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ARTICLE

RESEARCH ARTICLE

Salt tolerance of 'Hass' avocado grafted onto the West Indian 'Nachar' rootstock

Tolerancia a la sal del aguacate 'Hass' injertado sobre el patrón antillano 'Nachar'

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Abstract: *Aim of the study*: The nowadays avocado cropping world burst confronts water quality constraints as it unfolds throughout semi-arid climates. Therefore, many salt-tolerant rootstocks have been developed, with those from the West Indian avocado subspecies such as 'Nachar' standing out. However, the salt-tolerance of 'Nachar' had not been characterized and this study fills this knowledge gap. *Area of study*: Accordingly, an open-air trial was performed in Moncada (València). *Material and methods*: 'Nachar' seedling rootstocks grafted with 'Hass' avocado were irrigated with five nutritive solutions differing in chloride (Cl^-), but with low sodium (Na^+) adsorption ratio (SAR). Plant development and leaf nutrient status, including Cl^- and Na^+, were monitored, and the 'Nachar' salt-tolerance was characterized based on the accumulation rates of leaf Cl^- and Na^+ as a function of, respectively, Cl^- and SAR in the irrigation water. These parameters are seldom expressly assessed but are argued here as providing better insight into the actual Cl^- and Na^+ exclusion ability of rootstocks than the usual maximum permissible, —to avoid leaf injury— leaf Cl^- and Na^+. *Main results*: The 'Nachar' was found to rank high and very high in, respectively, Cl^- and Na^+ exclusion ability, when compared to other avocado rootstocks. However, more salt-driven leaf injuries and potential yield losses would still be expected in avocado grafted onto the 'Nachar' in comparison to other salt-sensitive woody crops. *Research highlights*: The 'Nachar' seems an interesting starting point in further rootstock improvement for salt-tolerance in avocado. However, if unproperly carried out, the propagation of salt-tolerant avocado rootstocks such as 'Nachar' and others may also result in the loss of the previously achievements of salt-tolerance.

Keywords: boron; chloride; irrigation; Mediterranean climate; sodium; water quality; water scarcity.

Resumen: *Objetivo del estudio*: La actual expansión mundial del cultivo del aguacate se enfrenta a limitaciones por calidad del agua a medida que se desarrolla en climas semiáridos. Por lo tanto, se han desarrollado muchos portainjertos tolerantes a la salinidad, destacando aquellos pertenecientes a la subespecie de aguacate antillano, como el 'Nachar'. Sin embargo, la tolerancia a la salinidad del 'Nachar' no había sido caracterizada y este estudio llena este vacío de conocimiento. *Área de estudio*: En consecuencia, se llevó a cabo un ensayo de campo en Moncada (Valencia). *Material y métodos*: Plántulas de semilla de 'Nachar' injertadas con aguacate 'Hass' fueron regadas con cinco soluciones nutritivas que diferían en su concentración de cloruro (Cl^-), pero con baja relación de adsorción de sodio (RAS). Se monitorizó el desarrollo de las plantas y el estado nutricional foliar, incluidos los niveles de Cl^- y Na^+, y se caracterizó la tolerancia a la salinidad del 'Nachar' en función de las tasas de acumulación de Cl^- y Na^+ foliar como respuesta, respectivamente, al Cl^- y a la RAS del agua de riego. Estos parámetros rara vez se evalúan explícitamente, pero aquí se argumenta que proporcionan una mejor comprensión de la capacidad real de exclusión de Cl^- y Na^+ por parte de los portainjertos, en comparación con los habituales valores máximos permitidos —para evitar daño foliar— de Cl^- y Na^+ en hoja. *Resultados principales*: Se encontró que el 'Nachar' presenta una capacidad de exclusión de Cl^- y Na^+ alta y muy alta, respectivamente, en comparación con otros portainjertos de aguacate. Sin embargo, aún se podrían esperar daños foliares inducidos por salinidad y posibles pérdidas de rendimiento en aguacates injertados sobre el 'Nachar', en comparación con otros cultivos leñosos sensibles a la salinidad. *Aspectos destacados de la investigación*: El 'Nachar' parece un punto de partida interesante para el mejoramiento futuro de portainjertos con tolerancia a la salinidad en aguacate. Sin embargo, si no se lleva a cabo adecuadamente, la propagación de portainjertos de aguacate tolerantes a la salinidad como el 'Nachar' y similares, podría comprometer los avances previamente logrados en cuanto a tolerancia a la salinidad.

Palabras clave: boro; calidad de agua; clima mediterráneo; cloruro; escasez de agua; regadío; sodio.

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Supplementary information ↓

1. INTRODUCTION

The avocado cropping (Persea americana Mill.) is expanding in the world often as an alternative to other fruit crops such as peach and plum in Mexico (Olvera-Pérez et al., 2022), coffee in Colombia (Arias et al., 2021) and citrus and persimmon in Spain (Zaragozá, 2024; Camacho, 2024). This fact is not surprising, given the economic profitability of avocado cultivation, which has been supported by relatively stable selling prices, e.g., ranging between $2.50 and $3.00 per kilogram in imports in the EU28 between 2019 and 2023 (World Bank, 2025). As a result, over the same five-year period, the avocado-planted area in the world increased by 27%, reaching a total of 954,689 ha, with a production of 10,466,560 tons (FAO, 2025).

Interestingly, this expansion of avocado cultivation is spreading from its original distributional area in the tropics, to other regions where its development confronts challenging soil and climate conditions such as in Mediterranean and other temperate subtropical areas of Andalusia, Canary Islands and the Valencian Community in Spain and Algarve in Portugal (Alcaraz & Hormaza, 2019), Southern coast of Turkey (Hürkul et al., 2021), Southeastern Queensland in Australia (Robson et al., 2017), central

Chile (Madariaga et al., 2021), etc. In these areas the avocado expansion occurs despite the specific requirements of this crop in terms of climate and soil, as well as irrigation water availability and quality are usually far from being met (Kourgialas & Dokou, 2021). Specifically, avocados should preferably be grown in areas that meet the following conditions: (i) a warm climate with low risk of frost, (ii) well-drained, loosely compacted, non-calcareous soil, (iii) adequate availability of irrigation water, and (iv) low salinity in soil and irrigation water (Wolstenholme, 2002). For example, these requirements contrast with the characteristics of the Valencian Community's territory in Eastern Spain, which is shaped by (i) its semi-arid Mediterranean climate, which, despite its mildness and the current global warming trend, still features non-negligible frost risk for crops (Arenes, 2018), (ii) its lime-dominated soils (Antolín, 1998) and (iii) its irrigation water, which is often not available in the required quantity and quality (de Paz et al., 2004).

