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Growth and yield responses of maize, beetroot, and quinoa to salinity and straw mulching

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Abstract: Vietnam's Mekong River Delta (MRD), where rice is the dominant crop, is increasingly impacted by salinity intrusion, highlighting the need for alternative cropping options. This study evaluated the growth and yield performance of quinoa, beetroot, and maize under three irrigation salinity levels (0, 2 and 4 g/L), with and without rice straw mulch (7 t/ha), in greenhouse conditions representative of the MRD dry season. Agronomic traits, physiological parameters, and changes in soil, including electrical conductivity (ECe), soluble sodium (Sol-Na^+), and exchangeable sodium percentage (ESP), were assessed. Results showed that quinoa demonstrated the greatest salinity tolerance, maintaining stable growth and yield under 4 g/L saline irrigation and soil ECe exceeding 15 dS/m. Beetroot's yield was not significantly different under 2 g/L saline irrigation with straw mulching. Maize was highly sensitive to salinity and environmental stress, failing to complete its growth cycle under high heat and humidity, even in non-saline conditions. Across treatments, rice straw mulching significantly reduced soil ECe, Sol-Na^+, and ESP, and improved crop performance under saline irrigation. Overall, quinoa and beetroot, especially when combined with mulching, offer promising alternatives for dry-season cropping in saline-prone areas of the MRD. In contrast, maize cultivation requires improved soil and environmental management under such conditions.

Keywords: alternative cropping system; crop resilience; mulch application; saline-affected soil

The Mekong River Delta (MRD) in southern Vietnam is the country's main rice bowl, contributing over 50% of the country's rice production (Kondolf et al. 2018, Dang et al. 2020). Farmers' livelihoods in the MRD depend mainly on rice cultivation (Tong 2017, Tran et al. 2018), but its sustainability is increasingly threatened by climate change, reduced upstream flows and salinity intrusion (Nhuan et al. 2019, Nguyen et al. 2020, Ngo et al. 2022). In recent years, dry-season rice cultivation has become unviable in many coastal areas due to saline irrigation water and freshwater scarcity, leading to fallow land, unstable farmer income, and soil degradation (Sebastian et al. 2016, CCNDPC 2020, Thach et al. 2023). Rice's high-water demand and long growth cycle make it poorly adapted to these conditions, while residual salts further elevate exchangeable sodium percentage (ESP) and damage soil structure (Salama et al. 1999, Rengasamy 2006).

Given the increasing constraints on dry-season rice cultivation and the long-term risks associated with saline irrigation, there is an urgent need to explore viable alternatives that can maintain soil health and sustain farmer livelihoods. One promising approach

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is the adoption of salt-tolerant, short-duration upland crops capable of growing under high salinity and limited freshwater availability (Kaveney et al. 2023) in the dry season of the MRD. In this context, maize, beetroot, and quinoa were selected as model crops because they combine (*i*) reported tolerance to salinity and drought stress; (*ii*) relatively short growth cycles suitable for dry-season farming, and (*iii*) potential adaptability to marginal soils. While maize has been cultivated in some coastal areas of the MRD with acceptable yields under moderate salinity, beetroot and quinoa have shown promise in other salt-affected agroecosystems but have not yet been tested under specific conditions of the MRD. The main varietal characteristics, tolerance thresholds, and growth durations of these crops are summarised in Table 1.

Alongside crop selection, rice straw mulching is an important agronomic strategy for improving crop establishment under saline irrigation and water scarcity, particularly in the coastal areas. Mulching reduces surface evaporation, enhances soil moisture retention, and moderates soil temperature, which are factors critical for improving root-zone conditions in salt-affected soils (Myburgh 2013, Hoitink et al. 2002, Song et al. 2025). In a salt-affected clay-textured soil, Paul et al. (2021) found that rice straw mulch increased soil moisture by 3–9%, reduced soil penetration resistance by up to 77%, and decreased crack volume by over 80%, resulting in a 23% increase in sunflower yield. Similarly, Liu et al. (2024) reported that straw mulching significantly increased soil catalase activity compared to no mulching and plastic film mulching, which in turn led to increased maize yield. These results underscore the dual role of straw mulch in mitigating salinity stress and enhancing soil fertility.

Furthermore, rice straw is an abundant by-product of wet-season paddy cultivation in the MRD. While farmers typically burn it in the field, contributing to greenhouse gas emissions and air pollution, it can instead be repurposed as organic mulch. This provides an environmentally sustainable and low-cost alternative to synthetic materials like plastic film. Straw mulching, therefore, offers high potential for integration into resilient dry-season cropping systems on salt-affected rice soils across the MRD.

Therefore, this study aimed to evaluate the growth and yield responses of maize, beetroot, and quinoa cultivated under defined saline irrigation levels and water-limited conditions representative of the dry season in the MRD. The effect of rice straw mulch was also assessed to determine its potential to mitigate the adverse impacts of salinity by enhancing soil moisture retention and reducing sodium accumulation. It was hypothesised that salinity would differentially affect crop performance depending on species tolerance, and that mulching would alleviate salinity-induced constraints by modifying soil physical and chemical properties, thereby enhancing overall crop productivity.

MATERIAL AND METHODS

Experimental site and design. The experiment was conducted in a greenhouse at Can Tho University, Vietnam, from January to May 2024. The greenhouse had a semi-controlled environment with natural light and ventilation. During the experimental period, average daytime and nighttime temperatures were 35.7 °C and 27.7 °C, respectively, with relative humidity ranging between 55.5% and 86.9%. No artificial lighting or heating was applied. The structure was covered with polyethylene film to prevent direct rainfall, and natural daylight was the sole illumination source.

