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Research article

Influence of Grafting on Crop Productivity and Performance Using Pepper Landrace Rootstocks Under Salinity Conditions

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Abstract

This study was conducted at Al-Karamah Research Station - National Agricultural Research Center in the Jordan Valley, the Hashemite Kingdom of Jordan during the 2021/2022 growing season to investigate the impact of grafting on crop productivity and fruit quality parameters of a commercial pepper variety (Passion) using three pepper local landraces as rootstocks under salinity stress conditions. A split-plot experimental design system was used, where two salinity levels were the main plot treatments (2.0 dS m^{-1} and 4 dS m^{-1}), and four sub-plot treatments were grafting combinations (JO 204 X Passion, JO 207 X Passion, JO 109 X Passion, and Passion as a non-grafted control treatment). Pepper productivity, total phenols, antioxidant enzyme (SOD) content, chlorophyll content in leaves, and plant leaf and root tissue minerals content were measured. The results revealed that grafting using landrace rootstocks mitigated the negative effects of salinity on nutrient uptake, accumulation, and distribution. All plants exhibited increased Na^+ content under salt stress but non-grafted plants exhibited higher accumulation of toxic ions under salt stress. Moreover, salt-tolerant pepper rootstock landraces selectively absorbed higher K^+ and Ca^{+2} ion levels than non-grafted plants. In addition, peppers grafted onto landraces exhibited enhanced antioxidant content and less oxidation stress measured as the content of MDA. All this led eventually to better productivity and fruit quality of the grafted pepper plants. Pepper Landrace (JO 207) was identified as a promising salt-tolerant accession, holding potential for future utilization in the production of grafted pepper seedlings.

Keywords: antioxidants; electrical conductivity; MDA; pepper; landraces; stress

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1. Introduction

Salinity stress poses a significant challenge to agricultural productivity, particularly in regions with high soil and water salinity. It adversely affects the growth, development, and overall quality of a range of crops, including pepper (*Capsicum annuum*). In recent years, researchers have been exploring innovative strategies to mitigate the negative impact of salinity stress on crop production. Grafting, in combination with suitable rootstocks of local landraces, has emerged as a promising approach to enhance the salt tolerance of various crops, including pepper. Vegetable plants exposed to excessive salinity are usually associated with reduced photosynthetic capacity (Liu et al., 2013).

Overall, a multidisciplinary strategy combining breeding, technology advancements, and alternative techniques like grafting or the use of landraces is needed to boost crop productivity under abiotic stress conditions. These strategies can improve crop production resilience and sustainability in a variety of environmental conditions while maintaining quality. Landrace peppers are highly prized for their agronomically significant characteristics since they have evolved over time to fit local habitat conditions. These landraces are excellent resources for crop improvement because they might be tolerant to different abiotic stressors (Kapazoglou et al., 2023).

Grafting was first employed to combat soil diseases (Oda, 2002). The ability of grafting to greatly increase plant resilience to abiotic stress, such as salinity, drought, high temperatures, and cold has just recently come to light (Schwarz et al., 2010; Huang et al., 2015). Hundreds of studies and in-depth evaluations of vegetables have been primarily motivated by the growth of grafting in recent years and its effects on horticultural production (Lee et al., 2010). Rootstocks that can tolerate salt can give the scion better defenses against salinity stress, which improves growth, production, and fruit quality. The effects of grafting and rootstock on pepper crop fruit quality indicators under saline stress circumstances have been the subject of several studies (Colla et al., 2012). These studies have shed light on the mechanisms underlying grafted plant responses to salt stress and its consequent effects on fruit quality. To determine the efficiency of grafting in enhancing fruit quality under saline stress, researchers have looked at a variety of factors, including changes in fruit size, shape, color, nutritional composition, taste, and postharvest characteristics. For instance, it was demonstrated that grafting increased the amounts of antioxidants, vitamins, and minerals that accumulated in pepper fruits, enhancing their nutritional value. It was determined that pepper can be successfully grafted onto tolerant rootstocks to lessen the detrimental effects of suboptimal Ca conditions on pepper crop performance and fruit quality (López-Serrano et al., 2022). Grafted plants' high antioxidant enzyme activity can lessen chlorophyll deterioration, lessen chloroplast membrane damage, and enhance photosynthesis (Zhang et al., 2019).

Landraces and closely related wild relatives can serve as valuable genetic sources for breeding stress-tolerant peppers, as found in a study using wild relatives of tomato as a genetic source for breeding tolerant tomatoes (Conesa et al., 2020). The rootstock-scion combination significantly influences the effect of grafting on pepper quality traits, and this interaction is further influenced by factors such as climate, cultural practices, stress duration and severity, water and nutrient availability, and sampling strategies.

Research on the performance of pepper plants under salinity conditions in Jordan is limited. Qaryouti et al. (2003) evaluated eight accessions of local pepper landraces based on morphological characteristics under greenhouse conditions in the Jordan Valley. Building on these findings, as well as two years of evaluations of ten pepper accessions under soil and water salinity conditions at the Karamah Research Station in the Jordan

Valley (VEG-ADAPT project), three elite pepper landrace accessions (referred to as VTAs) were identified for further study. These accessions were selected based on their favorable performance under salinity stress.

