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# Effects of pre-harvest brackish water exposure on leafy green growth in aquaponic systems

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Growing interest in brackish or saline aquaponics (also known as haloponics) has highlighted the need for production strategies that enable growers to utilize saltier, more nutrient rich, water sources without reducing crop yield. The present study was conducted at Virginia State University, located in central Virginia, USA, and assessed whether short-term, pre-harvest exposure to low-salinity water could improve leaf tissue mineral content while minimizing growth penalties in non-halophyte leafy greens cultivated in aquaponic systems. A 30-day greenhouse experiment was conducted with six replicated raft aquaponics systems stocked with Nile tilapia (*Oreochromis niloticus*) and planted with Kale (*Brassica oleracea* var. Black Magic), Swiss chard (*Beta vulgaris* var. Bright Lights), and Watercress (Nasturtium officinale). Three systems were subjected to brackish conditions (5 ppt marine salt) for five days before harvest, while three systems served as freshwater controls. Plant growth metrics, leaf tissue elemental composition, water quality, and fish performance were compared between treatments using two-sample t-tests. Pre-harvest salt exposure led to significant biomass reductions in Swiss chard and Watercress, while Kale biomass remained unchanged. All three crops showed significant increases in leaf sodium (Na), chloride (Cl), and boron (B) concentrations after salt exposure, and reductions in leaf calcium (Ca). Water quality remained within suitable ranges for aquaponic production across treatments, with salt addition increasing salinity-associated ions (including Na, Cl, Ca, Mg), alkalinity, pH, and turbidity, while reducing dissolved iron (Fe), zinc (Zn), and phosphate ($PO_4$) concentrations, but without adversely affecting fish performance. This research demonstrates that brief, pre-harvest exposure to low-salinity water can enhance leaf mineral accumulation in salt-tolerant crops such as Kale without reducing yield. This strategy may provide aquaponic producers with a practical method to manage moderately saline water sources or to produce value-added specialty greens in response to increasing freshwater limitations.

KEYWORDS
**aquaculture, hydroponics, kale, sustainable agriculture, swiss chard, controlled environment agriculture, floating raft, Watercress**

# 1 Introduction

Freshwater scarcity poses a growing threat to global food security, particularly in regions where agriculture already competes with industrial, municipal, and ecological demands for limited water resources (Ingrao et al., 2023; Liu et al., 2022). Accelerating salinization of soils and irrigation water further constrains crop productivity, diminishing arable land while increasing production costs for growers (Cuevas et al., 2019; Machado and Serralheiro, 2017; Mohanavelu et al., 2021). These converging challenges underscore the urgent need for system specific knowledge regarding the feasibility of cultivating crops under saline or brackish conditions. Understanding plant and system responses to elevated salinity is especially important for controlled environment agriculture (CEA), including aquaponics, where water is continually recirculated and even minor shifts in water quality can influence nutrient dynamics, biological filtration, and crop performance (Vidalis et al., 2024; Ma et al., 2020; Rakocy et al., 2006).

Coastal and low-lying regions are particularly vulnerable to saltwater intrusion, a phenomenon that is increasingly compromising both groundwater wells and municipal water supplies (Basack et al., 2022; Jasechko et al., 2020; Klassen and Allen, 2017). Thus, formerly reliable freshwater sources are becoming progressively saltier, creating uncertainty for growers who rely on consistent water quality for sensitive crops. Some producers have responded by installing reverse osmosis (RO) treatment systems to remove salts; however, RO infrastructure is costly, energy intensive, and may be unnecessary if moderate increases in salinity do not negatively affect production—or if they provide unexpected benefits (Shabib et al., 2025; Malaeb and Ayoub, 2011). There is some evidence suggesting that modest salinity exposure can alter plant secondary metabolites, potentially improving taste, texture, or nutritional quality (Gruda et al., 2024; Kishor et al., 2023; Saha et al., 2021; Rouphael et al., 2018). Recent interest in brackish aquaponics (also known as haloponics) supports this, with some studies demonstrating saltier or improved flavor from non-halophyte crops produced in brackish aquaponic systems (up to 20 ppt) (Fisk et al., 2026; Bordignon et al., 2024; Kimera et al., 2023). These potential positive outcomes could allow growers to market saline-conditioned produce as premium or specialty products, thereby transforming a perceived water quality liability into an economic opportunity.

Beyond potential sensory and nutritional enhancements, naturally occurring salts in brackish and marine waters contain a diversity of macronutrients and micronutrients relevant to plant growth (Tomlin et al., 2025; Ventura et al., 2011). Elements such as calcium and potassium, which typically require supplementation in freshwater aquaponic systems, are present at appreciable concentrations in many brackish waters (Septian et al., 2024; Meena et al., 2023; John et al., 2022; Weyhenmeyer et al., 2019). Their presence raises fundamental questions about whether low-saline water inputs could reduce reliance on synthetic nutrient additives or improve nutrient bioavailability within aquaponics. However, despite growing interest, there remains limited peer reviewed research directly comparing the effects of marine derived salts on plants and fish within integrated aquaponic production systems. Even less is known about the short-term, pre-harvest exposure of crops to brackish water. A pre-harvest low-saline exposure approach has the potential to also be synced with producers practicing fish depuration within their systems (Davidson et al., 2022).

This work combines the recent interests in brackish aquaponics as well as the potential to integrate brackish water as an organic supplemental nutrient source for producers utilizing recirculating systems (Fisk et al., 2026; Nair et al., 2025; Bordignon et al., 2024). While moderate salinity has generally not been found to impair fish growth or water quality in aquaponic systems (Bordignon et al., 2024), non-halophyte crops such as kale have shown reduced growth and nutrient uptake when exposed to long term elevated salinities (Fisk et al., 2026). Most salt-tolerant non-halophytes, such as *Beta vulgaris* (Swiss chard) or *Brassica oleracea* (Kale), can grow in brackish water (up to 20 ppt for Kale) but have significantly reduced yields (Fisk et al., 2026; Kimera et al., 2023). Although growth is reduced, when exposed to brackish water these plants have a saltier and potentially more desirable flavor (Fisk et al., 2026). Therefore, rather than long-term exposure, this study exposed plants to a low saline brackish water condition (5 ppt of salt) 5 days prior to harvest.

The aim of this study was to minimize the reduction in growth while still potentially maintaining the flavor benefits. This was a unique approach that has not been well explored, particularly within aquaponic systems. These findings aim to clarify whether strategic use of brackish water can contribute to sustainable aquaponic production while maintaining or enhancing crop quality in the context of increasing freshwater limitations.

# 2 Materials and methods

## 2.1 Study location and system design

A single 30-day trial (March 25th–April 23rd, 2025) took place within a 600 $m^2$ controlled environment greenhouse located at Virginia State University's Randolph Farm (Petersburg, VA, USA). The study utilized six replicated raft aquaponic systems (Figure 1) that were recirculating coupled-loop systems (Symbiotic LLC, McAlester, OK). The systems had been operating for approximately 1 week prior to fish stocking, using water from an existing mature aquaponic system to ensure cycling was completed. Each system was configured with one 757 L fish tank, one 568 L sump tank, one 379 L grow bed with a floating raft board (1.7 $m^2$ grow area), and one Endurance 2,000 bead filter (Aquaculture Systems Technologies; Lafayette, LA). A 1.8 kW EasyPlug electric titanium immersion heater (Process Technology, Mentor, OH) was located within the fish tank to stabilize temperature within the system. A 6″ airstone was located within the fish tank and grow bed of each system to provide sufficient oxygen for the fish and plants. Water within the systems was circulated by a Tiny Might water pump (Waterway Plastics; Oxnard, CA) as well as an Active Aqua pump (Hydrofarm; Shoemakersville, PA). These two pumps recirculated water from the sump tank into either the fish tank or grow bed, which then allowed water to flow back into the centralized sump tank (Figure 2). The water flow rate going into the fish tank or grow bed was controlled using ball valves. Each system also had one oscillating fan (WW Grainger, Moraine, OH) placed by each grow bed to provide additional airflow.

