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The effect of brackish water irrigation on crops cultivated in the Vietnamese Mekong Delta

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Abstract: Brackish water is formed when freshwater mixes with saltwater resulting in differential NaCl concentrations. To identify safe and effective ways of using brackish water in the VMD, we assessed its impact on soil salinity, and on productivity of beetroot, maize and peanut cultivated on loam-clayey soil under greenhouse conditions at Tra Vinh University. No to high salinity stress was induced by crop irrigation with 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5 or 4 ppt NaCl solution, as gradually increasing NaCl concentration (acclimatising saline experiment) or acute NaCl solution applied at different developmental growth stages (shock saline experiment). Continuous irrigation with ≤1.5 ppt NaCl solution does not significantly decrease yield within a single growing season while also leading to substantial enhancement of crop quality- sugar content of beetroot bulbs. Although both beetroot and peanut were negatively impacted under strong saline conditions, beetroot yield was minimally reduced stimulating responses expected of salt tolerant crops or varieties. Thus, beetroot performs better than peanut and maize under saline conditions, and can be cultivated as an alternative crop during dry, salinized seasons in the VMD. However, long term effect of brackish water irrigation on soil salinity and crop yield needs further evaluation.

Keywords: Beetroot; Maize; Peanut; Salinity; Vietnamese Mekong Delta.
Abbreviations: EC_electrical conductivity, NaCl_sodium chloride, ppt_parts per million, TVU_Tra Vinh University, VMD_Vietnamese Mekong Delta.

Introduction

The Vietnamese Mekong Delta (VMD) is recognised as one of the largest food-producing regions. It serves as home to millions of farmers who engage in crop cultivation and livestock rearing, with a significant portion exported globally (MARD 2022). Food production from the VMD accounts for approximately one-third of the national gross domestic profit of the agricultural sector. However, sustainability of agriculture in the VMD faces significant threat due to rising seawater level, groundwater abstraction, land subsidence and prolonged periods of drought and salinity. If these trends continue, salinized areas may increase by an additional 271-703 thousand hectares by 2050 that is equivalent to ~ 45% of total land area in the VMD (Eslami et al., 2021).

Saline soils and water bodies contain excessive soluble salts, mainly sodium chloride (NaCl) and sodium sulphate (Na_2SO_4) (FAO and ITPS, 2015). Elevated concentrations of Na^+ and Cl^- in water bodies or soil pose substantial risk to agricultural productivity by reducing water quality (Thorslund and van Vliet 2020), altering physical, chemical and biological characteristics of the soil (Yan et al., 2015; Rengasamy, 2016), and minimising crop growth, yield and quality (Geilfus 2018; Zörb et al. 2019). Furthermore, salinity poses several socio-economic challenges for the local population such as loss of income and employment, land abandonment, and rural-to-urban migration (Brown et al., 2018; Tri et al., 2019).

Of all the threats experienced in the VMD, saline intrusion is the most severe causing the biggest yield losses to rice production (Kaveney et al., 2023; Thach et al., 2023). Additionally, freshwater shortage due to increasing salinisation, is quickly becoming another major limiting factor for sustainable development of agriculture in the VMD (Tran et al., 2024). Although freshwater for agriculture is becoming increasingly scarce, brackish and saline water resources are seemingly boundless. Brackish water results from the mixing of intruding saline water with freshwater resulting in varying salt concentrations. By harnessing brackish or slightly saline water resources for crop cultivation, pressure on freshwater can be reduced.

Tra Vinh is a province located in the VMD. The province is situated between rivers Co Chien and Hau, and adjacent to the East Sea. Due to its location, this province is significantly impacted by climate change facing numerous challenges including saltwater intrusion, coastal erosion, flooding, freshwater scarcity, drought, and pollution from upstream activities. About 1.1 million people reside in Tra Vinh and a fourth of the population are farmers. Therefore, the local economy is heavily dependent on agriculture. Moreover, salinity poses a critical threat to agriculture in the province (Nguyen et al., 2020).

In response to challenges in the Mekong Delta, the Government of Vietnam issued Resolution 120/NQ-CP in 2017 which addresses sustainable development of the VMD in the context of climate change. This resolution highlights improving agriculture and aquaculture systems in the region, while simultaneously minimising the impact of climate change. It aims to facilitate implementation of high technological practices linked to development of the agricultural value chain by using sustainable approaches, although problems regarding shifting from current farming systems and adoption of other climate-resilient models remain (MARD 2023).

Cultivation of salt tolerant crops and varieties among others, have been proposed as one of the climate-resilient models to combat salinisation of the VMD (Nguyen, 2017; Brown et al., 2018). However, studies on salt tolerant crop cultivation in the VMD are limited. In dry season when salinity increases, freshwater is a limiting factor for crop production in the VMD. Additionally, continuous groundwater abstraction for irrigation is not a long term sustainable option. If brackish or partially saline water can be used to irrigate crops, it reduces pressure on limited freshwater resources, especially during dry seasons. The aim of our study was to examine the impact of saline irrigation on salt accumulation in the soil, crop growth and crop productivity. Three crops- beetroot, maize, and peanut- were carefully selected based on their relevance for local farmers, and grown under varying NaCl (salt) concentrations of salinity in a semi-controlled nethouse in Tra Vinh. Maize and peanut are classified as moderately salt senstive while beetroot is a moderately salt tolerant crop (Maas et al., 1977; Shannon, 1997). Both maize and peanut are already cultivated locally while beetroot is a newly introduced crop to Tra Vinh. Assessing crop response at differential salt concentrations provides valuable insights on salinity threshold of the crops as well as, potential utilisation of brackish or slightly saline water, especially during dry seasons when freshwater scarcity occurs.

Results

In our study, we examined changes in crop and soil parameters under saline conditions. Saline conditions in plant experiments were elicited by two different methods of saltwater irrigation of beetroot, maize and peanut. The two methods of saltwater irrigation were denoted as acclimatising saline experiment, and shock saline experiment. We investigated the three crops by treatment with either gradually increasing NaCl levels for the acclimatising saline experiment or challenged with acute NaCl levels for the shock saline experiment, to determine salinity response of the crops.

Beetroot and peanut experienced higher salt stress than maize in the acclimatising saline experiment

In the acclimatising saline experiment, salt increasingly accumulated in the soil over time (Fig 1). Large significant differences exisited among defined salt treatments of beetroot and peanut but smaller differences were observed among salt treatments in maize. Continuous irrigation with 4 ppt NaCl solution (the highest salt concentration) resulted in soil EC values of 6.5 and 7 dS/m for beetroot and peanut, respectively at the end of the acclimatising experiment (Fig 1A, C). In contrast, continuous irrigation of maize with the same 4 ppt NaCl solution caused soil EC of 3.75 dS/m only (Fig 1B). This lower soil EC can be linked to duration of salt treatment, and therewith different levels of salt accumulation in soil since saline irrigation was stopped after 42 days in maize but contined until 74 and 84 days in beetroot and peanut, respectively (Fig 1). Therefore, indicating that beetroot and peanut plants experienced strong salinity stress at higher salt treatments of 2 to 4 ppt that is equivalent to soil EC between 4 and 7 dS/m (Fig 1; FAO et al., 2021). Maize plants even at the 4 ppt treatment, were only moderately salt stressed due to lower soil EC of ˃ 4 dS/m, since their cropping cycle is shorter.