Table 1. Varietal characteristics, abiotic stress tolerance, and growth duration of potential selected crops identified as candidates for salinity-affected conditions

Crop species	Abiotic stress tolerance	Growth duration (days)	Reference
Maize (*Zea mays* L.)	salt tolerance (around 1.5–1.7 mS/cm), drought tolerance; contains anthocyanin	63–65	Maas and Hoffman (1977), Ajani et al. (2016), Pereira et al. (2023), East-West Seed Vietnam company
Beetroot (*Beta vulgaris* L.)	grows in poor soils; salt tolerance (~6 mS/cm)	75–95	da Silva et al. (2016)
Quinoa (*Chenopodium quinoa* Willd.)	tolerates high salinity (up to 35 mS/cm); low water requirement	85–120	Adolf et al. (2013), Nguyen et al. (2020)

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Table 2. Initial physicochemical properties of the experimental soil

Parameter	Value	Reference
pH_{H_2O} (1:5)	5.07	Rayment and Higginson (1992), Slavich and Petterson (1993)
Electrical conductivity (mS/cm)	5.42	Rayment and Lyons (2011)
Available nitrogen (mg/kg)	17.8	Bremner and Keeney (1966)
Available phosphorus (mg/kg)	11.2	Olsen (1954)
Sodium adsorption ratio (SAR)	5.81	Richards (1954)
Exchangeable sodium per cent (ESP, %)	7.91	Richards (1954)
Cation exchange capacity ($cmol_+$/kg)	15.6	Gillman (1979)
Soil texture (sand, silt, clay)	silty clay (28.5%, 42.6%, 29.0%)	Soil Survey Staff (1998)

The experimental design included five treatments per crop: T1 – non-saline irrigation water applied without straw mulching (the control); T2 – 2 g/L salinity in irrigation water applied without straw mulching; T3 – 2 g/L salinity of irrigation water applied with straw mulching (7 t/ha); T4 – 4 g/L salinity in irrigation water applied without straw mulching; T5 – 4 g/L salinity in irrigation water applied with straw mulching (7 t/ha). Each treatment was replicated three times and arranged in a completely randomised design. The soil used in the trial was collected from the top 0–20 cm in the paddy field of a coastal area in Tran De district, Soc Trang province (9°28'28.8''N, 106°06'06.5''E), which is subject to saline intrusion and unsuitable for rice cultivation during the dry season. The soil was classified as silty clay, with properties detailed in Table 2. Soil was air-dried, homogenised, and sieved through a 2 mm mesh before being packed into plastic pots (27 cm diameter × 32 cm height), with approximately 8 kg of soil per pot. Before sowing, the soil in each pot was wetted to field capacity three times with freshwater to regenerate natural structure.

Crop materials and cultivation. The selected crops were maize (cv. waxy corn Tim Ngot 099), beetroot (cv. Bohan), and quinoa (cv. 42-Test), chosen for their known tolerance to drought and salinity and their potential for short-cycle cultivation (Table 1).

Compost (17.2 g/pot) and lime (CaO, 11.5 g/pot) were incorporated three (03) days before sowing. All crops were sold manually on the same day: maize at 2 seeds per pot, beetroot at 3 seeds per pot (thinned to 1 plant), and quinoa at 10 seeds per pot (thinned to 3 uniform plants after emergence).

Rice straw mulch was applied to relevant treatments at a rate of 7 t/ha, corresponding to approximately 40.08 g per pot, forming a uniform surface layer of about 3 cm. The rice straw produced from a local rice cultivar (Dai Thom 8) was obtained from the locals after harvesting the previous rice season. The mineral fertiliser rate applied to crops is as follows Table 3.

Irrigation management. All pots were initially irrigated with freshwater at 80% field capacity for the first 3 weeks. At 14 days after sowing (DAS), saline irrigation treatments commenced using 2 g/L and 4 g/L salinity levels. A non-saline treatment was consistently applied throughout the experiment as the control. Saline water used for this trial was seawater collected from Soc Trang province, Vietnam, where the soil samples were collected. This seawater was

Table 3. The dosage of mineral fertiliser used for three selected crops in the greenhouse trial

Crop	Total N-P-K (g/pot)	Fertilisation schedule (DAS – days after sowing)
Maize	1.03 – 0.17 – 0.30	• 0.29 – 0.05 – 0.10 (25 DAS) • 0.34 – 0.05 – 0.10 (35 DAS) • 0.40 – 0.07 – 0.10 (45 DAS)
Quinoa	0.58 – 0.24 – 0.24	• 0.29 – 0.12 – 0.12 (30 DAS) • 0.29 – 0.12 – 0.12 (60 DAS)
Beetroot	0.60 – 0.15 – 0.71	• 0.11 – 0.05 – 0.19 (15 DAS) • 0.20 – 0.05 – 0.19 (35 DAS) • 0.29 – 0.05 – 0.33 (50 DAS)

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diluted with freshwater in the greenhouse to achieve the designed salinity concentrations.

At the same time, saline irrigation was managed using Chameleon soil moisture sensors, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and distributed through Virtual Irrigation Academy. These low-cost, colour-coded tensiometers provide real-time visual feedback on root-zone soil moisture status without the need for soil-type calibration. Each sensor displays one of three coloured lights: blue indicates wet soil (0 to –22 kPa), green indicates optimal moisture (–22 to –50 kPa), and red indicates dry conditions (> –50 kPa). In this study, irrigation was triggered when the Chameleon sensor turned red, corresponding to soil tensions exceeding –50 kPa, to simulate water-scarce conditions typical of the dry season in the MRD.

Soil sampling and analysis. In addition, the initial soil must be collected and analysed before sowing (Table 2). Soil samples were collected from each pot by inserting a 10 mm diameter core 15 cm into the soil, which were taken every 15 days after the Chameleon was applied for irrigation to analyse soil-saturated electric conductivity (ECe). For each sampling, the electrical conductivity of a 5 g subsample was measured using a 1:5 soil-distilled water suspension and conductivity probe (Rayment and Lyons 2011) before converting EC 1:5 to ECe based on the soil texture (Slavich and Petterson 1993).

At harvest, soluble sodium (Sol-Na^+) concentrations were measured from a 1:5 soil-distilled water suspension, shaken for 1 h and filtered using Advantech 5C filter paper. The sodium concentration in the filtrate was determined by flame photometry (BWB Technologies, Newbury, Berkshire, UK).

The exchangeable sodium percentage (ESP) was calculated as (Richards 1954):

$$ESP\ (\%) = exch\ Na^+/CEC \times 100$$

where both exchangeable sodium (Exch Na^+) and the cation exchange capacity (CEC) are expressed in $cmol_+/kg$ (Gillman 1979).