## 2.2 Experimental design and background

Each grow bed contained three varieties of crops that included Kale (*Brassica oleracea* var. Black Magic), Swiss chard (*Beta vulgaris* var. Bright Lights), and Watercress (*Nasturtium officinale*) (Johnny Seeds, Winslow, ME). These crops were selected for their commercial relevance—nutrient-dense leafy greens are widely marketable and

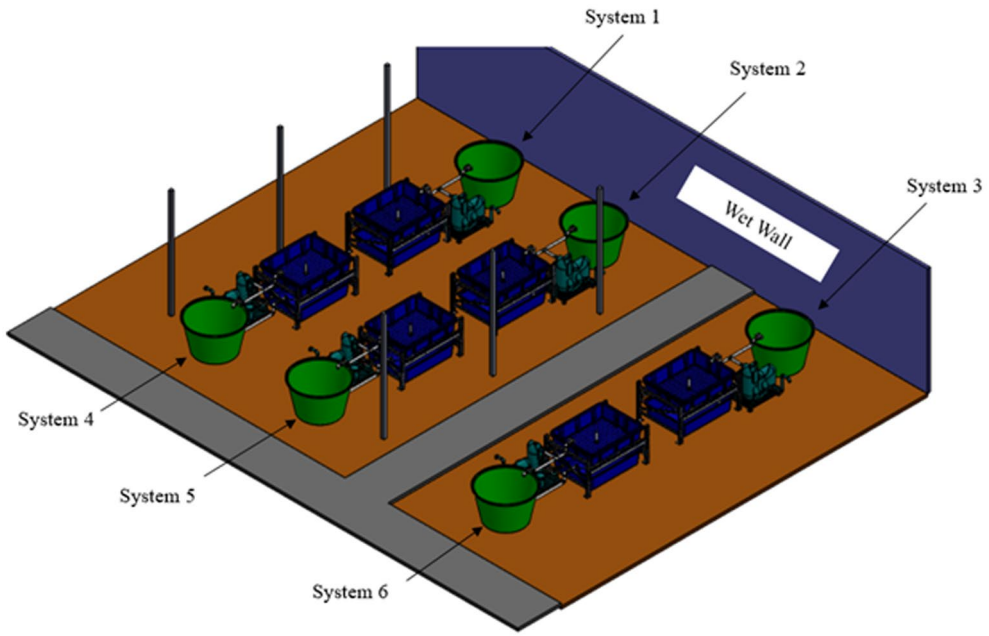



FIGURE 1
Overhead view of all six replicated systems within Greeenhouse at Virginia State University's Randolph Farm. Systems 1, 3, and 5 were the salt treatments while systems 2, 4, and 6 were the control (freshwater) treatments. This image was originally produced by Symbiotic, LLC (McAlester, OK) and edited for the purpose of this publication.

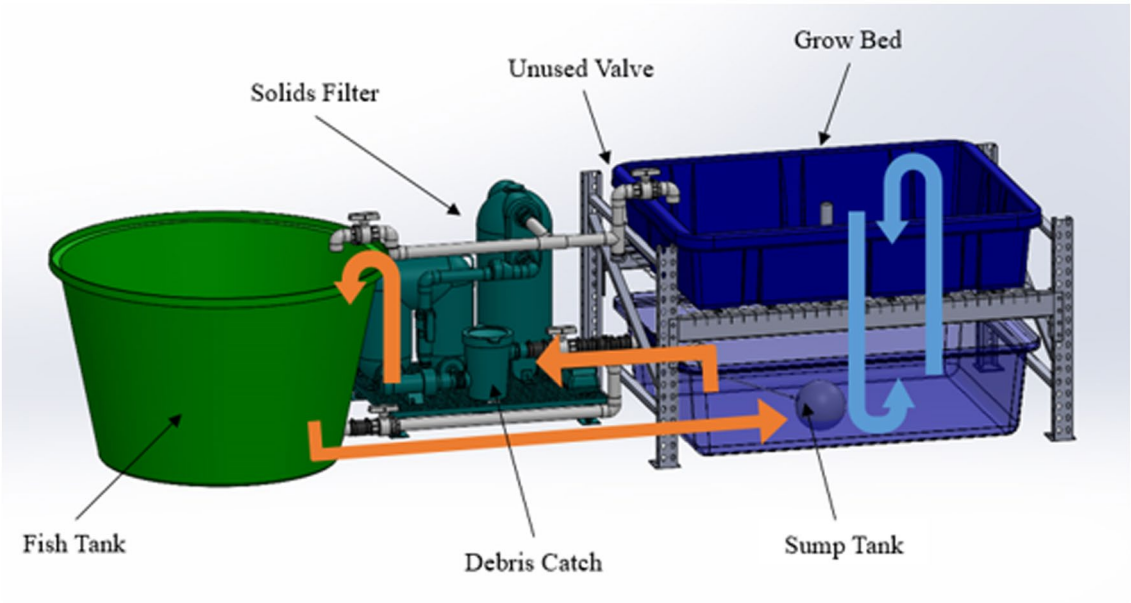



FIGURE 2
Individual configuration and components of each replicated system. The orange arrows indicate the flow of water between the sump tank and fish tank and the blue arrows indicate the flow of water between the sump tank and the grow bed. Flow of water for the fish tank went from the sump tank to the debris filter through the solids filter into the fish tank and then back into the sump tank. Flow of water for the grow bed went from the sump tank into the grow bed and back. This image was originally produced by Symbiotic, LLC (McAlester, OK) and edited for the purpose of this publication.

have high consumer interest in fresh produce markets. Additionally, these species had been used in previous research for brackish aquaponics, demonstrating some compatibility within brackish water conditions. Eighteen individual plants of each variety were stocked within each system for a total of 54 plants per system. Six total replicate systems (each containing 54 plants and a fish tank) were monitored. Each fish tank contained an average of 16 mixed sex Nile tilapia (*Oreochromis niloticus*) that were approximately 1 year of age (additional details in section 2.5 below). This fish species was selected for its fast growth rate, high consumer demand, and well-documented performance in aquaponic systems (Rakocy et al., 2026). Prior to each trial, all system water was homogenized and distributed equally to nullify any differences in water quality between treatments. One week prior to concluding the study, three of the replicate systems received

inputs of Instant Ocean Reef Salt (Spectrum Brands Holdings, Inc., Middleton, WI) to increase salinity to 5 ppt while the other three systems did not receive any salt inputs. The 5 ppt was maintained until the end of the trial to understand the effects of marine salt additions on late-stage plant growth and quality. Several types of data were collected to assess the effects of the pre-harvest salt additions, including: water quality, plant growth and quality, and fish growth. The protocols for data collection are outlined below.

