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Biochemical Responses of Date Palm *Phoenix dactylifera* L. to Combined Stress of Salinity and Nickel

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Abstract: This study examined the effects of nickel (Ni) at 0, 25, and 50 $mg.L^{-1}$ concentrations, applied alone or in combination with salinity (represented by NaCl at 0, 100, and 200 mM concentrations), on the biochemical traits of date palm. Hydrogen peroxide (H_2O_2), malondialdehyde (MDA), membrane stability index (MSI), peroxidase (POD) activity, superoxide dismutase (SOD), and proline content were among the parameters evaluated. The results revealed significant effects of nickel and salinity on the studied biochemical markers. Nickel at 50 $mg.L^{-1}$ significantly increased H_2O_2 (0.87 $\mu mol. L^{-1}$) and MDA (2.46 $nmol.g^{-1}$) levels, while decreasing MSI (75.85%). Moreover, it enhanced POD (25.09 $U.min^{-1}.g^{-1}$) and SOD (3.78 $U. min^{-1}.g^{-1}$) activity, as well as proline content (4.35 $\mu mol.g^{-1}$). Salinity at 200 mM significantly increased H_2O_2 (0.90 $\mu mol\ L^{-1}$) and MDA (2.54 $nmol.g^{-1}$) levels, decreased MSI (77.69%), and increased POD (27.61 $U. min^{-1}.g^{-1}$) and SOD (3.77 $U.min^{-1}.g^{-1}$) activity, along with increased proline content (4.54 $\mu mol.g^{-1}$). Additionally, the combined application of nickel and salinity, particularly at higher concentrations, resulted in significantly increased biochemical responses compared to individual treatments. The findings highlight the interactive effects of nickel and salinity on the oxidative and antioxidant mechanisms in date palm plants. This study contributes to our understanding of plant responses to abiotic stressors and provides insights for optimizing date palm cultivation under challenging environmental conditions.

Keywords: Antioxidants, hydrogen peroxide, Malondialdehyde, Membrane stability index, Peroxidase, Proline, Superoxide dismutase.

Introduction

Date palm (*Phoenix dactylifera* L.) is an economically significant crop cultivated in arid and semiarid regions worldwide due to its nutritional value and commercial importance (Al-Alawi *et al*., 2017; Al-Aradi *et al*., 2020). However, date palm growth and productivity are often hindered by various abiotic stresses, including salinity and heavy metal contamination (Akensous *et al*., 2022). Among heavy metals, nickel (Ni) is known to adversely affect plant physiology and biochemical processes (Kastori *et al.*, 2022). Additionally, salinity, primarily caused by excessive sodium chloride (NaCl) concentrations in soil and irrigation water, poses a significant threat to date palm cultivation (Dghaim *et al.*, 2021). Understanding the interactive effects of Ni and salinity on date palm biochemical characteristics is crucial for developing effective strategies to mitigate their adverse impacts. Previous studies e shown that Ni and salinity can induce oxidative stress in plants, leading to the accumulation of reactive oxygen species (ROS) and lipid peroxidation (Shahzad *et al.*, 2018; Hasanuzzaman & Fujita, 2022). Antioxidant enzymes, such as peroxidase (POD) and superoxide dismutase (SOD), play a crucial role in scavenging ROS and maintaining redox homeostasis (Gill & Tuteja, 2010). Proline, an important osmolyte, acts as an antioxidant and osmoprotectant under stress conditions (Mahdi *et al.*, 2022; Spormann *et al.*, 2023). Despite the significance of Ni and salinity in date palm cultivation, limited research has been conducted to investigate their combined effects on the biochemical characteristics of this crop. Therefore, this study aimed to assess the impact of Ni applied alone or in combination with salinity on selected biochemical parameters, including hydrogen peroxide, malondialdehyde, membrane stability index, peroxidase activity, superoxide dismutase activity, and proline content.

Materials & Methods

Plant material and growth conditions

Date palm (*Phoenix dactylifera* L.) offshoots of the Hillawi cultivar were used for this study. Healthy and uniformly sized seedlings at two years old were selected and acclimatized in a greenhouse at the Department of Horticulture and Landscape, College of Agriculture, University of Basrah. The plants were grown in plastic pots filled with soil. The properties of the soil are shown in table (1).

Table (1): Characteristics of the soil used in the experiment.

