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Scientific Article

Production and quality of pak choi grown in different hydroponic systems and electrical conductivities

Produção e qualidade de pak choi cultivado em diferentes sistemas hidropônicos e condutividades elétricas

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ABSTRACT - Pak choi is a leafy vegetable rich in important bioactives for human health. As this vegetable is cultivated predominantly in Europe and Asia, there is little information about it in the Brazilian literature. The aim of this study was to evaluate the production and quality of pak choi cultivated in hydroponic systems using nutrient solutions of different electrical conductivities. An experiment was set up following a randomized block design, in a 2 × 5 factorial scheme, with two hydroponic systems (NFT and Semi-hydroponic) and five levels of electrical conductivity (1.0, 2.0, 3.0, 4.0 and 5.0 dS m^{-1}). The plants were harvested 35 days after transplanting and evaluated for the following variables: plant height, number of leaves, stem diameter, leaf area, shoot fresh and dry mass, leaf succulence, specific leaf area, petiole firmness, juice pH and soluble solids. Growth and quality variables were affected by the interaction between EC levels and hydroponic systems. The semi-hydroponic system promoted the greatest development of pak choi plants and greater tolerance to salinity. Plants cultivated in the NFT system had a lower nutritional requirement to reach maximum growth. Increase in nutrient solution EC did not affect the visual quality of pak choi, but reduced the physicochemical quality of its leaves.

Keywords: *Brassica campestris* var. *chinensis*. Leafy vegetables. Soilless cultivation. Hydroponics. Salt stress.

RESUMO - O pak choi é uma hortaliça folhosa rica bioativos importantes para a saúde humana. Por ser cultivado predominantemente nos continentes europeu e asiático, existem poucas informações sobre esta hortaliça na literatura brasileira. Objetivou-se avaliar a produção e a qualidade do pak choi cultivado em sistemas hidropônicos utilizando soluções nutritivas de diferentes valores de condutividade elétrica. Para isto, o experimento foi instalado seguindo o delineamento em blocos casualizados, em esquema fatorial 2 × 5, sendo dois sistemas hidropônicos (NFT e Semi-hidropônico) e cinco níveis de condutividade elétrica (1,0; 2,0; 3,0; 4,0 e 5,0 dS m^{-1}). As plantas foram colhidas aos 35 dias após o transplantio e avaliadas quanto às seguintes variáveis: altura de planta, número de folhas, diâmetro do caule, área foliar, massa fresca e seca da parte aérea, suculência foliar, área foliar específica, firmeza do pecíolo, pH do suco e sólidos solúveis. As variáveis de crescimento e qualidade foram afetadas pela interação entre os fatores CEs e sistemas hidropônicos. O sistema semi-hidropônico proporcionou o maior desenvolvimento das plantas e maior tolerância à salinidade. As plantas cultivadas no sistema NFT apresentaram menor exigência nutricional para atingir o máximo crescimento. O aumento da CE da solução nutritiva não afetou a qualidade visual do pak choi, mas reduziu a qualidade físico-química das folhas.

Palavras-chaves: *Brassica campestris* var. *chinensis*. Hortaliças folhosas. Cultivo sem solo. Hidroponia. Estresse salino.

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INTRODUCTION

Pak choi (*Brassica campestris* var. *chinensis*) belonging to the Brassicaceae family, is also known as Chinese white cabbage. It is a vegetable rich in phenolic compounds, vitamins, fiber, soluble sugars, minerals, fat and carotenoids that are included in the human diet. Widely cultivated in Asian countries such as China, Korea, Taiwan, and Japan, pak choi is also becoming more popular and widely used in Western diets (Al UBEED et al., 2017).

Regarding salinity tolerance, pak choi is classified as moderately tolerant, with a threshold of 3.0 dS m^{-1}, with a relative reduction in yield of around 4% per unit increase in electrical conductivity (EC) of the soil saturation extract (SHANNON; GRIEVE, 1999). In hydroponic cultivation with NTF system, Fatemi, Carvajal and Rios (2020) did not observe a reduction in pak choi biomass in nutrient solution with electrical conductivity of 4.0 dS m^{-1}. This information highlights that the tolerance of plants to salinity depends on several factors, such as the genetic material and the cultivation system adopted.

According to Ding et al. (2018), a nutrient solution with low EC limits plant growth due to nutrient deficiency, while very high EC inhibits plant development due to salt stress, as plants need to increase antioxidant enzyme activity to adapt to stress conditions.

In Brazil, there is a predominance of the NFT (nutrient film technique) production system, which is used by about 90% of hydroponic growers, especially for leafy vegetables; recently, cultivation in substrate, also called semi-hydroponics, has been adopted by some researchers in the production of leafy vegetables (OLIVEIRA et al., 2022; SILVA et al., 2023). This system has shown advantages over NFT, especially due to a reduction in irrigation time, since the substrate maintains moisture in the root zone for longer, avoiding effects of osmotic and/or water stress between irrigation events (RODRÍGUEZ-ORTEGA et al., 2019).

However, in the Brazilian literature, there are few comparative studies on the performance of these systems in the cultivation of leafy vegetables. Considering that pak choi is still a little studied crop in Brazil, there is a need to conduct a study to determine which hydroponic system is the most appropriate, as well as the electrical conductivity of the nutrient solution, indicated for the cultivation of this vegetable. In view of the above, the objective of this study was to evaluate the production and postharvest quality of pak choi cultivated in hydroponic systems using nutrient solutions of different electrical conductivities.

MATERIAL AND METHODS

Location of the experimental area

The experiment was carried out from July to August 2022, in a protected environment (greenhouse) located in the experimental sector of the Department of Agronomic and Forestry Sciences (DCAF), on the West campus of the Federal Rural University of the Semi-Arid Region (UFERSA) in Mossoró, RN (5º 11' S; 37º 20' W; 18 m altitude).