Plant sampling and measurements. At 7 days after the last fertiliser application, measurements of plant height, leaf length and width, leaf area and SPAD index were recorded. Plant height was measured from the soil surface to the highest point of the plant (leaf tip or inflorescence), depending on the crop and growth stage. For maize, height was taken to the tip of the uppermost leaf or tassel; for beetroot, to the apex of the tallest leaf blade; and for quinoa, to the top of the main panicle or shoot tip. Leaf width and length were measured on the most recently fully expanded leaf for each crop species. Leaf area (LA) was then estimated using the formula:

$$LA = \alpha \times L \times W$$

where: L – leaf length; W – leaf width; α – crop-specific correction factor. For maize and beetroot, α was set to 0.75 (Montgomery 1911, Milford et al. 1985), while for quinoa, α was 0.64 (Talebnejad and Sepaskhah 2015).

SPAD index was estimated using a SPAD meter (MC-100, Apogee Instruments, Logan, USA). For each crop, three readings per leaf were averaged to represent the SPAD value for one plant. Following standard physiological sampling protocols, SPAD was measured on the third leaf from the top for maize, the outermost mature leaf for beetroot, and a mid-stem leaf for quinoa.

At the harvest, all plants were collected and separated into component parts (Table 4).

Table 4. Yield components and harvest measurement parameters

Crop	Parameter	Measurement description
Beetroot	fresh yield, Brix index	– Yield: root was harvested and weighed fresh; – Brix index: extract from the root and measure on the digital refractometer.
Quinoa	panicle length, dry biomass, fresh and dry grain yield, harvest index (HI).	– Panicle length was measured from the base to the tip of the main inflorescence (cm) – Dry biomass (stems, leaves, roots and grains) was measured by oven-drying at 70 °C until constant weight was achieved. – Grain yield: weigh at harvest time and calculate the yield (moisture of 14%); – Harvest index (HI) of a crop is a measure of biomass partitioning into economic yield (Brown 1984, Hay 1995). $HI=\frac{yield}{total\ biomass}$
Maize	dry biomass	– Dry biomass (stems, leaves and roots) was measured by oven-drying at 70 °C until constant weight was achieved.

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Table 5. Effect of saline irrigation and rice straw mulching on plant growth and yield of beetroot

	T1	T2	T3	T4	T5
Plant height (cm)	23.3 ± 0.7^{ab}	24.3 ± 0.3^{a}	23.4 ± 0.1^{ab}	20.7 ± 0.2^{c}	22.4 ± 0.6^{b}
Leaf length (cm)	23.1 ± 0.8^{a}	20.2 ± 0.1^{bc}	23.0 ± 0.0^{a}	19.6 ± 0.4^{c}	21.1 ± 0.1^{b}
Leaf width (cm)	10.6 ± 0.6^{a}	9.3 ± 0.2^{a}	9.4 ± 0.3^{a}	6.4 ± 0.3^{d}	8.0 ± 0.2^{c}
Leaf area (cm^2)	176.8 ± 7.9^{a}	143.5 ± 6.7^{b}	146.7 ± 4.7^{b}	97.5 ± 6.5^{c}	109.3 ± 8.3^{c}
SPAD index	52.5 ± 0.2^{b}	54.6 ± 1.2^{a}	52.8 ± 0.2^{ab}	49.7 ± 0.1^{c}	50.7 ± 0.8^{c}
Fresh yield (g/pot)	57.4 ± 0.7^{a}	50.3 ± 0.8^{b}	55.5 ± 0.6^{a}	44.3 ± 2.2^{c}	41.7 ± 0.8^{c}
Brix index	7.7 ± 0.5^{ab}	7.7 ± 0.5^{ab}	8.0 ± 0.0^{a}	6.3 ± 0.6^{b}	6.7 ± 0.6^{ab}

Values are expressed as *x* ± standard deviation. Values in the same row with different superscript letters are significantly different at $P \leq 0.05$ (Tukey's *HSD* (honestly significant difference)). ns – no significant difference; T1 – non-saline irrigation water applied without straw mulching (control); T2 – 2 g/L salinity in irrigation water applied without straw mulching; T3 – 2 g/L salinity of irrigation water applied with straw mulching (7 t/ha); T4 – 4 g/L salinity in irrigation water applied without straw mulching; T5 – 4 g/L salinity in irrigation water applied with straw mulching (7 t/ha)

Statistical analysis. Statistical analyses were conducted using Microsoft Excel (Microsoft Corp., Redmond, USA) and Minitab v20.0 (Minitab Inc., State College, USA). Data are presented as *x* ± standard deviation (SD). Treatment effects were evaluated by one-way or multifactor ANOVA (GLM), with Tukey's *HSD* (honestly significant difference) test applied at $P \leq 0.05$. Correlation and linear regression analyses assessed relationships between soil salinity (ECe) and crop dry biomass or yield.

RESULTS

Crop growth and yield under saline irrigation. Saline irrigation and rice straw mulching significantly affected beetroot growth and yield components ($P \leq 0.05$) (Table 5). In comparison with the control (T1), T2 reduced leaf length (20.2 ± 0.1 *vs.* 23.1 ± 0.8 cm), leaf area (143.5 ± 6.7 *vs.* 176.8 ± 7.9 cm^2), and fresh yield (50.3 ± 0.8 *vs.* 57.4 ± 0.7 g/pot), while increasing SPAD index (54.6 ± 1.2 *vs.* 52.5 ± 0.2). With mulching (T3), these parameters did not differ significantly from the control.

Under 4 g/L salinity, plants without mulch (T4) recorded the lowest values, with a leaf area of 97.5 ± 6.5 cm^2 and a fresh yield of 44.3 ± 2.2 g/pot. Mulching (T5) improved plant height (22.4 ± 0.6 cm) compared with T4, but yield remained lower (41.7 ± 0.8 g/pot) than the control.