Soil characteristic	Values	Unit
pH	7.10	
EC	5.86	ds m^{-1}
OM	0.58	%
Sand	18.13	%
Silt	42.74	%
Clay	39.13	%
Soil texture	Silty loam	
pH water	8.22	

Chemicals and solutions

Nickel chloride hexahydrate ($NiCl_2.6H_2O$) and sodium chloride (NaCl) were purchased from Sigma-Aldrich (St. Louis, MO, USA). All chemicals used in the study were of analytical grade. Stock solutions of $NiCl_2.6H_2O$ and NaCl were prepared separately and diluted to the desired concentrations.

Experimental design

A randomized complete block design (RCBD) with three replicates was employed in this study. The treatments included three concentrations of nickel (0, 25, and 50 mg. L^{-1}) applied alone and in combination with three salinity levels represented by sodium chloride (NaCl) concentrations (0, 100, and 200 mM). The experiment comprised a total of 9 treatment combinations, and each treatment combination was assigned to a separate pot. The pots were arranged randomly in a controlled greenhouse.

Nickel and salinity treatments

For the nickel treatments, nickel sulfate ($NiCl_2.6H_2O$) was dissolved in distilled water to prepare stock solutions of desired concentrations (25 and 50 mg.L^{-1}). The control treatment received distilled water without nickel sulfate. The nickel solutions were applied by carefully pouring the desired volume around the base of each plant.

To apply salinity, sodium chloride (NaCl) was dissolved in distilled water to prepare stock solutions of desired concentrations (100 and 200 mM). The control treatment received distilled water without NaCl. Salinity treatments were applied by uniformly irrigating the pots with the respective NaCl solutions.

Data collection and analysis

After 180 days of treatment application, biochemical analyses were performed on the leaf samples. Hydrogen peroxide (H_2O_2) content was determined following the method described by Velikova *et al.* (2000). Malondialdehyde (MDA) content was measured according to Heath & Packer (1968). Membrane stability index (MSI) was determined using the electrolyte leakage method (Singh *et al*., 2008). Peroxidase (POD) and superoxide dismutase (SOD) activities were determined according to the protocols described by Chance & Maehly (1955) and Giannopolitis & Ries (1977), respectively. Proline content was determined using the ninhydrin reagent method (Bates *et al*., 1973). The experiment was set up as a completely randomized block design(CRBD), with three replicates of each measurement and data were subjected to analysis of variance (ANOVA) using appropriate statistical software SPSS-22 software (SPSS In., Chicago, IL., USA). The least significant difference (LSD) was used to evaluate significant differences between means. Statistical significance was defined as a *P* value of less than 0.05.

Results & Discussion

Hydrogen peroxide (H_2O_2) accumulation

The results table (2) obtained from the study show significant differences in the content of hydrogen peroxide (H_2O_2) of date palm Hillawi cv. leaves with different treatments. The highest H_2O_2 concentration was observed in treatment with a nickel at 50 mg.L^{-1}, reaching 0.87 µmol.L^{-1}. This finding is consistent with previous studies showing elevated H_2O_2 levels in plants exposed to heavy metals such as nickel (Khan *et al*., 2016; Kumar *et al*., 2022). Nickel is known to induce oxidative stress by generating reactive oxygen species (ROS) in plant cells (Manna *et al*., 2021). The elevated H_2O_2 concentration in this study suggests that the application of nickel at 50 mg.L^{-1} increased the production of ROS, which caused oxidative damage to date leaves. Regarding the salinity treatments, the highest H_2O_2 content was recorded at a salinity level of 200 mM, measuring 0.90 µmol.L^{-1}. Salinity stress has been widely reported to cause oxidative stress in plants due to the accumulation of ROS (Gill & Tuteja, 2010; Suhim *et al*., 2023). The observed increase in H_2O_2 concentration in the current study is consistent with previous results in other plant species under salt stress conditions (Munns & Tester, 2008; Hasanuzzaman & Fujita, 2022). Higher saline levels are thought to have encouraged the generation of reactive oxygen species (ROS), resulting in the accumulation of H_2O_2 in date palm leaves. Furthermore, the interaction between nickel and salinity showed a synergistic effect on H_2O_2 accumulation. The highest H_2O_2 content was observed at a nickel concentration of 50 mg. L^{-1} and a salinity level of 200 mM, measuring 0.98 µmol.L^{-1}. This interaction may have enhanced ROS production, surpassing the individual effects of nickel or salinity alone. Similar interactive effects of nickel and salinity on oxidative stress have been reported in other plant species (Georgiadou *et al*., 2018; Awad *et al*., 2019; Dghaim *et al*., 2021).The control treatment exhibited the lowest H_2O_2 content, amounting to 0.71 µmol.L^{-1}. This reflects the normal physiological state of date palm leaves under optimal growth conditions, where ROS production is maintained at a basal level (Apel & Hirt, 2004).