The objective of this study was to explore the potential of grafting commercial pepper varieties onto salinity-tolerant rootstocks (VTAs) to enhance crop performance in salinity-affected soils. Specifically, the study aimed to compare the performance of the commercial pepper variety 'Passion' when grafted onto local VTAs with that of non-grafted 'Passion' plants. Key parameters under investigation included productivity, antioxidant capacity, and fruit quality, with a focus on identifying physiological traits associated with salinity tolerance.

2. Materials and Methods

2.1 Experimental site

The experiment was conducted at Al-Karamah Research Station - National Agricultural Research Center in the Jordan Valley, the Hashemite Kingdom of Jordan, during the 2021/2022 growing season. The geographical location of the experimental site was 31° 93' N latitude, 35° 57' E longitude, and 240 m altitude below sea level

2.2 Irrigation system and irrigation management

A drip irrigation system was used with 1.50 m between laterals of 16 mm diameter in-line pressure compensation emission with a spacing of 40 cm and 4 l h^{-1} flow rate.

Irrigation management based on the daily crop actual evapotranspiration was calculated using the crop coefficients in equation (1) (Allen et al., 1998):

$$ET_c = ET_0 \times K_c \quad (1)$$

Where

ET_c = crop actual evapotranspiration(mm)

ET_0 = potential evapotranspiration (mm) estimated from a nearby weather station

K_c = crop coefficients from tabulated FAO values

Irrigation quantity was monitored by digital water meters, one for each irrigation water quality. The irrigation intervals for each irrigation water quality were based on 30% of the available water being depleted, as determined by a tensiometer reading. Applied irrigation water was calculated based on the Penman-Monteith equation (Allen et al., 1998) taking into account irrigation leaching requirements of 10% and 24% for irrigation with 2 and 4 dS m^{-1} water salinity treatments, respectively. We chose these levels based on the quality of water sources available in the Al Karama area, which consisted in surface water coming from the King Talal Dam, which had an average salinity of about 2 dS m^{-1}, and salty water from groundwater wells, with an average salinity of about 4 dS/m. The amount of water applied was different for each irrigation water quality which were 5045 and 5975 m^3 ha^{-1} per growing season for 2 and 4 dS m^{-1} irrigation water salinity, respectively. Torsiometers were installed 20 cm in between two pepper plants and used to determine when to irrigate, while the amount of irrigation was calculated based on the crop water requirements using the estimated Eta and the crop growth stage. The applied water for each irrigation water salinity treatment was calculated using the following equation (2):

$$I_r = \frac{ET_c}{1 - LR} \tag{2}$$

Where

I_r = applied water (mm)
ET_c = actual crop evapotranspiration (mm)
LR = leaching factor using the following equation (3)

$$LR = \frac{EC_w}{5(EC_e) - EC_w} \tag{3}$$

Where

LR = the minimum leaching requirement needed to control salts within the tolerance (ECe) of the crop
EC_w = irrigation water salinity in dS m^{-1}
EC_e = average soil salinity tolerated by the crop as measured on a soil saturation extract.

2.3 Statistical experimental design

A spilt-plot experimental design system was used (Figure 1), in which the salinity levels were the main treatment, and the rootstocks and grafting were the sub-main treatments. Two salinity levels were applied, the first salinity treatment was irrigation with a salinity of 2.0 dS m^{-1} and the second treatment was irrigation with saline water of 4 dS m^{-1} so that the salinity of the irrigation water is raised after adding the recommended fertilizers by mixing it with the Dead Sea water (high salinity) to obtain the required salinity level.

The grafting combinations included JO 204 X Passion, JO 207 X Passion, and JO 109 X Passion. Passion (commercial verity) was used as the non-grafted control. During the season and the different stages of growth, the degree of salinity in the soil was constantly monitored by electronic sensors placed in the soil to collect the data on moisture and salinity levels. A data processor was used to adjust the fertilization and irrigation program accordingly.

2.4 Agricultural practices

When the pepper seedlings reached the 2-4 true leaves stage, grafting was carried out. The grafted seedlings were kept under controlled conditions of humidity (90%) for four days, and then transferred to the greenhouse under shading before planting for acclimatization. After ten days, grafted seedlings were ready for transplantation. During the season, the plants were monitored at the site and all operations related to irrigation, fertilization, agricultural pest control, and weeding were carried out, the plants at the site were carefully monitored, with all operations related to irrigation, fertilization, pest control, and weeding being conducted as needed. Chlorophyll content was measured before harvesting, and yield were tracked following the harvest, and samples of fruits, leaves, and roots were collected for laboratory analysis and productivity assessment.

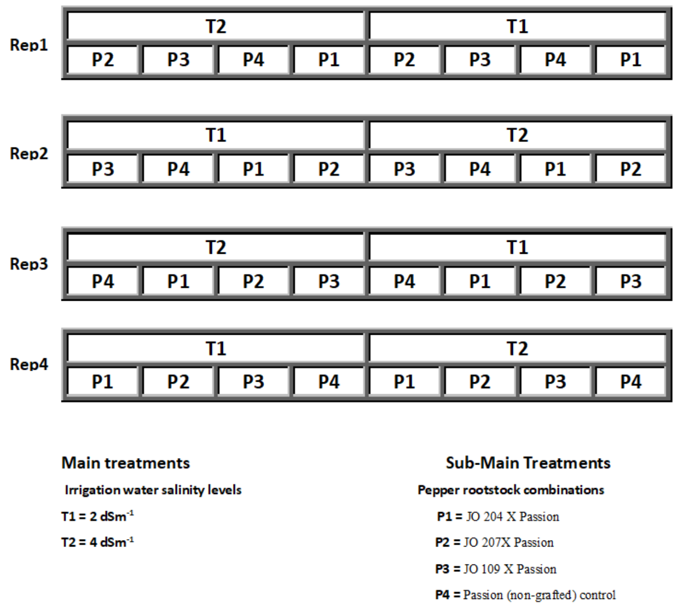


Figure 1. Experimental layout at Karamah Research Station during the 2021/2022 growing season