Although there were significant differences in leaf number per treatment, number of leaves did not always decrease with increasing salt treaments in the acclimatising experiment. Number of leaves increased over time in beetroot and peanut but in maize, leaf number dropped at 12 days post-salt induction and remained the same for the rest of the acclimatising experiment (Fig 2). This observation can be explained by maize generally

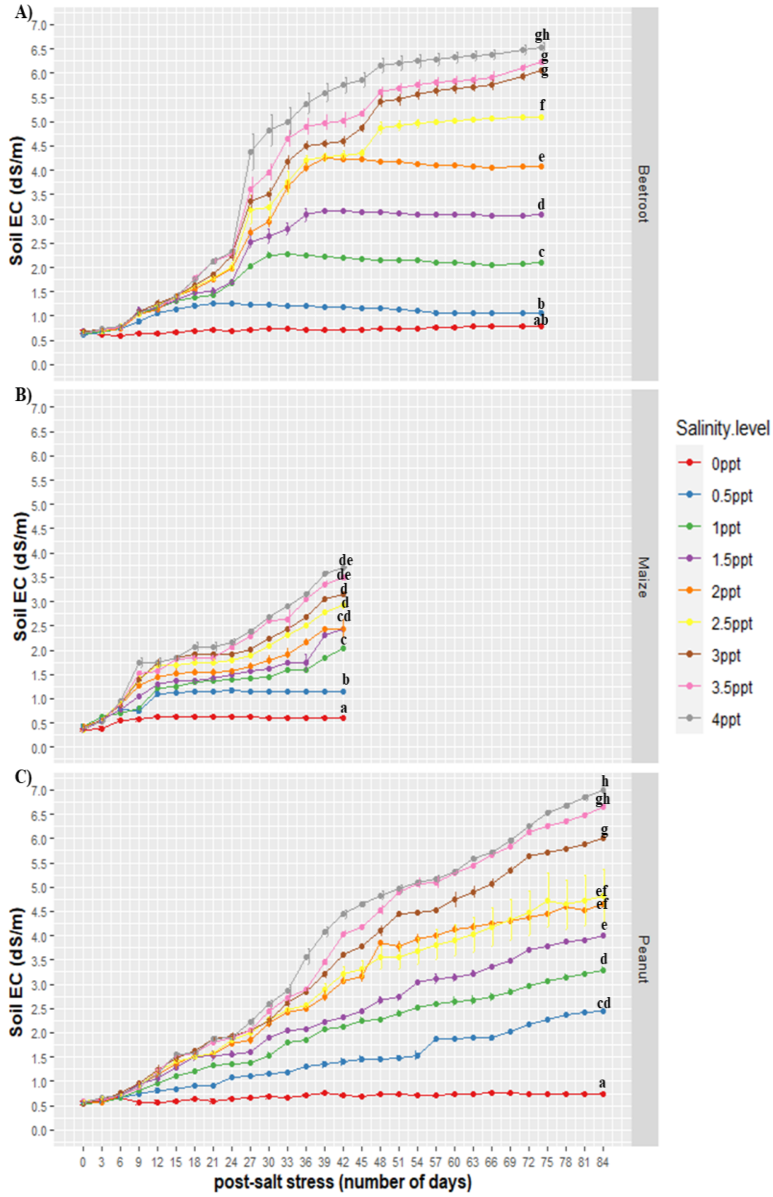

Figure 1. Soil salinity in acclimatising saline experiment. Steadily increasing soil EC for beetroot (A), maize (B) and peanut (C) measured every three days for varied duration of the acclimatising salt experiment. Control treatment (0 ppt) was established by irrigation of soil pots using water without NaCl. Salty treatments were achieved by increasing salt concentration by 0.5 ppt NaCl solution at every timepoint until the defined salt treatments of 0.5 to 4 ppt were reached and thereafter, irrigation with water containing only the specified NaCl concentration. Day 0 on the x-axis represents the first day of saline irrigation of 26-, 14- and 5-day old beetroot, maize, and peanut plants respectively, after crops have developed 3 to 4 true leaves. Statistics performed by one-way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

producing lower number of- but larger- leaves than beetroot and peanut.

Crops in nursery phase of development mostly had the highest salt accumulation in soil

Salt treated beetroot plants in the nursery phase of shock saline experiment accumulated more salt in the soil, compared to their corresponding acclimatising experiment (Fig 1A, 3A). Continuous irrigation with 4 ppt NaCl solution resulted in soil EC of ~8.6 dS/m (Fig 3A). Irrigation of beetrot in vegetative- or reproductive- phase of development caused less salt accumulation in the soil with EC values of 6.1 and 4.7 dS/m, respectively. Soil salt accumulation was either similar or higher than observations in the aclimatising experiment for maize (Fig 1B, 3B). A maximum soil EC of 3.7, 4.2 and 4.6 dS/m were reached for saline treatment of maize at nursery-, vegetative- and reproductive- phases of development, respectively (Fig 3B). On the other hand, soil EC of peanut in shock experiment were similar or lower than observed in their acclimatising experiment (Fig 1C, 3C). Soil EC was a maximum of 7.3, 5.1 and 5.7 dS/m for salt treatment at the nursery-, vegetative- and reproductive- phase of development, respectively (Fig 3C). This is in line with day length of the nursery phase which was much longer than the other two developmental phases in peanut and beetroot (Fig 3A, C).

In several conditions of the shock experiment, crops had similar number of leaves independent of salt treatment, per developmental stage (Fig 4). The exception was nursery phase of beetroot and maize where the 4 ppt treatment caused significantly lower leaf number (Fig 4A, B). Additionally for peanut reproductive phase, leaf number increased with increasing salinity level (Fig 4C).

Increased frequency of saline water irrigation resulted in higher soil EC and lower leaf number

Overall, maize plants experienced less salinity stress than beetroot and peanut (Fig 1, 3). Direct impact was observed as lower and/ or smaller variations in soil EC and number of leaves, independent of increasing salt concentration in irrigation solution for the maize plants (Fig 1-4). Additionally, salt accumulation in the soil is directly linked to frequency of saline irrigation. However, the absolute amount of salt administered through saline irrigation was not measured and, irrigation was not standardised in the experiments but based on crop need. Higher frequency or longer duration of salt treatments resulted in strongly saline soils. Based on Figures 1 and 3, only the 4ppt treatment of beetroot plants in nursery phase was considered as a severely salt stressed condition since soil EC was >8 dS/m (FAO et al., 2021). The 2-4 ppt treated beetroot and peanut plants were strongly salt stressed under most conditions since soil EC ranged from 4 to 8 dS/ m (FAO et al., 2021). Exceptions were 2 ppt treatment of peanut in vegetative and reproductive- phases of crop development that were only moderately salt stressed since soil EC was < 4 dS/m (FAO et al., 2021). Maize plants were mostly moderately salt stressed. In only a few conditions of the shock experiment did maize experience strong salinity stress with soil EC still below 5 dS/m in all cases (Fig 3B). In all crops, the highest number of leaves occurred at the 0.5 ppt salt treatment (Fig 3-4), synonymous with mild or low salt stress (Fig 1-2) that are known to slightly stimulate crop growth and yield (Tahjib-Ui-Arif et al., 2019; Liao et al., 2022).

As expected, soil pH remained similar in both acclimatising and shock saline experiments, independent of increasing salt treatment (SFig 1, 2). The soil pH remained slightly acidic to neutral with pH values between 5 and 7 in all cases. Soil pH slightly increased over time in some conditions while in other conditions, the pH remained stable. An example of the former is beetroot plants in both the acclimatising and shock experiments.

Poorer bulb yield and quality were associated with the saline shock experiment

Beetroot yield and quality varied depending on salt treatments (Fig 5). In general, bulb diameter and fresh weight decresed with increasing salt concentration while the opposite effect occured for total soluble solids since degrees of Brix, representing percentage of sugar content, increased with increasing salt concentration.

An initial significant decrease of bulb diameter occurred at 2 ppt treatment of the acclimatising experiment, with further substantial reduction at the 2.5 ppt treatment (Fig 5A). Furthermore, bulb diameter of the 2.5 to 4 ppt saline treatments remained between ~ 3.3-3.6 cm. This value was similar to the 2 ppt treatment of the shock experiment with a 3.68 cm average bulb diameter (Fig 5A, D). The smallest bulb diamater i.e., ≤ 3 cm, was achieved by shock saline irrigation with 3 and 4 ppt NaCl solution (Fig 5D). Beetroot bulbs in the acclimatising experiment had stepwise fresh weight reduction at the 2 and 3 ppt treaments (Fig 5B). Fresh weight of bulbs under these higher salt treatments (between 69 and 47 g, respectively) remained larger than bulbs obtained from similar treatments in the shock experiment where 2, 3 and 4 ppt treatments yielded bulbs of ~ 40, 31 and 30 g, respectively (Fig 5B, E). Total soluble solids of beetroot bulbs significantly increased at 1, 1.5, 2.5 and 4 ppt treatments in the acclimatising experiment (Fig 5C). In the shock experiment, total soluble solids although increasing with increasing salt concentration was again, lower compared to corresponding treatments in the acclimatising experiment (Fig 5C, F). For example, bulbs treated with 2 ppt NaCl solution in shock experiment had 8.8% sugar content that is similar to 1 ppt treatment (9% sugar content) but lower than the 2 ppt treatment (10% sugar content) in the acclimatising experiment.