In particular, the insufficient quality of irrigation water is one of the main factors that could limit the expansion of avocado cultivation in Mediterranean and other subtropical temperate areas featuring semi-arid conditions like the Valencian Community, as this fruit tree is considered highly sensitive to salinity (Oster et al., 2007). Specifically, avocado roots lack mechanisms to restrict the absorption of soil salts, especially the chloride ion (Cl-), and its subsequent transport to the leaves (Celis et al., 2018), where Cl^- accumulates and exerts its phytotoxic effects, impairing photosynthesis and triggering necrosis (Acosta-Rangel et al., 2019). The damage to photosynthesis results in yield loss, but foliar necrosis is the earliest, most apparent, and most distinctive symptom of Cl^- phytotoxicity, ultimately serving as the key warning sign for farmers.

To address the issue of salinity in avocado cultivation, various traditional strategies for mitigating and adapting to salinity in agriculture can be implemented (Plaut et al., 2013). Among these, grafting onto salt-tolerant rootstocks is one of the most popular approaches. In the case of avocados, certain subspecies—specifically the West Indian (ssp. americana)—have been reported to have a greater ability to exclude Cl^- compared to the two other most widespread avocado subspecies, i.e., the Guatemalan (ssp. guatemalensis) and, particularly, the Mexican (ssp. drymifolia), which are increasingly salt-sensitive in this order (Ben-Ya'acov & Michelson, 1995; Mickelbart & Arpaia, 2002). This means that when the plant absorbs water from the soil, the West Indian rootstocks help limit Cl^- uptake and transport in the xylem and its accumulation in the leaves better than the other rootstocks.

Among the West Indian avocado rootstocks are the well-known 'Waldin' and 'Lula' (Ben-Ya'acov & Michelson, 1995). However, more recently, the 'Nachar'—a rootstock developed in Israel likely within the Nachlat group with predominantly West Indian parentage—has joined them. 'Nachar' is gaining popularity because of its vigor, good affinity to commercial varieties including the predominant 'Hass', but also 'Fuerte', 'Lamb Hass', 'Reed', and 'Bacon', homogeneous orchard development despite being seed-propagated, as well as claimed good adaptation to the soil lime and salt levels that are common under semi-arid conditions, and to which other avocado rootstocks fail to withstand (Brokaw España, 2025).

The tolerance to salinity conferred to avocados has been previously characterized for several rootstocks mostly from the Mexican, e.g., 'Mexicola', 'Duke 7', 'Thomas', 'Toro Canyon', 'G6'. etc., and Guatemalan, e.g., 'Nabal', subspecies, as well as from likely crossings between both, e.g., 'Zutano', 'Zentmyer', 'Uzi' and 'Steddom' (Mickelbart & Arpaia, 2002; Oster et al., 2007; Castro et al., 2009; Celis et al., 2018). However, the salt tolerance traits of the West Indian rootstocks, e.g., 'Degania 117' (Castro et al., 2009) are not so easily found in the literature and, to our best knowledge, the salinity tolerance of the 'Nachar' rootstock has not been characterized at all. Provided the continuous spread of avocado cultivation to water-constrained areas, practitioners, breeders and researchers need reliable information on the avocado tolerance to salinity when grafted, particularly, onto the West Indian rootstocks, to which the 'Nachar' belongs. Therefore, the objective of this study was to assess the tolerance to salinity of avocado when it is grafted onto the West Indian 'Nachar' rootstock.

2. MATERIAL AND METHODS

2.1. Plant material

'Nachar' seedling rootstocks grafted with 'Hass' avocado were provided by the plant nursery Viveros Blanco S.L. (Rancho La Cañada, Torre del Mar, Málaga, Spain). The 'Hass' avocado variety was originally developed by Rudolph G. Hass in California (USA) during the 1920s–1930s and presents a mixed Mexican and Guatemalan ancestry (Rendón-Anaya et al., 2019). Today, the 'Hass' overwhelmingly dominates the global avocado production (Rincon-Patino et al., 2018), driving significant interest in researching all aspects of its cropping.

Regarding the 'Nachar' avocado, it is a seed-propagated descendant of the 'Nachlat' group, which was developed in Israel and came to Spain several decades ago (Iñaki Hormaza, personal communication on 2nd March 2025). It is likely closely related to the 'Maoz', along which it features a mother of the West Indian subspecies, but the father is unclear (Hormaza, 2019). Specimens from the 'Nachlat' group such as 'Nachar' and 'Maoz' are distinguished due to characteristics cracks under the graft (Figure 1) and are considered to withstand soil lime and salts like no other avocados can (Ben-Ya'acov & Michelson, 1995). This reputation has sparked interest in researching their performance as rootstocks for the 'Hass' scion under growing conditions of calcareous soils and semi-arid climates.

Figure 1. Typical pattern of cracks under the graft, which is considered distinctive of the avocado 'Nachlat' group, as observed on one of the plants used in the trial when it became an adult.

2.2. Experimental trial

The trial was carried out during the Northern Hemisphere 2018 avocado vegetative development season. The plants were established into plastic pots measuring 48 cm in height and 50 cm in major diameter filled with a commercial substrate of peat, perlite, and coconut fiber. Plants were allowed to acclimate for three and a half weeks in a greenhouse at the facilities of the Valencian Institute of Agricultural Research (IVIA) in Moncada (Spain). The plants were then staked with canes, moved outdoors on June 27, and subjected to salinity treatments from June 29 to October 17 for a total of 110 days. The salinity treatments were applied by irrigating the avocados with waters varying in salt content as explained below. Irrigation was performed by drip irrigation using one 2 L/h emitter per plant, with rates ranging from 6 and 10.5 L/plant per week for a total of 246.5 L/plant for the entire season (Supplementary material and Figure 2).

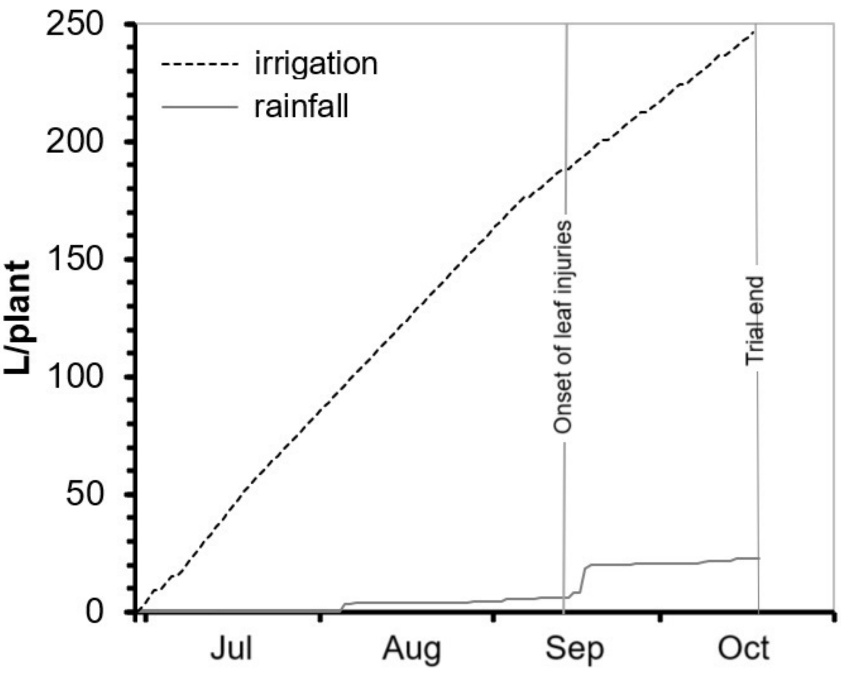

Figure 2. Cumulated irrigation and rainfall as recorded in the Moncada-IVIA station (100 m away from the study site) during the saline water irrigation treatments.