The seeds of the pepper accessions (landraces) were obtained from NARC- gene bank, and these were JO 204, JO 207 and JO 109. The seedlings of Passion variety were grafted onto them using the tube grafting method at the three- true leaves stage of seedling growth.

2.5 Laboratory readings

Samples were taken from the leaves, stems, and roots, and the fresh and dry weights were measured. Then, an analysis of the nutrient contents (sodium, chlorine, potassium, and calcium) was performed. Five plants from each replication were sampled. Leaves and roots were dried at 65°C for 48 h, ground and dissolved in 1%(v/v) HCl. For the analysis of Na^+, K^+ and Ca^{2+}, an atomic absorption spectrophotometer (Varian Spectra AA 220 FS) was used (Kuşvuran, 2012). While for Cl, titration procedure was followed as described in Taleisnik & Grunberg (1994) with spectrophotometer using AOAC method. The quality of the fruits and their biochemical characteristics were studied and expressed in terms of total phenols and *superoxide dismutase* (SOD) content. The total phenols were determined by Folin-Ciocalteu method using gallic acid as a standard compound (López-Serrano et al., 2020). SOD was assayed using UV-spectrophotometer (Model BK-D590, a Double Beam Scanning UV/Vis Spectrophotometer manufactured by BIOBASE.) The device operates over a wavelength range of 190 to 1100 nm, covering both ultraviolet (UV) and visible (Vis) spectra, and band width of 0.5-5 nm (Cakmak & Marschner, 1992) by monitoring the superoxide radical-induced nitro blue tetrazolium (NBT) reduction at 560 nm. One unit of SOD activity was defined as the amount of enzyme that caused 50% inhibition of the photochemical reduction of NBT. Lipid peroxidation was measured as the amount of malondialdehyde (MDA) determined by the thio-barbituric acid (TBA) reaction. Frozen samples were homogenized in a pre-chilled mortar with two volumes of ice-cold 0.1% (w/v) tricloro acetic acid (TCA) and centrifuged for 15 min at 15000 x g. The assay mixture containing 1 mL aliquot of the supernatant and 2 mL of 0.5% (w/v) thio-barbituric acid in 20% (w/v) tricloro acetic acid (TCA) was heated to 95°C for 30 min and then rapidly cooled in an ice-bath. After centrifugation (10000 x g for 10 min at 4°C), the supernatant absorbance (532 nm) was read and values corresponding to non-specific absorption (600 nm) were subtracted. The MDA content was calculated according to the molar extinction coefficient of MDA (155mM^{-1} cm^{-1}) (Talhouni et al., 2019b). Data obtained was subjected to statistical analysis using analysis of variance (ANOVA) to test the significant effect of all the variables investigated using MSTC. Means were separated using the Least Significant Difference Test (LSD) at $p \leq 0.05$ (Steel &Torrie, 1980).

3. Results and Discussion

3.1 Productivity

Productivity is one of the most important indicators taken into account in any study of this kind, as the economic return is linked to productivity. The results showed the negative effect of salinity on productivity in the pepper crop (Table 1), and it was noted that the effect of grafting commercial varieties on elite rootstocks of resistant local landraces had a positive effect in mitigating the effect of salinity on productivity.

Table 1 shows that grafting using the rootstock JO 204 gave the highest productivity (40.36 tons ha^{-1}) under high salinity, showing a decrease rate of 8.6% compared to the commercial variety without grafting (10.59 tons ha^{-1}) which showed a significant decrease rate of 62.55% of productivity when cultivated under salinity conditions. Using a vigorous rootstock, with a vigorous commercial cultivar as a scion can increase yield production and improve fruit quality under water stress conditions (Yetisir & Uygur, 2010; Abdulaziz et al., 2017).

Table 1. Productivity (ton ha^{-1}) as affected by irrigation water salinity and grafting

Grafting Compensations	Irrigation Water Salinity (dS m^{-1})	
	2	4
JO 204 X Passion	44.17 ^{a}	40.36 ^{b}
JO 207 X Passion	47.59 ^{a}	30.72 ^{c}
JO 109 X Passion	26.19 ^{d}	17.68 ^{e}
Passion (non-grafted) control	28.28 ^{cd}	10.59 ^{f}
LSD	**4.18**	
CV%	**7.65**	

3.2 Leaves content of chlorophyll (SPAD)

It is known that the content of leaves from the green matter (chlorophyll) decreases with increasing salinity, which affects the efficiency of photosynthesis in the plant and thus plant growth and productivity. A portable device (SPAD) was used to measure the percentage of chlorophyll in plants and record the readings (Table 2).