Saline irrigation and mulching treatments negatively affected quinoa growth and yield components

Table 6. Effect of saline irrigation and rice straw mulching on plant growth and yield of quinoa

	T1	T2	T3	T4	T5
Plant height (cm)	56.3 ± 0.8^{a}	51.2 ± 2.6^{ab}	55.5 ± 0.5^{a}	46.5 ± 1.0^{b}	46.8 ± 0.5^{b}
Leaf length (cm)	5.5 ± 0.3^{bc}	5.8 ± 0.2^{ab}	6.3 ± 0.1^{a}	5.3 ± 0.1^{c}	5.3 ± 0.0^{c}
Leaf width (cm)	5.2 ± 0.1^{c}	5.8 ± 0.1^{b}	6.2 ± 0.1^{a}	5.4 ± 0.1^{c}	5.2 ± 0.0^{c}
Leaf area (cm^2)	18.8 ± 1.2^{c}	21.9 ± 0.7^{b}	25.2 ± 0.5^{a}	18.6 ± 0.5^{c}	18.4 ± 0.4^{c}
SPAD index^{ns}	44.7 ± 1.1	49.0 ± 1.6	45.8 ± 0.7	47.7 ± 2.3	49.2 ± 1.8
Panicle length (cm)^{ns}	14.0 ± 0.9	17.8 ± 0.8	16.0 ± 1.0	15.0 ± 0.5	16.2 ± 0.3
Dry biomass (g/pot)^{ns}	14.7 ± 1.4	15.1 ± 3.7	15.1 ± 2.5	17.6 ± 1.0	15.2 ± 1.6
Grain yield (g/pot)^{ns}	5.6 ± 0.9	2.8 ± 0.7	4.7 ± 0.7	4.2 ± 0.7	5.5 ± 0.6
Harvest index	0.36 ± 0.0^{a}	0.16 ± 0.1^{b}	0.28 ± 0.0^{ab}	0.21 ± 0.1^{ab}	0.32 ± 0.0^{a}

Values are expressed as *x* ± standard deviation. Values in the same row with different superscript letters are significantly different at $P \leq 0.05$ (Tukey's *HSD* (honestly significant difference)). ns – no significant difference. T1 – non-saline irrigation water applied without straw mulching (control); T2 – 2 g/L salinity in irrigation water applied without straw mulching; T3 – 2 g/L salinity of irrigation water applied with straw mulching (7 t/ha); T4 – 4 g/L salinity in irrigation water applied without straw mulching; T5 – 4 g/L salinity in irrigation water applied with straw mulching (7 t/ha)

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(Table 6). Regarding plant height, the highest value was recorded in the control (T1), which was 56.3 ± 0.8 cm, but reduced significantly under both T4 and T5 treatments, with 46.5 ± 1.0 cm and 46.8 ± 0.5 cm, respectively. Leaf area was significantly higher in T3 (25.2 ± 0.5 cm^2) compared with T1 (18.8 ± 1.2 cm^2), while T2 (21.9 ± 0.7 cm^2) was intermediate. In contrast, T4 and T5 (around 18–19 cm^2) did not differ significantly from the control. Leaf length and width followed a similar trend. There were no significant differences among treatments in SPAD index, panicle length, dry biomass and grain yield ($P > 0.05$). Meanwhile, the harvest index of T2 was 0.16 ± 0.1, which was significantly lower than that of the control (0.36 ± 0.0).

For maize (Table 7), saline irrigation and mulching treatments significantly affected plant height, leaf length and width, leaf area, SPAD index and dry biomass ($P \leq 0.05$). Plant height was highest under mulching treatments, reaching 167.0 ± 2.2 cm in T3 and 163.5 ± 1.2 cm in T5, compared with 152.2 ± 1.0 cm in the control (T1), while T2 and T4 did not differ significantly from T1. Compared to T1, leaf length and width showed no significant differences, while leaf area was only significantly greater in T3 than in T4. Similarly, SPAD index decreased under 4 g/L with mulching (T5) relative to 2 g/L without mulching (T2) but remained statistically similar to the control (T1) and to T3–T4. However, the dry biomass dropped significantly ($P \leq 0.05$) with the salinity rise of irrigation water without mulching, from 67.7 ± 1.8 g/pot in T1 to 42.0 ± 1.7 g/pot in T4. Mulching helped sustain dry biomass under salinity stress, with T3 (66.6 ± 3.8 g/pot) and T5 (59.7 ± 0.5 g/pot) showing significantly higher dry biomass than their non-mulched counterparts. Despite the positive effects of straw mulching, not all treatments were harvested due to the high heatwave and saline stress in the greenhouse conditions.

Soil properties during upland crop cultivation under saline irrigation conditions. Saline irrigation substantially increased soil ECe over time across all crop species, with measurements taken every 15 days after the initiation of saline irrigation (Figure 1). For all crops, non-saline controls consistently maintained the lowest ECe values and were significantly lower than other treatments after 35 DAS.

Maize had the shortest growth duration among the three selected crops (Figure 3). Differences became more apparent after 35 DAS, with T4 showing a sharp increase in soil ECe compared to other treatments ($P \leq 0.05$). By 65 DAS, this treatment reached the highest salinity level (over 12 mS/cm), while T5 exhibited a significantly slower increase, suggesting that mulching effectively mitigated salinity accumulation. T2 and T3 maintained intermediate ECe values throughout the growing period, with mulching again reducing the magnitude of increase, but the differences were not significant.

For beetroot, which had the longest growth duration (95 days), soil ECe increased steadily throughout the growth period and followed a pattern similar to maize. However, there were no significant differences among T2, T3, T4 and T5, with average values ranging from 9–11 mS/cm.

