Research Article

Improvement of physio-biochemical characteristics of Peppermint (*Mentha piperita* L.) plants with nano-potassium under salinity stress conditions

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Abstract

Reliance on chemical fertilizers during the Green Revolution significantly increased agricultural productivity but also led to substantial environmental challenges. Nano-fertilizers, applied either to soil or leaves, enhance crop growth, yield, and quality by improving nutrient utilization, reducing fertilizer waste, and lowering cultivation costs. Foliar application, particularly beneficial under adverse soil and weather conditions, facilitates direct nutrient uptake by plants and minimizes losses. Therefore, this study investigated the effect of nano-potassium (NP) fertilizer (0.1 mg.ml^{-1}) on some physio-biochemical traits of peppermint under salinity conditions (0, 50, 100, and 150 mM NaCl). The experiment was conducted in 2023 using a factorial design based on a completely randomized design with three replications. The results indicated a significant decrease in physiological and photosynthetic parameters in plants under salinity treatment. However, nano-potassium improved salinity tolerance in peppermint plants by improving these physiological and photosynthetic parameters, as well as increasing the content of osmolytes (such as proline) and reducing stress markers (such as hydrogen peroxide and malondialdehyde) in plant tissues. Based on the physio-biochemical findings of this study, NPs fertilizer has a considerable ability to ameliorate damages produced by salinity treatment in peppermint plants under medium saline soils.

Keywords: Nano-fertilizer, Peppermint, Potassium, Salinity, Stress

Introduction

Mentha piperita L. (peppermint) is a natural hybrid of *Mentha aquatica* and *Mentha spicata*. Its aerial parts contain essential oil, phenolic compounds, flavonoids, fatty acids, vitamins, minerals, and salicylic acid (Makbul *et al*., 2023). The most important phytochemicals in peppermint are found in its essential oil, which is valued based on the amount of menthol, menthone, pulegone, and menthofuran (Kazemi *et al*., 2023). Therefore, this herb is widely used for medicinal and aromatic purposes, as well as for flavoring cosmetics and pharmaceutical items (Giannenas *et al*., 2020).

The expanding global population and the corresponding rise in fossil fuel consumption will increase the rate of global warming. The most significant consequence of global warming is the heightened frequency and severity of abiotic stress conditions, such as salinity and drought, which will result in diminished crop productivity in arid and semiarid regions (Sabagh *et al*., 2020). The quality and quantity of medicinal plants significantly reduce under adverse growth conditions due to alterations in many morphophysiological characteristics (Zhang *et al*., 2008).

Salinity stress is a significant limiting factor for plant growth, predominantly observed in arid and semi-arid environments (Ahmad *et al*., 2016). Soil salinity is defined as an electrical conductivity (EC) of four ds/m or more, which has a substantial impact on plant morphology, physiology, and biochemistry (Zaman *et al*., 2018b). Sodic soils are created when sodium ions accumulate excessively in the soil exchange complex. These have high pH and dispersibility, resulting in low soil transmissibility (Atta *et al*., 2023). There are two forms of salinity depending on salt accumulation: Dry

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land and irrigation. Dry land salinity occurs when salts accumulate on the soil surface of non-irrigated fields. Dryland salinity occurs through three processes: Deep drainage, groundwater migration, and discharge. This can be characterized as primary (naturally occurring) or secondary (induced by human activity like agriculture). Irrigation salinity occurs when groundwater is irrigated repeatedly, causing salt deposition on the soil's surface owing to leaching (Chakraborty *et al*., 2013; McFarlane *et al*., 2016; Stavi *et al*., 2021; Zaman *et al*., 2018a). Salt has adverse impacts on plant growth due to reduced osmotic potential, ion toxicity, and nutritional imbalance (Greenway and Munns, 1980; Lu *et al*., 2023;). Plants' salt tolerance depends on osmotic adjustment and ionic balance (Acosta-Motos *et al*., 2017). Plant cells accumulate osmolytes such as organic acids, sugars, and amino acids during salt stress to regulate osmotic conditions. Plants with higher osmolyte levels have a lower water potential, making it easier to absorb water from saline soils (Munns *et al*., 2020; Zhao *et al*., 2021). Plants rely on ion homeostasis to balance sodium (Na^+) accumulation and potassium (K^+) loss for appropriate cellular function. A high potassium-to-sodium (K^+: Na^+) ratio in tissues is an essential sign of increased salt tolerance in plants. Key efforts to maintain a greater K^+: Na^+ involve selective ion absorption and transport systems that allow plants to either exclude or compartmentalize excess Na^+ while retaining K^+ (Hasanuzzaman *et al.*, 2018; Ketehouli *et al*., 2019; Kumari *et al*., 2021; Tester and Davenport, 2003).