For the salinity treatments, five water solutions with increasing salt concentration and constant nutrient levels, except for calcium and chloride, and a low sodium adsorption ratio (SAR = $[Na^+]/([Ca^{2+}] + [Mg^{2+}])^{1/2}$) were used to irrigate the plants. These saline irrigation waters were prepared by dissolving increasing amounts of NaCl and $CaCl_2{\cdot}2H_2O$ and constant amounts of inorganic fertilizers (KNO_3, $Ca(NO_3)_2$, $MgSO_4{\cdot}7H_2O$, H_3PO_4 75%, Fe-EDDHA, H_3BO_3, $ZnSO_4$, $MnSO_4$, and H_2MoO_4), in well water that had been previously desalinated through reverse osmosis.

During the treatments, the Moncada-IVIA agrometeorological station, located 100 meters away, recorded 497 mm of reference evapotranspiration (ETo) and 115 mm of rainfall, with three-quarters of the precipitation occurring after September 14 (Figure 2). This rainfall amounted to 22.6 L/plant, which was 11 times less than the irrigation water applied for the entire season. Given the relatively low rainfall during the trial and its late occurrence, it was considered negligible and was not used to adjust the irrigation water salinity in the salt-tolerance assessment calculations.

In total, 25 plants were divided into five groups of five, each corresponding to one of the five irrigation water salinity levels (Figure 3). These salinity levels had an electrical conductivity at 25°C (EC_{25}) ranging from 0.6 dS/m to 3.1 dS/m, with chloride concentrations between 45 and 477 mg/L and sodium concentrations between 39 and 194 mg/L, as detailed in Table 1. In all irrigation treatments, the SAR, the Residual Sodium Carbonate (RSC = Alkalinity – 2 $[Ca^{2+}] + [Mg^{2+}]$), as well as the boron concentration, remained very low (SAR < 3 $(mmol/L)^{1/2}$, RSC < –17 $mmol_C/L^{-1}$, and $\rho_B < 0.09$ mg/L). The average concentrations of K^+, Mg^{2+}, NO_3^-, SO_4^{2-} and P-PO_4 were, 110, 100, 642, 410 and 18 mg/L, respectively.

Figure 3. View of the experimental trial.

Table 1. Average sodium, calcium, chloride and boron concentrations in the irrigation waters featuring each of the salinity treatments that were applied to 'Hass' avocado grafted onto 'Nachar' seedlings in this trial

Treatment	Na^+	Ca^{2+}	Cl^-	B
	mg/L			
T1	39	28	45	< 0.05
T2	92	181	102	< 0.05
T3	151	258	279	0.09
T4	157	225	323	0.05
T5	194	335	477	0.09

2.3. Plant measurements

Plant development in the four highest salinity treatments (T2, T3, T4, and T5) was monitored by measuring trunk diameter and plant height on August 7, 2018 (39 days after the salinity trial began), and December 3, 2018 (157 days after the salinity trial began and 47 days post-trial). Trunk diameter was measured at 7 cm above the ground, i.e., within the rootstock, as well as just below and above the graft union.

2.4. Leaf sampling

Fully expanded leaves from the third apical position were sampled on July 23 (24 days after the trial began) and on October 17 (at the trial end) to evaluate the avocado's response to the salinity conditions. At the end of the trial, necrotic (old) and non-necrotic (young) leaves were separately collected. Whatever the case, all leaf samples were stored in plastic bags, transported to the laboratory, and there washed with

Type 1 quality water. Then they were dried in a Dry Big forced-air oven (J.P. Selecta, Barcelona, Spain) at 65°C for 48 hours, and ground and stored in plastic pots at room temperature for later analysis.

2.5. Leaf analysis

In the ground leaf material, chloride was determined, along with macronutrients, micronutrients, and sodium. Chloride was measured by coulometric-amperometric titration (Cotlove, 1963) in 0.1 M HNO_3 and 1.7 M CH_3COOH leaf extracts (Miller, 1998a) by using a Chloride Analyzer 926 (Sherwood Scientific Ltd., Cambridge, UK). Carbon and nitrogen were determined through infrared CO_2 absorption spectroscopy and thermal conductivity measurement in the gases produced by quantitative dry combustion of the leaves with pure O_2 and quantitative NO_x copper-reduction in a CNS928 elemental analyzer (LECO Corp., St. Joseph, MI, USA). The remaining macro- and micronutrients, as well as sodium, were analyzed by inductively coupled plasma atomic emission spectrometry (ICP-AES) in concentrated HNO_3 and 33% H_2O_2 microwave digestion leaf extracts (Miller, 1998b), following the ISO 11855:1996 water analysis standard (ISO, 1996) in an iCAP 6500 Duo spectrometer (Thermo Fisher Scientific Inc., Waltham, MA, USA).

2.6. Data analyses

Mean calculations, as well as correlation and regression analyses were performed. Where appropriate, error intervals and mean comparisons were evaluated at the 95% confidence level using the Student's t-distribution. All data analyses were conducted without specialized software.

3. RESULTS

3.1. Nutritional status

The nutritional status of the avocado plants (Supplementary material) was assessed throughout the trial by comparing the measured leaf nutrient concentrations with the standards compiled for the 'Hass' variety by Robinson et al. (1997). Accordingly, on July 23 (24 days after the trial began) the leaf concentrations of all nutrients were considered adequate except for boron and zinc, which presented concentrations, respectively, below and over, the limits of adequacy (Table 2 and Table 3). However, the concentration of boron was diagnosed as just marginal, but not deficient, and the concentration of copper was diagnosed as just high, but not toxic. The leaf nutrient concentration of all nutrients was assessed again and could be considered also overall adequate in most treatments, except for sulphur in treatments from T2 to T5, in which it was low, however, just marginal, not deficient (Table 2). The same nutritional status was diagnosed for boron and zinc across all treatments, as well as for potassium, nitrogen and copper in one, one and three treatments, respectively (Table 2 and Table 3).