Table 2. Pepper leaves chlorophyll content (SPAD)

Grafting Combinations	Irrigation Water Salinity (dS m^{-1})	
	2	**4**
JO 204 X Passion	65.30 bc	58.85 c
JO 207 X Passion	75.17 a	66.73 bc
JO 109 X Passion	66.45 b	60.07 bc
Passion (non-grafted) control	65.07 bc	58.60 c
LSD	**6.68**	
CV%	**4.90**	

The results show a significant decrease in the percentage of chlorophyll under salinity compared to the control. The highest percentage of chlorophyll was found in treatment JO 207, followed by JO 109 (66.73 and 60.07%, respectively) under salinity conditions, while the lowest content was in the non-grafted plants (58.6%), which indicated that the effect of grafting was positive in alleviating salinity impact, especially when using tolerant roots such as JO 207 and JO 109. The results also showed the significant superiority of the grafting treatment using the accession JO 207 when irrigated with a salinity of 2 dS m^{-1}, while no significant differences were shown for the other treatments. Grafted peppers had higher chlorophyll content under salinity conditions compared to non-grafted plants (Talhouni et al., 2019a).

3.3 Antioxidants content

The antioxidants are considered important indicators in distinguishing plants that are tolerant under conditions of environmental stress such as salinity, as plants are considered more tolerant as their content of antioxidants such as total phenols have increased. Moreover, antioxidant enzymes such as superoxide dismutase SOD are also important as they work by fighting free radicals within plant tissues.

The results in Figures 2 and 3 indicated that accession JO 207 was superior in terms of its content of various antioxidants, as it had the highest total phenols and SOD. While it was observed that the non-grafted plants had the lowest content of antioxidants under salinity conditions, which was reflected of their tolerance to stress.

The results for SOD, the antioxidant enzyme, showed the significant superiority of all grafting treatments over the control (non-grafted) under salinity conditions. The activation of antioxidant systems utilizing rootstock grafting, and in particular the enzymatic antioxidants (SOD), was shown to be associated with the improvement of salt tolerance in rootstock-grafted plants (Yang et al., 2013; Kiran et al., 2019; Talhouni et al., 2019b).

Polyphenols are phytochemicals with antioxidant activity. The results in Figure 3 show that in comparison to non-grafted plants, pepper plants grafted with JO 207 had a significantly higher total phenolic content under saline circumstances. Reactive oxygen species are expected to be prevented and photosynthetic organs protected by phenolic substances (López-Serrano et al., 2020).

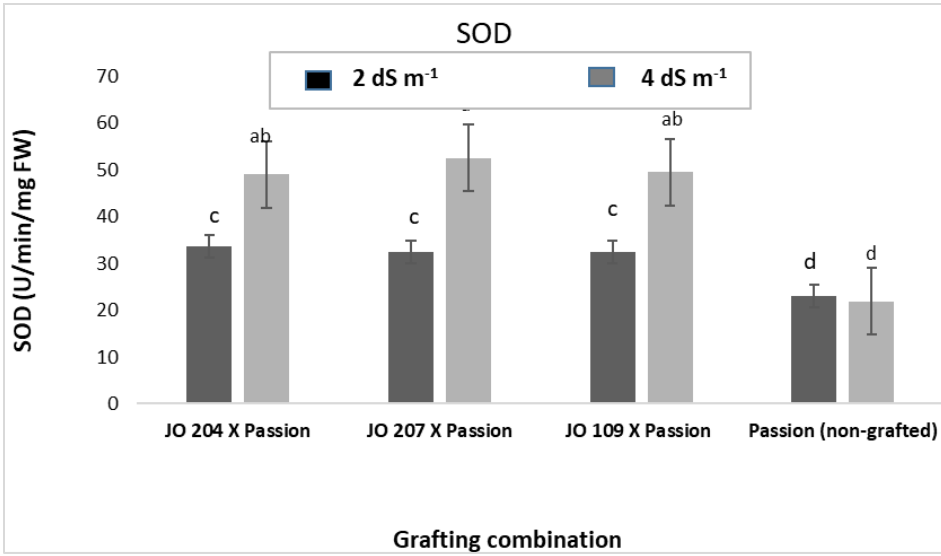


Figure 2. Superoxide dismutase (SOD) content (U/min/mg FW)