Fertilizers are a key strategy for improving soil nutrient availability for plants. On the other side, excessive fertilizer use is costly, harmful to the environment, disrupts ecosystems, and poses health risks, especially in developing countries (Raliya *et al*., 2017; Wu *et al*., 2021). To tackle the dual issues of salinity and excessive fertilizer use, nano-fertilizers offer an innovative solution. These nano-fertilizers provide a more targeted and efficient approach, enabling a reduction in the amount of fertilizer needed while improving both crop quality and yield. Additionally, they help reduce the environmental damage typically associated with conventional fertilization methods, offering a more sustainable farming system (Emamverdian *et al*., 2023; Ghorbani *et al*., 2024; Rady *et al*., 2023). In recent years, significant attention has been directed towards integrating plant biotechnology and nanotechnology within agriculture. These advanced techniques aim to increase crop productivity, enhance nutrient efficiency, improve plants' resilience to environmental stress, and minimize negative environmental impacts, offering a more effective alternative to conventional practices that rely on bulk materials (Mahmoud *et al*., 2019; Nongbet *et al*., 2022). Potassium nanoparticles (K-NPs) offer a modern solution to enhance nutrient efficiency and crop productivity. While traditional potassium fertilizers like KCl and K_2SO_4 are prone to leaching and soil fixation, K-NPs improve nutrient uptake, minimize losses, and enable controlled release (Erfani *et al*., 2022). The use of NPs not only ensures better absorption by plants due to their high surface area and reactivity but also helps in reducing the frequency and quantity of fertilizer application, making agriculture more sustainable. Recent studies have shown that potassium nanoparticles improve plant growth, increase yield, and enhance resistance to abiotic stresses, particularly salinity and drought conditions (Mousavi *et al*., 2024; Saedi *et al*., 2020). Therefore, this study focuses on assessing the impact of NPs, produced using sustainable green methods, on some physio-biochemical parameters of peppermint plants grown in saline soil.

Material and methods

Synthesis and characterization of NPs: The NPs used in this research were obtained from previous research conducted by Mousavi (2024). The leaves of *Morus alba* were rinsed twice with distilled water and then allowed to air dry at room temperature. A quantity of 10 g of dried leaf powder was mixed with 100 ml of distilled water and heated for 30 minutes in a bain-marie at 50ºC, after which the mixture was filtered to produce a clear extract. A potassium sulfate solution with a concentration of 0.5 M was created and set in the sonicator for 30 minutes. An identical quantity of potassium sulfate was isolated from the 0.5 M solution and incorporated into the extract using the titration method, while continuously stirring the extract on a heating stirrer set to a temperature of 50°C. Following this, the solution was sonicated for an additional 30 minutes at a temperature of 50°C. After 48 hours of incubation, the solution's color transitioned from dark brown to light brown, indicating the formation of NPs. The solution was then centrifuged for 30 minutes at 11,000 rpm, and the resulting sediment was washed twice with deionized water before being dried at room temperature. The properties of the biosynthesized K-NPs were examined using dynamic light scattering (DLS) and scanning electron microscopy (SEM).

Plant cultivation and treatments: Three rhizomes of peppermint were sown in plastic pots containing a 1:1 mixture of perlite and sand, with three replicates under greenhouse conditions. To investigate the response of peppermint plants to NP under salinity stress, the experiment involved four levels of salinity stress: 0 (control), 50, 100, and 150 mM NaCl, as well as two NP treatments: Control (no treatment) and 0.1 $mg.ml^{-1}$ of NPs. At the 12-leaf stage, both the NPs (foliar application) and salinity (applied into soil) were treated together. But in the second and third weeks, just NPs were sprayed on the plant leaves. After one month of treatment, samples were collected and processed to determine and quantify the relevant variables.

Plant growth measurements: The root and shoot lengths for each treatment were measured using a millimeter ruler. The fresh weight of plant roots and shoots was measured using a digital scale with an accuracy of 0.001 g. To determine dry weight, the root and aerial sections were dried at 75ºC for 48 hours in an oven. The Schonfeld *et al*. (1988) method is utilized to calculate the leaf relative water content (RWC).

Photosynthetic parameters: To calculate the content of photosynthetic pigments, the method of Arnon (1949) was used. The CL01 chlorophyll meter was used to measure relative chlorophyll content. The photochemical efficiency of photosystem II (Fv/Fm) was measured with a Handy PEA fluorimeter (Zhang *et al*., 2011). Leaf stomatal conductance was measured with an AP4 Leaf Prometer Delta-T.

Measurement of stress markers: The H_2O_2 level was measured using the Alexieva *et al*. (2001) method, which implied reacting H_2O_2 with KI. Stewart and Bewley's (1980) approach was utilized to determine MDA concentrations. The proline concentration in leaves was assessed utilizing the method established by Bates *et al*. (1973). The electrolyte leakage was determined using the formula below (Lutts *et al*., 1996):

EL (%) = EC1 ⁄ EC2×100

The study was conducted as a factorial experiment arranged in a completely randomized design with three replications. Data were analyzed using SPSS software (version 21), and mean comparisons were performed using Duncan's multiple range test at a significance level of $P \leq 0.05$.

Results

Synthesis and characterization of NPs: The particle size distribution acquired for NP by the DLS technique revealed that the average size of NP is 98.7 nm (Figure 1). Also, the SEM images showed that the synthesized NPs are irregularly polyhedral in shape and have a particle size of less than 100 nm (Figure 2).

Impact of NPs on some growth and physiological parameters of peppermint plants under salinity stress: The data demonstrated a significant decrease in RWC, fresh and dry weight of shoots, plant height, and root length under salinity stress. However, the application of NPs enhanced these parameters. Applying NPs showed enhancement in shoot fresh weight by 39.8 only at the 100 mM salinity level. Salt concentrations significantly reduced shoot dry weight. Applying NPs showed enhancement in shoot dry weight by 14.3 only at the 100 mM salinity level. Different concentrations of salinity stress increased root fresh weight. Also, the application of NPs further increased this parameter by 2.3 and 13.5% at 100 and 150 mM salinity levels, respectively. In this regard, the root dry weight was higher under salt stress compared to the control group. Applying NPs showed further enhancement in root dry weight by 23.6 only at the 150 mM salinity level. Salinity stress significantly decreased both shoot and root lengths. However, applying NPs showed enhancement in root length by 5.2 and 5.6% at 100 and 150 mM salinity levels, respectively. Also, NPs led to enhancement in shoot length by 8.7, 14.2, and 2.2% at 50, 100, and 150 mM salinity levels, respectively. Applying NPs enhanced RWC by 0.4, 0.5, and 1.1% at 50, 100, and 150 mM salinity levels, respectively (Tables 1, 4; Figure 3). Previous research has shown that nano-K_2SO_4 greatly enhanced shoot dry weight, plant height, number of flowers, number of tillers, root length, and both fresh and dry root weights of alfalfa plants under salinity conditions, which supports the observed results (El-Shal *et al*., 2022). These outcomes also align with the results of a study on *Melissa officinalis* (Mousavi *et al*., 2024).