## 2.3 Water quality

Water from the fish tank of each replicate system was tested daily for dissolved oxygen (DO–mg/l), temperature (°C), pH, Electrical Conductivity (EC–µs/cm), and salinity (PSU) using a Hanna multiparameter probe (Hanna Instruments; Woonsocket, RI) (Fisk et al., 2026; Dusci et al., 2021). Weekly measurements of Total Ammonia Nitrogen (TAN–mg/l), nitrite ($NO_2^-$–mg/l), nitrate ($NO_3^-$–mg/l), and Alkalinity ($CaCO_3$–mg/l) were done using a WaterLink Spin Touch (LaMotte Company; Chestertown, MD) (Fisk et al., 2026; Dusci et al., 2021). Weekly measurements of Iron (Fe–mg/l) were taken using a Hanna multiparameter photometer (Hanna Instruments; Woonsocket, RI). Weekly measurements of turbidity (NTU) were analyzed using a Hanna Turbidity meter (Hanna Instruments; Woonsocket, RI). Biweekly (two times a week) measurements of flow rate (l/min) into the fish tank and grow beds were taken using a timer and volumetric pitcher. Sludge from solids filters was drained twice a week and filter baskets were cleaned and rinsed during this time to prevent any organic waste build-up. Pre- and post-water samples were collected from each systems sump tank and sent to Waypoint Analytical (Chesterfield, VA) laboratory for analysis. This included analysis of four different cations (mg/l; $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $K^+$), four different anions (mg/L; $SO_4^{2-}$, $HCO_3^-$, $NO_3^-$, $PO_4^{3-}$), and seven other elements (mg/l; Cu, Zn, Mn, Fe, B, F, Mo) (Dusci et al., 2021).

Iron Chelate (DTPA 11%) was added after each weekly measurement to adjust iron concentration to 2.0 mg/L (Dusci et al., 2021; Kasozi et al., 2019). The pH of each system was maintained between 6.5–6.8 using potassium bicarbonate ($KHCO_3$) and calcium hydroxide ($Ca(OH)_2$) at equal quantities (1:1 ratio). These additions were added at a rate of 0.005 g/L of system water volume to increase the pH by 0.1. Dechlorinated freshwater additions were added on a weekly basis and recorded using a RESTMO electronic flowmeter (Restmo Innovations, Inc., Staten Island, NY), average total freshwater inputs (liters/system) were quantified at the end of the study. Flow rate entering the fish tank was maintained within 37–41 L/min while the flow rate entering the grow bed was maintained within 15–19 L/min (Tetreault et al., 2023). If the flow rate fell outside of this acceptable range, then it was noted and adjusted accordingly. A total of 7.5 g of $MgSO_4$ was added into each replicate on a weekly basis to balance K, Ca, and Mg ratios within the water column (Goddek et al., 2015).

Four YSI EXO2 (YSI Inc., Yellow Springs, OH) multiparameter sondes were deployed within one salt and one freshwater system to continuously monitor pH within the fish tanks and grow beds of the systems. Measurements were recorded at 30-min intervals throughout the experimental period. Upon completion of the experiments, all sensor data were downloaded using KOR software and subsequently processed in Microsoft Excel for data organization and graph development. Paired sample *t*-tests were performed to compare four system locations with Bonferroni adjustment for six pairwise tests.

## 2.4 Plant stocking and production

Kale, Swiss chard, and Watercress plants were used in this study. These crops were selected based on previous literature utilizing these crops within saline soil-less systems. Additionally, these crops allowed for various botanical characteristics to be explored within the data sets. Approximately 2 weeks prior to the beginning of the trial, Kale, Swiss chard, and Watercress seeds were sown into rockwool cubes and raised indoors under fluorescent lights in an external germination system (Bootstrap Farmers, Downingtown, PA), until first true leaves emerged. Upon first true leaf emergence, plants were then transplanted into the systems, which marked the official beginning of the study. Each system contained 18 plants of each plant variety, resulting in a planting density of ~31 plants/$m^2$ of grow area. Plant varieties were randomly grouped within a section of each grow bed to avoid any potential competition during growth.

At the end the trial, total fresh plant biomass was determined for each system. Four plants per variety per system were randomly selected to serve as representative plants to collect specific data during- and post-study to represent the population. These representative plants were used to quantify chlorophyll content (µmol/$m^2$) and plant height (cm) on a weekly basis. These samples were used to determine fresh weight (g of edible biomass), plant height (cm), brix (°Bx), and number of leaves. Additionally, these representative samples were freeze-dried until all moisture was removed and then sent for plant tissue elemental analysis at Waypoint Analytical (Richmond, VA). This included an analysis of 15 different elements (%–N, S, P, K, Mg, Ca, Na; mg/l–B, Zn, Mn, Fe, Cu, Al, Cl).

Fresh weight was determined by cutting the plant shoots at the top of the rockwool cube (Rockwool International; Hedehusene, Denmark) and then weighed without the roots. Chlorophyll was measured using an MC-100 Apogee Meter (Apogee Instruments, Inc., Logan, UT). Four leaves (two young and two old) per representative plant were used to calculate an average plant chlorophyll content. Plant height was quantified using a standard meter stick. Height was quantified by measuring from the top of the rockwool cube to the top of the plant shoots newest leaves. For watercress, this was done by gently lifting the plant into the air and running the longest stem up the meter stick. For Kale and Swiss chard, this was done by gently pushing the tallest leaf up the meter stick. Brix was quantified using a digital refractometer (Hanna Instruments; Woonsocket, RI). A mixture of both old and new leaves was juiced through a manual vegetable press; the juice was then strained to create a clean sample that was used to quantify Brix (Bumgarner and Kleinhenz, 2013). Lastly, air temperature (°C) and humidity (%) were recorded twice a day (AM and PM) using a digital hygrometer (Sper Scientific Instruments, Scottsdale, AZ) located on the grow beds of each system. These two readings were averaged to quantify daily air temperature and humidity.

## 2.5 Fish stocking and production

Each system was stocked with Nile Tilapia (mean individual weight of 231 g) to achieve an initial target biomass of ~3,600 g/system. The tilapia used were pureline mixed-sex sourced from Miami Aquaculture (Miami Aquaculture, Boynton Beach, FL) and were approximately 1 year of age. At the time of stocking, 10% of the population was randomly sampled as representatives for weight (g) and

length (cm). Throughout the study fish were fed a 3.5 mm floating commercial aquaponic specialty formula pellet that contained 38% protein and 8% crude fiber (Optimal Fish Food, Omaha, NE; now defunct). Fish were fed five out of 7 days per week. On feeding days, the fish were fed at a rate of 1.7% of their total biomass, which resulted in 60 g of feed input per day. This resulted in ~33 g fish feed input/$m^2$ of grow area/day (Krastanova et al., 2022). This 60 g was split into three separate 20 g feedings that occurred throughout the day (9 a.m.; 12 p.m.; 5 p.m.).

Throughout the study, any fish mortalities were recorded to quantify survival of fish within each treatment. At the end of the trial all surviving tilapia were counted and weighed within each replicate. The fish weights were then compared to initial weights to calculate total biomass gained, Food Conversion Ratio (FCR), and Specific Growth Rate (SGR; % weight gain per day). FCR (1) and SGR (2) were calculated using the equations below (Dusci et al., 2021):

$$FCR = \frac{Total\ Feed\ Input\ (g)}{Total\ Fish\ Biomass\ Gain\ (g)} \quad (1)$$

$$SGR\ (\%) = \frac{\ln W_2 - \ln W_1}{\Delta t} \quad (2)$$

Where $W_1$, $W_2$ and $\Delta t$ are body weight at the initial time (pre-study), body weight at the final time (post-study), and the period of time (30 days), respectively.

