

Enhancing salinity management strategies for *Amaranthus cruentus*: integrating EC models and salinity tolerance thresholds

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Abstract

Aim of the study: The objective of this study was to determine the salinity tolerance threshold of *Amaranthus cruentus* L. and evaluate its performance under various salinity conditions. Additionally, this research explored the feasibility of expressing the salinity threshold as pore water salinity (EC_w), which can be estimated using a capacitance probe in combination with the mathematical model proposed by Hilhorst (2000) (EC_wHi). The ultimate goal was to enhance salinity management strategies for sustainable agricultural practices.

Area of the study: Faculty of Agronomy Sciences of the University of Chile, Santiago, Chile.

Materials and Methods: The trial evaluated the development of *A. cruentus* irrigated with water of electrical conductivity levels of 1.75, 2.5, 5, 8, 10, and 15 dS m⁻¹ over a complete crop cycle (5 months). The variables measured included stem water potential, stomatal conductance, plant and panicle height, biomass, and yield. EC_w was measured using suction lysimeters, while EC_wHi was estimated using data from a GS3 capacitance probe and a mathematical model.

Main results: No significant differences were found in stem water potential, plant and panicle height, biomass, or yield, except at 15 dS m⁻¹. Based on these results a salinity tolerance threshold of 5.64 dSm⁻¹ was determined for the electrical conductivity of a saturated extract (EC_e). A strong correlation ($R^2 > 0.8$) between EC_w and EC_wHi was found, however the accuracy of this relationship decreased as the electrical conductivity increased from 3 to 14 dS m⁻¹. Thus, calibration is recommended for use with this specific model.

Research highlights: The study showed that *Amaranthus* spp. is a viable option for saline conditions, and underscore the importance of precise salinity management for sustainable agricultural practices.

Keywords: Andean crops; crop tolerance to salinity; Maas & Hoffman model; resilient crops; saline soils.

Mejorando las estrategias de gestión de la salinidad para *Amaranthus cruentus*: integración de modelos de CE y umbrales de tolerancia a la salinidad

Resumen

Objetivo del estudio: Determinar el umbral de tolerancia a la salinidad de *Amaranthus cruentus* L. y evaluar su desempeño en diversas condiciones de salinidad. Además, se exploró la viabilidad de expresar el umbral de salinidad como salinidad del agua de los poros (EC_w), la cual puede estimarse mediante una sonda de capacitancia en combinación con el modelo matemático propuesto por Hilhorst (2000) (EC_wHi). El objetivo fue mejorar las estrategias de gestión de la salinidad para prácticas agrícolas sostenibles.

Área de estudio: Facultad de Ciencias Agronómicas de la Universidad de Chile, Santiago, Chile.

Materiales y Métodos: El ensayo probó el desarrollo de *A. cruentus* regado con niveles de conductividad eléctrica del agua de 1.75, 2.5, 5, 8, 10 y 15 dS m⁻¹, durante un ciclo completo del cultivo (5 meses). Las

variables medidas fueron potencial hídrico del tallo, conductancia estomática, altura de planta y panícula, biomasa y rendimiento. La EC_w se evaluó mediante lisímetros de succión, mientras que EC_{wHi} se estimó utilizando datos de una sonda de capacitancia GS3 y un modelo matemático.

Resultados principales: No hubo diferencias significativas en el potencial del tallo, altura de la planta y panícula, biomasa o el rendimiento, excepto a 15 dS m⁻¹. En base a estos se determinó un umbral de tolerancia de 5.64 dS m⁻¹ para la conductividad eléctrica del extracto saturado (EC_e). Se encontró una fuerte correlación ($R^2 > 0.8$) entre EC_w y EC_{wHi}; sin embargo, la precisión de esta disminuyó a medida que la conductividad eléctrica aumentó de 3 a 14 dS m⁻¹. Por lo tanto, se recomienda una calibración para el uso de este modelo específico.

Aspectos destacados de la investigación: Se demostró que *Amaranthus* spp. es una opción viable para condiciones salinas y subraya la importancia de un manejo preciso de la salinidad para prácticas agrícolas sostenibles.

Palabras clave: cultivos andinos; cultivos resilientes; Modelo de Maas & Hoffman; suelos salinos; tolerancia a la salinidad de los cultivos.

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Introduction

Chile is experiencing a serious water availability crisis, especially in semiarid to arid climate areas (northcentral part of the country), where the demand/availability ratio for water is affected by the low rainfall received during the last 10 years (between 25 and 45% less) and by the high competition for this resource from different economic and social actors (Garreaud et al., 2017). Under these scarcity conditions, adaptation strategies are required to diversify the productive matrix to crops with lower water requirements and/or those adapted to lower-quality irrigation water, such as saline water. These crops must have agricultural and commercial potential, such as functional and nutritional properties that could increase farmers' resilience in these areas and enhance food security for the local population.