Altogether, the results indicated that crop yield was more affected by saline shock and beetroot coped better in the acclimating saline experiment (Fig 5). These observations cannot

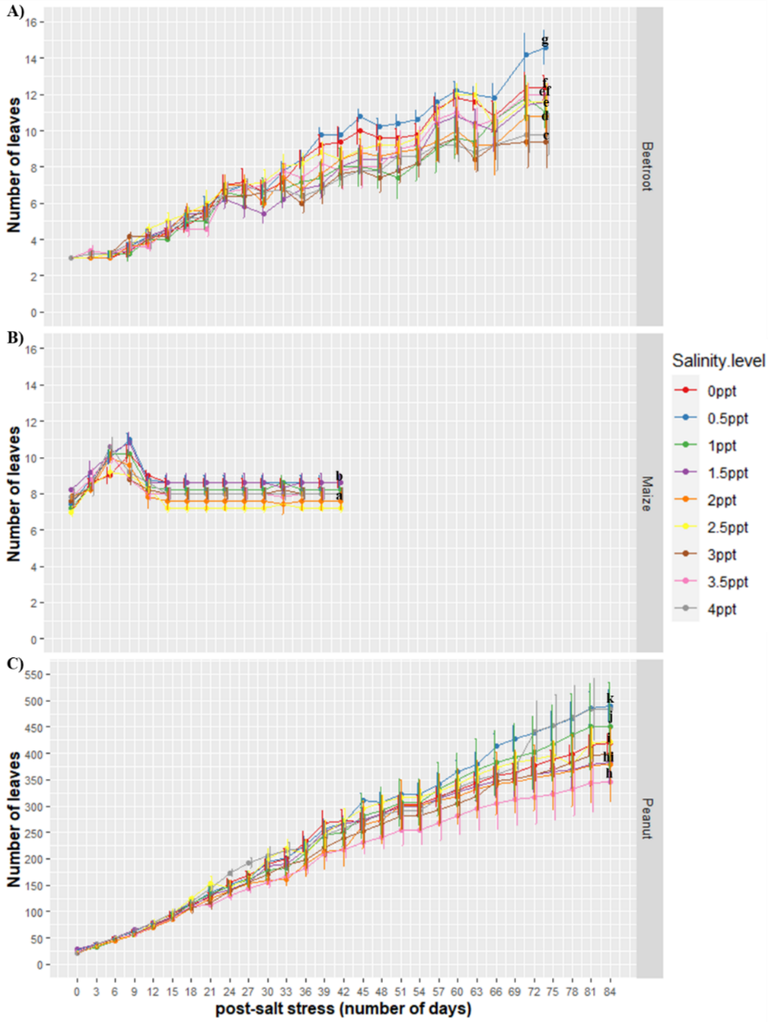

Figure 2. Crop development in acclimatising saline experiment. Increasing leaf number for beetroot (A), maize (B) and peanut (C) measured every three days for varied duration of the acclimatising salt experiment. Control treatment (0 ppt) was established by irrigation of soil pots using water without NaCl. Salty treatments were achieved by increasing salt concentration by 0.5 ppt NaCl solution at every timepoint until the defined salt treatments of 0.5 to 4 ppt were reached and thereafter, irrigation with water containing only the specified NaCl concentration. Day 0 on the x-axis represents the first day of saline irrigation of 26-, 14- and 5-day old beetroot, maize, and peanut plants respectively, after crops have developed 3 to 4 true leaves. Statistics performed by one-way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

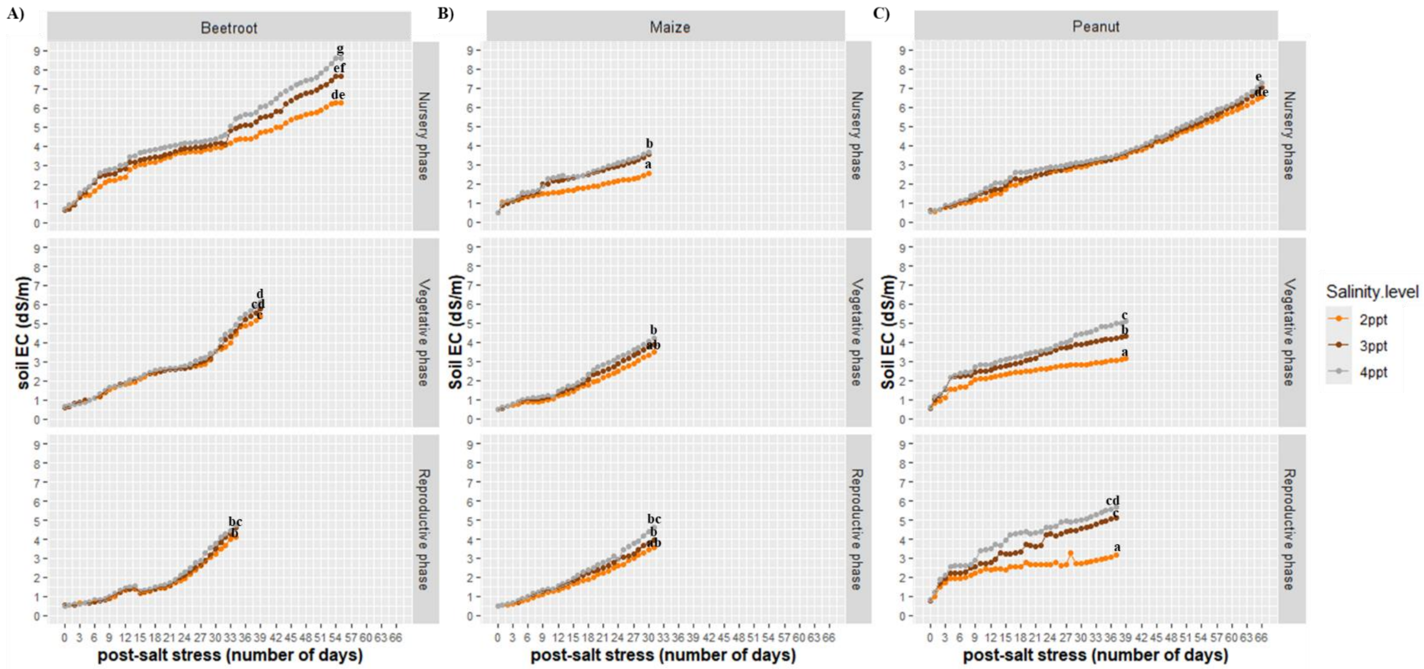

Figure 3. Soil salinity in shock saline experiment. Steadily increasing soil EC for beetroot (A), maize (B) and peanut (C) at different developmental growth stages- nursery phase, vegetative phase or reproductive phase. Measurements were taken daily for duration of the shock saline experiment. Here, salty treatments were achieved by irrigation with defined NaCl treatments of 2, 3 and 4 ppt every three days for experimental duration. Day 0 on the x-axis represents the first day of saline irrigation of the crops until a maximum of 66 days post-salt stress. Statistics performed by two-way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

be directly linked to salt accumulation in the soil since, 4 ppt treatment of the reproductive phase in the shock experiment only caused soil EC of 4.7dS/m compared to the corresponding treament in the acclimatising experiement i.e., 6.5 dS/m (Fig 1A, 3A). Poorer yield under the saline shock experiment is linked to osmotic shock caused by immediate irrigation with the 2, 3 or 4 ppt NaCl solution, rather than building up the salt concentration as performed in the acclimatising experiment (Shavrukov, 2013). Interestingly, sugar content of bulbs remained higher in the acclimatising experiment than shock experiment (Fig 5C, F), suggesting that better bulb yield and quality are obtained from the acclimatising experiment. Overall, continuous irrigation with a maximum of 1.5 ppt NaCl solution does not cause significant damage to crop yield in one growing season, while simultaneously improving crop quality (as sugar content).

Maize yield remained mostly unchanged except at 4 ppt saline treatments

Cob length of maize plants slightly differed resulting in significantly shorter cobs at the 3 and 4 ppt treatments of the acclimatising saline experiment (Fig 6A). Number of kernels per cob substantially decreased at 2 ppt treament and a further in the 4 ppt treatment (Fig 6B). Fresh weight of 1000 kernels remained similar independent of the varied salt treatments (Fig 6C).

Salt treated young seedlings at the nursery phase of development mostly had the shortest cobs and smallest number of kernels in the shock experiment, especially when irrigation with 4 ppt NaCl solution occured (Fig 6D, E). Thus, indicating that saline irrigation has the biggest negative effect on young maize seedlings resulting in much lower crop yield (assuming that total number of cobs did not decrease with increasing salt concentration) than when saline irrigation was performed at the vegetative or reproductive phase of development.