Table (2): The impact of salinity and nickel on the H_2O_2 content (µmol L^{-1}) of Hillawi date palm leaves.

Salinity (mM)	Ni (mg L^{-1})			Mean
	0	25	50	
0	0.71±0.01 f*	0.76±0.02 e	0.79±0.01 de	0.75±0.03C
100	0.80±0.01 cde	0.82±0.01 cd	0.84±0.01 c	0.82±0.01B
200	0.82±0.01 cd	0.89±0.01 b	0.98±0.01 a	0.90±0.07A
Mean	0.78±0.05C	0.82±0.05B	0.87±0.07A	

*The same letter above bars represents no significant difference between treatments, based on the range test at $p \leq 0.05$.

Malondialdehyde (MDA)

The results presented in table (3) demonstrate the impact of different treatments on the malondialdehyde (MDA) content in date palm Hillawi cv. leaves, reflecting the level of lipid peroxidation and oxidative damage. The most significant MDA level was found when treated with a nickel concentration of 50 mg. L^{-1}, reaching 2.46 nmol.g^{-1}. This results indicates that nickel-induced stress enhances lipid peroxidation in date palm leaves, resulting in the production of MDA, a measure of oxidative damage (Manna *et al*., 2021). Similar findings have been reported in other plant species exposed to nickel stress (Amjad *et al*., 2019; Kumar *et al*., 2022). The elevated MDA content in the present study highlights the role of nickel as a potent inducer of oxidative stress in date palm leaves. In addition, the salinity treatment at 200 mM produced the highest MDA level, reaching 2.54 nmol g^{-1}. Salinity stress has been shown to affect cellular homeostasis and initiate lipid peroxidation processes in plants, resulting in elevated MDA levels (Hasanuzzaman & Fujita, 2022; Mahdi *et al*., 2022).The observed increase in MDA content indicates the occurrence of oxidative damage in date palm leaves under high salinity conditions. Moreover, the interaction between nickel and salinity exhibited a significant effect on the MDA content. The highest MDA content was recorded at a nickel concentration of 50 mg.L^{-1} and a salinity level of 200 mM, reaching 2.69 nmol.g^{-1}. This interaction between nickel and salinity likely intensified oxidative stress and lipid peroxidation processes, resulting in elevated MDA levels. Similar interactive effects of nickel and salinity on MDA accumulation have been reported in other plant species (Yusuf *et al*., 2012; Awad *et al*., 2019; Naheed *et al*., 2022). In contrast, the control treatment displayed the lowest MDA content, amounting to 1.96 nmol.g^{-1}. This signifies the absence of significant oxidative damage and lipid peroxidation in date palm leaves under optimal growth conditions.

Table (3): The impact of salinity and nickel on the MDA content (nmol. L^{-1}) of Hillawi date palm leaves.

Salinity (mM)	Ni (mg L^{-1})			Mean
	0	25	50	
0	1.96±0.02 d*	2.23±0.02 c	2.29±0.01 bc	2.16±0.15 C
100	2.32±0.03 bc	2.36±0.02 bc	2.41±0.01 bc	2.36±0.85 B
200	2.42±0.02 bc	2.51±0.01 ab	2.69±0.24 a	2.54±0.13 A
Mean	2.23±0.20 B	2.37±0.13 A	2.46±0.17 A	

*The same letter above bars represents no significant difference between treatments, based on the range test at p ≤ 0.05.

Membrane stability index (MSI)

The findings from table (4) reveal the effects of different treatments on the Membrane Stability Index (MSI) in date palm Hillawi cv. leaves, which serves as an indicator of membrane integrity and stability under various stress conditions. The lowest MSI value was observed when treated with a nickel concentration of 50 mg. L^{-1}, measuring 75.85%. This indicates that nickel stress adversely affects membrane stability in date palm leaves, leading to increased membrane damage (Zaid *et al*., 2019; Suhim *et al*., 2023). Previous studies reported similar outcomes, highlighting the disruptive effects of nickel on membrane function in various plant species (Kumar *et al*., 2022; Naheed *et al*., 2022). Furthermore, the salinity treatment at a concentration of 200 mM resulted in the lowest MSI content, amounting to 77.69%. Salinity stress imposes osmotic and ionic imbalances on plant cells, leading to membrane dysfunction and reduced stability (Mahdi *et al*., 2023). The decreased MSI value in the present study indicates compromised membrane integrity under high salinity conditions. Moreover, the interaction between nickel and salinity exhibited a significant effect on MSI.