In this context, *Amaranthus* spp. is promoted as healthy foods because of their nutritional and functional value by the Food and Agriculture Organization (FAO) of the United Nations and the World Health Organization (WHO). Its excellent protein quality allows its use as food for human and animal consumption, as it is able to take advantage of both leaves and grains (Shukla et al., 2018; Dinsaa et al., 2020). Amaranth is considered a functional and nutraceutical food since its consumption lowers blood pressure (Ontiveros et al., 2020) and has beneficial effects on people with diabetes, obesity and cardiovascular diseases, as well as high antioxidant and anti-inflammatory activity (Tang & Tsao, 2017). Additionally, amaranth has been reported to be a drought-resistant species (Lavini et al., 2016, Netshimbupfe et al., 2022) because it improves its assimilated allocation to aerial biomass and grains when water stress occurs during vegetative growth (Mlakar et al., 2012; Pulvento et al., 2022). Nevertheless, there is little information on vegetative and productive responses under saline conditions. Omamt et al. (2006) reported that *Amaranthus* spp. develop well under mild to moderate salt stress, with slight effects on production. El Youssfi et al. (2012) evaluated the response of the growth and yield of three varieties of amaranth irrigated with saline water with an electrical conductivity of 0.92, 3.0 and 6.0 dS m⁻¹ and determined that the crop decreased its growth and yield by increasing the salinity of the irrigation water; however, they noticed that amaranth 'a 211' obtained a higher yield than the others, even with the highest salinity level, indicating that it was a promising variety for growth under these conditions. Lavini et al. (2016) developed a first approximation of the crop salinity tolerance model proposed by Maas & Hoffman (1977). By extrapolating their data, the *Amaranthus hyponcondriacus* L. genotype was classified as sensitive to moderate tolerance to salinity under well-hydrated conditions, with a salinity tolerance threshold

of 0.78 dS m^{-1} (electrical conductivity of a saturated extract, E_{Ce}). However, the salinity conditions of the soil where this research was carried out were heterogeneous throughout the growing season due to precipitation, which shortened the range of effective salinity reached by the crop. Consequently, no studies have been conducted to assess the salinity threshold in amaranth across a comparable E_{Ce} range throughout the entire crop cycle. This information is relevant when combining saline water with fresh water for the execution of resilient irrigation practices.

On the other hand, numerous techniques are available for field measurements of soil salinity. The predominant methods for assessing soil electrical conductivity include: obtaining the electrical conductivity of a saturated extract (E_{Ce}), employing a dilution test (E_{C1:x}), measuring the bulk electrical conductivity (E_{Cb}), and assessing the pore water salinity (E_{Cw}). While these measurements are interconnected and can be converted between each other, the interpretation of salinity varies for each measurement or parameter. E_{Ce} is the traditional and standard method used in plant salt tolerance studies, and most salinity thresholds are based on this method (Hanson & May, 2011; Grieve et al., 2012). In this method, soil salinity is determined by extracting a soil sample, creating a saturated paste with deionized water, extracting the water, and measuring the electrical conductivity of the resulting solution. However, this method, involving field soil samples and laboratory measurements, is impractical for irrigation management due to its time, labor, and cost intensiveness. Therefore, more efficient and practical methods for salinity measurement are needed. In this context, measuring E_{Cb} offers the advantage of automated measurement using in situ sensors such as time domain reflectometry (TDR) or frequency domain reflectometry (FDR). Soil salinity sensors directly measure the E_{Cb}, presenting a range of possibilities for enhancing irrigation management with saline water (Incrocci et al., 2009; Bañon et al., 2021). Nevertheless, interpreting salinity levels based on the E_{Cb} can be prone to errors, as it encompasses the combined electrical conductivity of substrate particles, air, and solution (Corwin & Lesch, 2005; Peter et al., 2011). Given the significant influence of soil water content on E_{Cb} (Scoggins & van Iersel, 2006; Lopes & Montenegro, 2019), its utility as a salinity index is limited. In practice, E_{Cb} requires adjustment of the soil water content or simultaneous measurement under consistent water content conditions for accurate interpretation (Scoggins & van Iersel, 2006; Bañon et al., 2021). In contrast, the E_{Cw} is considered a more robust index for irrigation management (Bañon et al., 2021) since it represents the salinity experienced by plant roots (Corwin & Yemoto, 2020); however, only a few salinity tolerance thresholds have been reported using this method (Bañon et al., 2022). E_{Cw} cannot be monitored automatically, as it requires extracting the solution from the porous medium, either by suction, compression, or displacement, before the electrical conductivity can be measured (Corwin & Yemoto, 2020). However, mathematical models such as the one proposed by Hilhorst (2000) that allows E_{Cw} to be estimated from sensor output variables (TDR or FDR), such as electrical permittivity and E_{Cb} (Kargas & Kerkides, 2012), can be parameterized and programmed to obtain continuous estimates of E_{Cw}.

Therefore, from the investigations carried out in *Amaranthus* spp., it has been shown that the crop has a certain tolerance to salinity; however, this information is not conclusive for the determination of its tolerance threshold, and consequently, the adjustment of the salinity tolerance model proposed by Maas & Hoffman (1977) is needed. In fact, farmers need to know the soil salinity levels at which yields start to decline and how much yield will be reduced at levels above the threshold. However, most salinity thresholds for crops are described under tedious and labor-intensive E_{Ce} methods, and quick and informed decisions cannot be made; therefore, the salinity index, such as the E_{Cw}, which can be estimated with sensors, is highly relevant for salinity management. Accordingly, the objectives of this research were (i) to evaluate the effect of different levels of salinity on the physiological and productive response of amaranth, (ii) to determine the fit of the Maas & Hoffman (1977) model for the specie under different salinity indices, E_{Ce} and E_{Cw}, and (iii) to characterize the response of the Hilhorst (2000) model to estimate E_{Cw} as a tool for irrigation scheduling.

Materials and Methods

Study location

The study was carried out at the Faculty of Agronomy Sciences of the University of Chile ($33^{\circ}57'$ South; $70^{\circ}63'$ West). The climate corresponds to a warm temperate Mediterranean with a prolonged dry season (6-7 months) and average annual precipitation of 378.5 mm, concentrated during winter, and potential evapotranspiration above 1200 mm per year.

The meteorological data were obtained from a weather station located 400 m from the test site; the information was recorded from September 11, 2018 (sowing), to January 14, 2019 (harvest). The temperature reached a minimum of 2.9 °C (October 3, 2018), with an average minimum of 9.2 °C. The highest temperature recorded was 35.3 °C (January 3, 2019), which reached an average maximum of 26.3 °C throughout the production cycle. The relative humidity during this period reached an average of 56%. There was no rain during the evaluated period.