Both cob length and number of kernels in the shock experiment were generally smaller than their corresponding treatments in the acclimatising experiment (Fig 6A-B, D-E). Fresh weight of 1000 kernels in the acclimatising conditions were unusually low, and much lower than in the shock experiment (Fig 6C, F). Interestingly, 1000 kernel fresh weight was mainly affected at nursery- and reproductive- phase of development, but salt treatment at the vegetative phase had smaller effect on its yield (Fig 6F). Again, indicating that the developmental stage of maize growth is another factor to consider when implementing irrigation with saline water.

Results from the maize experiments are largely similar making it difficult to decipher concrete trends. The exception is that the 4 ppt treatment consistently had the biggest negative effect on maize yield. Furthermore, it appears that plants in acclimatising conditions were better adjusted to salinity stress than those in shock saline conditions. All these observations can be linked to salt accumulation in the soil since maize plants experienced only moderate salt stress (Soil EC > 4 dS/m) in most cases, despite varied salt treaments (Fig 1B, 3B).

Peanut yield significantly reduced during irrigation with 2 ppt NaCl solution

Peanut yield generally decreased with increasing salt concentation (Fig 7). In the acclimatising experiment, ripe peanut pods remained mostly at ~ 75% of the total, irrespective of increasing salinity level (Fig 7A). The exception was the 4 ppt treatment where ripe pods dropped to ~ 60%. When saline irrigation occured at the vegetative phase of crop development in the shock experiment, only 60 to 70% of the total pods were ripe which is slightly lower than observations in acclimatising conditions, except for the 4 ppt tretament (Fig 7A, D). On the other hand, there was an increase in ripened pods with increasing salt concentration for peanut plants at the reproductive phase (Fig 7D).

A significant decrease in nut number occurred at the 2 ppt treatment with a further drop at 3 ppt, and again at 4 ppt in the acclimatising experiment (Fig 7B). A similar trend was observed in the shock experiment (Fig 7B, E). Information on both percentage of ripened pods and total number of nuts/ plant should be taken together to make concrete inferences. For example, in the 2 ppt treatment of the acclimatising experiment, number of nuts were -44% eventhough proportion of ripened pods remained similar to control (0 ppt) conditions (Fig 7A-B). In the same acclimatising experiment, the 4 ppt treatment caused reduction of both number of nuts and percentage of ripe pods i.e., - 76% nuts and -15% ripe pods. In all cases of the experiments,

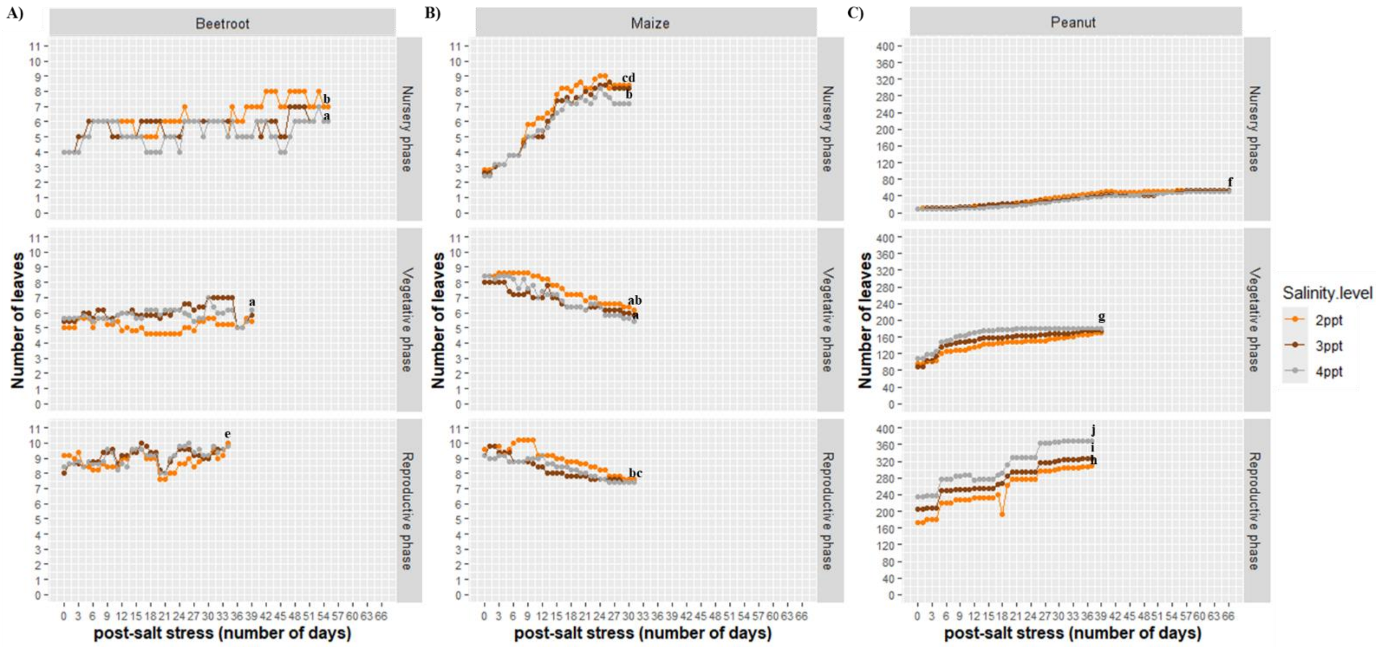

Figure 4. Crop development in shock saline experiment. Leaf number for beetroot (A), maize (B) and peanut (C) at different developmental growth stages- nursery phase, vegetative phase or reproductive phase. Measurements were taken daily for duration of the shock saline experiment. Here, salty treatments were achieved by irrigation with defined NaCl treatments of 2, 3 and 4 ppt every three days for experimental duration. Day 0 on the x-axis represents the first day of saline irrigation of the crops until a maximum of 66 days post-salt stress. Statistics performed by two-way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