TABLE 1 Results from daily water quality and weekly water quality sampling, daily temperature and humidity sampling, as well as system inputs.

| Data type | Parameter | Salt | Fresh | *p*-value |
|---|---|---|---|---|
| Daily | Water temp (°C) | 25.8 ± 1.3 | 25.6 ± 1.0 | 0.35 |
| | DO (mg/l) | 7.0 ± 0.9 | 7.1 ± 0.8 | 0.37 |
| | pH | 6.8 ± 0.3 | 6.7 ± 0.2 | 0.06 |
| | EC (µs/cm) | 2,000 ± 3,222[a] | 479 ± 154[b] | <0.01 |
| | Salinity (PSU) | 1.1 ± 1.8[a] | 0.2 ± 0.1[b] | <0.01 |
| | Air temp (°C) | 22.9 ± 1.8 | 22.8 ± 1.7 | 0.85 |
| | Air humidity (%) | 57.4 ± 3.5 | 57.2 ± 3.1 | 0.89 |
| Weekly | TAN (mg/l) | 0.1 ± 0.1 | 0.1 ± 0.1 | 0.18 |
| | $NO_2^-$ (mg/l) | 0.2 ± 0.1 | 0.1 ± 0.2 | 0.31 |
| | $NO_3^-$ (mg/l) | 80.1 ± 37.6 | 85.7 ± 32.0 | 0.67 |
| | Fe (mg/l) | 1.9 ± 0.3 | 1.9 ± 0.3 | 0.94 |
| | Alkalinity (mg $CaCO_3$/l) | 27 ± 7.8[a] | 21 ± 6.8[b] | 0.05 |
| | Turbidity (NTU) | 3.0 ± 0.8[a] | 2.2 ± 0.5[b] | <0.01 |
| | FT flow (l/min) | 39.9 ± 0.5 | 39.9 ± 0.3 | 0.60 |
| | GB flow (l/min) | 16.9 ± 0.6 | 16.6 ± 0.6 | 0.17 |
| Inputs | Iron (g) | 40 ± 3 | 41 ± 3 | 0.76 |
| | $Ca(OH)_2$ (g) | 59 ± 3 | 58 ± 2 | 0.58 |
| | $KHCO_3$ (g) | 59 ± 3 | 57 ± 1 | 0.29 |
| | $H_2O$ (l) | 765 ± 38 | 712 ± 38 | 0.17 |
| | $MgSO_4$ (g) | 30 ± 0 | 30 ± 0 | 1 |

Data are presented as mean ± SD. Different superscript letters within rows denote significant differences between treatments ($p \leq 0.05$).

## 2.6 Statistical analysis

A two-sample student's *t*-test was used to compare plant, fish, and water quality data between treatments using the jamovi (Sydney, AU) statistical software. Treatments included marine salt addition (salt) and a control (freshwater). Prior to analysis, all data sets were log transformed to address unequal variances, particularly for variables with low concentrations in the water quality and plant tissue datasets. However, results are presented in untransformed form to facilitate interpretation. Data in tables are reported as means ± standard deviation with corresponding *p*-values. Significant differences ($p \leq 0.05$) are indicated using numeric superscripts (Steel and Torre, 1980).

# 3 Results

## 3.1 Water quality data

There were no significant differences ($p > 0.05$) between systems with and without the salt additions in terms of the environmental parameters, water flow, or chemical inputs (Table 1). Overall means (± SD) were: air temperature of 22.9 ± 1.6 °C; air humidity of 57.3 ± 3.3%; fish tank flow rate of 40.1 ± 0.4 L/min; grow bed flow rate of 17.0 ± 0.6 L/min; Fe DTPA 11% inputs of 41 ± 3 g; $Ca(OH)_2$ inputs of 59 ± 3 g; $KHCO_3$ inputs of 58 ± 2 g; $MgSO_4$ inputs of 30 ± 0 g; and $H_2O$ inputs of 739 ± 38 L. Flow rates for the fish tanks resulted in an hourly turnover rate of 3.2 and flow rates for the grow beds resulted in an hourly turnover rate of 2.7. No significant differences in daily water quality measurements of pH, water temperature, and DO were found throughout the study, with means (±SD) of 6.8 ± 0.3; 25.7 ± 1.1 °C; and 7.1 ± 0.8 mg/L, respectively. However, significant differences in EC and salinity were found between the salt and freshwater systems (Table 1). These differences were likely caused after salt additions, where observable increases in salinity and EC were seen (Figure 3). EC and salinity levels remained stable after the salt additions with nominal changes caused by fish metabolic waste production and freshwater additions occurring within the 5-day period. Further insight into the daily recordings showed that prior to the addition of salt the average salinity and EC within the salt systems (0.2 ± 0.06 PSU; 496 ± 71.1 µs/cm) were not significantly different ($p > 0.05$) than the freshwater systems (0.2 ± 0.06 PSU; 454 ± 74.3 µs/cm). Whereas after the salt addition the salt systems showed a significantly higher level of salinity and EC (4.9 ± 0.3 PSU; 8,767 ± 523 µs/cm) as compared to the freshwater systems (0.3 ± 0.03 PSU; 509 ± 32.6 µs/cm).

The YSI Sonde data measuring daily pH dynamics showed that the fish tanks maintained a significantly ($p \leq 0.05$) higher pH (6.7 ± 0.03) as compared to the grow beds (6.5 ± 0.03) (Figure 4). Following the salt addition, these differences became more pronounced with a system wide upward pH shift. The salt system fish tank reached the highest mean pH (7.2 ± 0.02[a]), followed by the salt system grow bed (6.9 ± 0.02[b]), the freshwater fish tank (6.6 ± 0.03[c]), and the freshwater grow bed (6.5 ± 0.04[d]), with all pairwise comparisons remaining significant after the Bonferroni correction (Figure 4). Results from weekly water analyses only found significant differences ($p \leq 0.05$) for turbidity and alkalinity between salt (3.0 ± 0.8 NTU; 27 ± 7.8 mg $CaCO_3$/l) and freshwater systems (2.2 ± 0.5 NTU; 21 ± 6.8 mg $CaCO_3$/l). The remainder of the weekly water quality means were: 0.1 ± 0.1 mg TAN/l; 0.2 ± 0.2 mg $NO_2^-$/l; 82.9 ± 34.8 mg $NO_3^-$/l.