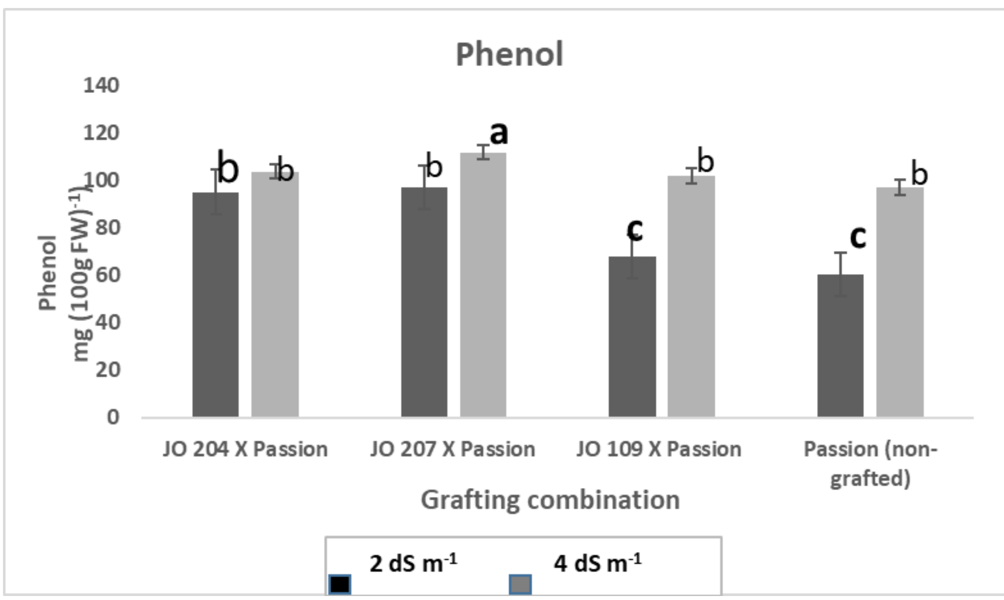


Figure 3. Total phenols in leaves under different salinity levels

3.4 Pepper leaves content of Malondialdehyde

An increase in the level of malondialdehyde (MDA) is an indication of the occurrence of oxidation stress catalyzed by free radicals that attack cells and destroy cell walls. The higher the content of this substance, the greater the intensity of oxidation as a result of salinity is found.

The results in Figure 4 indicated that the higher tissue content of (MDA) is due to higher water salinity. Furthermore, the non-grafted plants contained a greater amount of MDA compared to the grafted plants, which confirmed the importance of grafting with tolerant roots to reduce oxidation resulting from salinity (Hnilickova et al., 2021). The results in Figure 4 show that plants grafted on JO 207 contained a lower amount of MDA compared to plants grafted on other landraces rootstocks, which indicates that it was more tolerant to oxidation caused by salinity.

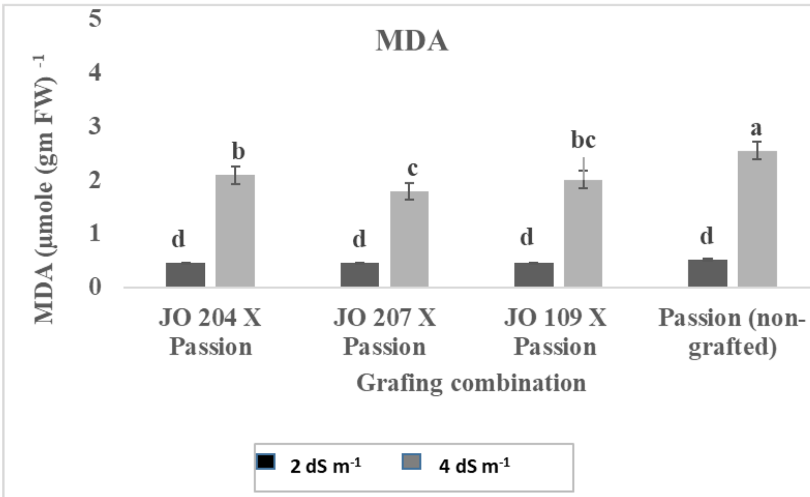


Figure 4. Pepper leaves content of MDA resulting of salinity stress

3.5. Tissues content of Na^+, Cl^-, K^+ and Ca^{+2} elements

It is scientifically confirmed that high levels of salinity in the soil affect the absorption and accumulation of various elements such as sodium, chlorine, potassium, and calcium in plant tissues. For example, under high salinity, the concentration of sodium increases in plant tissues (due to increase in its content in the soil and water), which has a toxic effect on the plant if its concentration exceeds the maximum concentration, i.e. the threshold that the plant can bear. A similar trend was observed with chlorine, where its concentration in plant tissues increased with increase in salinity, which negatively affected plant growth. On the contrary, with the nutrient potassium, it is expected that its concentration would decrease with the increase in salinity as a result of the increase in the concentration of sodium as sodium competing with potassium for absorption by plant roots. Also, the concentration of calcium tended to decrease under salinity conditions, which negatively affected the growth and productivity of the plant and the quality of the fruits, and symptoms of calcium deficiency appeared on the fruits (Kıran et al., 2014; Talhouni et al., 2019c).

As shown in Figure 5, the non-grafted pepper plants contained a higher amount of Na^+ in the leaf tissues than the grafted plants under salinity conditions, without significant differences. This was probably because of the ability of the grafted plants to sequester the sodium ion in their root cells and prevent it from moving to the leaf tissues and cause damage to them. This can be confirmed by the results of the Na^+ concentration in the roots where we see that the grafted plants contained a higher concentration of sodium ion in the roots than the non-grafted plants.