Plant material and soil

Seeds of *Amaranthus cruentus* L. (Amaranteca) were sown in pots of 293 mm in internal diameter and 386 mm in height (three plants per pot) using sandy soil with a bulk density of 1.77 Mg m⁻³, a volumetric water content at field capacity and a permanent wilting point of 6.5% and 4.4%, respectively, a pH of 7.91, an ECe of 0.68 dS m⁻¹ and an organic matter content of 0.77%.

Treatments

Deep well water with an average electrical conductivity during the season of 1.75 dS m⁻¹ was used for the study. The irrigation water for the treatments was salinized with the addition of different levels of KCl, except for the control. Therefore, the treatments consisted of 6 levels of electrical conductivity for the irrigation water (ECi): 1.75 (control), 2.5, 5.0, 8.0, 10.0 and 15.0 dS m⁻¹. Each treatment had 5 replicates (30 pots in total).

Agronomic management

The experiment was established in an area of 20 m², in which the pots were installed at an equidistance of 0.3 m, allowing proper management of the crop and avoiding shading between plants. An organic potassium humate amendment was applied to the soil at a total dose of 30 kg ha⁻¹, divided into 5 applications dissolved in the irrigation water before sowing. Sowing was carried out manually on September 11, 2018 (at the end of the winter-beginning of spring). After sowing, partial fertilization was carried out until reaching 80 kg ha⁻¹ of nitrogen, 60 kg ha⁻¹ of P₂O₅ and 40 kg ha⁻¹ of K₂O, which is enough to cover the requirements of the crop (Ramírez et al., 2011). Weed control was carried out manually during the first weeks of crop establishment.

In the initial growth phase of the crop, irrigation water without the addition of salt (ECi = 1.75 dS m⁻¹) was used. Once the crop reached 10 leaves, the treatments were started (November 11, 2018). The objective ECi for each treatment was obtained by dissolving potassium chloride (KCl) and mixing until a homogeneous solution was achieved (Kargas et al., 2012; Kremer et al., 2021). The solution was prepared and monitored prior to irrigation with a benchtop conductivity meter (model HI 4321, HANNA, Spain). Manual irrigation was carried out daily or every other day, and sufficient water was applied to avoid water stress and salt accumulation conditions (1 to 2 L/plant). The irrigation water was calculated based on the soil's water holding capacity, the total pot volume, and the interval between irrigations, with an additional 100% to encourage leaching. Additionally, to avoid a possible progressive accumulation of salts, irrigation equivalent to 100% of the total porosity was performed weekly or every two weeks. After each irrigation event, excess water drained freely, and cumulative water was not observed. The total amount of irrigation water across the whole cycle was 110 L/plant, the leaching fraction was close to 50% for all treatments. The soil water content was measured daily when the irrigation treatments began with a FDR sensor (GS3, Decagon Devices, WA, USA) in one replicate per treatment. Measurements were performed at midday or between 4 and 5 hours after irrigation.

Electric conductivity

To monitor the suggested electrical conductivity in the saline treatments during the experiment and simultaneously investigate our hypothesis regarding the utilization of capacitance sensors for soil salinity management, we assessed the ECw using suction lysimeters (Irrometer, CA, U.S.A.). These lysimeters were installed in two replicates per treatment at a depth of 20 cm. Sampling occurred twice a week when the

soil stopped draining, and the EC_w was determined using a tabletop conductivity meter (model HI 4321, HANNA, Spain). Additionally, EC_w was estimated according to Hilhorst (2000):

$$ECW_{Hi} = \frac{(\varepsilon_w \cdot ECb)}{(\varepsilon_b - \varepsilon_{b=0})} \quad (1)$$

where EC_{w_{Hi}} is the EC_w obtained through the Hilhorst (2000) model, EC_b is the bulk electrical conductivity measured directly by GS3, ε_b is the real portion of the permittivity of the bulk soil measured by GS3, $\varepsilon_{b=0}$ is the real portion of the permittivity when EC_b = 0 (offset), and ε_w is the real portion of the permittivity of the pore water, corrected for soil temperature using :

$$\varepsilon_w = 80.3 - 0.37(\text{Soil temperature } (^{\circ}\text{C}) - 20) \quad (2)$$

A value of $\varepsilon_{b=0}$ equal to 3.44 was obtained by fitting a linear equation that relates the permittivity (y axis) with the EC_b data (x axis) obtained from field measurements, following the method described by Hilhorst (2000).

Physiological variables

Stomatal conductance (gs) and stem water potential (Ψ_x) were measured by using two mature leaves per pot located in the upper third of the plant exposed to direct radiation. The determination of gs was carried out at midday with a porometer (model SC-1, Decagon, USA) in 4 relevant phenological periods. The first corresponded to 65 days after emergence (DAE) of the crop, which coincided with ten days after the first application of treatments (November 21, 2018); the second corresponded to 84 DAE in anthesis (December 10, 2018); the third corresponded to 91 DAE at the beginning of grain filling (December 17, 2018); and the fourth corresponded to 107 DAE in physiological maturity (January 2, 2019). For Ψ_x , the selected leaves were wrapped in a plastic bag with aluminum foil two hours before measurement to equilibrate the water potential of the leaves in balance with the water potential of the stem (Beyá-Marshall et al., 2022). A Scholander pressure chamber (PMS Model 600, USA) was used. The measurements were carried out between 12:30 and 13:30 hours, three times during the seasons: 62, 82 and 112 DAE. These values corresponded to approximately 7 days after the first application of the treatments (November 18, 2018), anthesis (December 8, 2018) and physiological maturity (January 7, 2019), respectively.