Experimental design and treatments

The experiment was carried out in a randomized block design, in a 2 × 5 factorial scheme, with two hydroponic systems (S1 - NFT, Nutrient Film Technique; S2 - Semi-hydroponic, cultivation in substrate) and five electrical conductivities of the nutrient solution (1.0, 2.0, 3.0, 4.0 and 5.0 dS m^{-1}), with three replicates. In the NFT system, each plot was represented by a 2.0-m-long hydroponic profile, containing seven plants spaced 0.25 m apart. In the semi-hydroponic system, the experimental unit was represented by a 20 dm^3 plastic tray containing four plants each.

All nutrient solutions were prepared using as reference the recommendation of Furlani et al. (1999) for macronutrients in the hydroponic cultivation of leafy vegetables, with the following concentrations of fertilizers, in g 1000 L^{-1}: 750 of calcium nitrate, 500 of potassium nitrate, 150 of monoammonium phosphate, and 400 of magnesium sulfate. Micronutrients were supplied using the commercial products Dripsol Micro Rexene Equilíbrio (magnesium, 1.1%; boron, 0.85%; copper (Cu-EDTA), 0.5%; iron (Fe-EDTA), 3.4%; manganese (Mn-EDTA), 3.2%; molybdenum, 0.05%; zinc, 4.2%) and Dripsol Micro Ferro Q48 (Iron Chelate Q48 EDDHA 6%, Dripsol SQM Vitas®). For both products (Dripsol Micro Rexene Equilíbrio and Dripsol Micro Ferro Q48), the dose of 30 g 1000 L^{-1} was used for the standard nutrient solution (100%).

The water used to prepare the nutrient solutions was collected from the supply system of the UFERSA Campus, and its physicochemical analyses showed the following characteristics: pH = 7.30, EC = 0.50 dS m^{-1}, Ca^{2+} = 3.10, Mg^{2+} = 1.10, K^+ = 0.30, Na^+ = 2.30, Cl^- = 1.80, HCO_3 = 3.00 and CO_3^{2-} = 0.20 ($mmol_c$ L^{-1}). 0.1 mol L^{-1} HCl solutions were applied to adjust the pH of the nutrient solutions between 5.5 and 6.5.

Planting was carried out using seedlings produced in expanded polystyrene trays with capacity for 200 cells, using coconut fiber substrate (Golden Mix®, Amafibra), sowing 5 seeds per cell. At 5 days after emergence, thinning was performed, leaving the most vigorous seedling in each cell.

After sowing, the trays were irrigated with drinking water using a fine-sprinkling watering can until thinning. Then, the seedlings were fertigated daily with a nutrient solution (FURLANI et al., 1999) diluted by 50%, using the capillary fertigation system with the floating system. The seedlings were transplanted when they had 4 to 5 true leaves (35 days after sowing, DAS).

NFT System

The benches of the NFT system were built with installation using sawhorses, with 1.0 m height from the soil surface in the highest part and 0.9 m in the lowest part, with a slope of 5%. The spacing used was 0.20 m between the profiles and 0.25 m between plants in the profile. A 0.6-m-wide corridor was left between the benches to facilitate transit and operations.

The experimental plot was represented by a hydroponic profile with 2.0 m in length, containing seven plants spaced 0.25 m apart. An independent pumping system was used for each nutrient solution, containing an electric pump to pump the nutrient solution from a lower reservoir (60 L) to the profiles, distributing it through 5-mm-diameter microtubes.

The nutrient solutions were monitored daily, with replacement of the volume of water consumed and adjustments to the nutrient solutions when detecting a 10% reduction in the initial electrical conductivities. Monitoring and control of the electrical conductivity and pH of the nutrient solutions were performed using a conductivity meter and pH meter, respectively.

Irrigation control was performed using an analog timer, adopting a 15-minute irrigation schedule with intervals of 15 minutes, from 5 a.m. to 6 p.m. During the night, the irrigation interval was 2 hours and each irrigation event lasted 15 minutes.

Semi-hydroponic system

In this system, each plot was represented by a plastic tray (14 x 37 x 60 cm, for height, width and length, respectively), with a capacity of 20 liters. The trays were filled with substrate composed of a mixture of coconut fiber and washed fine sand, in a 2:1 ratio (on a volume basis). The trays were arranged on benches made of wood and bricks, with 0.50 m in height and 0.40 m in width.

Each nutrient solution was applied using an independent irrigation system, consisting of an electric pump for pumping the nutrient solution from a lower reservoir (300 L), lateral line with a 16-mm-diameter hose and spaghetti-type microtube emitter, with internal diameter of

1.0 mm, length of 10 cm, and 6 emitters per tray.

The seedlings were produced following the same procedure applied to those used in the NFT system. Four seedlings were placed in each tray, at a spacing of 0.4 x 0.25 m.

Fertigation control was performed using a digital timer, programmed for six daily events, lasting 30 seconds with intervals of 2 hours. The nutrient solution was renewed when the reservoir level reached the suction height of the pump.

Variables analyzed

Plants were harvested 35 days after transplanting and evaluated based on the following variables:

Plant height (PH): determined using a ruler (scale in cm), measuring from the plant collar to the tip of the highest leaf, with results expressed in cm;

Number of leaves (NL): with leaves detached from the plants with petiole, the number of leaves produced by each plant was counted, with results expressed in units;

Stem diameter (SD): determined by measuring the diameter of the collar with a caliper (scale in millimeters, with accuracy of 0.01 mm) from the first node, with results expressed in mm;

Leaf area (LA): determined by the leaf disc method, which consisted of using a hole punch with internal diameter of 2.4 cm (estimated by image analysis of the removed discs). In each plant, 20 discs were collected from fresh leaves, with only fine veins, in the basal and apical portions, and in the median parts of the leaves (Equation 1).

$$\text{LA}=\frac{(\text{LDM x DA})}{\text{DDM}} \qquad (1)$$

Where:
LA – leaf area, cm2;
LDM – leaf dry mass, g;
DA – disc area, cm^2; and
DDM – disc dry mass, g.

Shoot fresh mass (SFM): determined from the average mass of two plants obtained using a precision scale (0.01 g), expressed in g plant^{-1}.

Shoot dry mass (SDM): obtained after the samples are dehydrated in a forced circulation oven with temperature set to 65 ºC (± 1 ºC) until reaching a constant mass on a scale with accuracy of 0.01 g, expressed in g plant^{-1}.