Table 2. Average leaf concentrations of the macronutrients on a dry weight basis at the start and at the end of the trial for each treatment, and limits of adequacy according to Robinson et al. (1997) [1]

Time	Treatment	C	Ca	K	Mg	N	P	S
		g/kg						
Jul. 23	All	493	12.1	9.8	4.1	24.3	1.58	2.07
Oct. 17	T1	488	20.7	7.8	5.0	22.6	1.49	2.89
Oct. 17	T2	489	20.7	7.4↓	7.4	20.1	0.91	1.72↓
Oct. 17	T3	475	18.5	7.8	6.2	15.1↓	1.15	1.85↓
Oct. 17	T4	492	20.6	8.5	5.9	19.0	1.20	1.77↓
Oct. 17	T5	498	16.2	9.0	4.3	19.8	0.97	1.65↓
Lower adeq. limit		—	10	7.5	2.5	16	0.8	2
Upper adeq. limit		—	30	20	8	26	2.5	6

[1] Over upper limit of adequacy (↑), under lower limit of adequacy (↓).

Table 3. Average leaf concentrations of micronutrients, as well as sodium, on a dry weight basis at the start and at the end of the trial for each treatment, and limits of adequacy according to Robinson et al. (1997) [1]

Time	Treat-ment	B	Cl	Cu	Fe	Mn	Na	Zn
		mg/kg	g/kg	mg/kg				
Jul. 23	All	34.6↓	3.3↑	17.3↑	108.4	273	39.9	25.4↓
Oct. 17	T1	23.3↓	1.5	5.5	68.2	105	26.9	22.4↓
Oct. 17	T2	16.8↓	5.5↑	2.3↓	78.0	238	22.4	17.0↓
Oct. 17	T3	17.0↓	8.1↑	2.2↓	82.9	267	40.2	22.2↓
Oct. 17	T4	23.0↓	10.5↑	13.1	78.3	197	71.4	21.0↓
Oct. 17	T5	20.1↓	10.4↑	3.5↓	62.6	110	68.0	16.7↓
Lower adeq. limit		40	—	5	50	30	—	30
Upper adeq. limit		100	< 2.5	15	200	500	< 2500	50

[1] Over upper limit of adequacy (↑), under lower limit of adequacy (↓).

3.2. Plant development

On August 7, following 39 days of treatment, the vegetative development of the avocados (Supplementary material) was already being somewhat affected by the salinity treatments as revealed by the correlation coefficient between the plant diameter under the graft and the irrigation water chloride (Figure 4). On December 3, 47 days after the trial ended, the vegetative development was found to be more affected by the salinity treatments as revealed by the increase in the correlation coefficient (in absolute value) between the plant diameter under the graft and the chloride in the irrigation water and, moreover, between the plant diameter 7 cm over the ground, i.e., also belonging to the rootstock, and the irrigation water chloride (Figure 4).

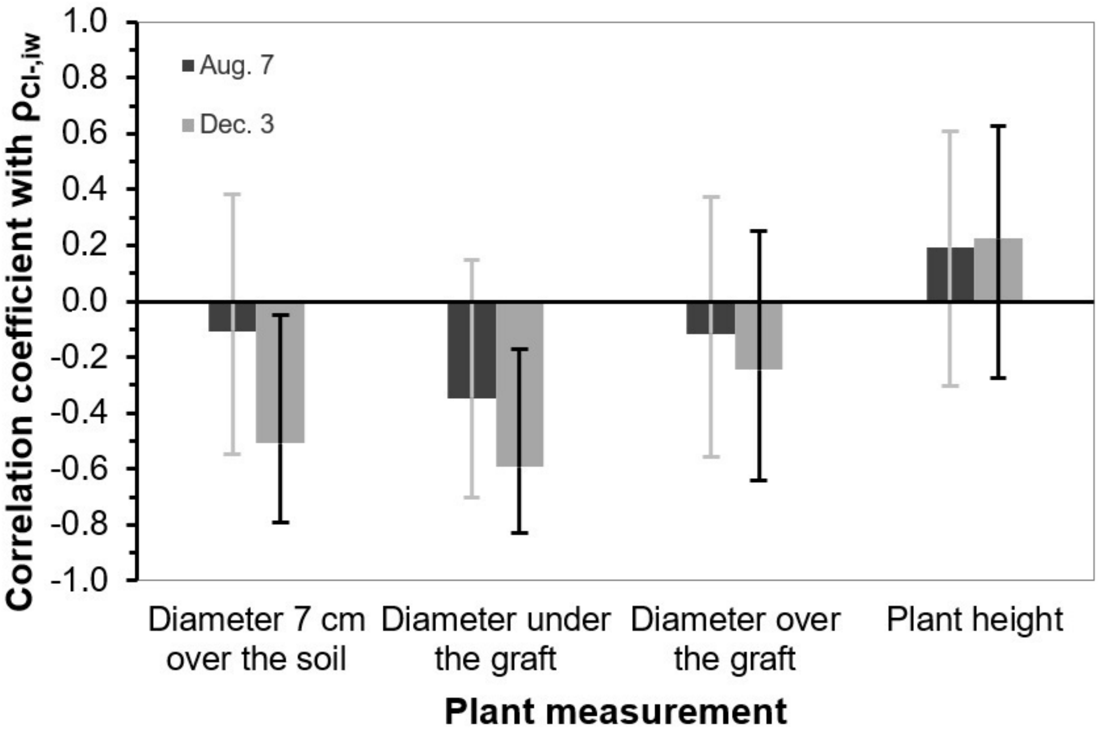

Figure 4. Pearson's product-moment correlation coefficients (r) alongside the corresponding 95% confidence intervals, between the chloride in the irrigation water and the plant development measurements that were taken on 7th August and 3rd December 2018.

Contrary to the correlations of chloride in the irrigation water with the diameter under the graft and at 7 cm over the ground, the correlations of chloride in the irrigation water with the diameter over the graft and with the plant height were very low and indeed not significant at the 95% confidence level. Therefore, it was the rootstock which was affected the most by salinity and not the scion.

3.3. Chloride phytotoxicity

On September 14, following 77 days of treatment, avocados started to show symptoms of leave necrosis in the higher salinity treatments, i.e. T4 and T5 (Figure 2 and Figure 5). At the trial end on October 17, the T2 and T3 joined the T4 and T5 in showing necrosis, but the T1 did not show any necrotic leaf. Indeed, irrigation with the high-quality water (EC_{25} = 0.6 dS/m, and ρ_{Cl-} = 45 mg/L, Table 1) featuring T1 kept leaf chloride below 2 g/kg, with no signs of leaf necrosis throughout the whole trial (Figure 6). However, in avocados irrigated with water having at least ρ_{Cl-} of 102 mg/L, leaf chloride reached a minimum of between 4 and 7 g/kg, and leaf injuries began to appear (Figure 5). At chloride concentrations over 102 mg/L in the irrigation water, a sustained increase in leaf chloride was observed, proportional to the increase in chloride concentration in the irrigation water (Figure 6).