Vegetative growth and yield

Plant height was measured from the soil surface to the top of its main branch, while the height of the main branch was measured from the top to the point where they became secondary branches. These measurements were made at physiological maturity (at the end of the test).

The harvest was carried out when the fall of the first grains was evident on January 14, 2019. First, the aerial parts of the plants were extracted, and then the roots from each of the pots were removed. Later, each of these structures was dried in a forced-air oven at 80 °C until a constant mass was reached. From the aerial parts, the grains were separated, which allowed the determination of the yield of each plant and the harvest index (HI), which was calculated as the ratio between the grain yield and the dry aerial biomass. Three plants per pot were processed, and the average (n=3) of each variable was calculated to obtain the replicate (n=5).

Crop tolerance to salinity

To establish the yield response as a function of salinity (evaluated as EC_e and EC_w), the proposed model of [Maas & Hoffman \(1977\)](#) was used, which represents the linear decrease in yield above a threshold as the EC_e or EC_w increases, as follows:

$$RY = 100 - p (EC - EC_m) \quad (3)$$

where:

RY: relative yield, in percentage, for a given soil electrical conductivity, either ECe or ECw, larger than the tolerance threshold.

p: percentage of yield that decreases per unit of increase in ECe or ECw.

EC: soil electrical conductivity expressed as ECe or ECw

ECm: soil electrical conductivity where the maximum yield was obtained (threshold value), expressed as ECe or ECw.

The ECe for each treatment was obtained by using the method proposed by [Sadzawka et al. \(2006\)](#) four times during the season, every 15 days from the beginning of the salinity treatments (November 11, 2018). The mean ECe values and yield for each treatment were contrasted to determine the parameters of Eq. 3.

Experimental design and statistics

The trials were established with a completely randomized block experimental design, with incident radiation being the blocking factor. The experimental unit corresponded to a pot with three amaranth plants with five replicates per treatment, for a total of 30 experimental units. We analyzed whether there were statistically significant differences for all the variables evaluated under the theoretical framework of linear mixed models. In all cases, when detecting significant differences, the DGC multiple comparison test was used ($\alpha \leq 0.05$). The statistical analysis program InfoStat version 2014 ([Di Rienzo et al., 2014](#)) was used.

Results

Soil water content and electrical conductivity

As the soil substrate was mainly sand and was frequently irrigated, it was possible to assess crop performance based only on salts that are present in the soil solution (pore water), in contrast to clay soils where more complex interactions can influence crop performance. Therefore, plants were only faced with the challenges of water uptake and not with any potential secondary effects that may occur in salt-affected clay soils. Consequently, the findings described in this report focused on crop salt tolerance alone rather than on a combination of stresses.

The measurements of soil water content for the treatments showed regularity within the soil water holding capacity range (Fig. 1) and closeness to field capacity (0.064 ± 0.090 ; $n = 170$), which confirmed the absence of water stress during the trial.

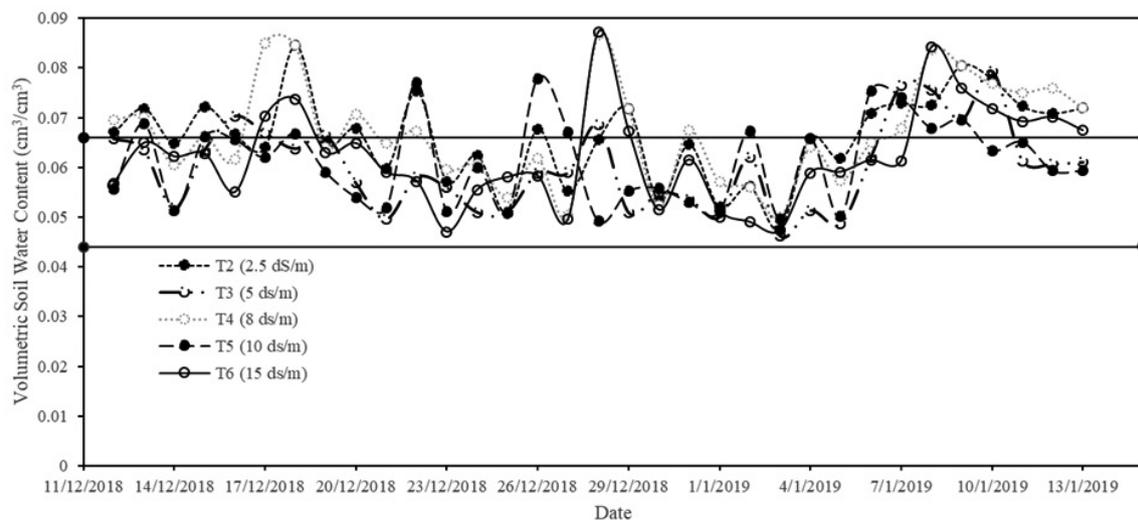


Figure 1. Dynamic of the volumetric soil water content for one-month data, of the different treatments (ECi: electrical conductivity for the irrigation water) in *Amaranthus cruentus* L. T1 data is not included due to sensor failure. Horizontal lines represent the soil water holding capacity range.

Similarly, the follow-up of EC_w in each treatment during the trial period remained relatively stable and close to the objective values sought with EC_i; though, no major differences were observed between the 1.75 and 2.5 dS m⁻¹ and between the 8.0 and 10.0 dS m⁻¹ treatments (Fig. 2, Table 1). Nonetheless, they were treated as independent treatments (Table 1).

