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Enhancing Cabbage Palm Resilience to Saltwater Stress through Silicon Applications

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***Abstract.* Saltwater intrusion driven by climate change increasingly imperils Florida's coastal ecosystems. This study investigated whether silicon amendments can buffer cabbage palm (*Sabal palmetto*) seedlings against saline stress. One-year-old seedlings were irrigated with seawater analogues at 10, 30, or 50 ppt (ranging from freshwater to hypersaline conditions) and supplemented with soluble silicon at 1%, 3%, or 5% (m/v). Vigor was quantified nondestructively using SPAD-502 and atLEAF+ meters that estimated the chlorophyll content and measurements of height and leaf number. Salinity alone decreased all growth variables, with the steepest declines observed with 50 ppt. Silicon markedly mitigated losses in chlorophyll content, height, and leaf production at 10 through 30 ppt and partially preserved performance at 50 ppt; however, overall survival remained poor at the highest salinity. The results revealed a low inherent salt-tolerance threshold during early ontogeny; however, they demonstrated that silicon can extend that threshold and improve the physiological status under moderate intrusion scenarios. These findings furnish actionable guidance for nursery production and restoration of cabbage palm as the rise in sea level accelerates saltwater encroachment in Florida's coastal landscapes.**

Climate change continues to drive substantial environmental shifts globally, and one of its most immediate threats to Florida's ecosystems is saltwater intrusion resulting from a rise in sea level. Broader biodiversity loss and ecosystem degradation have been well-documented and global temperatures have increased by 0.8 °C over the past century (Almond et al. 2022; Papacek et al. 2020); therefore, the regional consequences for coastal systems in Florida are particularly acute. Rising sea levels, which are projected to increase along US coastlines by 25 to 30 cm over the next 30 years (Wdowinski et al. 2016), are altering hydrological balances and allowing seawater to penetrate freshwater zones. Florida's highly porous limestone geology, with naturally high hydraulic conductivity, exacerbates this process by facilitating deep inland movement of saltwater through the aquifer systems (Bayabil et al. 2022).

This phenomenon poses a critical threat to native plant communities and nursery operations in coastal Florida. Saltwater intrusion degrades soil and water quality by increasing salinity levels, thus negatively affecting plant growth and development. Coastal soils in this region are often sandy and low in organic matter, thus making them particularly susceptible to nutrient leaching and chemical imbalances under saline stress. Essential nutrients such as nitrogen (N) and phosphorus (P) become less available, thereby compounding the physiological challenges that plants face in saline environments (Abd-Elaty et al. 2022; Sweet et al. 2022).

Sabal palmetto, commonly known as the Cabbage Palm, is a key species in tropical and subtropical regions such as Florida, Cuba, and the western coast of Mexico (Henderson et al. 1995). Economically, the Cabbage Palm contributes significantly to ornamental trade because it generates $10 to $13 billion annually and supports Florida's nursery and landscape industries, which collectively generated $31.4 billion and more than 260,000 jobs in 2020 (Novakovic 2022). The Cabbage Palm is culturally significant and was declared Florida's state tree in 1953 (Johnson et al. 2017); it provides food for wildlife as well as edible "swamp cabbage" for humans (Anderson 2020; Martin et al. 1961). This palm species occupies a diverse ecological niche, spanning from coastal marshes to hardwood hammocks and xeric scrub, and is noted for being moderately resistant to short-term saltwater inundation when fully mature (Chaerle and Van Der Straeten 2000; Martin 2018; Zona 1990).

In response to these challenges, this study investigated the role of silicon amendment in mitigating the effects of saline infiltration on Cabbage Palm growth. Silicon is considered a quasi-essential element and is typically absorbed by plants in the form of silicic acid (Luyckx et al. 2017; Souza Costa et al. 2024). Extensive research has shown that silicon enhances plant resistance to both biotic and abiotic stresses (Azeem et al. 2015; Sharma et al. 2023). The species *Butia capitata* (Arecaceae), for instance, underwent testing using a 1% silica solution, and the results showed that the added solution increased photosynthetic and transpiratory rates and improved growth in the leaf and root areas. Silicon, applied here as a superabsorbent polymer, has a sponge-like ability to retain water, thus making it a biodegradable and nontoxic amendment for crops (Coskun et al. 2016). Silicon enhances growth by improving physiological processes such as enzyme regulation and photosynthesis (Zellner et al. 2021) and by strengthening plant cell walls through increased production of cellulose and pectin (Behera and Mahanwar 2020).