All treatments for quinoa, the longest-duration crop, showed higher soil ECe values than those recorded for beetroot and maize. T4 was significantly higher than other treatments after 50 DAS and peaked at 15.9 mS/cm by 115 DAS ($P \leq 0.05$). At the same salinity level in irrigation water, T5 was significantly

Table 7. Effect of saline irrigation and rice straw mulching on plant growth and yield of maize

	T1	T2	T3	T4	T5
Plant height (cm)	152.2 ± 1.0^{c}	156.5 ± 1.0^{bc}	167.0 ± 2.2^{a}	151.8 ± 1.6^{c}	163.5 ± 1.2^{ab}
Leaf length (cm)^{ns}	99.0 ± 5.6	106.5 ± 4.0	105.8 ± 1.0	103.7 ± 3.8	108.0 ± 3.2
Leaf width (cm)^{ns}	6.7 ± 0.5	6.0 ± 0.2	6.8 ± 0.6	5.3 ± 0.1	6.0 ± 0.5
Leaf area (cm^2)	500.5 ± 25.4^{ab}	482.3 ± 27.7^{ab}	542.2 ± 24.1^{a}	409.5 ± 17.5^{b}	486.9 ± 15.1^{ab}
SPAD index	37.9 ± 1.9^{ab}	43.3 ± 3.2^{a}	39.9 ± 1.1^{ab}	37.6 ± 2.7^{ab}	34.7 ± 3.0^{b}
Dry biomass (g/pot)	67.7 ± 1.8^{a}	54.5 ± 1.3^{b}	66.6 ± 3.8^{a}	42.0 ± 1.7^{c}	59.7 ± 0.5^{b}

Values are expressed as x ± standard deviation. Values in the same row with different superscript letters are significantly different at $P \leq 0.05$ (Tukey's *HSD* (honestly significant difference)). ns – no significant difference. T1 – non-saline irrigation water applied without straw mulching (control); T2 – 2 g/L salinity in irrigation water applied without straw mulching; T3 – 2 g/L salinity of irrigation water applied with straw mulching (7 t/ha); T4 – 4 g/L salinity in irrigation water applied without straw mulching; T5 – 4 g/L salinity in irrigation water applied with straw mulching (7 t/ha)

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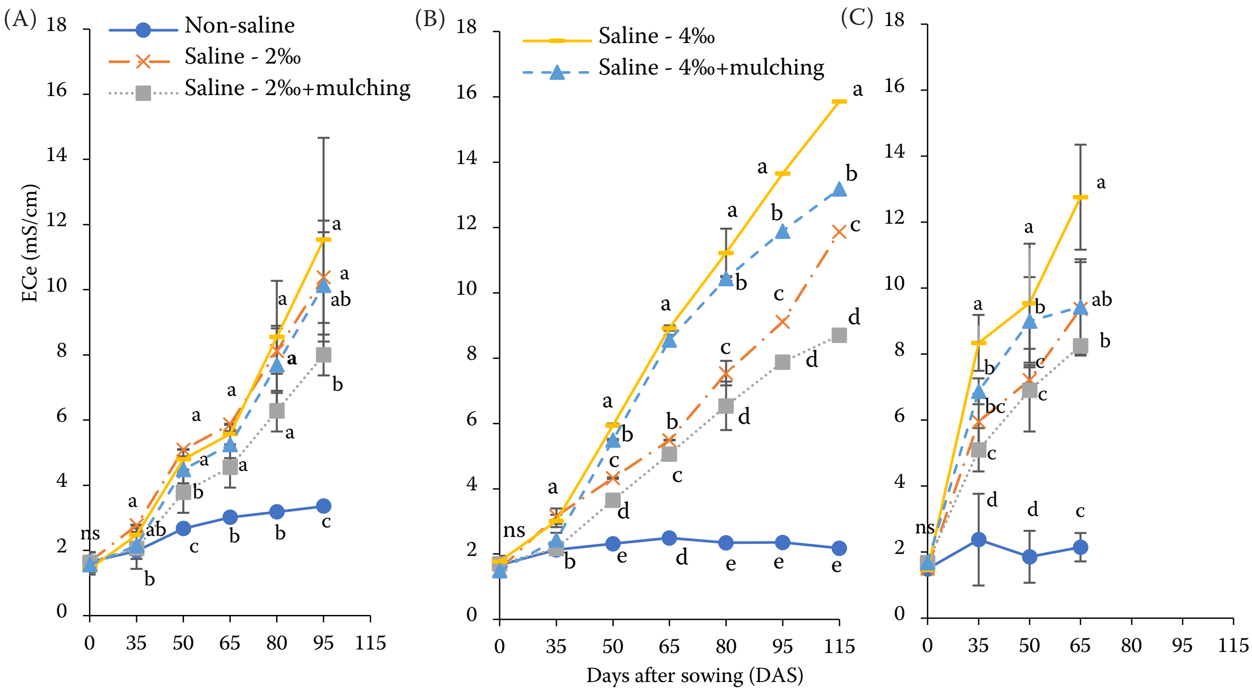

Figure 1. The effect of saline irrigation and mulching treatments on soil electrical conductivity (mS/cm) was recorded throughout (A) beetroot; (B) quinoa, and (C) maize crop cultivation. The saline irrigation levels (0, 2 and 4 g/L) commenced 14 days after sowing. On the same day after sowing, treatments with the same letter are not significantly different at $P \leq 0.05$

lower than T4 after 80 DAS. Similarly, T3 maintained significantly lower ECe than T2 throughout the growth period.

Soil soluble sodium (Sol-Na^+) and exchangeable sodium percentage (ESP) responded significantly ($P \leq 0.05$) to saline irrigation and mulching treatments across all crops (Table 8).

In beetroot, Sol-Na^+ in T2 and T4 were 3.5 ± 0.9 and 4.1 ± 0.3 $cmol_+$/kg, respectively, significantly higher than T1 (1.2 ± 0.4 $cmol_+$/kg). Similarly, ESP differed significantly ($P \leq 0.05$), with the highest value recorded in T4 (22.4%), followed by T2 (11.9%) and T1 (3.9%), in turn. Mulching under saline conditions (T3 and T5) significantly reduced these parameters relative to their non-mulched counterparts, though ESP in T3 (9.8%) and T5 (11.8%) remained higher than in T1.