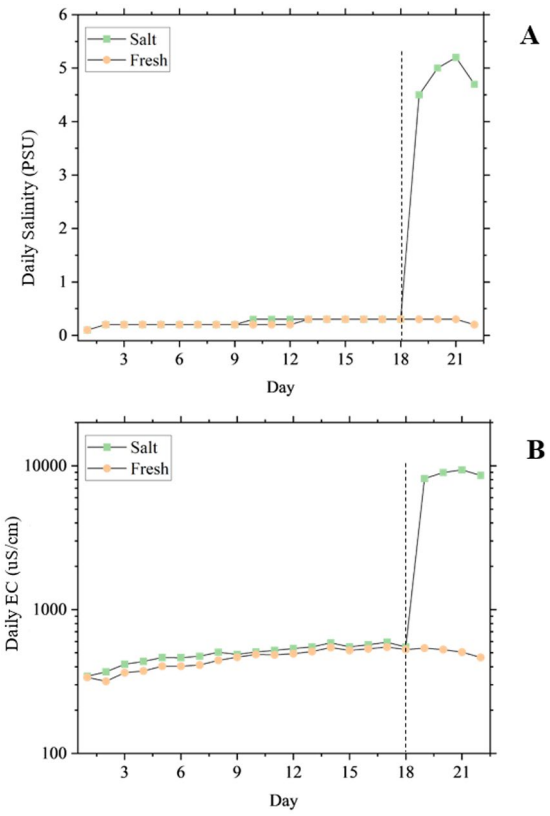



FIGURE 3
Graphs visualizing the increases in salinity **(A)** and EC **(B)** after the salt was added in on Day 17 (indicated by dotted line), or 04/17/2025. These readings were taken daily, in the morning, from the fish tank. Salt was added after daily morning readings on Day 17, which is why Day 18 shows the large jump.

Several significant differences ($p \leq 0.05$), some highly significant ($p \leq 0.01$), were determined by the waypoint analytical nutrient/elemental analysis of the water post-study (Table 2). Significantly higher concentrations of $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $K^+$, $Cl^-$, $SO_4^{2-}$, and B were found within the salt treatment (897 ± 182 mg $Na^+$/l; 56.0 ± 10.8 mg $Ca^{2+}$/l; 110 ± 27.4 mg $Mg^{2+}$/l; 54.0 ± 7.9 mg $K^+$/l; 1,457 ± 127 mg $Cl^-$/l; 258 ± 71 mg $SO_4^{2-}$/l; 0.38 ± 0.07 mg B/l) as compared to the freshwater control (30 ± 5.5 mg $Na^+$/l; 36 ± 4.3 mg $Ca^{2+}$/l; 7.3 ± 1.0 mg $Mg^{2+}$/l; 34 ± 6.1 mg $K^+$/l; 31 ± 4.0 mg $Cl^-$/l; 55 ± 9.8 mg $SO_4^{2-}$/l; 0.07 ± 0.03 mg B/l). Significantly lower concentrations of Fe, $PO_4^{3-}$, and Zn were found within the salt treatment (0.9 ± 0.3 mg Fe/l; 20 ± 3.8 mg $PO_4^{3-}$/l; 0.29 ± 0.01 mg Zn/l) as compared to the freshwater control (1.9 ± 0.2 mg Fe/l; 43 ± 7.3 mg $PO_4^{3-}$/l; 0.58 ± 0.08 mg Zn/l). Increases in most elements were seen between the pre- and post-study water quality results, regardless of treatment.

## 3.2 Plant growth and quality data

### 3.2.1 Kale

No significant differences ($p > 0.05$) were found between systems that did and did not receive salt for average individual weight (g/plant), height (cm), # of leaves, chlorophyll (μmol/m$^2$), or brix (°Bx) from the representative samples (Table 3). Additionally, no significant differences ($p > 0.05$) were found for average total fresh biomass harvested from the salt (1,107 ± 138 g) and freshwater systems (1,071 ± 178 g) (Figure 5). The leaf tissue elemental analysis did show several significant differences ($p \leq 0.05$) with many being highly significant ($p \leq 0.01$) (Table 4). Significant increases in Na, B, Mn, and Cl were found within the salt treatment (2.4 ± 0.3 Na %; 37.0 ± 1.0 mg B/l; 53.3 ± 6.1 mg Mn/l; 501 ± 50 mg Cl/l) as compared to the freshwater control (0.5 ± 0.2 Na %; 13.0 ± 2.0 mg B/l; 30.0 ± 11.0 mg/L; 208 ± 16 mg Cl/l). Significant decreases were found for Ca and Fe between the salt treatment (2.9 ± 0.3 Ca %; 63.7 ± 1.0 mg Fe/l) and freshwater control (4.0 ± 0.3 Ca %; 118.0 ± 19.3 mg Fe/l) (Table 4).

### 3.2.2 Swiss chard

No significant differences ($p > 0.05$) were found between systems that did and did not receive salt for average individual weight (g/plant), height (cm), # of leaves, chlorophyll (μmol/m$^2$), or brix (°Bx) from the representative samples (Table 3). The total biomass harvested was significantly lower ($p \leq 0.05$) in the salt treatment (1,597 ± 379 g) compared to the freshwater control (2,090 ± 100 g) (Figure 5). The leaf tissue elemental analysis did show significant differences ($p \leq 0.05$) with many being highly significant ($p \leq 0.01$) (Table 4). Significant decreases were found for K, Ca, Fe, and Al between the salt treatment (6.2 ± 0.3 K %; 0.9 ± 0.2 Ca %; 63.0 ± 10.8 mg Fe/l; 26.7 ± 7.8 mg Al/l) and freshwater control (7.2 ± 0.4 K %; 1.4 ± 0.0 Ca %; 162.3 ± 27.0 mg Fe/l; 60.3 ± 8.0 mg Al/l). Significant increases in Na, B, and Cl were found in the salt treatment (3.7 ± 0.4 Na %; 40.7 ± 1.2 mg B/l; 600 ± 25 mg Cl/l) as compared to the freshwater control (2.5 ± 0.2 Na %; 20.3 ± 4.2 mg B/l; 220 ± 36 mg Cl/l) (Table 4).

### 3.2.3 Watercress

No significant differences ($p > 0.05$) were found between systems that did and did not receive salt for average individual weight (g/plant) or brix (°Bx) from the representative samples (Table 3). Highly significant differences ($p \leq 0.01$) were found for height and chlorophyll between salt (51.9 ± 9.1 cm; 21.6 ± 2.7 μmol/m$^2$) and freshwater systems (67.5 ± 9.6 cm; 19.1 ± 2.9 μmol/m$^2$). Additionally, there was a highly significant ($p \leq 0.01$) decrease found in average total biomass harvested from the salt (1,410 ± 167 g) and freshwater systems (2,376 ± 213 g) (Figure 5). The leaf tissue elemental analysis did show significant differences ($p \leq 0.05$), with many being highly significant ($p \leq 0.01$) (Table 4). Significant increases of Na, Mg, B, Mn, and Cl were found within the salt treatment (2.4 ± 0.3 Na %; 0.5 ± 0.0 Mg %; 38.7 ± 2.5 mg B/l; 78.3 ± 10.5 mg Mn/l; 490 ± 51 mg Cl/l) as compared to the freshwater control (0.3 ± 0.0 Na %; 0.3 ± 0.0 Mg %; 27.3 ± 3.2 mg B/l; 45.0 ± 1.7 mg Mn/l; 299 ± 21 mg Cl/l). Significant decreases in Ca and K were found within the salt treatment (1.7 ± 0.3 Ca %; 3.6 ± 0.3 K %) as compared to the freshwater control (2.7 ± 0.3 Ca %; 7.7 ± 2.0 K %; %) (Table 4).