The lowest MSI content was recorded at a nickel concentration of 50 mg.L^{-1} and a salinity level of 200 mM, measuring 75.85%. This interaction between nickel and salinity intensified membrane damage, suggesting a synergistic effect of these stressors on membrane stability. Similar interactive effects of nickel and salinity on MSI have been reported in other plant species (Amjad *et al*., 2019; Al-Qatrani *et al*., 2021). In contrast, the control treatment displayed the highest MSI content, reaching 86.66%. This signifies the normal membrane stability and integrity in date palm leaves under optimal growth conditions, where no stressors are present.

Table (4): The impact of salinity and nickel on the Membrane stability index (MSI) (%) of Hillawi date palm leaves.

Salinity (mM)	Ni (mg .L^{-1})			Mean
	0	25	50	
0	86.66±1.02 a*	83.13±1.00 b	80.20±0.20 bc	83.33±2.89 A
100	82.22±0.10 bc	80.13±0.13 bc	77.68±0.10 cd	80.01±1.97 B
200	79.31±0.20 c	77.91±0.10 cd	75.85±0.18 d	77.69±1.51 C
Mean	82.73±3.24 A	77.91±2.32 B	75.85±1.90 C	

*The same letter above bars represents no significant difference between treatments, based on the range test at p ≤ 0.05.

Peroxidase (POD) activity

The results from table (5) indicated the activity of the Peroxidase (POD) enzyme in date palm Hillawi cv. leaves under different treatments. POD is an important enzyme involved in various physiological and defense responses in plants. The findings indicate notable variations in POD activity in response to nickel and salinity stressors. Firstly, when treated with a nickel concentration of 50 mg L^{-1}, the highest activity of POD enzyme was observed, reaching 25.09 $U.min^{-1}.g^{-1}$. Previous studies reported similar increases in POD activity under nickel stress, indicating its role in scavenging reactive oxygen species and maintaining cellular redox balance (Gajewska *et al*., 2006; Khan *et al*., 2016). Furthermore, the salinity treatment at concentration of 200 mM resulted in the highest activity of POD enzyme, measuring 27.61 $U.min^{-1}.g^{-1}$. Salinity stress induces the production of reactive oxygen species, leading to oxidative damage in plant cells.

The increase in POD activity in response to salt stress indicates its role in reducing oxidative stress by catalysing hydrogen peroxide detoxification (Nahar *et al*., 2022). Furthermore, the combination of nickel and salinity had a significant impact on POD enzyme activity. The interaction between a nickel concentration of 50 $mg.L^{-1}$ and a salinity level of 200 mM produced the highest activity for this enzyme, reaching 27.90 U. $min^{-1}.g^{-1}$. This results suggested that nickel and salt have a synergistic impact on the activation of POD activity, increasing the plant's antioxidative defence systems. Other plant species have shown similar interaction effects (Amjad *et al*., 2019). Conversely, the control treatment displayed the lowest activity of the peroxidase (POD) enzyme, with a measurement of 21.21 U. $min^{-1}.g^{-1}$. This indicates the typical baseline activity of POD in date palm leaves under optimal growth conditions without any external stress factors. Additionally, this baseline activity serves as a reference to assess the influence of stress treatments on the enzyme's activity.

Table (5): The impact of salinity and nickel on the peroxidase enzyme activity (POD) ($U.min^{-1}.g^{-1}$) of Hillawi date palm leaves.

Salinity (mM)	Ni ($mg.L^{-1}$)			Mean
	0	25	50	
0	21.21±0.10 d*	21.67±0.20 cd	22.94±0.30 bcd	21.94±0.79 C
100	23.11±0.10 bcd	23.85±0.10 bc	24.44±0.20 b	23.80±0.59 B
200	27.17±0.07 a	27.77±0.20 a	27.90±0.20 a	27.61±0.36 A
Mean	23.83±2.63 B	24.43±2.68 AB	25.09±2.21 A	

*The same letter above bars represents no significant difference between treatments, based on the range test at $p \leq 0.05$.