Impact of NPs on some photosynthetic parameters of peppermint plants under salinity stress: The data showed that photosynthetic parameters Such as chlorophyll a, chlorophyll b, and carotenoids decreased at 50 mM salinity concentration and increased at salinity concentrations of 100 and 150 mM. However, stomatal conductance and relative chlorophyll content showed an increase at the 50 mM salinity level and a decrease at 100 and 150 mM salinity levels.

Salt concentrations of 100 and 150 mM increased chlorophyll a content by 9.9 and 5.5%, respectively. Applying NPs showed further enhancement in chlorophyll a content by 5.7, 9 and 9.4% at 50, 100, and 150mM salinity levels, respectively. Also, salt concentrations of 100 and 150mM increased chlorophyll b content by 10.5 and 7%, respectively. Applying NPs showed further enhancement in chlorophyll b content by 6, 9.5, and 7.6% at 50, 100, and 150mM salinity levels, respectively. In line with this, salt concentrations of 100 and 150mM increased carotenoids content by 12.2 and 5%, respectively. Applying NPs showed further enhancement in carotenoids content by 5.26, 13.5, and 2.26% at 50, 100, and 150mM salinity levels, respectively. Salinity stress at different concentrations decreased maximum photochemical quantum yield of photosystem II (Fv/Fm), stomatal conductance and chlorophyll relative content. Applying NPs increased this parameter by 1.3 and 1.8% at 100 and 150mM salinity levels, respectively. As well, NPs led to increase of stomatal conductance by 9.7, 33.7, and 18.9% at 50, 100, and 150mM salinity levels, respectively. Also, chlorophyll relative content enhanced with NPs application by 17.8, 21.7, and 47.6% at 50, 100, and 150mM salinity levels, respectively (Table 2, 5; Figure 4).

Impact of NPs on some biochemical parameters of peppermint plants under salinity stress: Different concentrations of salinity led to an increase in electrolyte leakage (EL), malondialdehyde (MDA), hydrogen peroxide (H_2O_2), and proline content. Applying NP decreased EL by 14% only at a salinity level of 50 mM. As well, applying NP decreased MDA content by 29.8 and 65.1% at salinity levels of 50 and 100 mM. NPs application decreased H_2O_2 content by 10.3 and 17.4% at salinity levels of 50 and 100 mM. Also, applying NPs decreased proline content by 10.1% only at a salinity level of 150 mM (Table 3, 6; Figure 5). These outcomes also align with the results of a study on soybeans that explained increased K supply with higher

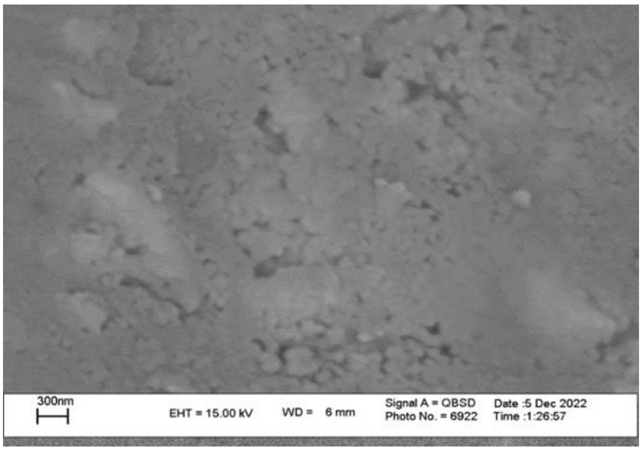

Figure 2. SEM image of the NPs.

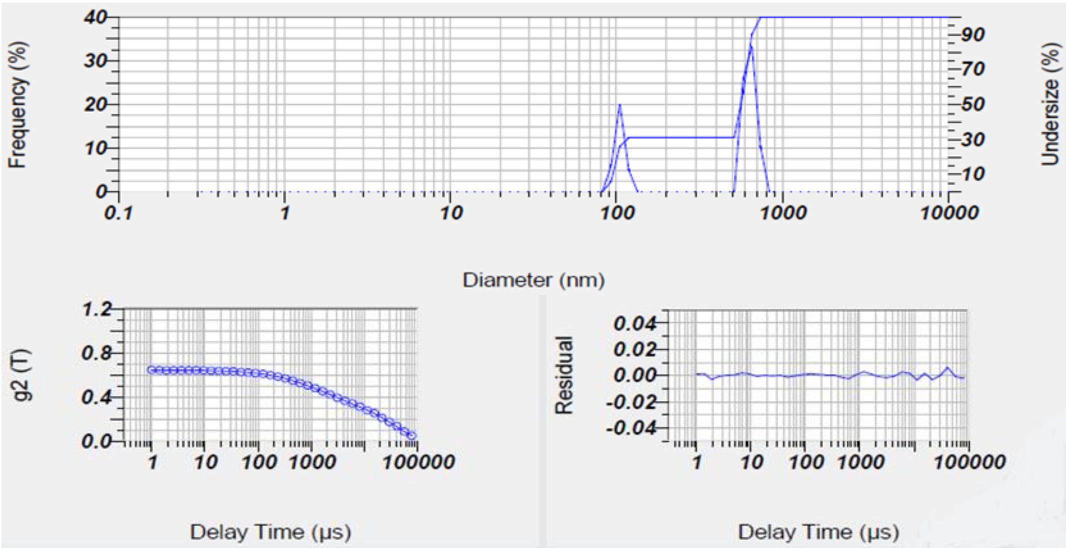

Figure 1. DLS size distribution histogram of the NPs.