## 3.3 Fish growth data

Both treatments had a 98% survival of fish, with both treatments losing a single fish throughout the study. The cause of death is unknown as the fish were not sent for analysis to determine if health related factors caused the mortalities. However, fish jumping out of the tank is likely the cause of death as the fish were found external to the fish tank on the ground. Overall, no significant differences

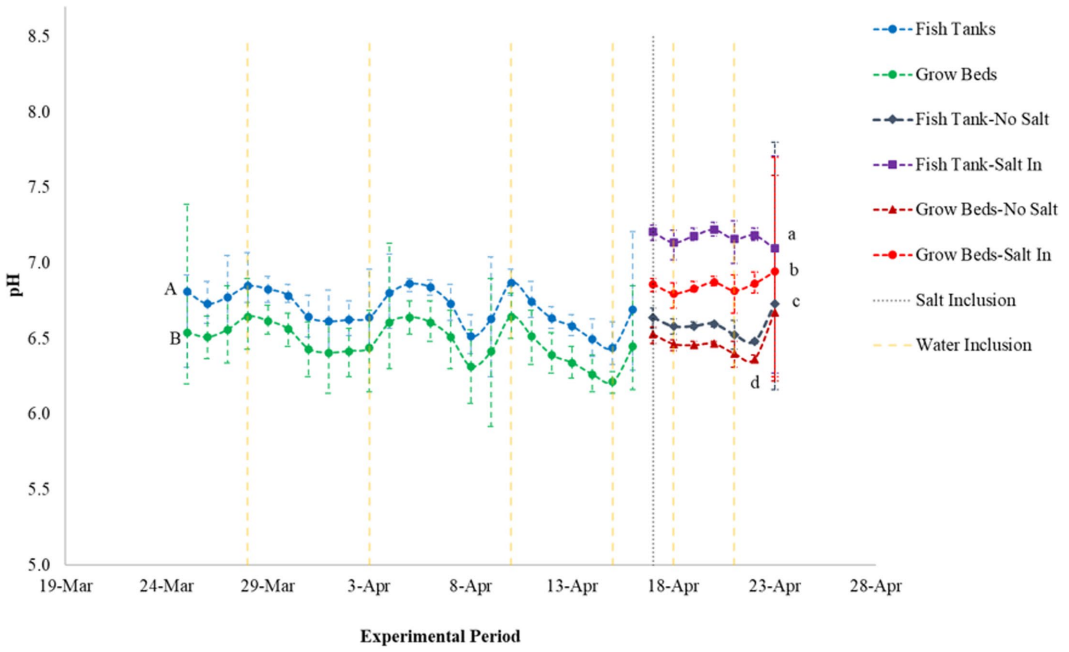



FIGURE 4
Daily pH variation in fish tanks and grow beds over the experimental period. Points represent daily mean pH values, and error bars indicate the minimum and maximum measurements recorded within each 24-h period. The vertical black dashed line denotes the time of salt addition, while vertical orange dashed lines indicate water addition events. Uppercase letters indicate significant differences among treatments prior to salt addition, and lowercase letters indicate significant differences following salt addition (paired *t*-tests with Bonferroni correction, $p \leq 0.05$). Treatments sharing the same letter are not significantly different.

TABLE 2 Results for the post-harvest water quality samples showing elemental concentrations of representative samples from both treatments.

| Element (mg/l) | Salt | Fresh | *p*-value |
|---|---|---|---|
| $Na^+$ | 897 ± 181[a] | 30 ± 6[b] | <0.01 |
| $Ca^{2+}$ | 56 ± 11[a] | 36 ± 4[b] | 0.03 |
| $Mg^{2+}$ | 110 ± 27[a] | 7 ± 1[b] | <0.01 |
| $K^+$ | 54 ± 8[a] | 34 ± 6[b] | 0.02 |
| $Cl^-$ | 1,457 ± 127[a] | 31 ± 4[b] | <0.01 |
| $SO_4^{2-}$ | 258 ± 71[a] | 55 ± 10[b] | <0.01 |
| $HCO_3^-$ | 82 ± 9 | 72 ± 1 | 0.12 |
| $NO_3^-$ | 46 ± 5 | 68 ± 23 | 0.15 |
| $PO_4^{3-}$ | 20 ± 4[a] | 43 ± 7[b] | <0.01 |
| Cu | 0.06 ± 0.04 | 0.06 ± 0.01 | 0.72 |
| Zn | 0.29 ± 0.02[a] | 0.58 ± 0.08[b] | <0.01 |
| Mn | 0.02 ± 0.02 | 0.01 ± 0.01 | 0.77 |
| Fe | 0.9 ± 0.3[a] | 1.9 ± 0.2[b] | 0.02 |
| B | 0.38 ± 0.07[a] | 0.07 ± 0.03[b] | <0.01 |
| Al | 0.10 ± 0.00 | 0.10 ± 0.00 | 1 |
| Mo | 0.03 ± 0.01 | 0.03 ± 0.01 | 1 |

Data are presented as mean ± *SD*. Different superscript letters within rows denote significant differences between treatments ($p \leq 0.05$).

($p > 0.05$) were found for Feed Conversion Ratio (FCR) or Specific Growth Rate (SGR) between the salt (2.3 ± 0.5 FCR; 0.5 ± 0.1% SGR) and freshwater systems (2.3 ± 1.8 FCR; 0.8 ± 0.7% SGR) (Figure 5).

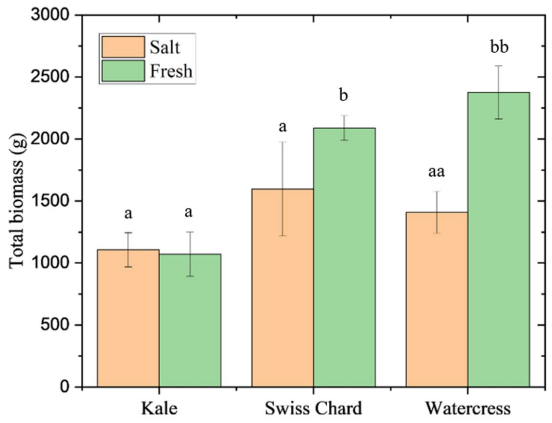



FIGURE 5
Average total biomass produced for each variety within the salt and freshwater systems. Significant differences were denoted by the different letters above columns, while highly significant differences between treatments were denoted with double letters. These data represent three independent statistical tests (one for each individual plant species).

## 4 Discussion

Minimal differences in environmental conditions, chemical inputs, water quality, and fish growth performance between treatments indicate that the observed plant growth responses and elemental tissue patterns were likely driven by the late addition of marine salts (5 ppt). Due to the salt additions occurring near the end of the production cycle, these results represent short-term, pre-harvest saline exposure, rather than long-term brackish cultivation.

TABLE 3 Results for various growth metrics taken from the four individual plant representative samples from each plant variety per system.

| Parameter | Kale | | | Swiss chard | | | Watercress | | |
|---|---|---|---|---|---|---|---|---|---|
| | Salt | Fresh | *p*-value | Salt | Fresh | *p*-value | Salt | Fresh | *p*-value |
| Weight (g) | 95 ± 38 | 73 ± 16 | 0.15 | 102 ± 47 | 175 ± 117 | 0.13 | 109 ± 48 | 197 ± 107 | 0.16 |
| Height (cm) | 42 ± 6 | 40 ± 7 | 0.36 | 46 ± 6 | 49 ± 10 | 0.47 | 52 ± 9[a] | 68 ± 10[b] | <0.01 |
| # of leaves | 11 ± 2 | 10 ± 2 | 0.11 | 7 ± 2 | 7 ± 2 | 0.80 | – | – | – |
| Chlorophyll | 67 ± 11 | 61 ± 10 | 0.22 | 10 ± 3 | 10 ± 2 | 0.86 | 22 ± 3[a] | 19 ± 3[b] | 0.04 |
| Brix (°Bx) | 3.8 ± 0.4 | 3.4 ± 0.6 | 0.41 | 4.1 ± 0.7 | 4.6 ± 0.6 | 0.40 | 3.7 ± 1.0 | 2.8 ± 0.2 | 0.15 |

Data are presented as mean ± *SD*. Different superscript letters within rows denote significant differences between treatments ($p \leq 0.05$).