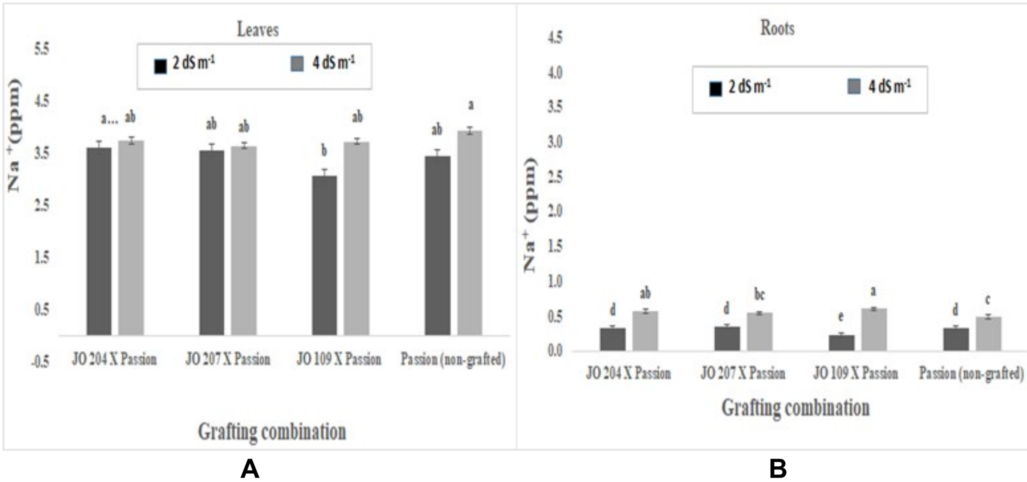


Figure 5. Leaf (A) and root (B) tissues content of sodium ion (Na^+) element in pepper as affected by rootstocks, salinity, and grafting

The data in Figure 6 shows an increase in chloride (Cl^-) concentration in plant leaf and root tissues when irrigated with a saline solution of 4 dS m^{-1} compared to plants at irrigated with 2 dS m^{-1} saline solution, which had a negative effect on the growth of plants. Furthermore, Figure 6 shows that there were no significant differences between the grafted and non-grafted plants cultivated under saline conditions, but the non-grafted plants contained a greater amount of Cl^- in the leaf tissues, while they contained a lower amount in the roots. It is worth noting that chloride (Cl^-) concentration varied among the grafting combinations, indicating that the choice of grafting combination can influence the ion balance within the plant, confirming the ability of grafted plants to retain elements in the root zone and prevent their increase in the leaves, thus enhancing their tolerance to salinity.

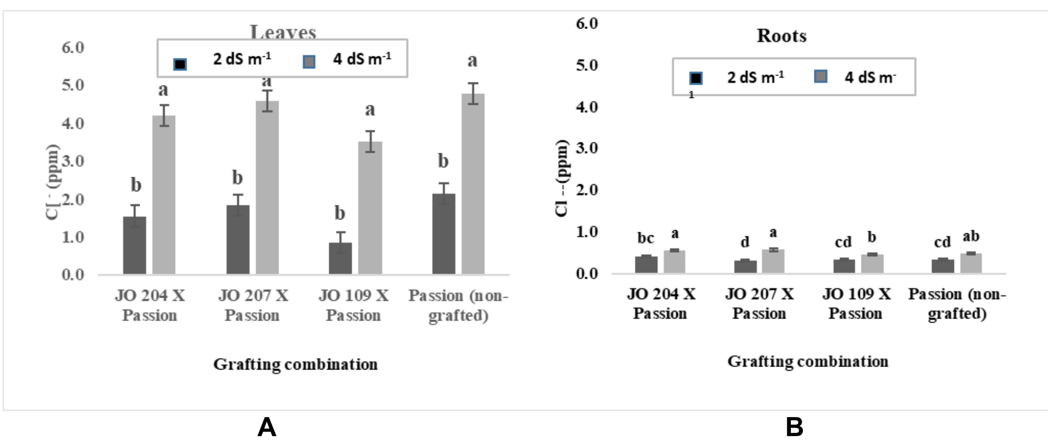
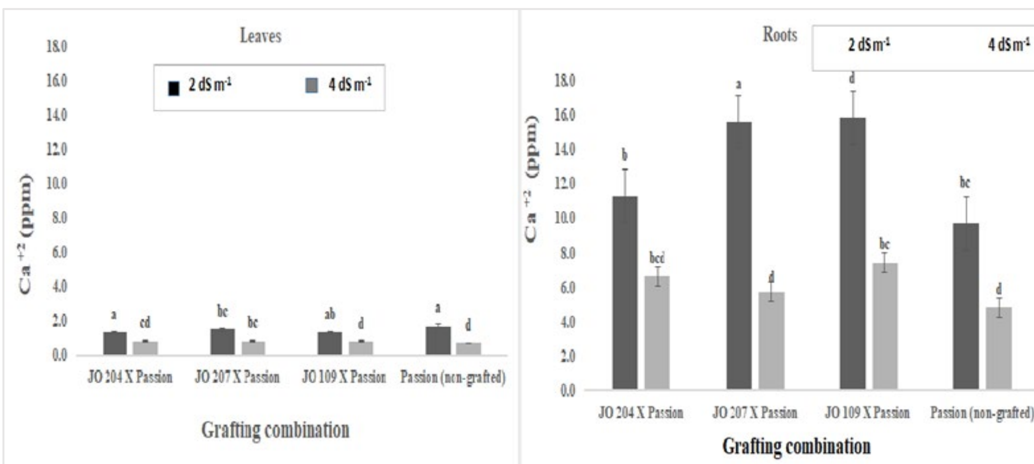


Figure 6. Leaf (A) and root (B) tissues of chloride ion (Cl^-) in pepper as affected by rootstocks, salinity, and grafting

Environmental conditions such as high soil salinity or saline irrigation water can contribute to a higher uptake and accumulation of sodium and chloride ions in pepper leaves. If the surrounding soil or water contains elevated levels of these ions, the plant's root system absorbs them along with water. As a result, the leaves may show higher concentrations compared to the roots (Talhouni et al., 2019c).