Superoxide dismutase (SOD) enzyme

Table (6) shows the activity of the Superoxide Dismutase (SOD) enzyme in date palm Hillawi cv. leaves in response to different treatments. SOD is an important enzyme in the defense against oxidative stress because it catalyses the dismutation of superoxide radicals. The results show that SOD enzyme activity varies significantly in response to nickel and salt stresses. To begin, the maximum activity of SOD enzyme was seen when treated with a nickel at 50 mg L^{-1}, reaching 3.78 $U.min^{-1}.g^{-1}$ fresh weight. This suggests that the antioxidant defense mechanism in plant leaves is being activated in response to nickel-induced oxidative stress (Gajewska *et al*., 2006; Ryan *et al*., 2015). Previous studies reported similar increases in SOD activity under nickel stress, highlighting its role in scavenging superoxide radicals and maintaining cellular redox homeostasis (Zaid *et al*., 2019). Furthermore, the salinity treatment at 200 mM resulted in the highest SOD enzyme activity, recorded 3.77 $U.min^{-1}.g^{-1}$ fresh weight. Salinity stress caused the formation of reactive oxygen species, which resulted in oxidative damage in plant cells. SOD activity increased in response to salt stress, indicating that it was involved in the detoxification of superoxide radicals, hence alleviating oxidative stress (Georgiadou *et al*., 2018; Dghaim *et al*., 2021). Moreover, the interaction between nickel and salinity exhibited a significant effect on the activity of the SOD enzyme. The highest activity was recorded in the interaction between a nickel concentration of 50 mg L^{-1} and a salinity level of 200 mM, measuring 4.19 $U.min^{-1}.g^{-1}$ fresh weight. This indicates a synergistic effect of nickel and salinity on the induction of SOD activity, enhancing the plant's antioxidant defense mechanisms. Such interactive effects have been observed in other plant species as well (Amjad *et al*., 2019; Al-Qatrani *et al*., 2021).

The control treatment, on the other hand, had the lowest SOD enzyme activity of 2.44 U $.min^{-1}.g^{-1}$ fresh weight. This is the baseline SOD activity in date palm leaves under ideal development conditions with no stresses. It is used as a baseline for assessing the effect of stress treatments on enzyme activity.

Table (6): The impact of salinity and nickel on the Superoxide dismutase (SOD) enzyme activity ($U.min^{-1}.g^{-1}$) of Hillawi date palm leaves.

Salinity (mM)	Concentration Ni (mg. L^{-1})			Mean
	0	25	50	
0	2.44±0.20 f*	3.01±0.01 de	3.25±0.25 cd	2.90±0.39 C
100	2.74±0.20 ef	3.56±0.20 bc	3.90±0.10 ab	3.40±0.53 B
200	3.12±0.10 de	4.00±0.20 a	4.19±0.10 a	3.77±0.50 A
Mean	2.77±0.33 C	3.52±0.45 B	3.78±0.44 A	

*The same letter above bars represents no significant difference between treatments, based on the range test at p ≤ 0.05.

Proline content: The results in table (7) showed that nickel and salinity treatments had an effect on the proline content of date palm leaves. When the plants were treated with nickel at a concentration of 50 $mg.L^{-1}$, the proline content reached 4.35 $\mu mol.g^{-1}$. Similarly, the salinity treatment at 200 mM increased proline content significantly, with a value of 5.45 $\mu mol.g^{-1}$. When the plants were subjected to 50 $mg.L^{-1}$ nickel and 200 mM salt, the interaction between nickel and salinity produced the highest proline content, with a value of 5.87 $\mu mol.g^{-1}$. The control treatment, on the other hand, had the lowest proline concentration, measuring 2.25 μmol $.g^{-1}$. A well-known adaptation process in plants is the accumulation of proline in response to stress conditions, such as heavy metals and salt. Proline acts as an osmoprotectant and antioxidant, aiding in the maintenance of cellular osmotic balance and the scavenging of reactive oxygen species. The observed increase in proline level in the treated plants showed that stress response mechanisms were activated to deal with the negative effects of nickel and salt. These findings are similar with prior research on other plant species exposed to similar stress situations (Gajewska *et al*., 2006; Dghaim *et al*., 2021; Mahdi *et al*., 2022; Suhim *et al*., 2023).

Table (7): The impact of salinity and nickel on the proline content (µmol.g^{-1}) of Hillawi date palm leaves.

Salinity (mM)	Ni (mg.L^{-1})			Mean effect
	0	25	50	
0	2.25±0.11 e*	2.43±0.20 de	2.66±0.18 de	2.45±0.43 C
100	2.98±0.10 d	4.00±0.24 c	4.51±0.10 bc	3.83±0.38 B
200	5.07±0.20 b	5.42±0.20 ab	5.87±0.33 a	5.45±0.68 A
Mean	3.43±0.48 C	3.95±0.36 B	4.35±0.51 A	

*The same letters above bars represents no significant difference between treatments, based on the range test at p ≤ 0.05.