Figure 5. Leaf necrosis in avocado because of chloride phytotoxicity as observed in this trial.

Specifically, leaf chloride increased at a rate of 18 ± 15 mg/kg per mg/L of chloride in the irrigation water (Figure 6), while symptoms of foliar injury due to chloride phytotoxicity clearly emerged from a leaf chloride of 8 ± 1 g/kg up. This threshold was calculated as the median between the minimum leaf chloride of 7 g/kg at which necrosis occurred, particularly in T2, and the maximum lead chloride of 9 g/kg at which necrosis did not occur, particularly in T4 (Figure 6).

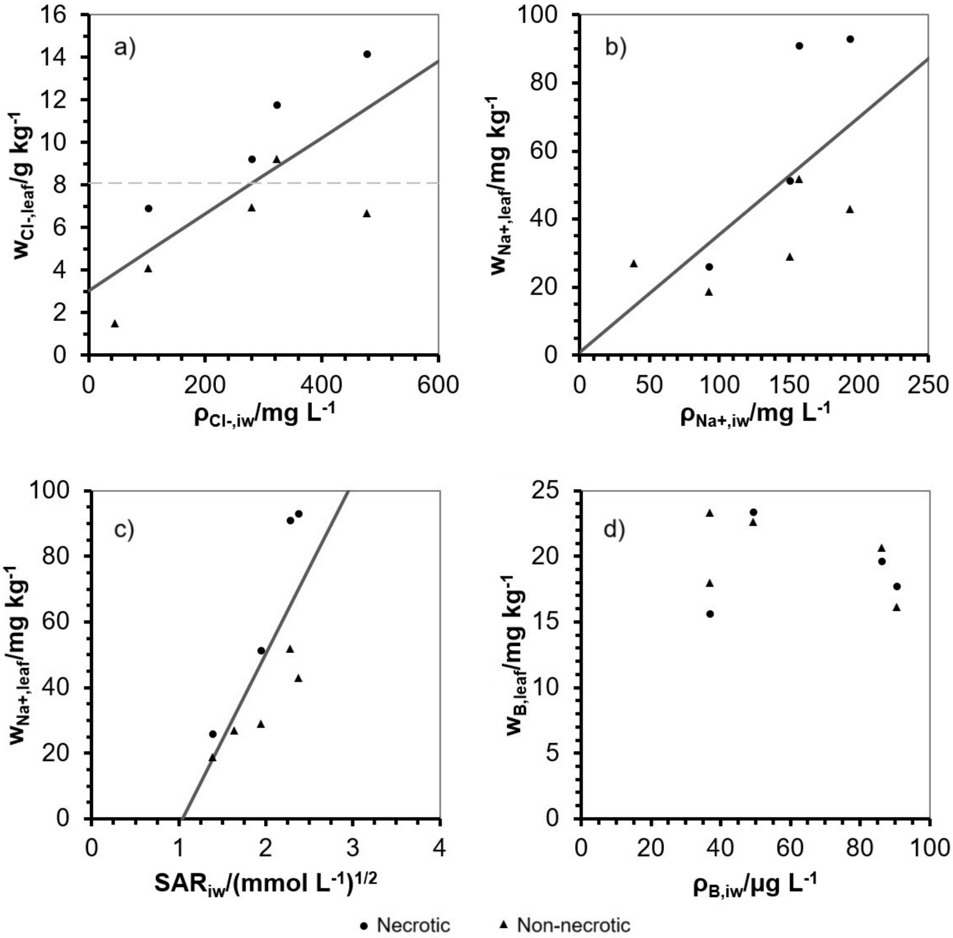

Figure 6. Concentration of chloride (a), sodium (b and c) and boron (d) in necrotic and non-necrotic avocado leaves at the trial end as a function of the concentrations of, respectively, chloride (a), sodium (b), SAR (c) and boron (d) in the irrigation water.

3.4. Sodium phytotoxicity

In addition to chloride, another ion associated with salinity that can cause phytotoxicity in avocado is sodium (Na^+). It should be noted that the aim of this study was not sodium, as the effect of chloride was tried to be isolated by keeping the irrigation water SAR (SAR_{iw}) as constant as possible. However, SAR_{iw} varied slightly (Figure 6), and based on this variation some interesting observations could still be made. Notably, the sodium concentration in leaves increased as its concentration in the irrigation water rose (Figure 6), but even more clearly as SAR_{iw} increased, with foliar sodium being highly correlated with foliar chloride (r = 0.9; Figure 7). By the end of the irrigation period, foliar sodium ranged between 22 and 71 mg/kg (Table 3), which are 40 to 180 times lower than foliar chloride. These sodium concentrations are also 30 to 90 times lower than the 2 g/kg threshold at which symptoms of sodium phytotoxicity in avocado begin to appear, according to Bingham & Nelson (1971). Therefore, it seems that in no way the observed leaf injuries could have been caused by sodium.