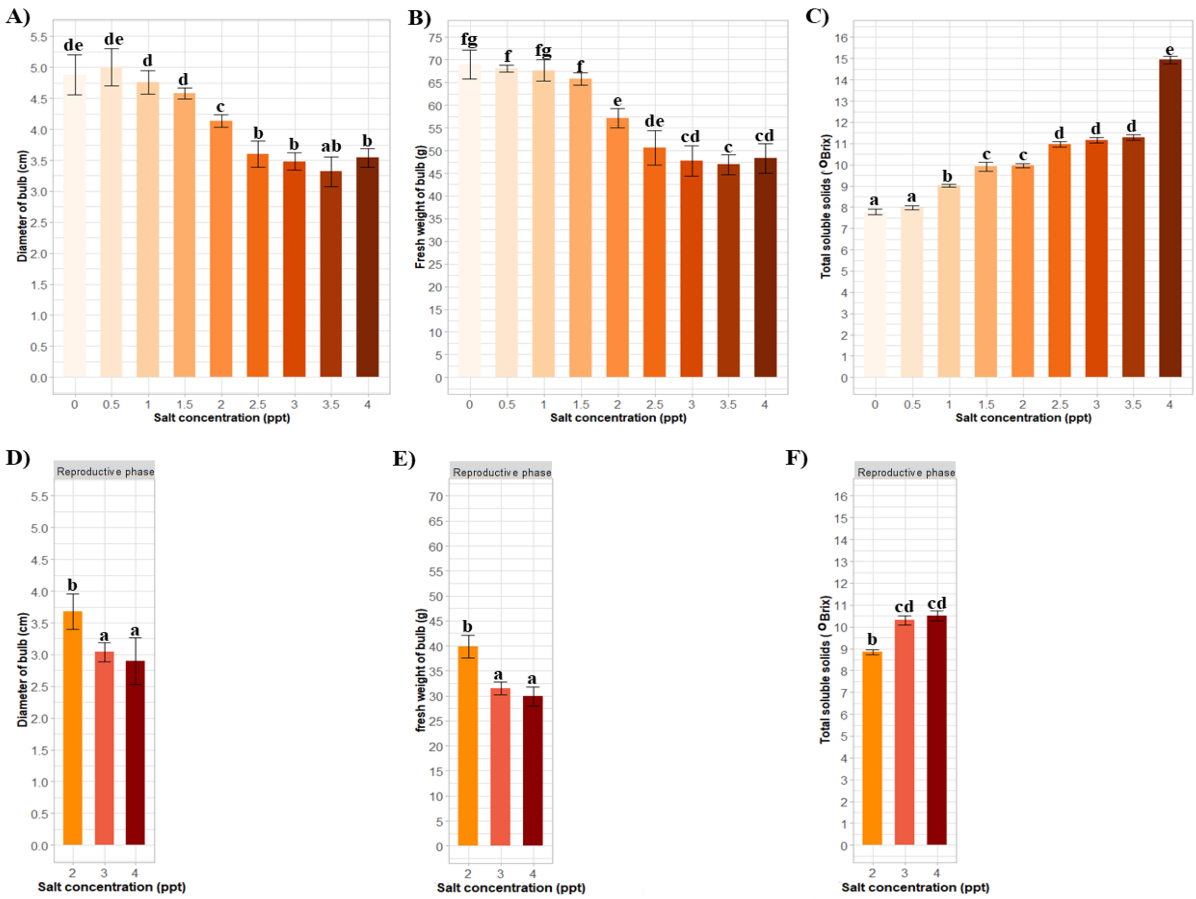

Figure 5. Bulb yield under salinized conditions. Beetroot yield and quality of 108-day old plants in acclimatising saline experiment (A-C) and 90-day old plants in shock saline experiment (D-F). Bulb diameter (A, D) bulb fresh weight (B, E) and total soluble solids (C, F) were assessed in both experiments. In the acclimatising salt experiment, control treatment (0 ppt) was established by irrigation of soil pots using water without NaCl. Salty treatments were achieved by increasing salt concentration by 0.5 ppt NaCl solution at every timepoint until defined salt treatments of 0.5 to 4 ppt were reached and thereafter, irrigation with water containing only the specified NaCl concentration. For the shock saline experiment, salty treatments were achieved by irrigation with defined NaCl solution of 2, 3 and 4 ppt every three days for experimental duration. We present data for salt treatment at the reproductive phase of development only since salt treated beetroot plants at nursery- and vegetative- stage of development in the shock experiment wilted, did not form tubers and eventually, died. Statistics performed by one-way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

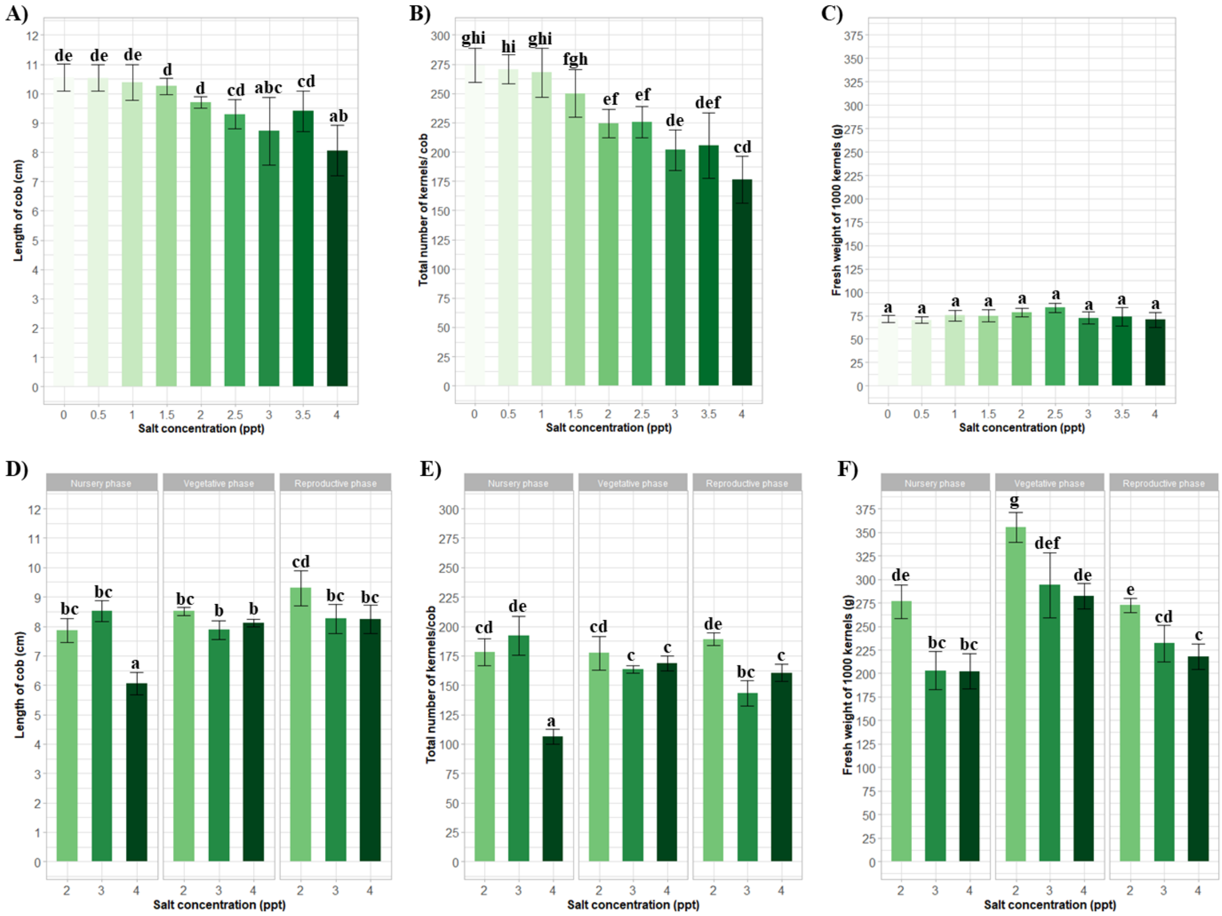

Figure 6. Maize yield under salinized conditions. Yield of 80-day old plants in acclimatising saline experiment (A-C); and 81-, 58- or 64-day old plants at nursery, vegetative-, or reproductive- phase of crop development respectively, in shock saline experiment (D-F). Cob length (A, D) kernel number (B, E) and fresh weight of 1000 kernels (C, F) were assessed in both experiments. In the acclimatising salt experiment, control treatment (0 ppt) was established by irrigation of soil pots using water without NaCl. Salty treatments were achieved by increasing salt concentration by 0.5 ppt NaCl solution at every timepoint until defined salt treatments of 0.5 to 4 ppt were reached and thereafter, irrigation with water containing only the specified NaCl concentration. For the shock saline experiment, salty treatments were achieved by irrigation with defined NaCl solution of 2, 3 and 4 ppt every three days for experimental duration. Statistics performed by one- (acclimatising experiment) or two- (shock experiment) way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

fresh weight of nuts similarly decreased with increasing salt concentration (Fig 7C, F).

Salt accumulation in the soil (EC ≥ 4 dS/m achieved with ≥ 2 ppt NaCl treatments) negatively impacts peanut yield, independent of the method of salt induction (Fig 1, 3, 7). This was already apparent as substantial reduction (-44%) of the number and fresh weight of nuts occurred at the 2 ppt treatment, compared to control. Thus, indicating that yield of peanut, like most glycophytes, are clearly affected by strong levels of salinity (Shannon 1997). In such cases, continuous irrigation with saline water containing ≥ 2 ppt NaCl even in one growing season, is not advisable.

Soil EC strongly correlated with crop yield and quality phenotypes

Correlation between agronomic phenotypes or parameters varied per salt induction experiment and per crop type (SFig 3-4). Generally, there were fewer strong associations between phenotypes analysed during plant growth compared to yield parameters.

During crop growth, beetroot had strong positive correlations between soil pH and number of leaves in the acclimatising experiment (SFig 3A). Additionally in the shock experiment, beetroot exhibited stong postive correlation between soil EC and pH only (SFig 3D). Both maize and peanut showed no strong associations between any of the analysed phenotypes in both their acclimatising and shock experiments (SFig 3B-C, E-F).

Soil EC had strong positive correlation with soil pH and total soluble solids of the bulbs as well as, strong negative correlations with yield phenotypes– diameter and fresh weight of beetroot bulbs, in the acclimatising experiment (SFig 4A). All yield and quality phenotypes also showed strong positive correlation with each other indicating that these traits may be physiologically related. In the shock experiment, soil EC exhibited strong negative correlation with fresh weight of bulbs, and strong positive correlation with total soluble solids only, similar to the acclimatising experiment but not with soil pH and diameter of bulbs (SFig 4A, D).