Table 1. Effects of different concentrations of NaCl, and NPs on physiological parameters of *Peppermint*.

Salinity (mM)	NPs (0.1 mg/ml)	Root length (cm)	Shoot length (cm)	FW Root (gr)	DW Root (gr)	FW Shoot (gr)	DW Shoot (gr)	RWC (%)
0	C	27.450±0.050^{b}	20.450±0.050^{e}	2.650±0.036^{b}	0.360±0.010^{h}	1.553±0.015^{a}	0.410±0.010^{a}	81.736±0.109^{b}
	NPs	29.950±0.050^{a}	24.550±0.050^{a}	2.776±0.025^{a}	0.973±0.015^{a}	1.123±0.020^{c}	0.340±0.010^{cd}	82.942±0.222^{a}
50	C	17.433±0.076^{d}	21.566±0.076^{d}	1.916±0.035^{c}	0.840±0.010^{b}	1.386±0.032^{b}	0.373±0.020^{b}	74.371±0.273^{g}
	NPs	18.350±0.050^{c}	23.450±0.050^{b}	1.960±0.020^{c}	0.763±0.015^{c}	0.963±0.015^{f}	0.260±0.010^{e}	74.724±0.300^{fg}
100	C	16.416±0.076^{f}	19.583±0.076^{f}	1.610±0.030^{f}	0.646±0.025^{d}	1.138±0.030^{c}	0.320±0.020^{d}	74.935±0.273^{f}
	NPs	17.350±0.050^{d}	22.383±0.076^{c}	1.736±0.015^{d}	0.630±0.020^{e}	1.510±0.036^{a}	0.366±0.015^{b}	75.349±0.308^{e}
150	C	15.450±0.050^{g}	17.850±0.050^{h}	1.473±0.025^{g}	0.453±0.015^{g}	1.126±0.030^{c}	0.350±0.010^{bc}	80.377±0.185^{d}
	NPs	16.250±0.050^{e}	18.250±0.050^{g}	1.673±0.015^{e}	0.560±0.020^{f}	1.050±0.040^{d}	0.256±0.015^{e}	81.290±0.023^{c}

Different letters within each column indicate significant differences according to Duncan's multiple-range test (P≤0.05). All data are expressed as mean ± SE (standard error).

accumulation in plants is an indication of a higher K^+/Na^+ ratio, and the Na^+-specific transporters or Na^+-K^+ co-transporters are directly involved in the tolerance mechanism, according to Parveen *et al*. (2021).

Discussion

It is widely recognized that abiotic stressors restrict crop growth, development, and productivity (Li *et al*., 2013). Peppermint, a consumable medicinal herb, has attracted increasing interest from researchers, emerging as a prominent field of study. The peppermint aerial portion is rich in salicylic acid, phenolic compounds, flavonoids, fatty acids, vitamins, and minerals in addition to essential oil. The essential oil of peppermint, which is evaluated based on the quantity of menthol, menthone, pulegone, and menthofuran, contains the plant's most significant phytochemicals (Omidbaigi, 2005; Rita and Animesh, 2011). The detrimental impacts of salt on plant growth are associated with a decrease in the osmotic potential of growth media,

Table 2. Effects of different concentrations of NaCl, and NPs on photosynthetic parameters of *Peppermint*.

Salinity (mM)	NPs (0.1 mg/ml)	Chlorophyll a (mg/gFW)	Chlorophyll b (mg/gFW)	Carotenoids (mg/gFW)	Fv/Fm	Relative content of Chlorophylls	Stomatal Conductance (μmol CO_2 $m^{-2}s^{-1}$)
0	C	0.161±0.008[cd]	3.159±0.166[cd]	5.880±0.315[cd]	0.816±0.002[d]	7.630±0.055[f]	1005.33±5.033[e]
	NPs	0.176±0.004[ab]	3.468±0.087[bc]	6.609±0.155[b]	0.835±0.003[b]	12.243±0.055[a]	1196.00±2.646[c]
50	C	0.156±0.008[d]	3.075±0.159[d]	5.740±0.226[d]	0.841±0.003[a]	8.190±0.030[e]	1133.33±2.082[d]
	NPs	0.165±0.003[cd]	3.260±0.064[cd]	6.042±0.087[cd]	0.827±0.002[c]	9.663±0.040[c]	1243.33±5.508[b]
100	C	0.177±0.003[ab]	3.491±0.067[ab]	6.601±0.390[b]	0.827±0.002[c]	7.253±0.055[g]	993.33±2.517[f]
	NPs	0.193±.007[a]	3.825±0.155[a]	7.493±0.228[a]	0.838±0.002[a]	8.833±0.045[d]	1328.33±3.512[a]
150	C	0.170±.006[bcd]	3.381±0.113[bc]	6.175±0.284[bc]	0.829±0.002[c]	6.786±0.061[h]	954.00±5.000[g]
	NPs	0.186±0.022[ab]	3.641±0.411[ab]	6.315±0.082[bc]	0.844±0.007[a]	10.020±0.020[b]	1135.00±4.000[d]

Different letters within each column indicate significant differences according to Duncan's multiple-range test (P≤0.05). All data are expressed as mean ± SE (standard error).