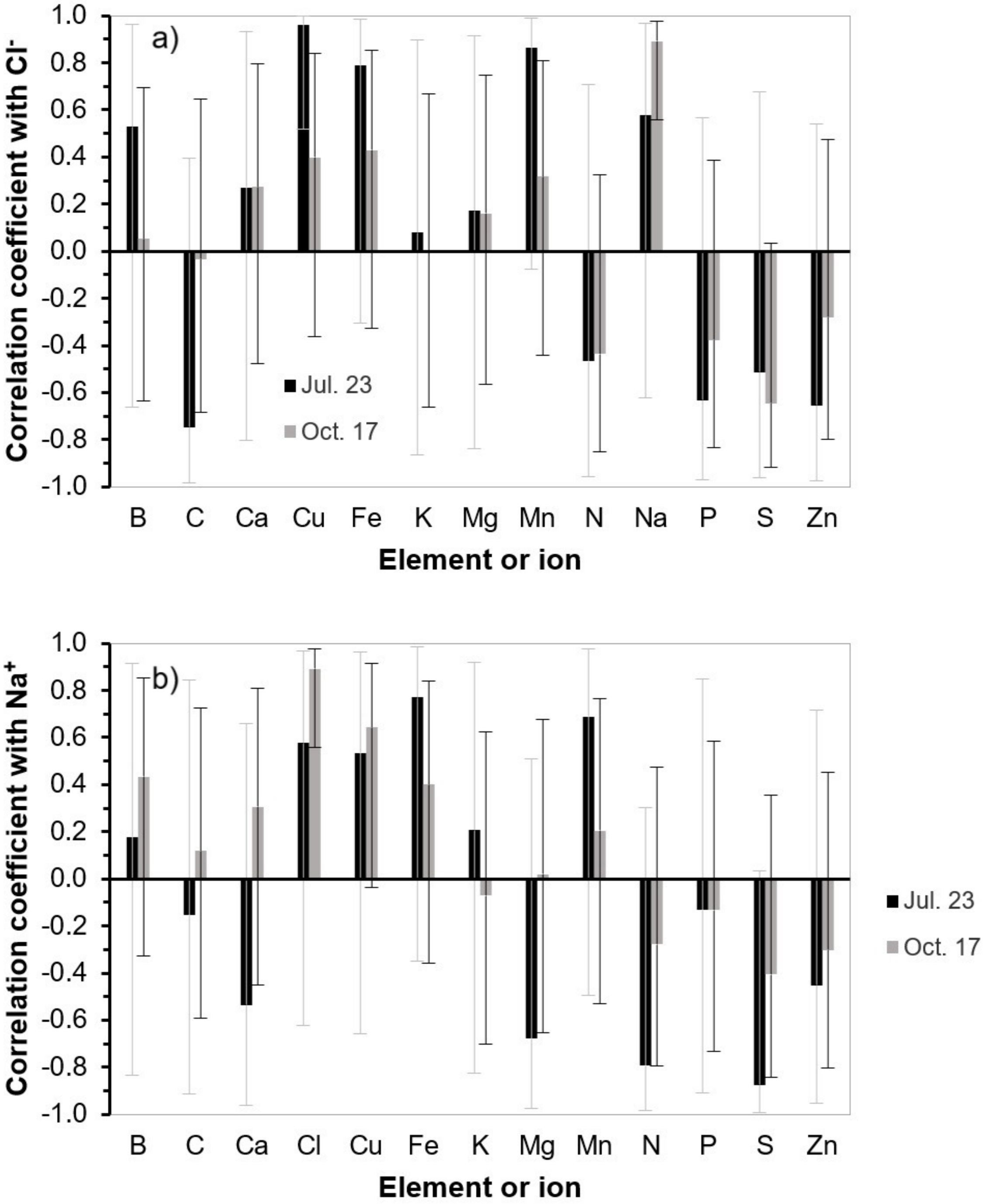

Figure 7. Pearson's product-moment correlation coefficients (r) alongside the corresponding 95% confidence intervals, of leaf chloride (a) and sodium (b) with the macro- and micronutrients on both 23rd July and 17 October 2018.

4. DISCUSSION

4.1. Nutritional status

The slight nitrogen (N) deficit observed in T3 was further explored because, additionally, it was accompanied by a trend for N decrease throughout the irrigation season and throughout the salinity treatments (Table 2). However, this tendency was not confirmed by the correlation analysis between chloride, sodium and the rest of nutrients. Although the correlation coefficient between leaf Cl^- and N was -0.44 at the trial end, it was not high enough to be significantly different from zero (Figure 7).

One of the ways salinity impacts plants is through hampering plant nutrition (Grattan & Grieve, 1999), with chloride specifically competing with nitrate (Kafkafi et al., 1982; Cerezo et al., 1997) and sodium competing with potassium (Wakeel, 2013), and with other nutrients that are absorbed in cationic form, e.g., calcium and magnesium (Grattan & Grieve, 1999). The equal charges of Cl^- and NO_3^- on the one hand, and Na^+ and K^+ on the other, in addition to the very similar hydrated radius of each member of these couples, mainly Cl^- and NO_3^-, which present, respectively, 0.33 and 0.34 nm, and then Na^+ and K^+, which present 0.36 and 0.33 nm (Israelachvili, 2011) can explain these effects. Indeed, the equal charge and very similar hydrated ion size of Cl^- and NO_3^- makes them share the same transport channels within plants (Deane-Drummond, 1986; Carillo & Rouphael, 2022). Therefore, the competition between Cl^- and NO_3^- for plant uptake is expected to be the most marked and, in fact, it seems to occur in avocados (Bar et al., 1997), and, particularly, in the avocados that exhibit less Cl^- exclusion ability. Indeed, a correlation coefficient between leaf Cl^- and N as high as -0.74, which was significantly different from zero at the 95% confidence level, was observed by Bar et al. (1997). However, in the present work with the 'Nachar' rootstock the effect of chloride on nitrate could not be confirmed by the correlation of leaf Cl^- and N (Figure 7) despite using a similar range of irrigation water Cl^- concentrations than Bar et al. (1997), who used between 71 and 567 mg/L. This observation might indicate enhanced Cl^- exclusion ability in the 'Nachar' rootstock.

Regarding the effect of sodium on potassium due to their resemblance as hydrated monovalent cations (Amtmann & Sanders, 1998), this was not seen at all in this work (Figure 7). This may suggest that the 'Nachar' rootstock has an improved ability to exclude Na^+. However, it might be also a consequence of the low SAR_{iw} values that were used. Furthermore, the likely effects of Na^+ on Ca^{2+} and Mg^{2+} were similarly negligible (Figure 7). This may be attributed to the same two reasons, in addition to the wider differences between the charges and hydrated radius of Na^+ (0.36 nm) in comparison to Ca^{2+} (0.41 nm) and Mg^{2+} (0.43 nm; Israelachvili, 2011).

4.2. Plant development

Uneven and stunted plant development are among the most characteristic salinity impacts on crops (Läuchli & Grattan, 2012). In avocado, previous studies have reported that salinity, particularly chloride, stunts development, with these effects primarily observed on the scion (Mickelbart & Arpaia, 2002; Celis et al., 2018). Indeed, in woody crops in general, salinity stimulates rootstock growth at the expense of the scion, which is an adaptative response indicative of salt tolerance, as the rootstock acts as a plant sink while expanding its root system to seek soil moisture, i.e., hydrotropism, and thus enhance soil water absorption (Zrig et al., 2023), and to avoid soil salts accumulations, i.e., halotropism. However, —contrary to the expected response—, in avocado and, particularly, in avocado grafted onto a West Indian rootstock like 'Degania 117', the opposite effect of salinity on roots has been found (Bernstein et al., 2004), which matches what has been observed in this work that occurs with 'Nachar'.