Plants have specific transport mechanisms for different ions. It is possible that under salinity stress, the transporters responsible for Ca^{2+} uptake or its transport from the roots to the leaves may be affected. This can result in reduced movement of Ca^{2+} from the roots to the leaves, leading to a lower concentration in the leaves. Calcium is also adversely affected by an increase in salinity, and under such conditions its absorption from the soil decreases, which leads to an increase in the incidence of calcium deficiency symptoms in plants (Kıran et al., 2014; Talhouni et al., 2019c). According to Figure 7, the grafted plants contained a greater amount of calcium compared to the non-grafted plants under salinity conditions, which indicated the superior ability of the grafted plants to absorb calcium. This was reflected in the superior strength and growth of the grafted plant, especially in the JO 204 and JO 207 (0.84 and 0.833%, respectively). The similar results can be seen in the roots.

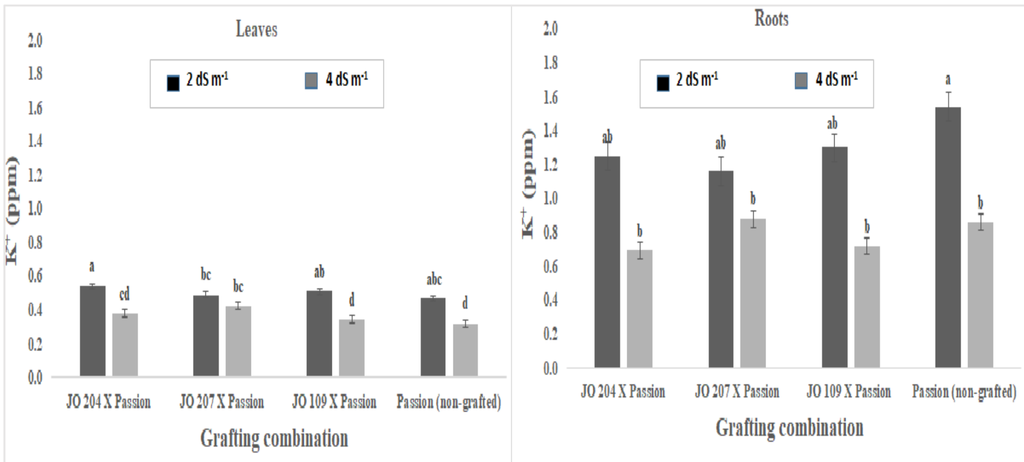


(A) (B)

Figure 7. Leaf (A) and root (B) tissues content of calcium ion (Ca^{+2}) (%) in pepper as affected by rootstocks, salinity, and grafting

Under a saline environment, the availability of calcium ions may be reduced due to the formation of insoluble compounds or precipitation. High levels of salt can affect the solubility of calcium in the soil solution, making it less accessible to plant roots (Yetisir & Uygur, 2010). Consequently, the limited availability of soluble calcium ions can lead to lower uptake and accumulation in the leaves.

On the other hand, the concentration of K^+ (Figure 8) in the roots and leaves remained relatively similar under salinity conditions. Plants have efficient and selective mechanisms for potassium uptake which allows them to maintain relatively stable concentrations in their tissues, including leaves, even under saline conditions.



(A) (B)

Figure 8. Leaf (A) and root (B) tissues content of potassium ion (K^+) (%) in pepper as affected by rootstocks, salinity, and grafting

Potassium is highly mobile within the plant, meaning it can easily be transported from the roots to the shoots via the xylem. Therefore, even if the uptake of K^+ is slightly reduced in the roots due to salinity stress, the plant can still maintain a relatively constant concentration of K^+ in the leaves by redistributing it from other tissues. It is important to note that the response of plants to salinity can vary depending on the species, cultivar, and severity of salinity stress. The mechanisms mentioned above are general explanations and may not apply uniformly to all pepper plants. Figure 8 shows that the leaf tissue content of K^+ decreased under salinity conditions. It was also noted that the grafted plants contained a greater concentration of the K^+ compared to the non-grafted plants, especially those grafted on JO 207. As for the roots, there were no significant differences between the grafted and non-grafted plants, and the higher value was also for the grafted plants using JO 207 as rootstock (0.88%).

Under high salinity conditions, the concentrations of Ca^{+2} (calcium) and K^+ (potassium) tended to decrease in both leaf and root tissues (Figures 7 & 8), while the concentrations of Na^+ (sodium) and Cl^- (chloride) increased (Figures 5 & 6). As mentioned earlier, high salinity can cause the precipitation or formation of insoluble compounds with calcium ions, reducing their availability for uptake by the plant roots. This can further contribute to the decrease in calcium concentrations in the leaf tissues.

It is important to note that these trends are general patterns observed in response to high salinity, but the specific responses can vary among plant species, cultivars, and even individual plants. Additionally, prolonged exposure to high salinity can have detrimental effects on plant growth and health, regardless of the accumulation of sodium and chloride ions. Managing soil salinity and providing suitable agricultural practices like grafting are crucial for mitigating the negative impacts of high salinity on plant physiology. Grafting can influence the efficiency of nutrient transport within the plant. The rootstock and scion form a compatible vascular system, allowing for better nutrient flow between the roots and shoots. This improved transport system can facilitate the movement of calcium from the roots to the leaves, resulting in higher calcium concentrations in both tissues and eventually leading to better plants growth and productivity.