Across the three crops, biomass varied in response to marine salt additions. Both Swiss chard and Watercress exhibited substantial reductions in fresh biomass under the salt treatment, whereas Kale showed no significant change (Figure 5). Visible symptoms of salt stress such as leaf curling, wilting, and browning, particularly of new growth, were observed only in watercress and appeared within 24 h of the salt addition that subsequently intensified over the 5-day exposure. These symptoms were absent in Kale and Swiss chard, suggesting species-specific tolerance to rapid changes in osmotic conditions. Watercress anatomy likely contributed to its heightened sensitivity: thin leaves and creeping vine-like shoots may limit the ability of the plants to maintain water and ion transport to new growth under rapid osmotic stress (Kaddour et al., 2013).

Despite differences in biomass response, all crops accumulated significantly higher concentrations of Na and Cl in leaf tissue under the salt treatment, consistent with findings from other studies using low-saline brackish water (Fisk et al., 2026; Puccinelli et al., 2022; Lira et al., 2018; Nozzi et al., 2016). Although flavor analyses were not conducted, elevated sodium within the leaf tissue is likely to impart a saltier taste, as demonstrated by Fisk et al. (2026) for Kale. Cases where biomass are unaffected, but tissue sodium increases, may represent a potential value-added trait if consumer preference or market premiums support such flavor modifications. For Swiss chard and Watercress, however, the reductions in biomass are likely to outweigh potential flavor benefits. Future work should directly evaluate sensory quality and consumer acceptance to quantify the economic tradeoffs of pre-harvest salinity exposure.

Several other nutrients exhibited treatment-dependent differences across crops, including K, Ca, B, Mn, Fe, and Al—patterns also commonly reported for plants under salinity stress in other studies (Fisk et al., 2026; Puccinelli et al., 2022; Ievinsh et al., 2022; Lira et al., 2018; Nozzi et al., 2016). These shifts are consistent with known physiological mechanisms. Increased uptake of $Na^+$ and $Cl^-$, often reduces the root uptake or translocation of $K^+$, $Ca^{2+}$, $Fe^{2+}$, and $Al^{3+}$ while increasing uptake of $Mn^{2+}$ and B (likely in boratic acid form–$H_3BO_3$). In the case of $K^+$, $Ca^{2+}$, $Fe^{2+}$, and $Al^{3+}$, there was likely direct competition with $Na^+$ at root uptake sites (Balasubramaniam et al., 2023) as well as reduction of ion transport (primarily $Fe^{2+}$ and $Al^{3+}$) through channels within the plant (Atta et al., 2023). This ultimately led to reduced concentrations of these minerals in the plants exposed to salt compared to plants not exposed to salt. In the case of Mn, when plants are under salt stress, increased Reactive Oxygen Species (ROS) are known to be produced within the cells of the plant. As a result, antioxidant enzymes such as Manganese Superoxide Dismutase (Mn-SOD) are produced by the plant to reduce the excess ROS's, leading to increased Mn concentrations in the leaf tissues (Upadhyay and Singh, 2025). For B, the reduced transpiration within the plants and interactions with $Ca^{2+}$ could be the result of the higher B concentrations within the tissue. However, Fisk et al. (2026) reported that increased B concentrations in plant leaves was likely caused by their salt mix containing B. The water quality results showed a significantly higher ($p \leq 0.01$) concentration of B in the water of the salt systems compared to the freshwater systems. Although not reported within the marine salt manufacturing safety data sheet, trace quantities of B within the salt mixture may have also contributed to the increased B concentrations found within the water and plant tissues.

Weekly and post-study water chemistry results indicated significantly higher concentrations of $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $K^+$, $Cl^-$, and $SO_4^{2-}$ in the salt systems compared to the freshwater systems. This was expected due to the addition of the salt mixture, which contained all of these elements. Interestingly significantly lower concentrations of $PO_4^{3-}$, Zn, and Fe were found within the salt systems compared to the freshwater systems. This is likely caused from the increased salinity which can lead to $Fe^{2+/3+}$ and $PO_4^{3-}$ precipitating to form iron hydroxide ($Fe(OH)_2$) or iron phosphate ($FePO_4$) which would not have been detected in the post-study water quality results due to the analysis only measuring dissolved $PO_4^{3-}$, or the inorganic readily available form of Orthophosphate (Lama et al., 2025). Similarly, $Zn^{2+}$ is known to precipitate into insoluble compounds under higher pH and alkalinity, which would not have been detected in post-experiment water quality laboratory results (Sambo et al., 2019). Significantly higher levels of alkalinity and pH were observed in the salt systems as compared to the freshwater systems, after the salt was added into the systems. The difference in average alkalinity throughout the study between the salt and freshwater systems was 6 mg/L, however a closer examination revealed the difference in alkalinity after the salt was introduced into the system increased to a difference of 24 mg/L between the two treatments. Similarly, the difference in average pH between the treatments throughout the study was only 0.1, with the difference increasing to 0.4 after the salt was introduced (Figure 3). These shifts in pH and alkalinity likely caused precipitation of these elements resulting in the differences found within the post-experiment of water quality results.

In addition to the weekly and post-study water chemistry results, the high-frequency sonde measurements provided further insight into how the systems components may vary in terms of pH. Differences between fish tank and grow bed pH values suggest biological and hydraulic drivers. Grow beds exhibited lower pH than fish tanks, which is likely due to plant roots releasing acid exudates during nutrient uptake, locally acidifying the rhizosphere and influencing grow bed water chemistry (Camli-Saunders and Villouta, 2025; Senff et al., 2022). Hydraulic retention time may have further contributed to component specific differences, with longer

TABLE 4 Results from plant leaf tissue analysis for individual plant representative samples from each plant variety.