Specific leaf area (SLA): obtained by the ratio of leaf area to leaf dry mass (LA/LDM), expressed in cm^2 g^{-1} of LDM. LDM was considered to be SDM, since the aerial part of the plants is basically composed of leaves (Equation 2).

$$\text{SLA}=\frac{\text{LA}}{\text{LDM}} \qquad (2)$$

Where:
SLA – specific leaf area, cm^2 g^{-1} LDM;
LA – leaf area, cm^2 plant^{-1}; and
LDM – leaf dry mass, g.

Leaf succulence (SUC): obtained by the ratio between the constituent water mass and leaf area (Equation 3).

$$\text{SUC} = \frac{(\text{LFM - LDM})}{\text{LA}} \qquad (3)$$

Where:
SUC – leaf succulence, g H_2O cm^2;
LFM – leaf fresh mass, g;
LDM – leaf dry mass, g; and
LA – leaf area, cm^2.

Petiole firmness (FIRM): measured in petioles of five leaves, with two readings per petiole, using a penetrometer. The results obtained in pounds were converted to Newton (N), using a conversion factor of 4.45.

The leaves (leaf blade plus petiole) were processed using a food processor to obtain the juice (Philips Walita Live 500W Centrifuge - RI1836).

Soluble solids (SS): determined directly in the juice, using a digital refractometer (model ATAGO PR-1000), with the results expressed in ºBrix, as recommended by the Association of Official Analytical Chemistry (AOAC, 2005).

Hydrogen potential (pH): determined directly in the juice, using a digital potentiometer with a glass membrane, according to Instituto Adolfo Lutz – IAL (2008).

Leaf color: determined using a Konika Minolta colorimeter, model CR400s (Konica Minolta Sensing Americas, Inc., New Jersey, USA). The instrument was previously calibrated on a white surface according to the International Commission on Illumination (CIE 1976 L, a*, b* – CIELAB). Readings were performed on three selected leaves of two plants of each treatment, in a total of 6 readings.

The effects of color were analyzed using the parameters L, a*, b*, hue and chroma, which represent the objective measurements of color evaluated by the human eye. The L value represents the lightness or tone of the color of the product, ranging from zero (black) to one hundred (white).

The indices hue and chroma angles were obtained by transforming the parameters a* and b*, according to Equations 4 and 5.

$${}^{\text{o}}\text{H} = \text{arc tg}\frac{a}{b} \qquad (4)$$

Where:
Hº = hue angle;
Arc tg = arc tangent of the parameters a* and b*.

$$\text{C} = \sqrt{a^{2}+b^{2}} \qquad (5)$$

Where:
C = chroma angle.
a = parameter a*; and
b = parameter b*.

Statistical analysis

The data obtained were subjected to analysis of variance (F test), and the factors were further analyzed whenever there was a significant effect of the interaction between factors. Variables related to the hydroponic systems were analyzed by a means comparison test (Tukey, 0.05), while the effect of electrical conductivity was assessed by regression analysis. Statistical analyses were performed using SISVAR software (FERREIRA, 2014).

RESULTS AND DISCUSSION

Growth and Production

Analysis of variance showed a significant effect of the interaction between the factors hydroponic systems (HS) and nutrient solutions (NS) for the variables leaf area (LA), shoot fresh mass (SFM) and shoot dry mass (SDM), at 1% probability level. Hydroponic systems individually affected the number of leaves (NL) ($p \leq 0.05$). There was an individual effect of nutrient solutions on NL and specific leaf area (SLA) ($p \leq 0.01$), as well as on leaf succulence (SUC) ($p \leq 0.05$). There was no significant effect ($p>0.05$) of the single factors or of the interaction between them for plant height (PH) and stem diameter (SD) variables (Table 1).

Table 1. Summary of the analysis of variance for plant height (PH), stem diameter (SD), number of leaves (NL), shoot fresh mass (SFM), shoot dry mass (SDM), leaf area (LA), leaf succulence (SUC) and specific leaf area (SLA) in pak choi grown in two different hydroponic systems (HS) and electrical conductivities of nutrient solutions (NS).

Sources of variation	DF	Mean squares							
		PH	SD	NL	SFM	SDM	LA	SUC	SLA
HS	1	12.30^{ns}	4.01^{ns}	15.36*	33580.45**	51.35**	1190642.31**	691.49^{ns}	110.63^{ns}
NS	4	28.86^{ns}	5.71^{ns}	19.29**	38590.01**	59.68**	3040143.97**	1555.49*	2271.54**
HS×NS	4	12.51^{ns}	3.06^{ns}	5.56^{ns}	18844.08**	24.71**	904624.49**	202.74^{ns}	222.08^{ns}
Blocks	2	9.83^{ns}	4.48^{ns}	0.21^{ns}	408.24^{ns}	1.96^{ns}	232708.33^{ns}	140.36^{ns}	578.87^{ns}
Residual	18	13.31	2.6	2.74	726.92	1.65	72006.11	493.24	253.08
CV (%)		14.05	15.08	9.53	11.80	10.35	13.42	18.84	10.32
		PH	SD	NL	SFM	SDM	LA	SUC	SLA
		cm	mm	unit	----------- g plant^{-1} -----------		cm^2 plant^{-1}	g H_2O cm^2	cm^2 g^{-1} LDM
Mean		25.96	10.78	17.37	228.45	12.42	1999.64	117.88	154.17

ns = not significant; * = $p \leq 0.05$; ** = $p < 0.01$.