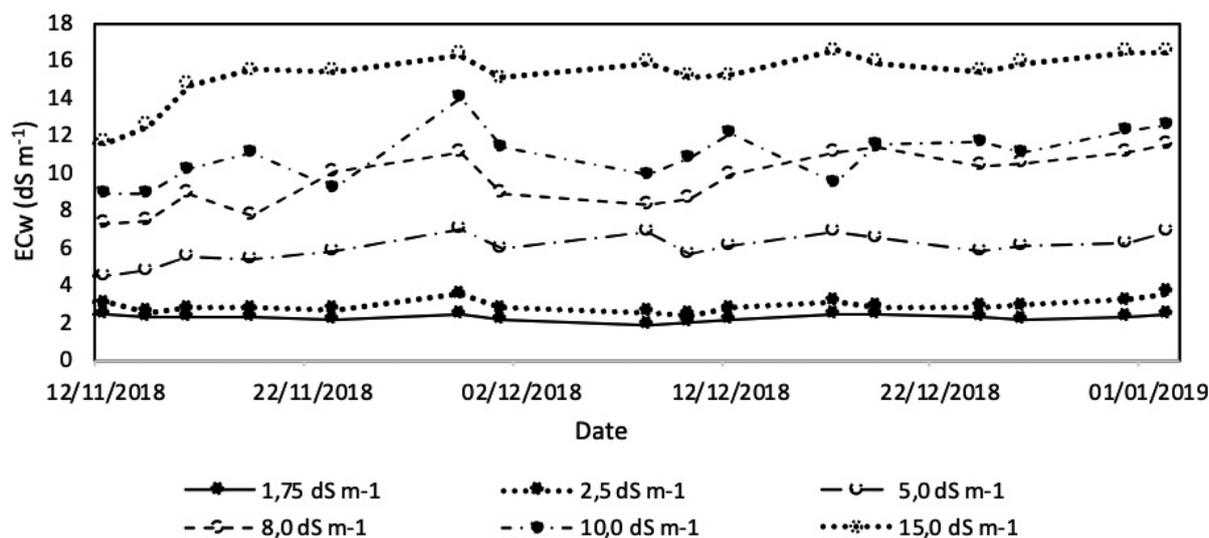


Figure 2. Variation in pore water salinity (EC_w) throughout the evaluated period. Each dot represents the mean value obtained for each treatment (EC_i: electrical conductivity for the irrigation water) in *Amaranthus cruentus* L.

Table 1. Average electrical conductivity of the saturated extract (EC_e, n=4) and pore water salinity (EC_w, n=18) during the trial for each of the salinity treatments (EC_i: electrical conductivity for the irrigation water) in *Amaranthus cruentus* L. Average values ± standard deviation.

Treatments, EC _i (dS m ⁻¹)	EC _e (dS m ⁻¹)	EC _w (dS m ⁻¹)
1.75	1.25(±0.18)	2.27(±0.19)
2.5	1.76(±0.27)	2.89(±0.29)
5.0	2.95(±0.10)	6.06(±0.72)
8.0	3.98(±0.09)	9.55(±1.35)
10.0	5.64(±0.24)	10.92(±1.37)
15.0	8.26(±0.10)	15.12(±1.28)

The average values of EC_e and its standard deviation (SD) are presented in Table 1. The low SD achieved for each treatment is consistent with the stability obtained with EC_w, so its use is suitable for estimating the parameters of [Maas & Hoffman \(1977\)](#).

Relationships among electrical conductivity measurements

The mean values of EC_e, EC_w, and EC_{w_{Hi}} during the experimental period increased as EC_i increased (Fig. 3A). Regression analysis indicated that the three linear regression models shown in Figure 3A were significant. EC_w was quite similar to EC_i, although the values of EC_w became more dispersed as EC_i increased. As expected, EC_e had a lower value but was highly correlated with EC_i. The slope of the EC_{w_{Hi}} – EC_i was lower

than that of the $EC_w - EC_i$ (Fig. 3A); hence, $EC_{w_{Hi}}$ underestimates the actual value of EC_w at field capacity. Additionally, Figure 3B shows a significant linear fit for $EC_w - EC_{w_{Hi}}$ and $EC_w - EC_e$ ($R^2=0.92$), suggesting that $EC_{w_{Hi}}$ and EC_e can be used as indicators to estimate the salinity of the pore water (EC_w). However, despite their linear correlation, a three-step regression was evident for the $EC_w - EC_{w_{Hi}}$ relationship ($R^2=0.92$). At low EC_w values (between ~ 2 and ~ 3 $dS\ m^{-1}$), the relationship exhibited high uniformity; at medium EC_w values (~ 3 and ~ 14 $dS\ m^{-1}$), the variability increased, and beyond ~ 14 $dS\ m^{-1}$, the GS3 sensor saturated its estimation, resulting in minimal or reduced correlation and slope between EC_w and $EC_{w_{Hi}}$ (Figure 3B). [Kargas & Kerkides \(2012\)](#) found that the [Hilhorst \(2000\)](#) model over-estimated EC_w for salinity values up to 1.2 $dS\ m^{-1}$, while it significantly underestimated EC_w for higher electrical conductivity values, as observed in our experiment.