Conclusion

The findings of the experiments revealed that nickel and salt had a substantial influence on numerous biochemical parameters of date leaves. At 50 mg.L^{-1}, nickel treatment enhanced the accumulation of hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) while decreasing the membrane stability index (MSI), suggesting oxidative stress. Increases in POD and SOD enzyme activity, as well as proline accumulation, indicate that antioxidant defense mechanisms have been activated. The same findings were obtained with salt treatment at 200 mM. The interaction of nickel and salinity enhanced these effects. The control treatment showed lower values of these parameters, indicating the absence of stress-induced responses. These findings highlight the sensitivity of date palm leaves to nickel and salinity stress and emphasize the importance of antioxidant systems and osmoprotectants in mitigating the adverse effects. Understanding these responses is crucial for developing strategies to enhance date palm tolerance and productivity in challenging environments.

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Contributions of authors

H.M. G., Suggesting the research**.**

A.Z.R., designing the experimental approach**.**

K.M.A., writing the manuscript;

A.A.S. and A.H.A.; Practical experiments and analyzing the data.

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Conflicts of Interest

The authors declare no conflicts of interest.

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الاستجابة الكيموحيوية لنخيل التمر *Phoenix dactylifera* L. لاجهاد الملوحة والنيكل المشترك

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المستخلص: تمت دراسة تأثير النيكل (Ni) بتراكيز 0 و 25 و 50 ملغم.لتر$^{-1}$، بشكل مفرد او متداخل مع الملوحة (الممثلة بتراكيز 0 و 100 و 200 مليمول من كلوريد الصوديوم)، على الصفات الكيموحيوية لنخيل التمر. تم تقييم عدة مؤشرات بينها بيروكسيد الهيدروجين (H_2O_2) ومالونديالدهايد (MDA) ومؤشر ثباتيه الاغشية (MSI) وفعالية انزيمي بيروكسيديز (POD) والسوبر أكسيد ديسموتيز (SOD) ومحتوى البرولين. أظهرت النتائج تأثيرات معنوية للنيكل والملوحة على الصفات الكيموحيوية المدروسة. اثرت معاملة النيكل بتركيز 50 ملغم.لتر$^{-1}$بشكل معنوي من مستويات H_2O_2(0.87 ميكرومول. لتر$^{-1}$) و MDA (2.46 نانومول. غم$^{-1}$)، في حين انخفض مؤشر ثبات الاغشية MSI (75.85%). علاوة على ذلك، زاد من فعالية POD (25.09 وحدة .دقيقة$^{-1}$.غم$^{-1}$) و SOD (3.78 وحدة.دقيقة$^{-1}$.غم$^{-1}$)، بالإضافة إلى زيادة محتوى البرولين (4.35 ميكرومول.غم$^{-1}$). زادت الملوحة بتركيز 200 مليمول بشكل معنوي من مستويات H_2O_2 (0.90 ميكرومول. لتر$^{-1}$) و MDA (2.54 نانومول.غم$^{-1}$)، وانخفضت MSI(77.69%)، وزاد فعالية POD (27.61 وحدة.دقيقة$^{-1}$.غم$^{-1}$) و SOD (3.77 وحدة.دقيقة$^{-1}$.غم$^{-1}$)، بالإضافة إلى زيادة محتوى البرولين (4.54 ميكرومول.غم$^{-1}$). بالإضافة إلى ذلك، أدت معاملة التداخل للنيكل والملوحة، خاصة بالتراكيز العالية، إلى زيادة ملحوظة في الاستجابات الكيموحيوية مقارنة بالمعاملات الفردية. تسلط هذه النتائج الضوء على التأثيرات التفاعلية للنيكل والملوحة على آليات الأكسدة والمضادة للأكسدة في نباتات نخيل التمر. تساهم هذه الدراسة في فهمنا لاستجابة النباتات للعوامل الإجهادية غير الحيوية وتقدم نصائح لتحسين زراعة نخيل التمر في ظروف بيئية صعبة.

الكلمات المفتاحية: مضادات الاكسدة، بيروكسيد الهيدروجين، مالونديالديهايد، مؤشر ثباتية الاغشية، بيروكسيديز، برولين، سوبر اوكسيد ديسميوتيز.