Using optical sensor technology for plant health assessments aids in evaluating the impacts of various stressors, including drought, disease, and nutrient loss (Qin et al. 2023). Nondestructive optical sensor technology is important in the horticultural field because it allows cost-effective assessments of plant health parameters, including soil readings, biotic/abiotic stress detection, and canopy data. Some sensors used are handheld devices, including GreenSeeker, a nondestructive reflective handheld crop sensor that measures normalized difference vegetation index (NDVI) values by taking canopy light readings 2 to 3 ft above the highest point of the plant (Khoddamzadeh and Dunn 2016; Souza Costa et al. 2023). The soil plant analytical development (SPAD) sensor is a handheld sensor that clamps onto small leaves and helps estimate nitrogen and chlorophyll content (Khoddamzadeh and Dunn 2016; Khoddamzadeh and Souza Costa 2023; Souza Costa and Khoddamzadeh 2025). The SPAD-502m was the specific sensor used in this study to measure transmittance of red and infrared radiation at wavelengths between 650 and 940 nm

(Minolta 1989), which can be correlated to the amount of chlorophyll contained in the leaf (Uddling et al. 2007). The atLEAF+ is a noncontact handheld sensor that is considered a less expensive alternative to SPAD that takes the same measurements at similar wavelengths (Costa et al. 2023; Khoddamzadeh et al. 2016). The LI-COR 600 is a portable contact sensor that is clamped onto the leaf to record measurements of stomatal conductance and chlorophyll fluorescence on an LCD screen to determine any changes caused by different stressors such as salt and drought (Adhikari 2022). Additionally, the LI-COR 600 measures the electron transport rate, ambient light, leaf temperature, and vapor pressure of each plant. Other sensors are larger-scale, including the PSR 3500 Spectroradiometer, which is used to measure light reflectance and absorbance ranging from 350 to 2500 nm (Maimaitiyiming et al. 2016).

By examining these physiological and phenotypic responses of seedlings treated with silicon, this research aimed to provide insights into effective strategies for enhancing the resilience of these ecologically and economically important species in the face of climate change. Given the increasing threats posed by saltwater infiltration to Cabbage Palm seedlings, it is critical to explore how silicon additions can affect natural leaf growth. Therefore, this study addressed the role of silicon in reducing the effects of saline stress in 1-year-old Cabbage Palm seedlings.

Materials and Methods

For this project, 96 1-year-old potted seedlings of Cabbage Palm were used at Montgomery Botanical Center's "Greenhouse 1" in Coral Gables, FL, USA. The seedlings, originally 10 months old, were collected from Jupiter, FL, USA, and Hendry County, FL, USA, and sent to Montgomery Botanical Center in Oct 2021. Then, the seedlings were transferred from 3-gallon community pots into individual 7 in tubes. The growing medium was a commercially available ProMIX BX gardening mixture composed of 79% to 87% sphagnum peatmoss, 10% to 14% perlite, limestone, and mycorrhizae (*Rhizophagus irregularis*), which helps improve nutrient uptake, expand root development, and promote plant vigor. A low dosage of 14–4–14 N–P–K Nutricote slow-release fertilizer was applied at the beginning of the experiment.

Saline solutions were measured in parts per thousand (ppt), with salinity calculated by grams of dissolved salt per thousand grams of water. Instant Ocean commercial sea salt, composed of 47.5% Cl, 6.6% SO_4^{2-}, 26.3% Na^+, and 3.2% Mg^{2+}, was used to create saline treatments. Reverse osmosis (RO) water was used because of its purity. Concentrations ranged from 0 ppt (control) to 10 ppt, 30 ppt, and 50 ppt. These levels were determined based on measuring local salinity levels in Montgomery Botanical Center's numerous lakes and surrounding areas in the Coral Gables region, which yielded similar salinity contents in ppt as well as by considering a high/lower buffer to capture fringe effects. Solutions were prepared by adding 60 g of sea salt for the 10 ppt treatment, 120 g for the 30 ppt treatment, and 240 g for the hypersaline treatment to 1 gallon of RO water. A commercial-grade aquarium refractometer was used to confirm salinity levels.

The silicon amendment was applied in the form of a superabsorbent silicic acid polymer, with concentrations based on the soil volume to achieve 1%, 3%, or 5% m/v ratios. These were calculated as 0.24 g, 0.58 g, and 0.84 g, respectively. The silicon amendment was added at the beginning of the project in Nov 2022. Irrigation was conducted at least two to three times weekly, depending on temperature and weather conditions, with 50 mL of the respective water treatment applied for each specimen during each irrigation cycle. This meant that each plant received 100 to 150 mL of their respective treatment water each week.