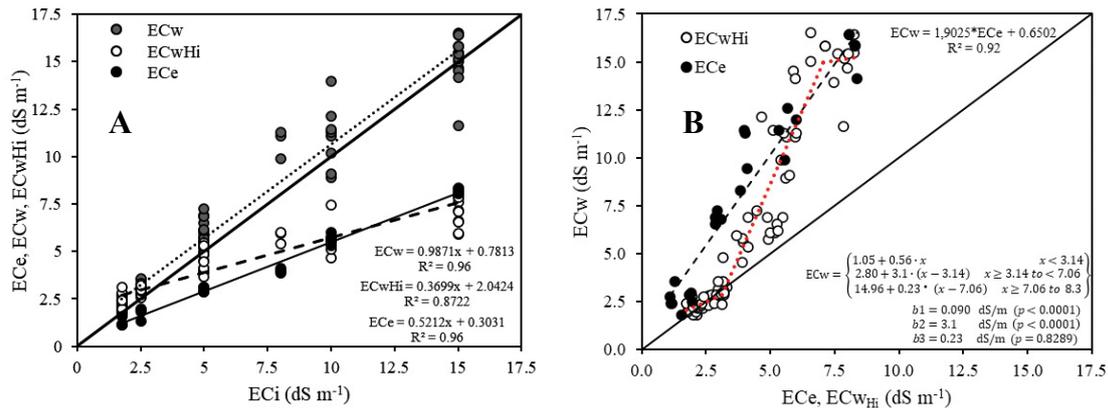


Figure 3. A) Relationships among the EC_i (EC_i : electrical conductivity for the irrigation water) treatments, and the electrical conductivity measurements across the trial period (EC_e : electrical conductivity of the saturated extract, EC_w : pore water salinity, $EC_{w_{Hi}}$: pore water salinity estimated with [Hilhorst \(2000\)](#)), B) Linear relationship of EC_w as a function of $EC_{w_{Hi}}$ and EC_e measurements at field capacity.

Physiological variables of growth and production

The g_s presented significant differences with respect to the control treatment (1.75 $dS\ m^{-1}$), reaching a value 17.5% higher than the average for saline treatments (2.50 and 15.0 $dS\ m^{-1}$); however, no significant difference was detected between the latter, which presented an average value of 374.8 $mmol\ m^{-2}\ s^{-1}$. On the other hand, the stem water potential was not affected by the saline treatments, reaching an average of -0.21 MPa (Table 2).

Table 2. Stomatal conductance (g_s) and stem water potential (Ψ_x) for each of the salinity treatments (EC_i : electrical conductivity for the irrigation water) in *Amaranthus cruentus* L.

Treatment (EC_i , $dS\ m^{-1}$)	g_s ($mmol\ m^{-2}\ s^{-1}$)	Ψ_x (MPa)
1.75	454.13 (± 63.27) a	-0.22 (± 0.04) ^{n.s.}
2.50	384.98 (± 64.92) b	-0.23 (± 0.02)
5.0	391.63 (± 39.26) b	-0.21 (± 0.04)
8.0	388.19 (± 67.18) b	-0.22 (± 0.03)
10.0	360.94 (± 70.20) b	-0.18 (± 0.03)
15.0	348.22 (± 46.99) b	-0.21 (± 0.07)

Each value represents the mean of the four measured periods. Means with different letters in the same column indicate significant differences between treatments according to DGC (p value < 0.05). n.s.: no significant differences.

Plant height, with the exception of the 15 dS m⁻¹ treatment, did not significantly differ among the treatments, with a mean height of 137.66 cm. The 15.0 dS m⁻¹ treatment resulted in a slight but significantly lower mean height (129.3 cm), which was 6.1% below the average of the other treatments (Table 3). This scenario was repeated with respect to panicle height, with the treatment with the highest salinity (15.0 dS m⁻¹) presenting a significantly lower value (13.8% lower) than the average value obtained for the other treatments, which did not show significant differences between them, with an average value of 48.5 cm (Table 3).

Table 3. Plant height, main panicle height, aerial dry biomass and root dry biomass in grams per plant for each of the salinity treatments (ECi: electrical conductivity for the irrigation water) in *Amaranthus cruentus* L.

Treatment (ECi, dS m ⁻¹)	Plant height (cm)	Main panicle height (cm)	Aerial biomass (g DM plant ⁻¹)	Root biomass (g plant ⁻¹)
1.75	141.00 (±6.57) a	49.73 (±2.87) a	147.77 (±18.9) a	20.00 (±1.2) a
2.50	138.60 (±3.14) a	49.33 (±2.32) a	143.13 (± 6.0) a	16.90 (±0.9) b
5.0	137.67 (±6.64) a	49.13 (±5.57) a	137.53 (±42.6) a	13.57 (±3.2) b
8.0	135.73 (±6.35) a	47.27 (±5.06) a	127.33 (±31.8) a	13.10 (±2.6) b
10.0	135.33 (±6.16) a	46.93 (±2.03) a	109.67 (±15.6) a	8.13 (±1.0) c
15.0	129.33 (±6.49) b	41.80 (±3.04) b	81.80 (±12.9) b	7.03 (±0.6) c

Adjusted means ± standard deviations. Different letters indicate statistically significant differences between the means of each parameter measured. According to DGC (p value <0.05).

Biomass production showed a detrimental effect as salinity increased in both aerial biomass and roots, where the underground part was the most affected (Table 3, Fig. 5). In fact, only the most saline treatment (15 dS m⁻¹) significantly decreased the aerial biomass, reaching an average value 38.5% lower than the average, which was 133.1 grams per plant (Table 3). On the other hand, the treatments with the highest salinity (10.0 and 15.0 dS m⁻¹) generated the greatest decrease in root biomass, reaching an average of 7.58 g plant⁻¹, followed by treatments with 8.0, 5.0 and 2.5 dS m⁻¹ with an average value of 14.52 g plant⁻¹. Finally, the 1.75 dS m⁻¹ treatment had a value of 20 g plant⁻¹ (Table 3).

Only the yield of the treatment with the highest salinity (15.0 dSm⁻¹) was significantly lower than that of the other treatments, reaching a value 29.2% lower than the average of the other treatments, which reached 43.1 g plant⁻¹. The harvest index did not vary between treatments, although a trend toward a higher HI was observed as the salinity increased. The average HI value obtained was 0.34 (Table 4).