Table 3. Effects of different concentrations of NaCl and NPs on biochemical parameters of *Peppermint.*

Salinity (mM)	NPs (0.1 mg/ml)	Electrolyte Leakage (%)	Hydrogen peroxide (μmol/gFW)	Malondialdehyde (nmol/gFW)	Proline (μmol/gFW)
0	C	15.978±0.114[g]	0.519±0.009[f]	0.129±0.034[a]	0.148±0.005[f]
	NPs	13.318±0.101[h]	0.466±0.004[g]	0.051±0.038[b]	0.171±0.005[e]
50	C	23.303±0.015[a]	0.852±0.039[d]	0.144±0.048[a]	0.154±0.004[f]
	NPs	20.037±0.037[b]	0.764±0.002[e]	0.101±0.009[ab]	0.172±0.003[e]
100	C	16.694±0.110[f]	1.01±0.001[c]	0.135±0.023[a]	0.260±0.006[b]
	NPs	18.756±0.015[d]	0.834±0.001[d]	0.047±0.045[b]	0.311±0.007[a]
150	C	18.269±0.782[e]	1.359±0.004[b]	0.092±0.037[ab]	0.217±0.007[c]
	NPs	19.299±0.103[c]	1.847±0.020[a]	0.111±0.024[ab]	0.195±0.004[d]

Different letters within each column indicate significant differences according to Duncan's multiple-range test (P≤0.05). All data are expressed as mean ± SE (standard error).

Table 4. Results of variance analysis of the effects of the levels of salinity and NPs on physiological parameters of *Peppermint*.

Treatment	df	Mean of squares						
		Root length	Shoot length	FW Root	DW Root	FW Shoot	DW Shoot	RWC
Salinity	3	64174.365**	7054.620**	2296.006**	301.143**	65.307**	34.373**	1637.042**
NPs	3	2983.781**	8433.361**	132.940**	504.914**	162.000**	113.357**	54.660**
Salinity × NPs	9	295.615**	969.806**	8.836**	506.629**	294.133**	44.024**	4.397*

***, ** = significant in probability value of P ≤ 0.05 and P ≤ 0.01, respectively; ns = not significant.**

Table 5. Results of variance analysis of the effects of the levels of salinity and NPs on photosynthetic parameters of *Peppermint*.

Treatment	df	Mean of squares					
		Chlorophyll a	Chlorophyll b	Carotenoids	Fv/Fm	Relative content of Chlorophylls	Stomatal Conductance
Salinity	3	6.583*	8.101*	24.264**	10.759**	1822.316**	1561.196**
NPs	3	11.563*	12.877*	26.940**	30.184**	19949.440**	15796.053**
Salinity × NPs	9	0.163ns	0.185ns	3.149ns	26.438**	1500.425**	843.274**

***, ** = significant in probability value of P ≤ 0.05 and P ≤ 0.01, respectively; ns = not significant.**

Table 6. Results of variance analysis of the effects of the levels of salinity and NPs on biochemical parameters of *Peppermint*.

Treatment	df	Mean of squares			
		Electrolyte Leakage	Hydrogen peroxide	Malondialdehyde	Proline
Salinity	3	7418.085**	5067.312**	94.241**	659.439**
NPs	3	442.478**	38.281**	933.621**	61.143**
Salinity × NPs	9	1547.353**	532.339**	241.828**	43.769**

***, ** = significant in probability value of P ≤ 0.05 and P ≤ 0.01, respectively; ns = not significant.**

specific ion toxicity, and nutritional imbalance (Lu *et al*., 2023). Salinity first influences plant morphology by inducing seed dormancy, inhibiting root growth, altering leaf structure, and ultimately diminishing the rate of photosynthesis and energy production (Johnson and Puthur, 2020). In environments where plants have access to enough water, important activities lead to growth phenomena; in the absence of this supply, height reduction occurs because growing cells' turgor pressure will be reduced, which will affect the length of the cells