Correlations in maize were obvious in the acclimating experiment but not in the shock experiment (SFig 4B, E). Soil EC had negative correlations with cob length, and kernel number but had no correlation with fresh weight of 1000 kernels (SFig 4B). In this same acclimatising experiment, strong positive association was found between cob length and kernel number. In constrast, strong negative correlations occured between Soil EC and total nut number as well as, soil EC and fresh weight of nuts in both peanut acclimatising and shock experiments (SFig 4C, F). Thus, indicating a general trend of strong correlation between Soil EC and phenotypes measured during crop harvest, especially visible in beetroot and peanut.

Overall, soil EC significantly correlated with phenotypes analysed during crop harvest but not always with phenotypes measured during crop growth. This infers the importance of measuring salt concentrations in the soil even when vegetative growth of the crop has not yet been severely inhibited, since high salt (NaCl) concentration in the soil would ultimately result in changes to crop yield and quality over time.

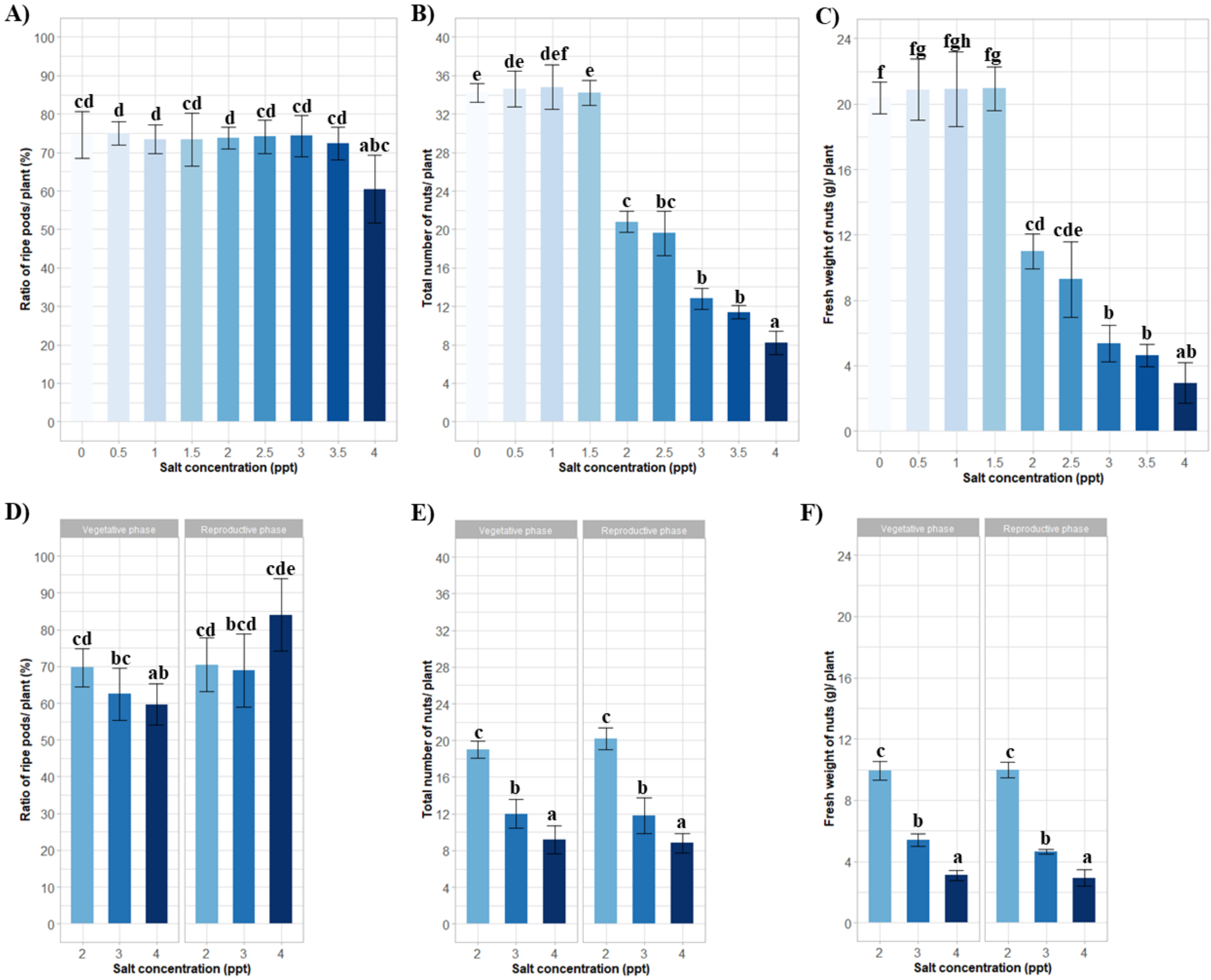

Figure 7. Peanut yield under salinized conditions. Yield of 100-day old plants in acclimatising saline experiment (A-C); and 86- or 93-day old plants at vegetative-, or reproductive- phase of crop development respectively, in shock saline experiment (D-F). Ratio of ripe pods (A, D), nut number (B, E) and fresh weight of nuts (C, F) were assessed in both experiments. In the acclimatising salt experiment, control treatment (0 ppt) was established by irrigation of soil pots using water without NaCl. Salty treatments were achieved by increasing salt concentration by 0.5 ppt NaCl solution at every timepoint until defined salt treatments of 0.5 to 4 ppt were reached and thereafter, irrigation with water containing only the specified NaCl concentration. For the shock saline experiment, salty treatments were achieved by irrigation with defined NaCl solution of 2, 3 and 4 ppt every three days for experimental duration. Data for salt treatment at the nursery phase of development is missing since the salt treated peanut plants in the shock experiment wilted, did not form pods and eventually, died. Statistics performed by one- (acclimatising experiment) or two- (shock experiment) way ANOVA with Tukey post hoc where different letters represent p-values ≤ 0.05.

Discussion

Maize and peanut sensitivity threshold to increasing salinisation

Crop cultivation on highly salinized soils negatively affects development, growth and yield of most plants. Our results agree with studies by Schubert et al. (2009) and Mindari et al. (2011), indicating that maize can tolerate irrigation with mild salt treatment equivalent to ≤ 2 ppt NaCl solution. Furthermore, irrigation of maize plants with water containing even higher salt concentration caused only slight changes to crop development in our experiments (Fig 2, 4). This was linked to the observed much lower than expected soil salinity levels of ~ 4 dS/m with the 4 ppt salt treatment (Fig 1, 3), that are actually synonynmous with expected soil EC values for continuous irirgation with 2 ppt NaCl treatment (Table 2). Interestingly, even this moderate salt stress condition (soil EC ~ 4 dS/m achieved by continuous saline irrigation with 4 ppt NaCl solution) still resulted in signifcantly smaller maize cobs and fewer kernels (Fig 6). Our results are also synonymous with studies showing that continuous irrigation with water of EC 4.5 dS/m throughout the growth cycle reduced cob weight, kernel number and kernel weight (Barbosa et al., 2012; Rodrigues et al., 2020). Overall, indicating that maize is a salt sensitive crop.

Peanut results (Fig 1-4, 7) are consistent with the cultivation activities of Duong and Pham (2012), indicating that saline water containing less than 2 ppt NaCl can be used for irrigation of peanut plants. Additionally, Meena et al. (2012) demonstrated that water and soil salinity levels of ≤ 4.0 and 1.6 dS/m respectively, stimulating mild salt stress, actually boosted peanut yield, consistent with our observations that lower salinity levels achieved by irrigation with the 0.5 or 1 ppt treatment, actually slightly enhanced crop growth and yield (Fig 2, 7). Higher salinity stress negatively impacted both pod and nut yield (Zhang et al., 2020; Nithin et al., 2023), similar to our record of smaller and/ or fewer pods and nuts under these higher salt stress conditions created by irrigation with ≥ 2ppt NaCl solution.

Beetroot copes better under increasing saline conditions

The maximum salinity threshold of beetroot is 3.5 ppt resulting in soil EC of ~ 7 dS/m (Bower et al., 1954). This is much higher than salinity thresholds of maize and peanut. Only high salinity stress caused considerable negative impact of beetroot growth and yield (Fig 1-5), similar to a study by Gadelha et al. (2021)

where reduced tuber productivity only happened under highly salinized conditions. When exposed to similar levels of salinity stress with the 4 ppt NaCl treatment, the yield- fresh weight of bulbs- of beetroot decreased by 27% compared to peanut that had an 86% decrease in fresh weight of nuts (Fig 5, 7).