For quinoa, Sol-Na^+ values in all saline treatments (T2–T5) were significantly higher than T1 (1.4 ±

Table 8. Effects of saline irrigation and rice straw mulching on soil soluble sodium (Sol-Na^+, $cmol_+$/kg) and soil exchangeable sodium percentage (ESP, %) during the cultivation of beetroot, quinoa, and maize

Crop	Soil property	T1	T2	T3	T4	T5
Beetroot	Sol-Na^+	1.2 ± 0.4^b	3.5 ± 0.9^a	1.6 ± 0.6^b	4.1 ± 0.3^a	1.5 ± 0.2^b
	ESP	3.9 ± 0.7^c	11.9 ± 0.3^b	9.8 ± 0.2^b	22.7 ± 2.0^a	11.8 ± 1.1^b
Quinoa	Sol-Na^+	1.4 ± 0.0^e	3.9 ± 0.2^c	3.2 ± 0.2^d	7.6 ± 0.4^a	6.5 ± 0.3^b
	ESP	3.4 ± 0.2^b	9.2 ± 0.9^a	9.4 ± 0.4^a	7.3 ± 1.3^a	7.1 ± 1.8^a
Maize	Sol-Na^+	1.6 ± 0.9^b	4.2 ± 0.5^{ab}	2.9 ± 0.8^{ab}	5.2 ± 0.8^a	3.5 ± 0.5^{ab}
	ESP	1.4 ± 0.7^b	2.0 ± 0.8^b	2.6 ± 0.6^b	13.1 ± 1.6^a	3.0 ± 0.4^b

Values are expressed as x ± standard deviation. Values in the same row with different superscript letters significantly differ at $P \leq 0.05$ (Tukey's *HSD* (honestly significant difference)). ns – no significant difference. T1 – non-saline irrigation water applied without straw mulching (control); T2 – 2 g/L salinity in irrigation water applied without straw mulching; T3 – 2 g/L salinity of irrigation water applied with straw mulching (7 t/ha); T4 – 4 g/L salinity in irrigation water applied without straw mulching; T5 – 4 g/L salinity in irrigation water applied with straw mulching (7 t/ha)

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0.0 $cmol_+/kg$), with T4 (7.6 ± 0.4 $cmol_+/kg$) being the highest, followed by T5 (6.5 ± 0.3 $cmol_+/kg$). ESP increased significantly under saline treatments compared with the control (T1: 3.4 ± 0.2%), but there were no significant differences among the saline treatments (7.1–9.4%).

In maize, only T4 caused a significant increase, with Sol-Na^+ rising to 5.2 ± 0.8 $cmol_+/kg$ and ESP to 13.1 ± 1.6%, compared with 1.6 ± 0.9 and 1.4 ± 0.7% in T1 ($P \leq 0.05$). Other treatments (T2, T3, T5) showed no significant difference from the control.

Correlation between soil salinity parameters and crop performance. The correlation analysis (Table 9) illustrated the relationships between soil salinity indicators (ECe, soluble sodium, and exchangeable sodium percentage) and beetroot, quinoa, and maize agronomic traits – the magnitude and significance of these correlations varied by crop.

For beetroot, soil ECe was significantly negatively correlated with leaf length, leaf width, leaf area, fresh biomass, dry biomass, and fresh yield ($P \leq 0.01$ or 0.05). Similarly, ESP exhibited strong negative correlations with all measured agronomic parameters. Sol-Na^+ also significantly negatively associated with leaf dimensions, biomass, and yield traits. A correlation was observed between ESP and leaf width ($P \leq 0.01$) and leaf area ($P \leq 0.05$).

For quinoa, both soil ECe and Sol-Na^+ were significantly negatively correlated with SPAD index and plant height ($P \leq 0.01$). Harvest index (HI) was negatively associated with ECe and ESP ($P \leq 0.05$). In contrast, ESP showed positive correlation with leaf width ($P \leq 0.01$) and leaf area ($P \leq 0.05$).

For maize, significant negative correlations were observed between soil ECe and leaf width ($P \leq 0.05$), fresh biomass, and dry biomass ($P \leq 0.01$). Both Sol-Na^+ and ESP were negatively correlated with both biomass traits, with the strongest correlation found between ESP and dry biomass ($P \leq 0.01$). Yield-related traits were not evaluated due to crop failure before harvest.

DISCUSSION

Crop tolerance and responses under saline-affected conditions in the MRD. Soil salinisation has become an increasingly critical challenge in the MRD, especially during the dry season, when seawater intrusion, reduced upstream freshwater inflows, and high evapotranspiration rates exacerbate salt accumulation in the root zone (Hoa et al. 2019, Apel et al. 2020, Thach et al. 2023). This accumulation imposes significant osmotic and ionic stress on plants, limiting water uptake, disrupting nutrient balance, and impairing physiological processes (Shrivastava and Kumar 2014, Deolu-Ajayi and Tran 2024, Ibrahimova et al. 2025). The vulnerability of crop production under saline conditions is especially pronounced in low-lying coastal regions, where rice

Table 9. Pearson correlation coefficients between soil salinity indicators (electrical conductivity (ECe); soluble sodium (Sol-Na^+) and exchangeable sodium percentage (ESP)) and agricultural parameters of beetroot, quinoa, and maize

Plant parameter	Soil property								
	beetroot			quinoa			maize		
	ECe	Sol-Na^+	ESP	ECe	Sol-Na^+	ESP	ECe	Sol-Na^+	ESP
SPAD index	-0.3^{ns}	-0.2^{ns}	-0.7^{**}	0.6^{*}	0.6^{*}	0.1^{ns}	-0.0^{ns}	-0.0^{ns}	-0.2^{ns}
Plant height	-0.5^{ns}	-0.5^{ns}	-0.7^{**}	-0.8^{**}	-0.9^{**}	-0.2^{ns}	0.2^{ns}	-0.0^{ns}	-0.3^{ns}
Leaf width	-0.7^{**}	-0.7^{*}	-0.8^{**}	0.0^{ns}	-0.2^{ns}	0.7^{**}	-0.6^{*}	-0.7^{**}	-0.7^{**}
Leaf length	-0.9^{**}	-0.6^{*}	-0.7^{**}	-0.4^{ns}	-0.5^{ns}	0.2^{ns}	0.5^{*}	0.2^{ns}	-0.0^{ns}
Leaf area	-0.8^{**}	-0.7^{**}	-0.8^{**}	-0.2^{ns}	-0.4^{ns}	0.6^{*}	-0.4^{ns}	-5.6^{*}	-0.7^{**}
Flower length	–	–	–	-0.4^{ns}	-0.5^{ns}	0.2^{ns}	–	–	–
Fresh biomass	-0.6^{*}	-0.5^{*}	-0.7^{**}	-0.2^{ns}	-0.2^{ns}	-0.3^{ns}	-0.8^{**}	-0.6^{*}	-0.8^{**}
Dry biomass	-0.7^{**}	-0.5^{ns}	-0.7^{**}	0.3^{ns}	0.3^{ns}	0.0^{ns}	-0.8^{**}	-0.7^{**}	-0.8^{**}
Fresh yield	-0.6^{*}	-0.5^{*}	-0.7^{**}	–	–	–	–	–	–
Grain yield	–	–	–	-0.3^{ns}	-0.1^{ns}	-0.5^{ns}	–	–	–
Harvest index	–	–	–	-0.6^{*}	-0.3^{ns}	-0.6^{*}	–	–	–
Brix	-0.4^{ns}	-0.5^{ns}	-0.6^{*}	–	–	–	–	–	–