| Parameter | | Kale | | | Swiss chard | | | Watercress | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Salt | Fresh | *p*-value | Salt | Fresh | *p*-value | Salt | Fresh | *p*-value |
| % | N | 5.6 ± 0.2$^{a}$ | 6.0 ± 0.1$^{b}$ | 0.03 | 5.8 ± 0.0 | 5.8 ± 0.0 | 0.18 | 6.2 ± 0.4 | 6.3 ± 0.2 | 0.48 |
| | S | 1.9 ± 0.1 | 1.8 ± 0.1 | 0.49 | 0.4 ± 0.1 | 0.5 ± 0.0 | 0.22 | 1.3 ± 0.1 | 1.3 ± 0.2 | 0.84 |
| | P | 0.7 ± 0.1 | 0.8 ± 0.0 | 0.49 | 0.6 ± 0.1 | 0.8 ± 0.1 | 0.10 | 1.0 ± 0.1 | 1.0 ± 0.0 | 0.43 |
| | K | 3.3 ± 0.4 | 4.1 ± 0.5 | 0.09 | 6.2 ± 0.3$^{a}$ | 7.2 ± 0.4$^{b}$ | 0.02 | 3.6 ± 0.3$^{a}$ | 7.7 ± 2.0$^{b}$ | <0.01 |
| | Mg | 0.8 ± 0.1 | 0.6 ± 0.2 | 0.12 | 1.2 ± 0.1 | 1.2 ± 0.2 | 0.75 | 0.5 ± 0.0$^{a}$ | 0.3 ± 0.0$^{b}$ | <0.01 |
| | Ca | 2.9 ± 0.3$^{a}$ | 4.0 ± 0.3$^{b}$ | 0.01 | 0.9 ± 0.2$^{a}$ | 1.4 ± 0.0$^{b}$ | 0.02 | 1.7 ± 0.3$^{a}$ | 2.7 ± 0.3$^{b}$ | 0.02 |
| | Na | 2.4 ± 0.3$^{a}$ | 0.5 ± 0.2$^{b}$ | <0.01 | 3.7 ± 0.4$^{a}$ | 2.5 ± 0.2$^{b}$ | <0.01 | 2.4 ± 0.3$^{a}$ | 0.3 ± 0.0$^{b}$ | <0.01 |
| ppm | B | 37 ± 1$^{a}$ | 13 ± 2$^{b}$ | <0.01 | 41 ± 1$^{a}$ | 20 ± 4$^{b}$ | <0.01 | 39 ± 3$^{a}$ | 27 ± 3$^{b}$ | 0.01 |
| | Zn | 57 ± 4 | 50 ± 12 | 0.36 | 60 ± 19 | 52 ± 3 | 0.60 | 130 ± 26 | 166 ± 24 | 0.16 |
| | Mn | 53 ± 6$^{a}$ | 30 ± 11$^{b}$ | 0.05 | 75 ± 11 | 59 ± 16 | 0.26 | 78 ± 11$^{a}$ | 45 ± 2$^{b}$ | <0.01 |
| | Fe | 64 ± 9$^{a}$ | 118 ± 19$^{b}$ | <0.01 | 63 ± 11$^{a}$ | 162 ± 27$^{b}$ | <0.01 | 74 ± 14 | 122 ± 53 | 0.16 |
| | Cu | 5.7 ± 0.6 | 6.3 ± 0.6 | 0.23 | 7.3 ± 0.6 | 8.0 ± 0.0 | 0.12 | 10 ± 2 | 12 ± 1 | 0.29 |
| | Al | 44 ± 5 | 56 ± 12 | 0.18 | 27 ± 8$^{a}$ | 60 ± 8$^{b}$ | 0.01 | 33 ± 3 | 23 ± 9 | 0.20 |
| | Cl | 501 ± 50$^{a}$ | 208 ± 16$^{b}$ | <0.01 | 600 ± 25$^{a}$ | 220 ± 36$^{b}$ | <0.01 | 490 ± 51$^{a}$ | 299 ± 21$^{b}$ | <0.01 |

Data are presented as mean ± *SD*. Different superscript letters within rows denote significant differences between treatments ($p \leq 0.05$).

retention in the grow beds likely allowing more time for plant-mediated chemical modification, whereas the fish tanks were more rapidly mixed and thus less sensitive to localized biological processes (Tetreault et al., 2023; Fang et al., 2018). Our study provides rare high-resolution observations of short-term pH fluctuations in aquaponic systems. This variability would have been entirely missed with typical daily or weekly sampling. Such pH shifts highlight the potential value of multiple sensors located within different components of aquaponic systems along with automated sensing and dosing technologies which could help stabilize system pH during salinity transitions by adjusting alkalinity or acid/base additions in real time (Sinchai et al., 2026).

While plant growth and quality were the primary focus of this study, it is important to assess any negative effects on fish growth and performance because they are critical aspects of aquaponic system function. The tilapia in this study performed similarly in terms of survival, FCR, and SGR between the salt and freshwater systems. While long-term exposure to higher concentrations of salt (3–8 ppt) has been shown to be beneficial for Tilapia growth (Abd El-Hack et al., 2022; Luo et al., 2017), the exposure to the fish under this experimental design was likely not long enough to present any benefits in fish growth. Additionally, no data was collected during this study that would indicate any potential benefits to fillet quality or fish health through the short-term salt exposure. However, a standard practice for aquaculture or aquaponic producers is a depuration or a salt purge (3–5 ppt) 1–6 days prior to harvesting their fish (Xue et al., 2025; da Rodrigues Silva et al., 2024; Davidson et al., 2022). The short-term and pre-harvest exposure used in this study was not sufficient to produce measurable differences in these performance metrics, and no fish mortalities were attributable to the salinity treatment, rather the mortalities were likely caused by the fish jumping out of the tank, which occurred on days 15 and 21 of the study. This depuration system is external to the main grow-out system and is done to remediate any off-flavor and cleanse the fish of any left-over feed or contaminates prior to harvesting (Xue et al., 2025; Davidson et al., 2022). This period of depuration, as well as the salinity levels the fish undergo as part of this process, co-align with the protocols used in this study. To date, studies explicitly testing integrated depuration-salinization systems would be needed to confirm feasibility and efficacy. Therefore, there is potential for a producer to sync up the fish depuration and plant harvest times to create the effects of pre-harvest salt exposure of both fish and plants under a commercial setting. The addition of a hydroponic loop could also alleviate challenges associated with water usage during fish depuration (Davidson et al., 2022). However, proper planning of harvest times and the addition of a hydroponic loop into depuration systems would need to be considered to effectively integrate the practice of pre-harvest salt exposure for plant production.

## 5 Conclusion

Overall, this study highlights the complex interactions among water chemistry, plant ion uptake, and crop performance under short-term, low-salinity exposure. Pre-harvest low-salinity exposure to plants strongly influenced leaf sodium and chloride accumulation across all crops, while growth responses were species-specific. Kale demonstrated the greatest tolerance showing stable biomass despite the salinity shift and accumulating potential desirable flavor-enhancing ions. In constrast, Swiss chard and Watercress exhibited reduced growth and visible symptoms of stress. Future research should refine exposure protocols (e.g., duration, salinity level, timing before harvest), evaluate additional non-halophyte salt tolerant cultivars, assess economic tradeoffs, and incorporate direct measurements of fish health and plant flavor chemistry. Additionally, future studies could include measurements of phenolic compounds and reactive oxygen species (ROS)-related parameters (e.g., antioxidant enzyme activity) to more rigorously characterize plant stress responses under saline conditions, which represents a limitation of the current study. Such work will be essential for developing practical, integrated salinization strategies for aquaponics and other Controlled Environment Agriculture (CEA) systems.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The animal study was approved by Virginia State University IACUC Board. The study was conducted in accordance with the local legislation and institutional requirements.

## Author contributions

JD: Conceptualization, Validation, Writing – review & editing, Funding acquisition, Formal analysis, Supervision, Methodology, Software, Data curation, Project administration, Resources, Investigation, Writing – original draft, Visualization. NB: Formal analysis, Software, Writing – original draft, Investigation, Resources, Funding acquisition, Conceptualization, Methodology, Project administration, Writing – review & editing. YF: Software, Conceptualization, Funding acquisition, Writing – original draft, Resources, Project administration, Writing – review & editing, Methodology, Formal analysis, Data curation, Visualization. NR: Methodology, Writing – review & editing, Funding acquisition, Conceptualization. CC: Resources, Project administration, Methodology, Investigation, Supervision, Writing – review & editing. BA: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Visualization, Software, Investigation, Validation.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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