Saltwater irrigation additionally induced higher sugar content in beetroot (Fig 5). To combat salinity, plants accumulate compatible solutes such as sugars (sucrose) and proline to maintain osmotic balance (Munns and Tester, 2008). Like our study, these compounds accumulated in sugar beets at higher salt stress (Tahjib-Ui-Arif et al., 2019; Abd El-Mageed et al., 2021). Overall, indicating that beetroot is a moderately salt tolerant crop. Irrespectively of these observations, high salt stress still affects beetroot yield (Hossain et al., 2017; Tahjib-Ui-Arif et al., 2019; Abd El-Mageed et al., 2021) and thus, to maintain high yield and good quality of the bulbs, it is still advisable to ensure water used for continuously irrigation should contain > 2 ppt NaCl.

Short-term and long-term impact of continuous saline irrigation

Salt tolerant crops can withstand irrigation with saline water containing high NaCl concentration (van der Heijden et al., 2013). In our studies, continuous irrigation with up to 1.5 ppt NaCl solution did not impact crop yield, indicating the potential of using mildly saline or brackish water for irriagtion. Beetroot had the smallest reduction in crop yield even with increasing salt concentration of the irrigation water and salt accumulation in soil. Thus, beetroot presents as the most suitable of the three tested crops for saline agriculture. Our results on using mildly salinized water for irrigation should be taken with care, since our experiments were performed in only one growing season, and the long term impact (years) of continuous saline irrigation still remains unknown. For example, whether the salt accumulated in the soil would be flushed out after one growing season or would it continue to build up over time, leading to severly salinized soils in the future.

In addition, care should be taken with sudden administration of water with high salt concentrations especially at early developmental stages of the crop. Our plants in the shock experiment appeared to be strongly weakened by saltwater irrigation resulting in several beetroot plants wilting and finally dying, when saline irrigation was applied at the earlier stages of crop development i.e., at nursery or vegetative stage. The same experience occurred for peanut plants in nursery phase of crop development. We recommend validating these findings with repeated experiments.

Role of beetroot as an alternative crop for one of the rice cropping seasons

All 13 provinces in the VMD cultivate rice as one of their main crops. However, this region faces considerable risks from climate change and extreme weather conditions leading to substantial loss of rice yield annually. It is imperative to identify alternative crops, and management practices that can supplement or compensate for the seasonal decline in rice income. For example, crops that have low water requirement and are salt tolerant are better suited for cultivation during dry season in the VMD, when drought and salinisation are prevalent. By identifying viable alternative crops such as beetroot (Tahjib-Ui-Arif et al., 2019; Zörb et al., 2019), farmers may seize new income-generating opportunities to offset economic losses incurred from dry season rice cultivation. Other crops such as quinoa and mustard green may also serve as alternative crops and have similar water use efficiency and salinity tolerance as beetroot (Kaveney et al., 2023). However, other factors such as existing market, technology (including cultivation expertise) and machinery must be equally considered before crop selection and cultivation is initiated.

Adoption of effective management practices like mulching, soil moisture conservation and drainage are additional practises that should be simultaneously implemented with the introduction of alternative crops (Nguyen, 2017; Kaveney et al., 2023). Mulching was found to further improve beetroot productivity under saline conditions (Gadelha et al., 2021). The documentation of factors that contribute to successful diversification, and adapting cropping sytems can play a pivotal role in guiding decision-making processes and fostering collaboration among farmers, agribusinesses, and government agencies.

Materials and Methods

Location of study

Plant experiments were performed in Tra Vinh, a province located in the VMD. The province is situated between rivers Hau and Co Chien, and adjacent to the East Sea (Fig 8). Although most areas of Tra Vinh still have freshwater in wet seasons due to recurring rainfall, some areas almost permanently have salinized ground- and surface- water (Nguyen et al., 2021). Due to increasing periods of drought and salinity intrusion, salt (NaCl) concentration of 4 ppt have already been detected 50-130 km deep into the main rivers Hau and Co Chien that run through Tra Vinh, since 2020 (Loc et al., 2021). Simulations based on backcasting also indicate a steady increase in salinity annually in the VMD (Eslami et al., 2021; Loc et al., 2021; Kaveney et al., 2023) thus, water resources found in Tra Vinh are expected to have salt concentrations of at least 4ppt. Intruding saline water mixes with freshwater obtained from rivers, lakes and ponds (surface water) replenished by rainfall, resulting in brackish water with differential saline concentrations. This is the main reason why Tra Vinh was selected as the location for our experiments since several farmers in this area need interventions to adapt to permanent salinity, while others may still benefit from interventions that minimise use of freshwater resources.

Salinity experiments were conducted in two nethouses at the agricultural experimental station (9° 55′ 19.2″ N, 106° 20′ 49.2″ E) of Tra Vinh University (TVU) in 2022 and 2023 (Fig 8). Each nethouse had an area of 18 m x 9 m. The nethouses were covered with white plastic tarpaulin to protect plants from rainfall and maintain salinity levlels for the duration of our experiments.

Soil preparation

Textured loam-clayey soil (Table 1) obtained from a farming field (9°39'23.2"N 106°19'02.6"E) at Ham Giang commune, Tra Cu district in Tra Vinh province was used in the experiment. Top layer (20 cm depth from the surface) of the loam-clayey soil was transferred to the TVU experimental station. The soil had an initial pH of 6.2, 0.52 dS/m soil EC, and organic matter content of 1.26% (Table 1). Soil moisture content was adjusted and maintained at 70-80% via irrigation during the plant experiments. Compost containing dried cow manure, rice husk and coconut coir in a 5:3:2 ratio was used. The organic compost mixture was then treated with Emzeo microbial product and bacteria *Trichoderma* sp. for 7 days. This is a commonly recommended formula to prepare compost in the VMD. The final compost mixture was combined with soil in a 1:1 ratio and dispensed into pots at 8-10 kg of soil mixture per pot.

Experimental design

Three crops were included in the experiments. Beetroot (*Beta vulgaris* TN23), maize (*Zea mays* Milky 36), and peanut (*Arachis hypogaea* MD7) were cultivated at the TVU experimental station. Seeds were purchased from a local agricultural seed center and are widely cultivated varieties in Vietnam. Generally, maize and peanut are classified as salt sensitve crops since their yields are critically affected under highly salinized conditions while beetroot is considered a salt tolerant crop (Maas et al., 1977; Shannon, 1997). The selected varieties of the crops have not yet been classified for their salinity responses however, some have other desirable traits. For example, peanut variety MD7 has high yield, improved protein content and is mildly susceptible to leaf spot disease (Nguyen et al., 2022).

Seeds were sown in plastic pots measuring 42 x 32 x 33 cm (top diameter x height x bottom diameter). The soil was supplied with sufficient water and nutrients to support growth and development based on crop requirement guidelines QCVN 01-

Figure 8. Location of Tra Vinh province in the Vietnamese Mekong Delta (adapted from Nguyen, 2016). The province (highlighted with a red star) is bounded by river Hau on the left and river Co Chien on the right. Plant experiments were performed at Tra Vinh University indicated with a location marker in the province.

Figure 9. Experimental setup in nethouses (9° 55′ 19.2″ N, 106° 20′ 49.2″ E) at Tra Vinh University. Plants were cultivated in pots placed in a randomised complete block design. There was a total of 5 pot replicates per treatment (per developmental stage) per crop type.

56:2011/BNNPTNT for maize, QCVN 01-57:2011/BNNPTNT for peanut, and Starke Ayres (2019) for beetroot. At the start of the experiment, three seeds were sown which was reduced to a single seedling per pot when the plant developed three to four true leaves. Only healthy seedlings of uniform size per crop were left in the soil pots. The plants were arranged in a randomised block design (Fig 9).

Saline irrigation of crops
Brackish water occurs from saline water mixing with freshwater from rivers (in estuaries) or groundwater in coastal aquifers. This slightly saline water usually has chloride levels between 0.5 to 5ppt, and sodium content of 1 to 10 ppt (EnviroSci Inquiry, 2011). The Vietnamese authorities suggest that salinity threshold for crop irrigation should not surpass 4 ppt since this concentration is already regarded as detrimental to rice productivity (Tuan et al., 2007). Therefore, in our experiments, this 4 ppt NaCl concentration was not surpassed.
Salinity treatments were introduced by irrigation with differential concentrations of NaCl solution until expected soil saline conditions were reached, or the crops reached full maturity and were harvested. Two methods for saline induction were used denoted as acclimatising saline experiment, and shock saline experiment (Table 2).