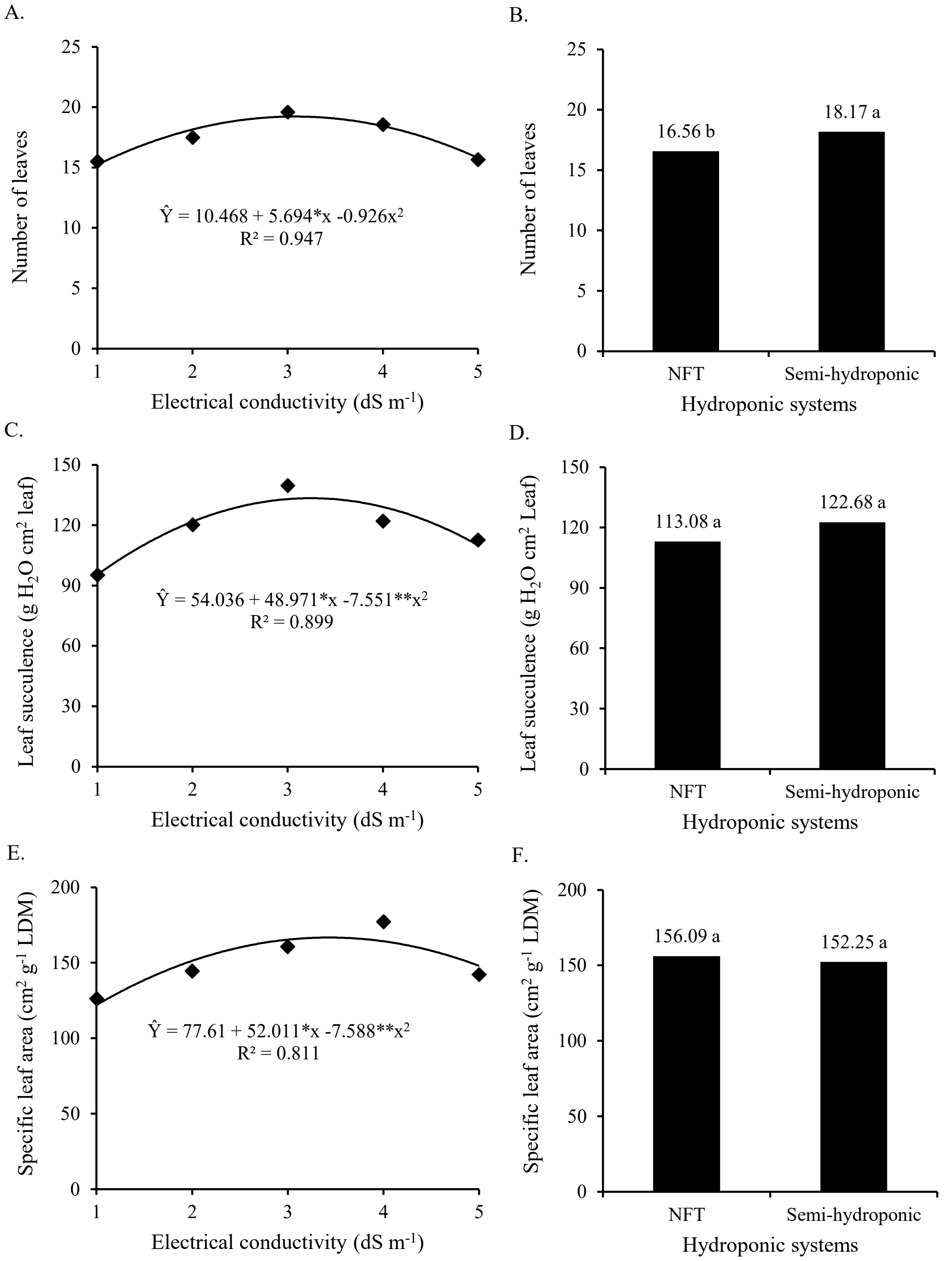
The variables number of leaves (NL), leaf succulence (SUC) and specific leaf area (SLA) were quadratically affected by the increase in nutrient solution EC, regardless of the cultivation system adopted (Figures 1A, 1C and 1E). The highest values occurred at EC levels of 3.1 dS m^{-1} (19.2 leaves), 3.2 dS m^{-1} (133.4 g H_2O cm^2) and 3.4 dS m^{-1} (166.7 cm^2 g^{-1} MSF) for NL (Figure 1A), SUC (Figure 1C) and SLA (Figure 1E), respectively. When comparing these values with those obtained at the lowest EC, increments of 26.2%, 39.8% and 36.6% were observed for NL, SUC and SLA, respectively.

Considering the hydroponic systems used, plants grown in the substrate system had higher NL, 9.7% higher than that obtained in the NFT system (Figure 1B). There was no difference between the hydroponic systems for SUC and SLA, with mean values of 117.9 g H_2O cm^2 for SUC (Figure 1D) and 154.2 cm^2 g^{-1} LDM for SLA (Figure 1F).

The effect of the nutrient solution on the number of leaves (Figure 1A) shows that the leaf production was favored by the increase in nutrient solution EC up to a certain level and then decreased, showing that at very high concentrations of nutrients plants tend to reduce growth in terms of production of new leaves. These results corroborate those reported by other authors who worked with other leafy vegetables, such as kohlrabi (*Brassica oleracea* var. gongylodes) (OLIVEIRA et al., 2022).

Increase in leaf succulence caused by salt stress can be considered indicative of an effective osmotic adjustment in the plants, allowing them to regulate the concentration of salts in the leaf tissues. Increase in leaf succulence is an effective strategy to improve water use efficiency in plants, avoid or mitigate water stress, and increase salinity tolerance (LIM et al., 2020).

SLA expresses the relationship between leaf area and leaf dry mass and indicates leaf thickness, so the increase in EC up to a certain level promoted the development of thinner leaves. On the other hand, at the highest EC there was a proportionally greater reduction in leaf area than in leaf weight, causing the leaves to have greater leaf blade thickness. The increase in SLA as salinity increased occurs because the effect of salt stress was more pronounced on the net assimilation rate than on the formation of phytomass, revealing the capacity of plants to regulate transpiration due to a greater number of cell strata or an increase in intercellular spaces (TAIZ et al., 2017), thus representing a mechanism for acclimatization of the crop to salt stress.