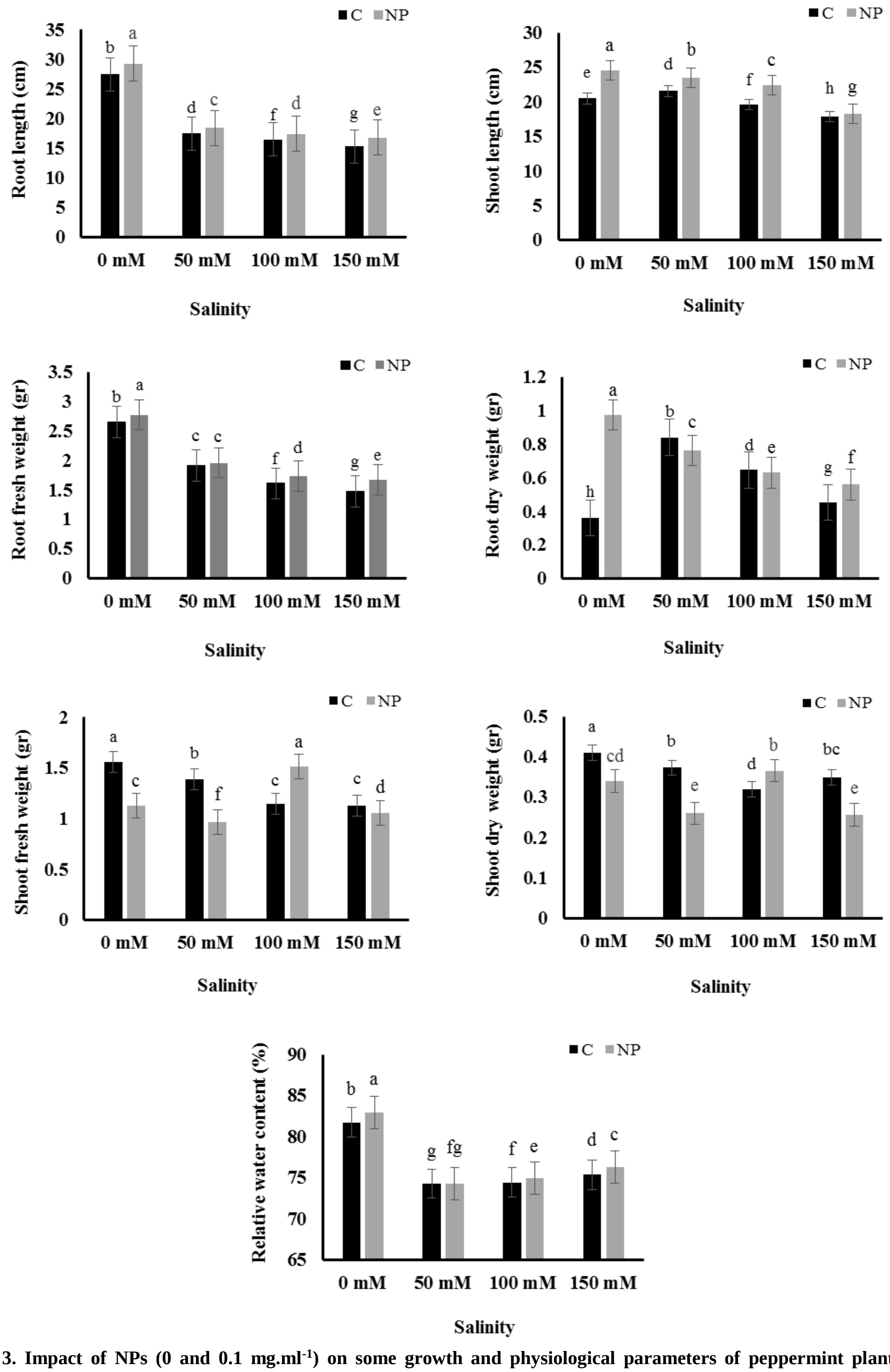

Figure 3. Impact of NPs (0 and 0.1 mg.ml^{-1}) on some growth and physiological parameters of peppermint plants under different salinity stress levels (0, 50, 100 and 150 mM NaCl). Different letters within each column define significant differences based on Duncan's multiple range test (P ≤ 0.05). Data are presented as mean ± SE (standard error). C represents the control.