A factorial randomized complete block design was used with four salinity treatments (0, 10, 30, and 50 ppt) and four silicon treatments (0%, 1%, 3%, and 5%) in 16 combinations, with each replicated six times, totaling 96 seedlings. Treatment groups mentioned in this text may be referred to using a code name corresponding to the different saline treatments and silicon amendments. The S0, S1, S2, and S3 treatments correspond to 0 ppt, 10 ppt, 30 ppt, and 50 ppt saline treatments, respectively. The D0, D1, D2, and D3 treatments correspond to 0 g, 0.24 g, 0.58 g, and 0.84 g of silicon treatment, respectively. For example, S0D3 treatment refers to no saline water and only 0.84 g of silicon amendment added to the treatment.

Leachate was collected from the soil using the pour-through method once each month (Wright 1986). Then, the samples were analyzed to understand how salt and silicon amendments affected the concentrations of various nutrients, soil pH, and electrical conductivity (EC). Phenotypic properties of the seedlings were closely monitored to see how added salinity and silicon additions affected the observable physical properties of the plant through changes in nutrient contents and deficiencies. Leaf initiation and heights were recorded to see how silicon amendment affected natural leaf growth. Chlorophyll content was recorded by using a color value from 0 to 5, with 0 indicating complete decay of the seedling and 5 indicating a deep green color indicative of a high chlorophyll count in the leaves. This protocol was adapted from the International Rice Research Institute leaf color chart, which is an inexpensive diagnostic tool originally used to determine greenness of rice leaves to indicate the plant's nitrogen status (Alam et al. 2005).

Leachate extraction was performed monthly using the pour-through method, with RO water applied until saturation and 25 to 30 mL of leachate collected from each seedling. The experiment ran from Nov 2022 to Nov 2023, with baseline data collected in Oct 2022. Sodium, nitrate, potassium, and calcium ion levels were measured using the Horiba Instruments LAQUAtwin series of nutrient sensors. Three-point calibration was conducted before each test to ensure the most accurate readings.

The SPAD, atLEAF+, and GreenSeeker NDVI handheld sensors were used each month for 1 year, with readings taken 2 ft above the canopy under clear, sunny conditions for accuracy. Initial LI-COR-600 readings were recorded in Feb 2023, at 3 months into the experiment, and repeated in Feb 2024 for comparison. Additionally, a PSR 3500 spectroradiometer was used in Oct 2023 (month 11), with calibration and artificial lighting used for accurate readings because of overcast weather conditions.

Phenotypic characteristics, including height, leaf count, chlorophyll content, and light readings, were measured monthly to assess physical changes in the seedlings under salt and silicon amendment treatments. Chlorophyll content was rated using a scale from 0 (dead) to 5 (excellent pigmentation). Light flux was measured using an iPower 3-in-1 soil moisture/light/pH probe. The leachate analysis included measurements of nutrient content (potassium, calcium, sodium, nitrate) and pH using Horiba Ltd. sensors and an Extech Instruments waterproof pH meter to determine EC and pH levels.

Data were analyzed using GraphPad Prism 10. A one-way analysis of variance assessed differences among treatments, and Tukey's

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The authors declare no competing interests.

No human participants or animals were involved in this study; therefore, ethical approval was not required. All experimental procedures followed institutional and national guidelines for plant research.

The authors confirm that the data presented in this study are available within this article and its supplementary materials.

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test was used for the post hoc analysis. Correlation matrices using Pearson R were constructed monthly and paired observations were reported (N = 6).

Results

The results reflect the averages of all phenotypic parameters assessed, including leaf count, plant height, and chlorophyll content (Fig. 1). Cabbage Palm plant heights did not show significant ($P < 0.05$) differences during the first 2 months of treatment. However, by the third month, a significant decline in average heights was observed in the 50 ppt salt treatment group ($P < 0.05$). A similar decline was noted with some 30 ppt treatments, including the 30 ppt + 0.58 g group (Fig. 1). By the fourth month, height measurements for the 50 ppt control group were discontinued because of the complete mortality of seedlings. By the fifth month, the 30 ppt treatment groups exhibited a more pronounced decline that persisted until most of the specimens died by the eighth month. For the remainder of the experiment, only the control and 10 ppt treatment groups survived. Within these groups, a significant difference in height was observed, with the control group showing notably lower average heights ($P < 0.05$). No significant differences ($P < 0.05$) were observed between the remaining control and 10 ppt groups (Fig. 1).