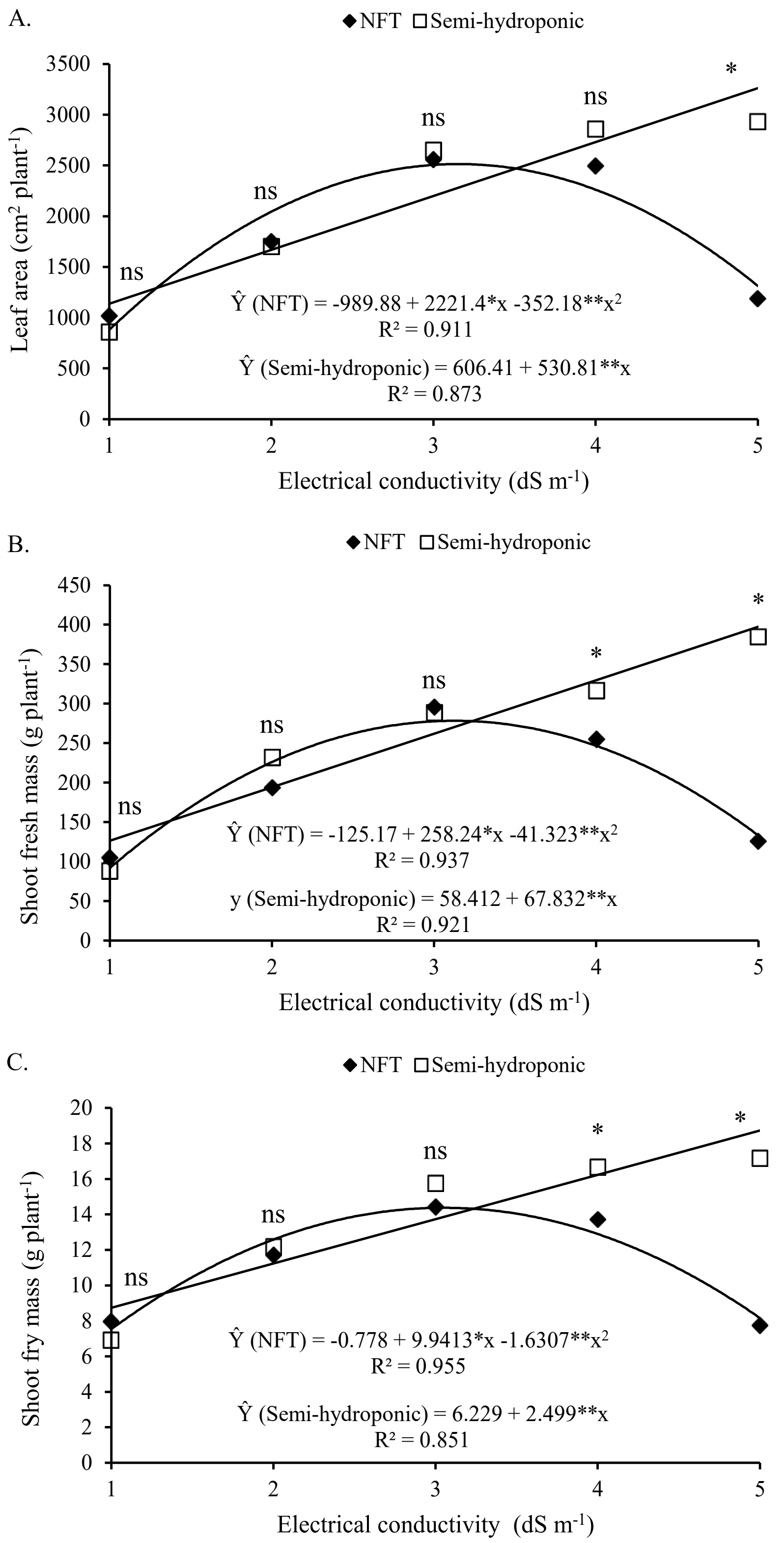
*, ns - significant and non-significant differences between the cultivation systems for each level of electrical conductivity by Tukey test ($p \leq 0.05$). Mean values followed by different letters (Figures B, D and F) differed statistically by Tukey test ($p \leq 0.05$).

Figure 1. Number of leaves (A and B), leaf succulence (C and D) and specific leaf area (E and F) of pak choi subjected to different electrical conductivities in two hydroponic systems.

The LA of pak choi plants was affected by the increase in nutrient solution EC in both cultivation systems, but the response varied according to the system used. In the NFT system, there was a quadratic response, in which the increase in EC promoted an increase in LA up to the level of 3.1 dS m^{-1} (2513.0 cm^2 $plant^{-1}$), while at the lowest EC the value obtained was 879.3 cm^2 $plant^{-1}$, equivalent to an increase of 185.8%. For cultivation in substrate, there was a linear effect of EC on LA, with the highest value (3260.5 cm^2 $plant^{-1}$) obtained at EC of 5.0 dS m^{-1}, while at the lowest EC the value obtained was 1137.2 cm^2 $plant^{-1}$. When comparing these values, it can be observed that plants subjected to the highest EC showed an increase of 186.7% in LA (Figure 3A).

Leaf area is one of the variables most affected by the high EC of irrigation water or nutrient solution, since the increase in EC can compromise physiological processes, such as photosynthesis and stomatal conductance, which results in reduced leaf development (OLIVEIRA et al., 2022; SILVA et al., 2023).

Regarding the effect of the cultivation systems, there was a significant difference between them only for the highest EC, at which the cultivation in substrate was superior to the NFT by 148.4% (Figure 2A).



*, ns - significant and non-significant differences between cultivation systems for each level of electrical conductivity by Tukey test ($p \leq 0.05$).

Figure 2. Leaf area (A), shoot fresh mass (B) and shoot dry mass (C) of pak choi subjected to different electrical conductivities in two hydroponic systems.

As the leaves are the edible part of pak choi, it is important to adequately adjust the nutrient concentration in the nutrient solution according to the adopted cultivation system. Reduction in the LA of pak choi in response to elevated EC of the nutrient solution was also observed by Ding et al. (2018). Other studies conducted with various Brassicaceae species, such as cauliflower (SOARES et al., 2020), kale (SILVA et al., 2023), and kohlrabi (OLIVEIRA et al., 2022), have also reported reductions in the LA of plants subjected to salt stress.