Table 4. Grain yield and harvest index (HI) according to salinity treatment (ECi: electrical conductivity for the irrigation water) in *Amaranthus cruentus* L.

Treatment (ECi,dS m ⁻¹)	Yield (g plant ⁻¹)	HI
1.75	42.10 (±6.6) a	0.29 (±0.08) n.s.
2.50	47.10 (±2.1) a	0.33 (±0.01)
5.0	43.00 (±15.1) a	0.31 (±0.02)
8.0	43.80 (±14.9) a	0.34 (±0.09)
10.0	39.23 (±2.2) a	0.36 (±0.04)
15.0	30.50 (±3.6) b	0.38 (±0.09)

Adjusted means ± standard deviations. Different lowercase letters indicate statistically significant differences between means of grain yield according to DGC (p value <0.05). n.s.: no significant differences.

In summary, root biomass was shown to be the most significantly sensitive variable to increasing salinity; however, the majority of the measured variables, particularly yield, did not significantly differ with increasing EC_i until reaching the most extreme treatment (15 dS m^{-1}).

Based on the yield results presented in Table 4, the **Maas & Hoffman model (1977)** was adjusted. To achieve this, an E_{Ce} of 5.64 dS m^{-1} and an E_{Cw} of 10.92 dS m^{-1} ($EC_i = 10 \text{ dS m}^{-1}$, Table 1) were considered as the threshold electrical conductivity, while the potential yield (100%) was estimated as the mean among the treatments without significant differences. Subsequently, the relative yield of the crop decreased by 11.12% and 6.93% for each incremental unit of E_{Ce} and E_{Cw} , respectively, until reaching an E_{Ce} of 8.26 dS m^{-1} and an E_{Cw} of 15.12 dS m^{-1} ($EC_i = 15.0 \text{ dS m}^{-1}$, Table 1), with an approximate yield decrease of 30% (Fig. 4).

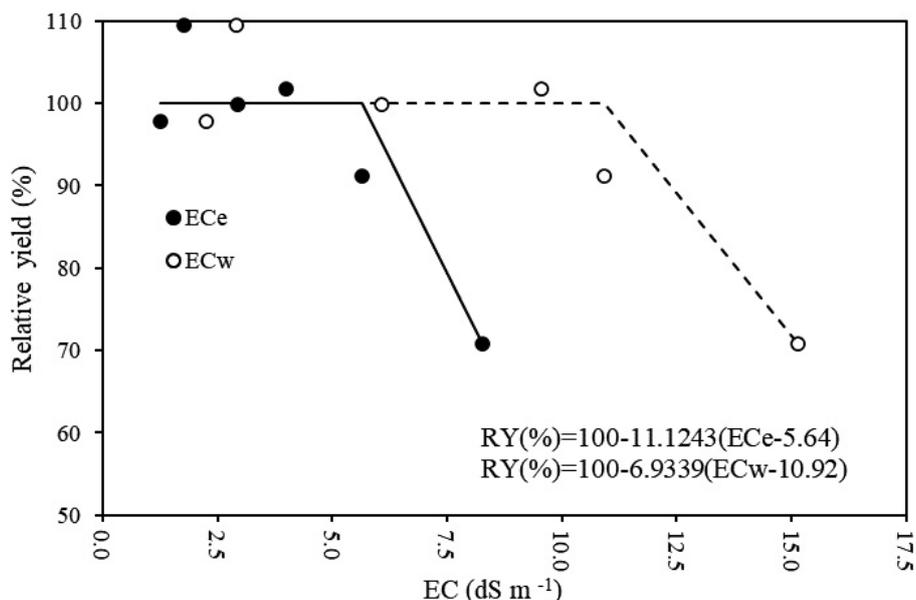


Figure 4. The Maas & Hoffman (1977) model applied to the treatments. The electrical conductivity of the soil saturated paste (E_{Ce}) and pore water salinity (E_{Cw}) represent the mean values obtained during the trial (Table 1). The 100% yield was computed as the mean of the treatments without significant differences (Table 4).

Discussion

An increase in soil salt concentration leads to a decrease in soil water potential, primarily attributed to a reduction in osmotic potential. Crops perceive this decline as a reduction in available soil water, triggering a water stress response under threshold conditions. This response includes a decrease in stomatal conductance and stem water potential, impacting photosynthesis and overall growth (Dinneny, 2014). Although the test carried out showed a significant decrease in g_s at 2.5 dS m^{-1} with respect to the control, no significant differences were found in this variable among the higher salinity treatments, and a similar response was found in *Amaranthus caudatus* L. (Quispe & Jacobsen, 1999). Liu & Stützel (2002) reported that the g_s of *A. cruentus* ranged from 530 to $620 \text{ mmol m}^{-2}\text{s}^{-1}$ for well-hydrated plants and from 50 to $60 \text{ mmol m}^{-2}\text{s}^{-1}$ for severely stressed plants. These values coincide with those obtained here for the control treatment ($454 \text{ mmol m}^{-2}\text{s}^{-1}$); however, for the other treatments, their average value ($375 \text{ mmol m}^{-2}\text{s}^{-1}$) would correspond, according to these authors, to a condition of moderate water stress, which was not reflected in the variables measured, with the exception of the 15 dS m^{-1} treatment.

No significant differences were detected in ψ_x , nor did it tend to decrease in response to an increase in salinity, which varied between -0.18 and -0.22 MPa . Omami & Hammes (2006) in *A. cruentus* and *Amaranthus tricolor* L. and Jacobsen et al. (2001) in the *A. caudatus* 'Oscar blanco' mentioned a tendency to decrease the leaf water potential with increasing salinity stress, obtaining values that varied between -0.4 and -1.5 MPa . These findings indicate that one of the defense mechanisms of the crop against saline stress is a

decrease in the osmotic potential that is coupled with a decrease in the leaf potential due to an adjustment of the concentration of inorganic salts that allows it to regulate cell turgor in the leaf (Munns, 2002). However, these studies contemplate conditions of water stress, an effect not considered in the present study. No data were found in the literature that mentioned ψ_x measurements in *Amaranthus* spp., despite being considered more stable than leaf measurements (Shackel et al., 1997).