A significant decline began in month 2, with both the 30 ppt and 50 ppt treatments showing a steady decrease in the average number of healthy leaves ($P < 0.05$) (Fig. 2). By month 3, this decline became more pronounced, particularly in the 50 ppt hypersaline treatments. However, the 50 ppt + 0.84 g (S3D3) treatment group exhibited significantly higher leaf averages during this month ($P < 0.05$) (Fig. 2). In month 4, leaf numbers in this group sharply declined, along with all other hypersaline treatments. A similar trend was observed in the 30 ppt treatment groups, with significant ($P < 0.05$) decreases in leaf numbers recorded from months 5 through 7, regardless of the silicon amendment. By month 8, all 30 ppt treatment group plants had died. Among the remaining control and 10 ppt treatment groups, a significant difference in leaf numbers was noted within the S0D1, S0D2, and S0D3 groups, all of which were control treatments with no salt added and only silicon amendments ($P < 0.05$) (Fig. 2).

There were no significant differences in chlorophyll values until month 2, when the S3D1 treatment group exhibited significantly higher chlorophyll values compared with those of other groups ($P < 0.05$) (Fig. 3). However, in the following month, a sharp decline in chlorophyll values was observed for this group and all 50 ppt groups (Fig. 3). In the 30 ppt treatment groups, a similar decline occurred in month 4 and continued until the groups' complete mortality in month 8. As expected, by the end of the experiment, chlorophyll values were most significant ($P < 0.05$) among the S0D1, S0D2, and S0D3 treatment groups. No significant differences ($P < 0.05$) in chlorophyll averages were observed among the remaining treatment groups at the end of the experiment (Fig. 3).

Leachate samples were evaluated monthly for NO_3^-, Na^+, K^+, and Ca^+ contents. Sodium levels in the 10 ppt to 50 ppt treatments increased sharply following the first saline water applications (Fig. 4). In treatments without added saltwater, concentrations remained negligible from the first month, ranging from 5 to 15 ppm. Sodium levels increased progressively with each saline treatment, although fluctuations were observed, particularly at the 4-month mark (Fig. 4). For instance, the 30 ppt + 0.24 g treatment showed an average of 8817 ppm in month 3 that dropped to 3500 ppm in month 4 (Fig. 4). Potassium levels were highest in all 50 ppt treatments until month 4, after which the 30 ppt treatments exhibited the highest potassium concentrations for the remainder of the study. Calcium levels were initially higher in control groups but averaged higher in the 50 ppt treatments during the first 4 months and in the 30 ppt treatments for the remainder of the experiment. Nitrate levels showed considerable variation across all treatment groups throughout the study; however, by the end, the 10 ppt treatment groups had the highest average nitrate readings (Fig. 4).

There were significantly high P values ($P < 0.05$) between sodium and potassium concentrations throughout much of the experiment. In contrast, P values between calcium and sodium were mostly insignificant ($P < 0.05$), indicating a stronger correlation (Table 1). Higher significance ($P < 0.05$) was observed between nitrate and sodium levels, suggesting a stronger relationship between these concentrations ($P < 0.05$). Calcium and sodium correlations were generally weak, while calcium and potassium correlations fluctuated between low and high significance (Table 1). High significant ($P < 0.05$) P values of nitrate and pH were recorded in months 3, 9, and 10. The pH showed low significance for calcium and potassium in month 6, but high significance for sodium and nitrate ($P < 0.05$). A significant correlation between pH and nitrate was observed in months 6 and 7 ($P < 0.05$). Nitrate only showed high significance between nitrate and sodium in month 3, nitrate and potassium in month 4, and nitrate and sodium in month 6 ($P < 0.05$) (Table 1). The EC had the highest significance with pH in month 2 and with calcium and potassium in month 3 ($P < 0.05$).

Although soil pH showed no significant ($P < 0.05$) changes early in the experiment, EC readings for 0 ppt plants averaged between 0.00 and 1.99 mS/cm. The EC levels in 10 ppt plants ranged from 11.00 to 19.00, with peaks in months 4 through 6 (Table 1). For 30 ppt plants, EC readings started lower but increased to 16.00 to 18.60 mS/cm by month 3. Although the 50 ppt treatment plants died early, their EC levels initially increased, peaking at 20.0 mS/cm before plant mortality occurred because of excessive salinity (Table 1).