However, it can be seen that there was no effect of the increase in EC on the LA of plants grown in substrate. This occurred because of the root accommodation conditions provided by the cultivation system itself, since the substrate favors greater water and thermal balance of the root system, favoring the absorption of water and nutrients by plants. According to Maclellan (2019), the greater availability of water favors the increase in the diameter of vascular structures in the roots, as the development of root hairs is influenced by aeration and texture of the medium.

Shoot fresh mass (SFM) was affected differently by the increase in EC according to the cultivation system used (Figure 2B). For the NFT system, there was a quadratic response, with the highest SFM (278.3 g plant^{-1}) obtained at EC of 3.1 dS m^{-1}, representing an increase of 203.3% compared to the SFM obtained at EC of 1.0 dS m^{-1} (91.7 g plant^{-1}). For cultivation in substrate, there was an increasing linear response, with the highest SFM (397.6 g plant^{-1}) at EC of 5.0 dS m^{-1}. This value represents a gain of 214.9% compared to the SFM obtained at the lowest EC (126.2 g plant^{-1}) (Figure 2B).

Thus, it can be seen that the semi-hydroponic system allows greater tolerance of pak choi to nutrient solution salinity, which can be attributed to the characteristics of each hydroponic system. In the NFT system, the roots only come into contact with the nutrient solution at the time of irrigation, with no contact during the rest of the time. On the other hand, in the substrate, water content and salt concentration do not vary much between irrigation events (RODRÍGUEZ-ORTEGA et al., 2019).

Regarding the effect of hydroponic systems on SFM, there was a significant response only in plants subjected to nutrient solutions with EC of 4.0 and 5.0 dS m^{-1}, at which the cultivation in substrate was superior to the NFT by 33.7 and 199.0%, respectively (Figure 2B).

As observed in the variable SFM, there was also a different response to the increase in EC for shoot dry mass (SDM) according to the system used. There was a quadratic effect for the NFT system and the highest SDM occurred at EC of 3.0 dS m^{-1} (14.4 g plant^{-1}), corresponding to a 90.8% increase compared to the SDM found at EC of 1.0 dS m^{-1} (7.5 g plant^{-1}). The increase in EC promoted a linear increase in the SDM of plants grown in substrate, with the highest value (18.7 g plant^{-1}) obtained at EC of 5.0 dS m^{-1}, while the lowest value (8.7 g plant^{-1}) was obtained at EC of 1.0 dS m^{-1} (Figure 2C).

Cultivation in substrate promoted higher SDM compared to the NFT system in plants subjected to EC levels of 4.0 and 5.0 dS m^{-1}, for which the values were 25.8 and 129.4% higher, respectively, with no significant difference between the cultivation systems in the other nutrient solutions (Figure 2C).

In general, it was possible to observe that in the NFT system the plants reached the maximum development in less concentrated nutrient solution, while in the cultivation in substrate the plants responded significantly to the increase in EC. Based on this behavior, it can be seen that plants grown in substrates showed higher tolerance to high EC.

The lower tolerance to salinity of plants in the NFT system can be attributed to the intervals in the irrigation periods in this system. Plants may have undergone osmotic and/or water stress, which in turn compromised their development (RODRÍGUEZ-ORTEGA et al., 2019).

The lower tolerance to salinity observed in the NFT system can be attributed to the functioning system itself, since water and nutrients are supplied with intermittent periods of application of the nutrient solution, and plants may have suffered osmotic and/or water stress between irrigation events, because in this system, the roots only come into contact with the nutrient solution when irrigation is applied, with no contact during the rest of the time, which has a negative effect on their growth (RODRÍGUEZ-ORTEGA et al., 2019).

As previously discussed, plants grown in the NFT system showed significant reduction when they were subjected to the more concentrated solutions. These reductions occurred due to the osmotic effect caused by the increase in nutrient solution salinity (SOARES et al., 2020).

A joint analysis of the variables LA, SFM and SDM showed that the highest plant growth occurred close to EC of 3 dS m^{-1} for the NFT system. These results are consistent with those obtained by Ding et al. (2018), who worked with pak choi plants in a floating hydroponic system and observed greater development in nutrient solution with EC ranging from 2.4 to 4.8 dS m^{-1}. Niu, Sun and Masabni (2018), when working in an NFT system with two pak choi cultivars, observed better performance in solutions with EC between 2.4 and 3.2 dS m^{-1}, classifying the cultivars as moderately tolerant to salinity.

In the literature, there are few studies analyzing cultivation systems for pak choi; however, there are studies conducted with other leafy vegetables. Nunes et al. (2020) worked with parsley crop and also observed higher growth in plants grown in substrate compared to the NFT system. Mouroutoglou et al. (2021) worked with Greek sweet onion (*Allium cepa* L.), comparing floating system (DFT), aeroponics, NFT, and cultivation in substrate, and also observed that cultivation in substrate promoted greater development compared to the NFT system.

According to Mouroutoglou et al. (2021), the performance of plants grown in NFT systems is lower because their transpiration flow is less efficient, resulting in lower water use efficiency due to the hysteresis effect caused by the intermittent flow of the nutrient solution.

Post-harvest quality

The interaction between the HS and NS factors significantly affected the postharvest quality variables firmness (FIRM), at 1% probability level, and soluble solids (SS) content and pH, at 5% probability level (Table 2).

Table 2. Summary of the analysis of variance for petiole firmness (FIRM), soluble solids (SS) and pH in the juice of pak choi grown in different hydroponic systems (HS) and under different electrical conductivities of nutrient solutions (NS).

Sources of variation	DF	Mean squares		
		FIRM	SS	pH
HS	1	18.89*	0.49^{ns}	0.19*
NS	4	114.05**	3.62**	0.10*
HS × NS	4	54.38**	0.62*	0.09*
Blocks	2	2.29^{ns}	0.18^{ns}	0.03^{ns}
Residual	18	2.96	0.14	0.03
CV (%)		10.88	10.86	3.06

ns = not significant; * = $p \leq 0.05$; ** = $p < 0.01$.