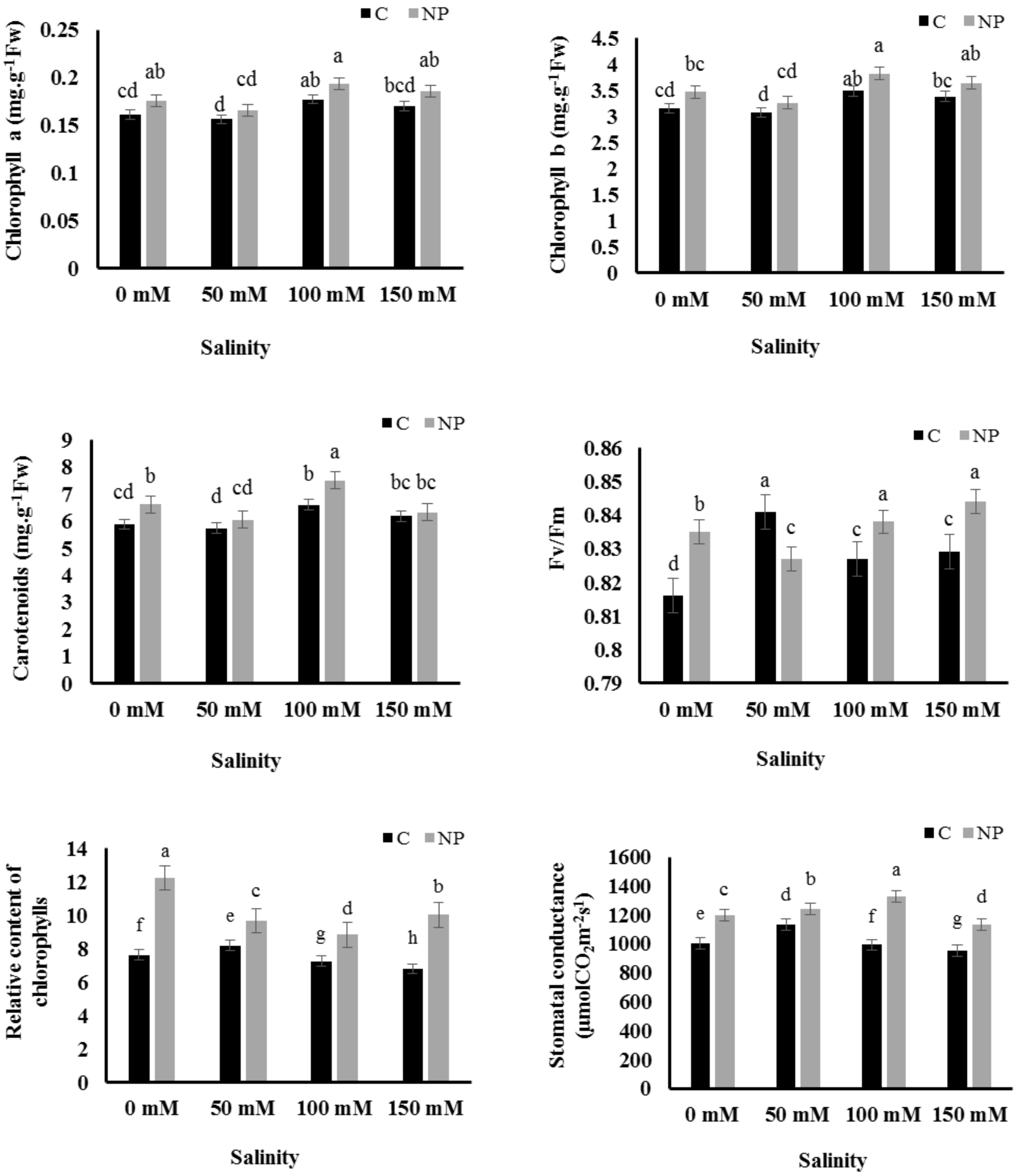

Figure 4. Impact of NPs (0 and 0.1 mg.ml^{-1}) on some photosynthetic parameters of peppermint plants under different salinity stress levels (0, 50, 100 and 150, mM NaCl). Different letters within each column define significant differences based on Duncan's multiple range test (P ≤ 0.05). Data are presented as mean ± SE (standard error). C represents the control group.

(Ahmadi and Baker, 2002). It seems reasonable to observe increased plant height and other morphological traits in response to the use of potassium fertilizers, specifically nanoforms, which are absorbed more effectively than other fertilizers, given the role that potassium plays in maintaining the water potential of cells and aiding in the plant's ability to absorb water (DeRosa *et al*., 2010). It is essential to prioritize the external delivery of potassium using various techniques in order to mitigate the effects of salt and K^+ shortage. Potassium has several benefits, such as increasing the surface area of leaves and roots, promoting the growth of pigments involved in photosynthetic processes, increasing absorption rate, preserving osmotic potential and turgor, activating enzymes, facilitating stomatal movement, and reducing the excessive absorption of ions like Na^+ and Cl^- (Cherel, 2004). Numerous studies have suggested that potassium pretreatment could reduce reactive oxygen species (ROS) in a variety of plant species that are caused by salt stress (Assaha *et al*., 2017; Mousavi *et al*., 2024). The nutrients in potassium nano-fertilizers can be released gradually and steadily (Mahil and Kumar, 2019). As a result, potassium nano-fertilizers can modify the rate at which nutrients are released and lessen the impact of water scarcity on peppermint development.

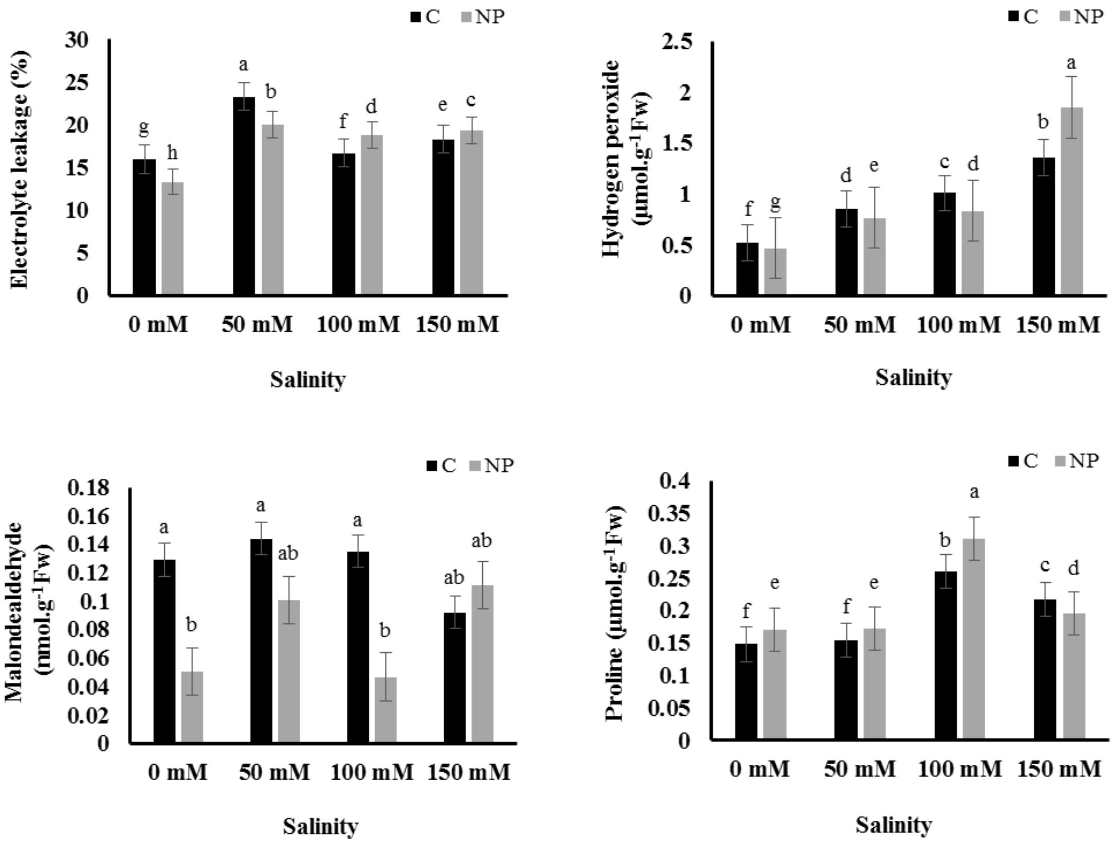

Figure 5. Impact of NPs (0 and 0.1 mg.ml^{-1}) on some biochemical parameters of peppermint plants under different salinity stress levels (0, 50, 100, and 150 mM NaCl). Different letters within each column define significant differences based on Duncan's multiple range test (P ≤ 0.05). Data are presented as mean ± SE (standard error). C represents the control group.

