., 31(38): 50464-50477.
- PARIHAR P., SINGH S., SINGH R., SINGH V.P., PRASAD S.M., 2015 - *Effect of salinity stress on plants and its tolerance strategies: A review*. - Environ. Sci. Pollut. Res., 22: 4056-4075.
- PRADHAN S., PATRA P., MITRA S., DEY K.K., JAIN S., SARKAR S., ROY S., PALIT P., GOSWAMI A., 2014 - *Manganese nanoparticles: Impact on non-nodulated plant as a potent enhancer in nitrogen metabolism and toxicity study both in vivo and in vitro*. - J. Agric. Food Chem., 62: 8777-8785.
- REFAHI A., SHAHSAVAR A., 2017 - *Effects of salinity stress on certain morphological traits and antioxidant enzymes of two Carica papaya cultivars in hydroponic culture*. - Adv. Hort. Sci., 31(2): 131-139.
- SAHU G.K., SABAT S.C., 2011 - *Changes in growth, pigment content and antioxidants in the root and leaf tissues of wheat plants under the influence of exogenous salicylic acid*. - Braz. J. Plant Physiol., 23: 209-218.
- SHAHI S., SRIVASTAVA M., 2016 - *Foliar application of manganese for increasing salinity tolerance in mungbean*. - Int. J. Appl. Biol. Pharm. Technol., 7(1): 148-153.
- TESTER M., DAVENPORT R., 2003 - *Na⁺ tolerance and Na⁺ transport in higher plants*. - Ann. Bot., 91: 503-527.
- TOUNEKTI T., VADEL A.M., BEDOUI A., KHEMIRA H., 2008 - *NaCl stress affects growth and essential oil composition in rosemary (Rosmarinus officinalis L.)*. - J. Hortic. Sci. Biotechnol., 83(2): 267-273.
- VOJODI MEHRABANI L., GHESHLAGH Y.A., AZAR A.M., 2022 - *Foliar application of nano Fe and Se affected the growth and yield of Pelargonium graveolens under salinity stress*. - J. Hortic. Sci., 36(1): 213-228.
- VOJODI MEHRABANI L., HASSANPOURAGHDAM M.B., RASOULI F., OKCU Z., MARC R.A., 2023 - *Foliar application of graphene oxide, nano-Fe, and selenium mitigates salinity depression on Ocimum basilicum*. Turk. J. Agric. Fores., 47(4): 510-528.
- WANG C., TANG R.J., KOU S., XU X. LU Y., RAUSCHER K., VOELKER A., LUAN S., 2024 a - *Mechanisms of calcium homeostasis orchestrate plant growth and immunity*. - Nature, 627: 382-388.
- WANG Z., HONG Y.C., LI D.J., WANG Z.Q., CHAO Z.F., YU Y.D., ZHU G.T., ZHU J.K., 2024 b - *Association analysis provides insights into molecular evolution in salt tolerance during tomato domestication*. - Plant Physiol., 196(4): 1-9.
- YANG Y., ZHANG R., ZHANG X., CHEN Z., WANG H., LI, P.C.H., 2022 - *Effects of graphene oxide on plant growth: A Review*. - Plants (Basel), 11(21): 2826.
- YANO J., YACHANDRA V., 2014 - *Mn₄Ca cluster in photosynthesis: Where and how water is oxidized to dioxygen*. - Chem. Rev., 4205: 4175-4205.
- YE Y., COTA-RUIZ K., HERNÁNDEZ-VIEZCAS J.A., VALDES C., MEDINA-VELO I.A., TURLEY R.S., PERALTA-VIDEA J.R., GARDEA-TORRESDEY J.L., 2020 - *Manganese nanoparticles control salinity-modulated molecular responses in Capsicum annuum L. through priming: A sustainable approach for agriculture*. - ACS Sustain. Chem. Eng., 8(3): 1427-1436.
- YE Y., MEDINA-VELO I.A., COTA-RUIZ K., MORENO-OLIVAS F., GARDEA-TORRESDEY J.L., 2019 - *Can abiotic stresses in plants be alleviated by manganese nanoparticles or compounds?* - Ecotoxicol. Environ. Saf., 184: 109671.
- YIN X.C., XIA Y.Q., XIE Q., CAO Y.X., WANG Z.Y., HAO G.P., SONG J., ZHOU Y., JIANG X.Y., 2019 - *The protein kinase complex CBL10-CIPK8-SOS1 functions in Arabidopsis to regulate salt tolerance*. - J. Exp. Bot., 71(6): 1801-1814.
- ZARIFI M., VOJODI MEHRABANI L., VALIZADEH KAMRAN R., KHOSHAMARAM L., PESSARAKLI, M., 2025 - *Growth enhancement and physiological responses of Tanacetum balsamita L. by cerium oxide, zinc oxide, and activated carbon nanoparticles foliar treatment under salinity stress*. - Commun. Soil Sci. Plant Anal., 56(6): 966-983.

- ZEESHAN M., LU M., SEHAR S., HOLFORD P., WU F., 2020 - *Comparison of biochemical, anatomical, morphological, and physiological responses to salinity stress in wheat and barley genotypes differing in salinity tolerance.* - Agronomy, 10: 127.
- ZHANG H., LIU N., ZHAO J., GE F. , XU Y., CHEN Y., 2019 - *Disturbance of photosystem II oxygen evolution complex induced the oxidative damage in Chlorella vulgaris under the stress of cetyltrimethylammonium chloride.* - Chemosphere, 223: 659-667.
- ZHANG M., HU C., SUN X., ZHAO X., TAN Q., ZHANG Y., LI N., 2014 - *Molybdenum affects photosynthesis and ionic homeostasis of chinese cabbage under salinity stress.* - Commun. Soil Sci. Plant Anal., 45(20): 2660-2672.
- ZHANG X., CAO H., ZHAO J., WANG H., XING B., CHEN Z., LI X., ZHANG J., 2021 - *Graphene oxide exhibited positive effects on the growth of Aloe vera L.* - Physiol. Mol. Biol., 27: 815-824.
- ZULFIQAR F., ASHRAF M., 2021 - *Nanoparticles potentially mediate salt stress tolerance in plants.* - Plant Physiol. Biochem., 160: 257-268.