Leaf petiole firmness (FIRM) was quadratically affected by the increase in EC for both cultivation systems. The highest values occurred at the lowest EC, equal to 26.6 N for NFT and 21.7 N for substrate. The increase in EC initially caused a reduction up to the EC levels of 3.8 and 3.5 dS m^{-1}, with minimum values of 11.5 and 11.2 N for the NFT and substrate systems, respectively. From these levels, there was little variation in FIRM for the cultivation systems (Figure 3A). Difference between the cultivation systems was observed only in plants subjected to EC levels of 1.0 and 2.0 dS m^{-1}, at which FIRM values were 22.5 and 19.0% higher in the NFT system, respectively (Figure 3A).

Reduction in leaf firmness in response to the increase in electrical conductivity was also observed by Amoruso et al. (2022) in a study with sea fennel (*Crithmum maritimum* L.). Leaf succulence, combined with firmness, determines leaf texture, which is an important sensory attribute to determine postharvest quality and consumer acceptance (DAMERUM; CHAPMAN; TAYLOR, 2020). Also according to these last-mentioned authors, leaves with smaller, well-compacted cells and higher cell wall content are firm and less succulent.

The soluble solids (SS) content was affected by the increase in EC in both cultivation systems; however, the response varied according to each system. For the NFT system, there was a decreasing linear response, with variation from 4.4 °Brix (1.0 dS m^{-1}) to 2.2 °Brix (5.0 dS m^{-1}), resulting in a reduction of 48.9%. For cultivation in substrate, the highest SS content occurred at the lowest EC (4.8 °Brix), and the increase in EC had a quadratic effect, causing reduction in SS up to the level of 4.0 dS m^{-1} (3.0 °Brix). From this level onwards, there was little variation in SS content at the other EC levels (Figure 3B). The cultivation systems differed in SS only at the highest EC, with cultivation in substrate promoting a 40.8% higher SS compared to the value obtained in the NFT system (Figure 3B).

The results obtained for SS are consistent with those reported by Ding et al. (2018), who also observed a reduction in SS content in pak choi in response to salt stress. According to Karić, Vukašinović and Žnidarčič (2005), this reduction in sugar content occurs due to high respiration rate under high EC conditions. Also according to these authors, photosynthates that are not fully used in the synthesis of organic compounds and sugars are accumulated at levels of limited nutrient availability, represented in the present study by the more dilute nutrient solutions that had lower EC.

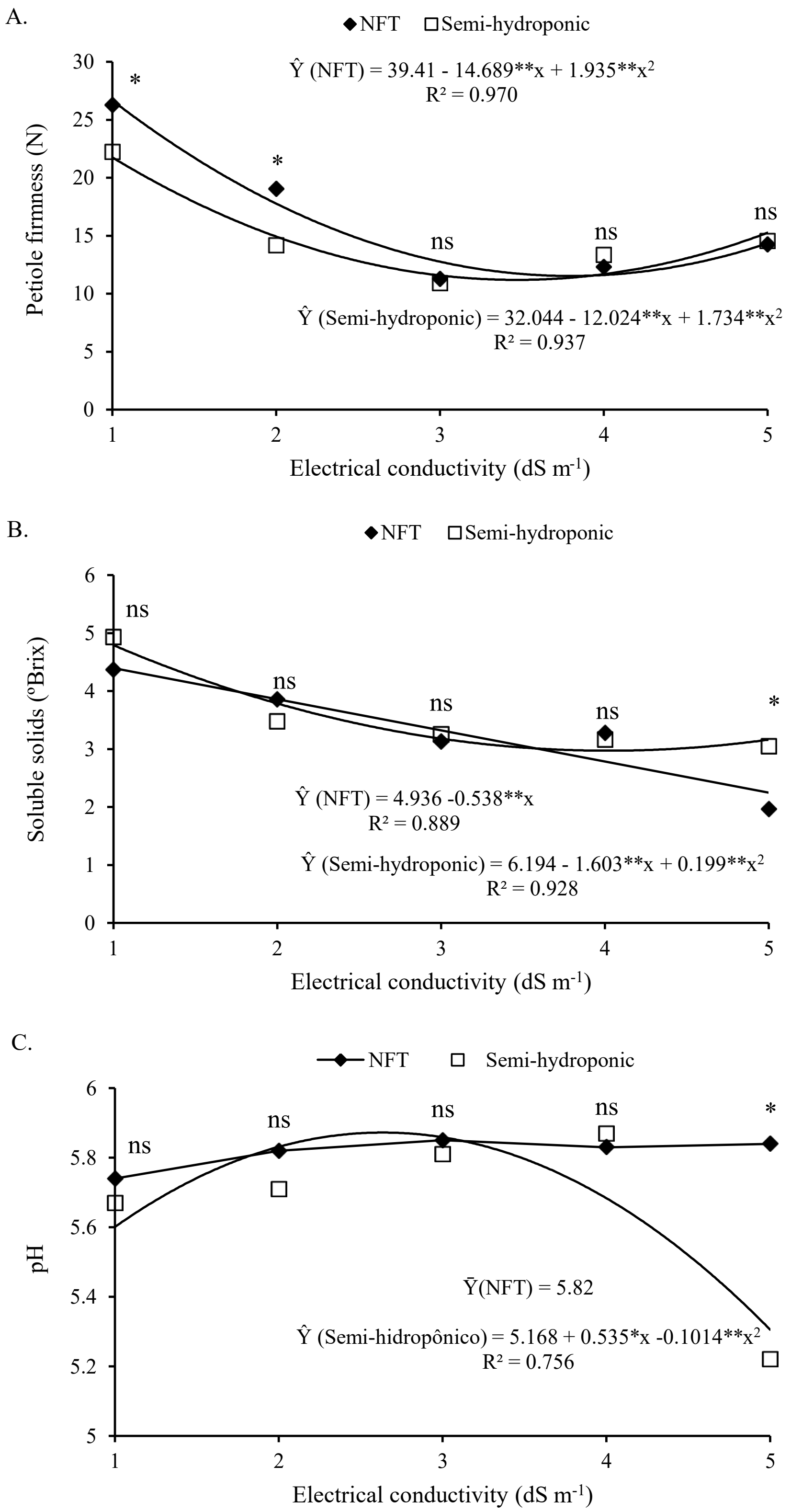
On the other hand, some authors have reported increase in SS in leafy vegetables, such as lettuce, in response to salt stress (SARMENTO et al., 2014). According to Beckles (2012), the increase in sugar content in response to salt stress occurs due to the reduction in cell turgor, concentrating the amount of salts, which results in higher SS contents under these conditions. Therefore, the reduction in SS at the highest EC levels may also have been due to the dilution effect, as the increase in EC up to a certain level caused an increase in leaf water content.