It is well-known that avocados develop relatively poor root systems featuring low degree of branching, low soil penetration ability and scarcity of root hairs (Eliot Coit, 1940; Burgis & Wolfe, 1945). Moreover, seed-propagated avocados show more underdeveloped root system architectures than clonal-propagated ones (Fassio et al., 2020). It has been hypothesized that these characteristics of the avocado roots may make these fruit trees more vulnerable than other woody crops to water and nutrient fluctuations once planted on soils (Bernstein et al., 2004). Furthermore, it can be hypothesized that the avocado's root system architecture may exacerbate the incipient effect of chloride on nitrate as suggested by the moderate negative correlation between leaf Cl^- and N (Figure 7). Therefore, being the 'Nachar' seed-propagated, its likely root characteristics might compromise, in the medium to long term, any salt-tolerance this rootstock might confer to the 'Hass' scion.

4.3. Chloride phytotoxicity

The leaf chloride threshold of 8 ± 1 g/kg for phytotoxicity to develop in individual leaves is close to the lowest range of 4 – 7 g/kg, which characterizes the most Cl^--sensitive crops (White & Broadley, 2001). Notably, it aligns well with results from studies on ‘Hass’ avocados grafted onto various clonal and seedling rootstocks. However, it is somewhat higher. This is likely because leaf necrosis is typically assessed based on its appearance in leaves scattered throughout the tree, rather than in individual leaves, but leaf samples are collected and chloride determined regardless of whether the leaves are injured or not for the sake of representativeness. Accordingly, Oster et al. (2007) observed no foliar necrosis in avocados with leaf chloride concentrations ranging from 3.9 g/kg to 4.4 g/kg, while Mickelbart & Arpaia (2002) similarly reported no foliar necrosis at 4.6 g/kg leaf chloride, but did observe early-stage necrosis at 6.4 g/kg.

The leaf chloride accumulation rate of 18 ± 15 mg/kg per mg/L of chloride in the irrigation water is comparable to that of other avocado rootstocks, which range from 13 to over 56 mg/kg per mg/L (Table 4). It should be noted that the inclusion of leaves with markedly different levels of injury in this study increased variability, producing wide error intervals that cannot be regarded as true confidence intervals of the mean and that preclude meaningful statistical comparisons. However, by taking only the mean, ‘Nachar’ exhibits one of the lowest leaf chloride accumulation rates within the observed range being, in fact, very similar to ‘Nabal’ and ‘UCV 7’, which have been classified as salt-tolerant rootstocks for avocado (Castro et al., 2009; Castro et al., 2015).

Traditionally, the development of salt tolerance in crops is assessed based on two parameters. These are i) the threshold salinity up from which crops begin to feature yield loss, and ii) the yield decline per unit increase of salinity beyond that threshold (Maas & Hoffman, 1977; Maas, 1984). In this context, salinity refers to soil salinity, expressed as the electrical conductivity at 25 ºC of the saturation extract (EC_e). However, it may also refer to irrigation water salinity, expressed as its electrical conductivity at 25°C (EC_{iw}), provided that an appropriate calculation of EC_{iw} from EC_e is made. To calculate EC_{iw} from EC_e, different types of models may be used, ranging from a multiplication by a single factor, e.g., 1.5 (Ayers & Westcot, 1994), to increasingly complex simulation models (Visconti et al., 2012).

In contrast to salinity, tolerance to chloride phytotoxicity in crops is expressed as the maximum chloride concentration in the soil water, or irrigation water, beyond which crops experience leaf injury (Maas & Grattan, 1999). However, similarly to salt tolerance, it can also be proposed that the development of chloride phytotoxicity in crops can be assessed based on two parameters. On the one hand, there is the threshold concentration of chloride in leaves from which necrotic symptoms appear. On the other hand, there is the rate at which leaf chloride concentration increases in response to the chloride concentration in the irrigation water. The advantage of this latter approach is that it can be reasonably hypothesized that the leaf chloride threshold concentration for the appearance of leaf necrosis depends mostly on the scion, whereas the leaf chloride increase rate depends mostly on the rootstock. Therefore, if this accumulation parameter is used to arrange the avocado rootstocks, the ‘Nachar’ ranks high in conferring the scion tolerance to chloride phytotoxicity (Table 4).

Comparing avocado to other woody crops in the Valencian Community that experience chloride phytotoxicity, such as citrus and persimmon, these have leaf chloride thresholds of, respectively, 7 g/kg (Ferguson & Grattan, 2005) and 13 g/kg (de Paz et al., 2016) when similarly young, i.e., 12% lower and 63% higher than that of avocado. This comparison highlights that the leaf chloride sensitivity of ‘Hass’ avocado is as high as that of citrus, but lower than that of persimmon.

Regarding the ability to accumulate chloride in leaves, persimmon grafted onto the *Diospyros lotus* rootstock exhibits an average rate of foliar chloride increase of 33 mg/kg per mg/L of chloride in the irrigation water (Visconti et al., 2017). In contrast, mandarin grafted onto Citrange Carrizo (Citrus sinensis × *Poncirus trifoliata*) shows an average foliar chloride increase rate of 8 mg/kg per mg/L in irrigation water (Arbona et al., 2005). Therefore, the observed mean leaf chloride accumulation rate of 18 mg/kg per mg/L in avocado grafted onto ‘Nachar’ falls between that of persimmon on *D. lotus* and that of mandarin on C. Carrizo. This comparison highlights that the ‘Nachar’ rootstock for avocado

Table 4. Leaf chloride and sodium increase rates with irrigation water chloride and sodium adsorption ratio (SAR), respectively, in young avocados grafted onto different rootstocks

Rootstock	Sub-species	Scion	Trial length	Cl^- increase rate	Na^+ increase rate	Reference
			day	mg/kg per mg/L	mg/kg per $(mmol/L)^{1/2}$	
225.00	West Indian	Hass	153	37	480	Alvarez-Acosta et al. (2019)
Degania 117	West Indian	Hass	130	16	–	Castro et al. (2009)
Degania 117	West Indian	Non grafted	126	27	–	Bar et al. (1997)
Duke 7	Mexican	Hass	130	29	–	Castro et al. (2009)
Duke 7	Mexican	Hass	130	30	–	Castro et al. (2015)
Dusa	Mexican ×	Hass	3 × 365	44	940	Celis et al. (2018)
Gallo 2	Guatemalan	Hass	153	51	310	Alvarez-Acosta et al. (2019)
Gallo 3	West Indian	Hass	153	36	650	Alvarez-Acosta et al. (2019)
Julian	Guatemalan × West Indian	Hass	153	34	460	Alvarez-Acosta et al. (2019)
Mexícola	West Indian	Hass	130	18	–	Castro et al. (2009)
Nabal	Mexican	Hass	130	13	–	Castro et al. (2009)
Nabal	Guatemalan	Hass	130	19	–	Castro et al. (2015)
Nachar	Guatemalan	Hass	110	18 ± 15	50 ± 40	This work
Smith	West Indian	Non grafted	126	23	–	Bar et al. (1997)
Steddom	Mexican	Hass	3 × 365	39	190	Celis et al. (2018)
Thomas	Mexican	Hass	3 × 365	56	1600	Celis et al. (2018)
Thomas	Mexican	Hass	153	22	220	Alvarez-Acosta et al. (2019)
Topa-Topa	Mexican	Hass	153	25	160	Alvarez-Acosta et al. (2019)
UCR PP40	Mexican	Hass	3 × 365	43	–	Celis et al. (2018)
UCR PP45	Guatemalan?	Hass	3 × 365	> 56	–	Celis et al. (2018)
UCV 7	Mexican?	Hass	130	17	–	Castro et al. (2015)
Uzi	West Indian	Hass	3 × 365	> 56	–	Celis et al. (2018)
Westfalia R0.05	Mexican	Hass	3 × 365	55	850	Celis et al. (2018)
Westfalia R0.06	?	Hass	3 × 365	> 56	–	Celis et al. (2018)
Westfalia R0.07	?	Hass	3 × 365	> 56	–	Celis et al. (2018)
Westfalia R0.16	?	Hass	3 × 365	> 56	–	Celis et al. (2018)
Westfalia R0.17	?	Hass	3 × 365	> 56	–	Celis et al. (2018)
Westfalia R0.18	?	Hass	3 × 365	38	620	Celis et al. (2018)
Zentmyer	?	Hass	3 × 365	47	1300	Celis et al. (2018)
Zutano	Mexican	Hass	130	23	–	Castro et al. (2009)