$^{**}P \leq 0.01$; $^{*}P \leq 0.05$; ns – no significant difference. Symbols (–) mean without the parameters of the crop

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monoculture becomes less viable during prolonged droughts. In response, selecting salt-tolerant crops and appropriate irrigation strategies is essential for sustaining agricultural productivity and promoting climate resilience. This study investigated the physiological responses and yield performance of maize, beetroot, and quinoa under saline irrigation, providing evidence for their adaptability and suitability for dry-season farming in salt-affected soils of the MRD. Maize proved to be the most sensitive crop among the three tested species, with pronounced reductions in plant height, SPAD index, and dry biomass of T4 (Table 7). Even under non-saline control conditions (T1), maize could not complete its growth cycle, suggesting that high greenhouse temperatures and humidity contributed significantly to plant stress and decline. In T5, growth was delayed, and biomass slightly improved, but still insufficient for harvest. These findings align with previous reports showing that maize is susceptible to both salinity and heat stress, which impair chlorophyll biosynthesis, leaf expansion, and dry matter accumulation (Farooq et al. 2015, Rahman et al. 2015, Zaidi et al. 2022, Khalid et al. 2023). The reduction in SPAD values reflects decreased chlorophyll content under environmental stress (Hussain et al. 2019). Maize's vulnerability is further linked to its limited capacity for osmotic adjustment and Na^+ exclusion, consistent with recent insights into weak ion homeostasis under salinity stress (He et al. 2025). This outcome emphasises the need for integrated environmental control and salt-tolerant genotypes if maize is considered for dry-season cropping in the MRD.

While capable of growing in mildly saline conditions, beetroot exhibited significant yield reductions as salinity levels increased to 4 g/L in this study. Plant growth and yield of T2 declined modestly compared to the control, but under T4 treatment, sharp reductions were observed in leaf length, leaf width, leaf area, and fresh yield (Table 5). These findings confirm beetroot's classification as moderately salt-sensitive, consistent with previous studies reporting yield suppression at soil salinity levels exceeding 6 dS/m (≈3.8 g/L) (da Silva et al. 2016, Yolcu et al. 2021). In the experiment, soil ECe reached 11 dS/m (≈7 g/L) under the 4 g/L saline irrigation without mulching treatment, exceeding the threshold and resulting in a 22.7% ESP, which further highlights the salt stress imposed (Table 8). Prior research has shown that beetroot's growth and tuber development are particularly vulnerable to elevated salt concentrations in the root zone, especially without soil management practices (Zaidalkilani et al. 2024, He et al. 2025). Despite its tolerance, the significant reductions observed at higher salinity indicate that beetroot may not be suitable for areas experiencing severe saline intrusion unless combined with effective mitigation measures.

Quinoa demonstrated the highest tolerance to saline irrigation among the three tested crops. In this study, its agronomic parameters, including SPAD index, leaf area, and yield, were not significantly reduced even under 4 g/L saline irrigation (Table 6), particularly when mulching was applied. This suggests that quinoa can maintain physiological function under moderate salinity, consistent with its known halophytic characteristics (Morales et al. 2011, Adolf et al. 2013, Iqbal et al. 2020, Qureshi et al. 2020).

The lack of correlation between soil ECe and yield parameters (Table 9) further confirmed quinoa's resilience in saline conditions. This tolerance is attributed to several mechanisms, including Na^+ exclusion, vacuole sequestration, K^+ retention, and osmotic adjustment through proline accumulation (Hinojosa et al. 2018, Rasouli et al. 2022). These responses help sustain photosynthesis and biomass production under salt stress.

However, the quinoa grain yield in this study (maximum ~5.6 g/pot) was lower than values reported in other greenhouse studies, such as 7.2–9.5 g/pot under similar salinity levels (Koyro and Eisa 2008, Hariadi et al. 2011). This suggests that environmental factors such as high temperature and humidity in the MRD greenhouse conditions, or genotype-specific responses, may have limited its full yield potential. These findings confirm quinoa's suitability for saline-prone areas but also underscore the need to evaluate high-yielding, stress-adapted cultivars under delta-specific conditions.

Among the three tested crops, maize was the most sensitive to salinity and environmental stress, failing to complete its growth cycle even under non-saline conditions due to the combined effects of high temperature and humidity in the greenhouse. Beetroot showed moderate tolerance, maintaining acceptable growth under 2 g/L of saline irrigation but experiencing significant declines in yield and biomass at 4 g/L of saline irrigation, especially without mulching. In contrast, quinoa exhibited the highest resilience, with stable growth and yield parameters under all salinity levels tested. These results support the potential of quinoa, and to a lesser extent, beetroot,

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as alternative dry-season crops in the saline-prone areas of the MRD.

Effect of rice straw mulching on alleviating the salt accumulation from saline water into the soil. Rice straw mulching has demonstrated potential in mitigating the negative effects of saline irrigation on soil health and crop growth (Song et al. 2019, Yolcu et al. 2021, El-Beltagi et al. 2022, Xue et al. 2022, Nhien et al. 2025). In this study, rice straw mulching significantly reduces soil ECe (Figure 1), soil Sol-Na^+ and soil ESP values (Table 8) across all tested crops. In 4 g/L saline treatments, mulching lowered soil EC levels compared to non-mulched treatments, with beetroot showing a reduction from 11.5 to 10.1 mS/cm and quinoa from 15.9 to 13.2 mS/cm. This effect is attributed to improved soil moisture retention, reduced evaporation, and a barrier against salt accumulation (Song et al. 2019). This is further demonstrated by the reduction in Sol-Na^+ values in treatments with straw mulch compared to treatments without straw mulch at the same salinity level. Sol-Na^+ concentrations in beetroot decreased from 4.1 $cmol_+$/100 g (T4) to 1.5 $cmol_+$/kg (T5), and similar trends were observed in quinoa and maize (Table 8).