Acclimatising saline experiment
Acclimatising saline experiment defined by continuous and increasing saline irrigation was initiated when plants had 3-4 true leaves (Table 2). Thus, the experiment began at the nursery phase of crop development. There was a total of 9 treatments per crop type in the acclimatising saline experiment ranging from 0 to 4 ppt.
Control condition was established by irrigation with water containing no NaCl and so denoted as 0 ppt. Here, salty conditions in the pots were achieved by irrigating with NaCl solution that increased by 0.5 ppt every 3 days until the defined soil salinity level for that treatment was reached (Table 2). For example, for a 4 ppt salt treatment, first a 0.5 ppt NaCl solution was used for irrigation at timepoint denoted as day 0 of salt induction. This was increased to 1-, 1.5-, 2-, 2.5-, 3-, 3.5- and finally, 4 ppt NaCl solution on day 3, 6, 9, 12, 15, 18 and 21 post-salt stress induction, respectively. After which, salt treatment added to the pots every 3 days was the 4 ppt NaCl solution, until the desired salt concentration in the soil was reached or the crop was fully mature and ready for harvest. In cases where the expected soil salinity level was reached prior to crop harvest, especially at lower salt treatments, crops were then irrigated with non-saline water (0 ppt) to maintain salt concentration in the soil.
There were 5 replicates per NaCl treatment (0, 0.5, 1-, 1.5-, 2-, 2.5-, 3-, 3.5-, or 4 ppt) per crop (beetroot, maize or peanut) in the acclimatising saline experiment.

Shock saline experiment
Shock saline experiment was defined by saline irrigation initiated at different developmental stages of crop growth (Table 2). Again, a total of 9 treatments per crop type, were investigated in the shock saline experiment.
Shock experiment differed from acclimatising experiment since crops were immediately irrigated with the specific salt treatment, and not increasing salt concentration over time, as in the acclimating experiment (Table 2). Here, only three different salt concentrations i.e., 2- 3- or 4 ppt NaCl solution were used for crop irrigation. Additionally, salt treatments in the shock experiment were added per crop from the beginning of any of the three specified developmental stages namely nursery-, vegetative- or reproductive- phase of crop development. Saline irrigation occurred every 3 days for the duration of that developmental stage. The rationale of including differential salt treatment at different crop developmental stages was to evaluate the sensitivity of plant growth phase to increasing salinity.
There were 5 replicates per salt treatment (2-, 3-, or 4 ppt) per developmental stage (nursery-, vegetative-, or reproductive-

Table 1. Physical and chemical properties of loam-clayey soil used in the plant experiments. Soil was obtained from 20 cm depth of a farm field (9°39'23.2"N 106°19'02.6"E) in Tra Cu district, Tra Vinh province.

Soil characteristic	
pH H_20	6.2
Electrical conductivity (ECe)	0.52 dS/m
Density	1.46 g/cm^3
Moisture content	42.07 %
Sodium exchange	1.38 meq/100g
Calcium exchange	7.88 meq/100g
Magnesium exchange	8.94 meq/100g
Cation exchange capacity (CEC)	18.50 meq/100g
Organic matter content	1.26 %
Sand	24.86 %
Loam	39.91 %
Clay	35.23 %

Table 2. Overview of salt treatments in plant experiments. The type of saline induction, developmental stage of crop growth, salt level or concentration of the NaCl solution used for irrigation (and serving as salt treatments), and expected salinity levels in the soil are in the defined table rows.

Type of saline induction	Developmental stage of the crop	Salt level in water (NaCl solution) for irrigation (ppt)	Expected soil EC (dS/m)
Acclimatising saline experiment	Continuous saline irrigation. Salt treatment begins when crops have 3 to 4 true leaves, which is equivalent to the nursery phase of crop development.	0	~0
		0.5	1
		1	2
		1.5	3
		2	4
		2.5	5
		3	6
		3.5	7
		4	8
Shock saline experiment	Nursery phase	2	4
		3	6
		4	8
	Vegetative phase	2	4
		3	6
		4	8
	Reproductive phase	2	4
		3	6
		4	8

Table 3. List of agronomic parameters (phenotypes) analysed in the experiments. The crop type, type of saline induction, phenotypes measured during crop growth, and those measured at crop harvest are represented in specified table columns.

Crop	Type of saline induction	Crop growth phenotype	Crop yield phenotype
Beetroot	Acclimatising saline experiment	Soil EC, soil pH, number of leaves	Bulb diameter, bulb fresh weight, total soluble solids
	Shock saline experiment		
Maize	Acclimatising saline experiment		Cob length, number of kernels per cob, fresh weight of 1000 kernels
	Shock saline experiment		
Peanut	Acclimatising saline experiment		Percentage of ripe pods, number of nuts per plant, fresh weight of nuts per plant
	Shock saline experiment		

phase) per crop type (beetroot, maize or peanut) in the shock saline experiment.

Plant care

Plants were watered once in the late morning, daily and soil moisture content maintained between 70-80%. In cases of salt treatment, NaCl solution was addded to the soil surrounding the plants, and never directly on the plant foilage.

Water was obtained from the surrounding river and pumped to a reservoir for use in the experiments. Plants were fertilised periodically according to their nutritional requirement and developmental stage of the crop based on recommendations from guidelines mentioned in the "experimental design" section. It should be noted that not all beetroot and peanut plants survived until harvest in the shock saline experiment only. Salt treated beetroot plants at nursery- and vegetative-stage of development wilted and ultimately died. Thus, did not form tubers. Similarly in peanut, salt treatment at the nursery phase eventually resulted in plant death and therfore, no production of pods or nuts under this condition.

Data collection and analysis

For the duration of the experiment, several agronomic parameters or phenotypes were measured and further analysed (Table 3). In all cases independent of crop type and salt induction experiment, soil EC, soil pH and leaf number were assessed. Crop yield parameters differed per crop type.

Statistical analysis was performed in R. R-studio packages 'plyr' and 'ggplot2' (Wickham 2009, 2011) were used for data processing and graphs, while packages 'nlme' and 'multcomp' (Hothorn et al., 2008; Pinheiro et al., 2023) were used for calculating statistics significance for the difference in means. Statistics was performed by a one-way (factor: salt treatment) or two-way (factors: developmental stage and salt treatment) ANOVA with Tukey Posthoc where different alphabets represent p-values ≤ 0.05. Correlation and principal component analysis was performed using packages 'ggcorrplot' and 'factominer' (Lê et al., 2008; Kassambara and Patil, 2023). Future Perspectives and Conclusion

The national agenda on sustainable agricultural development in Vietnam promotes saline agriculture to improve productivity in the VMD. Nevertheless, it is vital to avoid exploitation of limited freshwater resources. Using brackish water for crop irrigation has potential but also clear limitations. By understanding plant tolerance to salinity stress, we can optimise irrigation practices, make informed decisions, and effectively adapt to sustainable agricultural systems. For instance, it is relevant to know that peanut should not be irrigated with saline water containing more than 1.5 ppt NaCl in one growing season. It is therefore important that farmers have practical tools to measure water quality used for irrigation.

Ultimately, this knowledge empowers stakeholders to effectively manage water resources and mitigate salt accumulation in the soil that impacts overall agricultural sustainability. The positive quality response of beetroot to continuous irrigation with 1.5 ppt NaCl solution is promising and needs further result validation. To encourage farmers to use water with mild salt concentration for irrigation, it is essential to conduct long term muti-year measurements in field conditions. This study should be complemented with research on factors that may support or hinder adoption of salinity response solutions by farmers as well as, the role of other stakeholders in the agri-food value chain of the VMD. It is equally important to discuss challenges and solutions related to the entire beetroot production value chain with identified food system stakeholders. This will enable a comprehensive understanding of the viability of using water with salt concentration up to 1.5 ppt for irrigation of commonly cultivated crop.

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CRediT authorship contribution statement

BTNT: Conceptualisation, Methodology, Investigation, Writing – original draft, Writing – review & editing. UHN: Conceptualisation, Methodology, Investigation, Writing – original draft. AOD-A: Data Curation, Visualisation, Writing – original draft, Writing – review & editing. PMN: Conceptualisation, Methodology. MS-S: Methodology, Writing – review & editing, Funding acquisition.

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