The results provide insights into the concentration of the minerals in pepper roots, and the grafted combinations generally exhibited higher mineral concentrations in the roots compared to the non-grafted Passion variety. Under higher salinity (4 dS m^{-1}), these grafting combinations showed increased levels of potassium (K^+), calcium (Ca^{+2}), and sodium (Na^+) in the roots. These findings suggest that grafting can facilitate enhanced mineral absorption and accumulation in the root system, potentially improving the plant's ability to withstand salinity stress (Talhouni et al., 2019c). In general, when irrigation water salinity increased, the Na^+/K^+ ratio in the leaves and roots of grafted and non-grafted plants dramatically increased (Figure 9). Although under the same salinity stress, the ratio of Na^+ to K^+ in the leaves and scion stem of grafted plants was significantly less than that found in the non-grafted plants, the Na^+/K^+ ratio in the roots was significantly greater than the ratio in the non-grafted plants. This was similar to the Na^+ contents. Additionally, under the same salinity stress, the Na^+/K^+ ratios in the leaves of grafted and non-grafted "JO 109" plants were noticeably lower than those of the grafted "JO 207" and non-grafted plants, respectively. To the degree that maintaining a low Na^+/K^+ ratio is crucial for salt tolerance, the Na^+/K^+ ratio in the leaves of plants under salt stress is a better overall predictor of the capacity of the plant to select and utilize K^+ under Na^+ salinity (Santa-Cruz et al., 2002). The Na^+/K^+ ratio in the foliage of pepper plants in this study dramatically rose during water salinity stress, whether the plants were grafted or not, in a manner comparable to the Na^+ contents. However, under salinity stress, the Na^+/K^+ ratio in the foliage of grafted plants was noticeably lower than the ratio in non-grafted plants (Figure 9), indicating that grafting increased salt tolerance by restricting Na^+ accumulation and enabling the transfer of K^+ to the leaves to lower the Na^+/K^+ ratio.

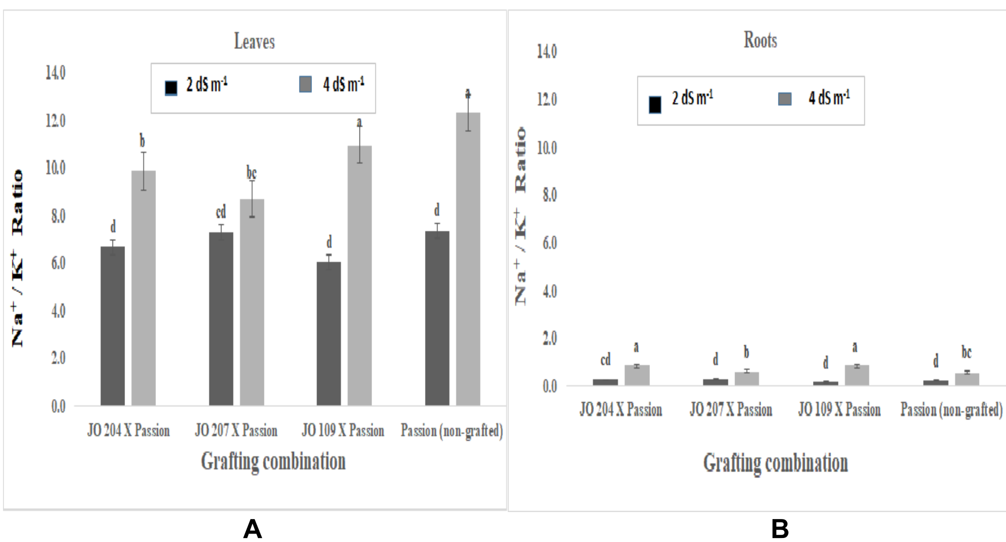


Figure 9. Na^+/K^+ ratio in the leaves (A), and roots (B) of grafted and ungrafted pepper seedlings at two irrigation water salinity levels. Bars with the same letter are not significantly different ($p < 0.05$) according to a LSD test.

4. Conclusions

The results unequivocally demonstrated that the local landraces of pepper utilized in this study possess a significantly higher ability to tolerate the salinity stress in comparison to the commercial variety. This is a direct result of the adaptation of these strains to the prevailing environmental conditions in their habitat over the years, under the influence of climate change. Among the majority of accessions of local landraces, it can be concluded that the accession JO 207 was significantly superior to the rest of the other accessions. It can be recommended also that plants from these accessions can be used as rootstocks in grafting programs for varieties that are sensitive to environmental stresses such as salinity. It can also be utilized by those interested in breeding programs to produce hybrid strains that can tolerate environmental stresses. It is imperative to continue to evaluate these original landraces in the laboratory to identify the genetic factors or genes responsible for resistance traits, and leverage this knowledge to build strategic partnerships with local seed production companies in order to create new strains of high-value commercial varieties. However, further research is needed to elucidate the underlying mechanisms and optimize grafting combinations to maximize the benefits in terms of mineral nutrition and plant resilience to salinity stress in pepper crops.

5. Acknowledgements

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6. Conflicts of Interest

The authors declare that there are no conflits of interest related to the research presented in this study.

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