Juice pH was affected by nutrient solution EC only in plants grown in substrate, showing a quadratic response, with the highest value (5.87) at EC of 2.6 dS m^{-1}. This value corresponds to an increase of 4.8% in pH compared to the value obtained at the lowest EC, 5.60 Plants grown in the NFT system were not affected by EC in relation to juice pH, obtaining a mean value of 5.82. A significant difference was observed between the cultivation systems only in plants subjected to the highest EC, at which the NFT system was 9.7% superior (Figure 3C).

In the literature, several results are found about the effect of nutrient solution EC on the pH of leaves, varying mainly according to the genetic material and the cultivation system used. Sarmento et al. (2014) found no significant response in lettuce grown in substrate.

Regarding the color characteristics of the leaves, it was found that the color parameters b, c and °h were affected only by the cultivation system, with significance levels of 5% for b, and 1% for c and °h (Table 3).

Cultivation in substrate promoted higher values for the color parameters b and c, while plants grown in the NFT system showed higher °h. The coordinate b can vary from -50 to +70, with intensity from blue to yellow, and high values indicate yellowish color. Chroma (c) values range from 0 (zero) for neutral colors to 60 for vivid colors, with greater color intensity (MCGUIRE, 1992). For the Hue angle, the farther away from 90°, the greener the color, and the closer to 90°, the more yellowish the color (MCGUIRE, 1992). In this context, plants grown in substrate showed a yellowish color (b), more intense (c), and lower intensity of green color (°h) (MCGUIRE, 1992).



*, ns - significant and non-significant differences between cultivation systems for each level of electrical conductivity by Tukey test ($p \leq 0.05$).

Figure 3. Petiole firmness (A), soluble solids content (B) and pH (C) in the juice of pak choi grown in different hydroponic systems and under different electrical conductivities of nutrient solution.

Table 3. Summary of the analysis of variance and mean values for the color parameters of leaves of pak choi grown in different hydroponic systems (HS) and under different electrical conductivities of nutrient solutions (NS).

Sources of variation	DF	Mean squares				
		a	b	L	c	ºh
HS	1	0.17^{ns}	40.83*	5.63^{ns}	49.41**	15.41**
NS	4	0.48^{ns}	1.79^{ns}	20.71^{ns}	2.10^{ns}	1.79^{ns}
HS × NS	4	0.73^{ns}	3.55^{ns}	9.47^{ns}	5.42^{ns}	2.22^{ns}
Blocks	2	0.03^{ns}	5.08^{ns}	1.67^{ns}	4.76^{ns}	0.91^{ns}
Residual	18	0.64	5.77	11.05	5.24	1.39
CV (%)		9.45	7.46	9.37	6.82	1.13
		Means				
		a	b	L	c	ºh
Hydroponic systems						
NFT		-8.54 a	31.07 b	35.89 a	32.27 b	105.32 a
Substrate		-8.39 a	33.40 a	35.03 a	34.84 a	103.89 b
Electrical conductivity (dS m^{-1})						
1.0		-8.52 a	31.70 a	38.15 a	32.82 a	105.05 a
2.0		-8.75 a	32.28 a	35.15 a	34.10 a	105.23 a
3.0		-8.05 a	31.88 a	36.10 a	33.23 a	104.20 a
4.0		-8.32 a	32.28 a	33.08 a	33.42 a	103.95 a
5.0		-8.68 a	33.12 a	34.82 a	34.22 a	104.58 a

ns = not significant; * = p≤0.05; ** = p < 0.01. means followed by the same letter do not differ by Tukey test (p≤0.05).

However, despite the significant difference in these variables (b, c and ºh), there was a small difference between the cultivation systems, so the difference in leaf color was imperceptible to the human eye.

No effect of EC on any color parameter was observed, regardless of the cultivation system used (Table 3).

Leaf color is one of the most important parameters for the consumer, playing a crucial role in product choice, preference and acceptability, and can also be considered an indicator to estimate the antioxidant properties of leafy vegetables (COLONNA et al., 2016).

Thus, the results presented show that the different electrical conductivities of the nutrient solutions used did not alter the color of the leaves to the point of affecting consumer choice.

Although there was a significant variation in the size of the plants as a function of nutrient solution EC and the cultivation system adopted, no deleterious symptoms that could be attributed to salinity were detected, such as wilting, chlorosis and necrosis of leaves, which could prevent or hinder the commercialization of the plants. This result confirms those obtained by Freitas et al. (2021), when working with lettuce cultivars in hydroponic systems (NFT and DFT), and by Alves et al. (2019) in a study on chicory (*Cichorium endivia* L) in a DFT hydroponic system.

As previously discussed, leaf color was little affected by the treatments applied (Table 3), corroborating, in part, the results presented by Bonasia et al. (2017), who observed little effect of the cultivation system and nutrient solution EC on leaf color.

Color is a visual characteristic of great importance to consumers, for whom the most appreciated characteristics are the presence of signs of freshness, shiny and undamaged leaves, and color intensity without yellowing or discoloration (AGÜERO et al., 2008). In addition, the color of the leaf blade, caused by the balance of chlorophyll, anthocyanins, and carotenoids, can also influence the quality of leaves, as pigmentation is often associated with the presence of antioxidant compounds (ZHU et al., 2016).

CONCLUSIONS

Pak choi crop develops best in hydroponic cultivation using substrate. The hydroponic system with substrate promotes greater tolerance of pak choi to nutrient solution salinity. Pak choi is less demanding on nutrients to achieve maximum growth when grown in NFT system. The increase in nutrient solution EC did not affect the visual quality of pak choi, but reduced the physicochemical quality of its leaves.

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