has a lower capacity to avoid foliar chloride accumulation than C. Carrizo for citrus, but higher capacity than *D. lotus* for persimmon, the latter being a rootstock known for its remarkable low tolerance to chloride phytotoxicity (Visconti et al., 2017).

However, when considering both factors—sensitivity to foliar chloride concentration and the ability to avoid its leaf accumulation—it becomes evident that the 'Hass' avocado grafted onto the salt-tolerant 'Nachar' rootstock has high susceptibility to chloride phytotoxicity, which is greater than that of citrus and similar to that of persimmon grafted onto the very salt-sensitive *D. lotus* rootstock. Therefore, it may be inferred that under the same salt stress cropping conditions 'Hass' avocados on 'Nachar' are likely to develop more chloride phytotoxicity symptoms in comparison to citrus and similar to persimmon. This is interesting considering that citrus and persimmon are the crops avocado is replacing in the Valencian Community.

4.4. Sodium phytotoxicity

It is interesting to note, additionally, that by extrapolation of the relationship between leaf sodium and SAR_{iw} (Figure 6), SAR_{iw} should climb to an uncommon value of 40 $(mmol/L)^{½}$ to attain the 2 g/kg threshold for sodium leaf injury (Bingham & Nelson, 1971). Note that the atypicality of the 40 $(mmol/L)^{½}$ value is made evident by the estimate of only 0.4% of the World's waters having over 40 $(mmol/L)^{½}$ SAR, according to data collected by Ayers & Westcot (1994). Therefore, according to the leaf sodium increase rate per unit increase of SAR_{iw} of 50 ± 40 mg/kg per $(mmol/L)^{½}$, the sodium exclusion of 'Nachar' is highly remarkable in comparison to other rootstocks, which present a leaf sodium increase rate with SAR_{iw} ranging between 160 and 1600 mg/kg per $(mmol/L)^{½}$ (Table 4), i.e., between 4 and 40 times higher than 'Nachar'.

Na^+ and Cl^- exclusion from the scion likely proceeds by restriction of their transfer through the xylem once water is absorbed from the soil, with avocado showing a stronger ability of Na^+ exclusion than of Cl^- exclusion, as similarly observed in other woody crops (Munns & Tester, 2008). However, among avocado rootstocks the 'Nachar' seems to have remarkable ability to exclude Na^+. To better clarify the sodium exclusion ability of the 'Nachar' rootstock compared to other rootstocks, a sodium-focused trial should be performed, analyzing not only the leaves but also the roots for Na^+ determination. If this sodium exclusion ability of 'Nachar' rootstock was confirmed, it would be a highly valuable piece of information for both avocado producers, breeders and researchers, given that Na^+ more than doubles Cl^- in its metabolic disruption potential of avocado leaves (Alvarez-Acosta et al. 2019).

Interestingly, the overall salt tolerance (encompassing both Cl- and Na^+) demonstrated by the 'Nachar' rootstock in this trial appears unmatched by other rootstocks in the 'Nachlat' group, otherwise considered salt-tolerant (Ben-Ya'acov & Michelson, 1995). Indeed, the 'Nachlat 3' rather joins salt-sensitive rootstocks like Waldin, and some Degania, despite the West Indian ancestry of both (Lazare et al., 2021). Being many of these rootstocks seed-propagated, this observation highlights the importance of preserving by proper crossings and, perhaps, clonal reproduction the salt-tolerance of rootstocks once this trait has been selected.

5. CONCLUSIONS

The salt-tolerance of 'Hass' avocado when grafted onto the 'Nachar' rootstock has been characterized based on the accumulation rates of leaf chloride and sodium relative to, respectively, the chloride concentration and the sodium adsorption ratio of the irrigation water. These leaf ion accumulation rate parameters are not reported explicitly in salt-tolerance studies. However, they provide scion-independent information that reflects rootstock-specific ion regulation capacity and is therefore of the highest relevance. Accordingly, the values of 18 mg/kg per mg/L for chloride and 50 mg/kg per $(mmol/L)^{½}$ for sodium makes the 'Nachar' to lay among the best for chloride exclusion and at least 3 times better than the known second-best for sodium exclusion. Although this last finding should be confirmed by a Na-devoted trial because of the low SAR values used in this study, the 'Nachar' rootstock seems to stand out in conferring overall salt tolerance to 'Hass' avocados. However, leaf injuries are still expected for avocado grafted onto 'Nachar' under salinity conditions that are known to barely affect other salt-sensitive woody crops. Obviously, the findings in this work are very informative for avocado producers but, additionally, for avocado researchers and breeders in their quest for improving this crop salt-tolerance. However, if not properly carried out, the usual seed-propagation of the 'Nachar' and other rootstocks may jeopardize the achievement of further salt-tolerance improvements and even, lose the achievements made so far.

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Supplementary material

A spreadsheet with the data accompanies the paper on the SJAR's website.

Data availability

The data used in this research has been made available as a supplementary material.

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Authorship contribution statement

Fernando Visconti: Conceptualization, Methodology, Validation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Julio Climent: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Supervision.

Enrique Peiró: Investigation, Resources, Writing - Review & Editing.

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José Miguel de Paz: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization, Supervision, Project administration, Funding acquisition.

Competing interests

The authors have declared that no competing interests exist.

Statement on the use of Artificial Intelligence

Not applicable.

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