In the measurements of plant height and main panicle height, it was observed that the treatment with the highest salinity (ECi: 15.0 dS m⁻¹) was the only one significantly affected (Table 3). The observed values are within the normal ranges reported by other research for amaranth, which vary between 129 and 190 cm for plant height and between 28 and 54 cm for main panicle height (Hernández et al., 2014; Jiménez et al., 2018). This behavior coincides with the measurement of aerial biomass, where only the treatment with the highest salinity was affected. Root biomass reached its maximum values for the treatment without the addition of salts and the lowest for the more saline treatments (10.0 and 15.0 dS m⁻¹). According to Jung & McCouch (2013), salt stress decreases cell division and, consequently, the root growth rate. A lower root/shoot growth ratio under saline stress conditions is functionally associated with the plant's need to restrict ion uptake while maintaining its high growth rate (Munns, 2002; De Pascale et al., 2003), especially in conditions where the water content in the soil is not limiting. This decrease in root biomass did not affect aerial biomass production, similar to that observed by Omamt et al. (2006), who determined that *A. cruentus* is more strongly affected by saline stress at the root level than by aerial growth. The grain yield did not show a clear tendency to decrease when the salinity of the irrigation water increased between 1.75 and 10.0 dS m⁻¹, showing a significant decrease only when the salinity reached 15 dS m⁻¹. On the other hand, the harvest index was not affected by the applied treatments, indicating that saline stress did not affect the ratio between aerial biomass and crop grain yield.

These results are different from those reported by other researchers, who reported significant reductions in growth and dry matter production with increasing salinity (Omamt et al., 2006; Omami & Hammes, 2006). This difference could be explained by the time the measurements were made. Although the abovementioned authors measured the dry matter at the end of the vegetative stage of the crop, in our study, the measurements were performed at maturity. In addition, Omamt et al. (2006) and Omami & Hammes (2006) carried out a discontinuous application of saline water, contrary to the present study, in which continuous saline water was applied; this could indicate a mechanism of adaptation to conditions of stable salinity.

One of the effects of irrigation with saline water was qualitative, since as the season advanced, the pots watered with 10.0 and 15.0 dS m⁻¹ showed necrosis in their old leaves, as shown in Fig. 5. These leaves gradually fell while the crop remained functional by sprouting new leaves until the end of the season. Taiz & Zeiger (2010) mentioned that some crops develop response mechanisms to salinity, through which they accumulate ions in their vacuoles to continue functioning normally. This is one of the mechanisms that would explain the adaptability of this crop and, therefore, its ability to sustain most of the physiological and morphological parameters up to a threshold ECe value of 5.64 dS m⁻¹ (ECw = 10.72, Table 1). This value was defined as the salinity tolerance threshold for the crop, and an ECe of 10.1 dS m⁻¹ and ECw = 18.13 dS m⁻¹ (from Fig. 4 adjustment) were used as the electrical conductivity when production was reduced by 50%, characterizing it as a moderately tolerant crop (Maas & Hoffman, 1977; Grieve et al., 2012). This threshold value is approximately 7 times greater than the previously reported value (Lavini et al., 2016). The differences could be explained by the differences between species, but mainly in the type of test carried out, where greater control of salinity and soil water was possible during the present study.

The relationships between ECw and ECw_{Hi}, estimated from suction lysimeters and GS3 measurements, respectively, indicate that the expression proposed by Hilhorst (2000) using GS3 sensor data fits well (R² > 0.8) with ECw. However, it does not consistently provide accurate estimates of ECw as the electrical conductivity increases from 3 to 14 dS m⁻¹. Although the linear relationship between them may be valuable in recognizing trends or significant changes in pore water salinity during the growth season or under different irrigation management practices, it is important to note that, depending on the sensor reliability and performance, specific models should be developed to adjust the estimated ECw_{Hi} to the actual ECw, coinciding with Bañon et al. (2021). Consequently, to take advantage of this technology and enhance water management efficiency for controlling soil salinity, using ECw as a measurable and comparable value from the Maas & Hofmann (1977) model developed in this research, it may be advisable to verify the accuracy of the ECw by simultaneously measuring it with suction lysimeters during relevant crop phases and to calibrate the sensors accordingly for irrigation scheduling.



Figure 5. Images of amaranth plants watered with irrigation water with electrical conductivities of 1.75 dS m⁻¹, 10.0 dS m⁻¹ and 15.0 dS m⁻¹ at 78 days after emergency (anthesis).

In conclusion *A. cruentus* showed good tolerance to irrigation with saline water up to a value of 10 dS m⁻¹ (ECi). The growth, aerial biomass and yield were not affected by water with salinities equal to or less than 10 dS m⁻¹; however, root biomass was affected, but it did not affect the other variables. *A. cruentus* showed tolerance thresholds of 5.64 and 10.92 dSm⁻¹ ECe and ECw, respectively, which is 7 times greater (ECe) than the values previously reported. However, in the comparative analysis, it should be considered that this trial, unlike other trials, did not impose water stress conditions. Subsequently, the relative yield of the crop decreases by 11.12% for each unit of electrical conductivity of ECe that is increased, reaching a value of 10.1 dS m⁻¹ for a reduction of 50% of the potential yield, classifying it as a moderately tolerant species to salinity. These results validate *Amaranthus* spp. as a productive alternative under irrigation water and saline soil conditions.

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