The results of this study were in line with those of some researchers (Abdel-Aziz *et al*., 2018; Mahmoud *et al*., 2022; Mousavi *et al*., 2024), who found that applying various potassium nano-fertilizers under salinity stress conditions improved plant growth and morphology characteristics and reduced the effects of salinity stress. High-molecular-weight components (including proteins, carbohydrates, and cellulose) are synthesized at significantly higher rates in plants when they receive adequate potassium (Marschner, 2011). Additionally, past research has shown that sufficient potassium increases total phenol levels, which are essential for plant resistance and strength (Prasad *et al*., 2010; Qiu *et al*., 2023). Therefore, it is expected that NPs, as opposed to bulk particles, will enhance the synthesis of organic components such as phenols, chlorophyll, and proteins, improving plant development and physiological properties.

Stated differently, the enhancement of plant development traits following NPs application could indicate a reduction in sodium ion absorption and integrity of cell membranes, as seen by the increase in antioxidant capacity and the decrease in oxidative damage. Potassium improves growth by promoting chlorophyll synthesis and maintaining appropriate ion homeostasis, which is essential for plant health (Kumar *et al*., 2020). The enhancement of both stomatal and non-stomatal components of photosynthesis following the application of NPs highlights the positive contributions of these particles to improving photosynthetic efficiency in peppermint. The improvement in photosynthetic performance resulting from NPs treatment can be ascribed to enhanced RWC and maintenance of redox homeostasis, accompanied by a marked reduction in oxidative damage. This, in turn, contributes to the structural and functional stability of the photosynthetic apparatus. Lack of potassium affects photosynthesis by lowering the amount of chlorophyll, the number of chloroplasts, grana, and lamellae, while simultaneously increasing ROS levels considerably (Qi *et al*., 2019). According to the current study, NPs are the most effective at preventing salinity-induced damage to photosynthesis; nevertheless, more molecular research is needed.

Furthermore, plants treated with NPs were able to maintain noticeably reduced H_2O_2 and MDA concentrations, thereby preventing damage to macromolecules such as proteins and lipids. As a result, lipid peroxidation was significantly reduced, thereby maintaining the structural and functional integrity of membranes. Previous studies have shown that applying potassium (Qi *et al*., 2019) and K-NPs (Mousavi *et al*., 2024) can enhance membrane functioning by lowering the generation of harmful ROS molecules. The up-regulation of the antioxidant system, along with the accumulation of secondary metabolites and osmolytes, may contribute to the reduced oxidative damage observed in NP-treated plants (both individually and in combination). This would improve salinity stress amelioration through the mediation of rapid ROS elimination (Ahanger and Agarwal, 2017a, 2017b). By preserving ideal ROS levels, the activation of the antioxidant system, achieved through the application of potassium (Ahmad *et al*., 2016) and K-NPs (Mousavi *et al*., 2024), has been shown to safeguard growth and other important cellular pathways, such as photosynthesis.

The use of NP, both separately and in combination with salt, greatly enhanced the accumulation of compatible osmolytes. Researchers suggest that the plant metabolism gets protected from the damaging effects of stress by compatible osmolytes (Ahanger *et al*., 2020; Dey and Bhattacharjee, 2020; Elkelish *et al*., 2019). In the current study, plants treated with NPs showed the maximum accumulation of compatible osmolytes under 100 mM salinity, resulting in higher salt stress tolerance, as evidenced by increased growth, photosynthesis, biomass accumulation, and yield productivity. An increase in osmolyte accumulation can help maintain ion homeostasis, trigger stress signaling, and preserve enzyme activity. Salinity tolerance is largely dependent on osmolyte accumulation, which plays a crucial role in maintaining toxic ion exclusion (Behzadi *et al*., 2021). In the current study, the application of NPs led to a significant decline in ROS accumulation, resulting in the protection of important cellular pathways, such as photosynthesis.

Conclusion

From the early stages of growth to vegetative growth and in stressful environments, K^+ is essential for plants. It plays a role in chemical structures and, when present in high levels in cells, can mitigate the negative effects of a variety of stresses, such as high temperatures, salinity, water stress, and metal toxicity. High levels of potassium in the cytosol are also necessary for protein activity to maintain optimal cellular functioning. However, in severely stressed environments, endogenous potassium levels are insufficient to counteract the detrimental effects of the stressor, so exogenous potassium supply can lessen the stress responses, such as oxidative stress reduction, increased production of antioxidative enzymes and ROS scavengers, and interactions with other molecules to improve plant growth under stress. We discovered in this experiment that NP are beneficial for the peppermint plant's preservation under salinity stress. NP show great potential as stress-relieving agents in salty conditions due to their efficacious reduction of ionic, osmotic, and oxidative stress resulting from salinity. Our results show that peppermint plants grew more quickly when they were sprayed with NPs because they preserved larger quantities of photosynthetic pigments and increased photosynthetic capabilities. According to the study's results, NPs can serve as efficient biological agents and supplements in peppermint cultivation under moderately saline soil conditions, contributing to improved crop management.

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