Soil ESP also declined significantly with mulching under 4 g/L saline irrigation during the period of beetroot and maize cultivation (Table 8). Lower ESP prevents soil structural degradation and maintains water infiltration, which is crucial for crop performance under saline irrigation (Watanabe et al. 2013, Rezapour et al. 2023, Zhang et al. 2024).

Yield responses further affirmed mulching benefits. For beetroot (Table 5), the fresh yield at 2 g/L salinity increased significantly from 50.3 g/pot (non-mulched) to 55.5 g/pot (mulched). Similar positive trends were observed in quinoa and maize: quinoa grain yield remained stable under both salinity levels with mulch, while maize, the most salinity-sensitive crop, showed an increase in dry biomass from 43.6 g to 52.5 g/pot at 4 g/L salinity with mulch application (Table 6). Although not enough to reverse maize's overall vulnerability to salinity, this indicates that mulch can partially mitigate stress effects (Amer 2010). Across species, the effectiveness of mulching varied. Beetroot responded strongly, with significant reductions in EC and ESP translating into improved biomass and yield (Yolcu et al. 2021). Quinoa, with its inherent salinity tolerance, maintained stable yields under mulching, like non-saline conditions, indicating enhanced resilience due to better soil conditions and water use efficiency (Cai and Gao 2020). Despite these benefits, mulch alone was insufficient to fully counteract the effects of high salinity, particularly in maize. This highlights the need for integrated management strategies combining mulch application with salt-tolerant cultivars and precise irrigation scheduling to support maize cultivation under saline irrigation in the MRD.

Overall, rice straw mulching is a practical, locally available measure to reduce salt accumulation, especially for beetroot and quinoa, which responded positively in terms of yield and soil health indicators. Its application represents a valuable component of sustainable dry-season cropping systems in the MRD, though further studies are needed to optimise mulch quantity, timing, and integration with crop-specific water demands under saline conditions.

Potential for diversification of upland crops on saline-affected rice soil in the Mekong River Delta. The increasing salinity intrusion in the MRD presents significant challenges for traditional rice cultivation, necessitating the exploration of alternative crops to ensure sustainable agricultural productivity. The diversification of upland crops like beetroot, quinoa, and maize on saline-affected rice soils offered promising opportunities.

Quinoa emerged as the most promising alternative crop under saline conditions in this study, maintaining stable yields even under 4 g/L saline irrigation without mulching, where soil EC exceeded 15 mS/cm. However, its grain yield (2.8–5.6 g/pot, equivalent to ~0.5–1.0 t/ha) was still lower than previously reported values of 1.5–2.5 t/ha under 10–15 dS/m salinity in field conditions in Egypt and Chile (Morales et al. 2011, Adolf et al. 2013). This discrepancy suggests that while quinoa tolerates salinity, yield performance in the MRD may be constrained by other local factors such as heat stress, photoperiod sensitivity, or planting density. Further research should investigate varietal selection, sowing time, and agronomic practices optimised for delta conditions.

Beetroot, although less tolerant than quinoa, also exhibited resilience to saline conditions. The application of rice straw mulching significantly reduced soil salinity, which in turn supported better growth and yield outcomes. Although beetroot still experienced yield reductions under high salinity (4 g/L), mulching mitigated some of these negative effects, making it a feasible option for slightly saline-affected soils in the MRD (Yolcu et al. 2021). The potential for beetroot lies in its nutritional value and marketability as a root vegetable, but successful cultivation

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will require effective soil and water management practices, salt monitoring, and timely sowing to avoid peak salinity periods (Ezlit et al. 2010, Devkota et al. 2022, Paz et al. 2023). Further studies should also evaluate postharvest quality and market acceptance under saline stress.

Maize was the most salt-sensitive among the tested crops, particularly during reproductive stages. The study showed that even with mulching, maize could not sustain growth beyond 55 days under 4 g/L saline irrigation. This aligns with earlier findings that maize is vulnerable to salinity-induced reproductive failure, particularly during flowering and grain filling stages (Farooq et al. 2015, Hussain et al. 2019). However, early sowing to synchronise flowering with lower salinity levels, prior to peak intrusion in the late dry season, could enhance its viability. Maize remains a key crop due to its versatility and market value, and its inclusion in crop rotations should be considered for areas with low to moderate salinity, especially when paired with salt-tolerant cultivars and controlled irrigation.

Beyond individual crop performance, seasonal planning and cropping calendar adjustments are essential for minimising salinity-related risks in dry-season farming systems of the MRD. The dry season typically begins in December and lasts through May, with canal water salinity and soil salinisation peaking between March and late April (Nguyen et al. 2020, Thach et al. 2023). During this period, canal water salinity often exceeds 4 g/ L (≈6.25 mS/cm). In severely affected regions, it may reach up to 15 g/L, posing significant threats to crop productivity (Eslami et al. 2019).

To mitigate exposure to these peak salinity levels, early sowing of upland crops immediately after rice harvest in November–December is recommended over delayed planting in January–February. Those selected crops with short growing durations are more likely to complete their life cycle before salinity concentrations reach their seasonal maximum, thus avoiding stress during sensitive reproductive stages. Thus, an alternative crop should possess both a relatively short growth duration (less than 120 days) and sufficient salinity tolerance, especially during its reproductive stage. Implementing early planting not only reduces exposure to peak salinity but also improves flexibility in aligning with wet-season rice cultivation, thereby contributing to more consistent yields under saline irrigation conditions (Kaveney et al. 2023).

Overall, diversification with suitable upland crops, supported by adaptive agronomic strategies and farmer education, presents a viable pathway for enhancing the resilience of MRD agriculture under increasing salinity stress. The integration of quinoa, beetroot, and, to a limited extent, maize offers realistic alternatives to mono-rice systems, paving the way for sustainable intensification in the delta.

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