Overall, Cabbage Palm seedlings exposed to 50 ppt salinity and treated with 1%, 3%, and 5% silicon amendments ultimately exhibited no survivability. While silicon amendment extended survival by approximately 2 weeks to 1 month, population decline was still rapid, with untreated plants dying within 2 to 3 months after the initial application (Fig. 5). By 3 months, NDVI readings for hypersaline specimens

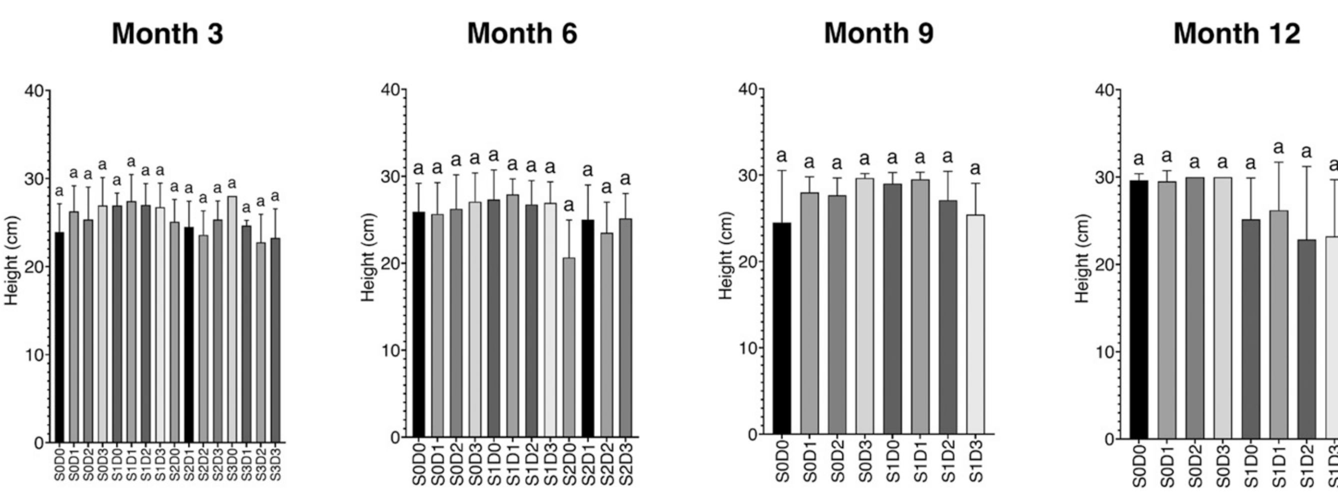

Fig. 1. Average height of seedlings by salinity and silicon treatments. Error bars represent standard errors. Letters denote significant differences ($P < 0.05$).

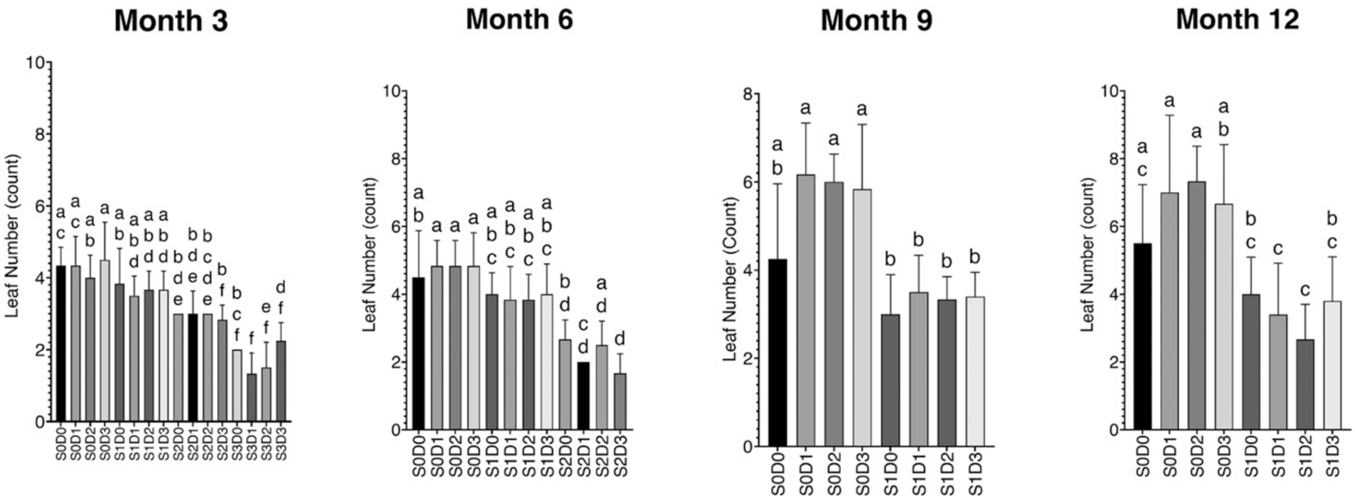

Fig. 2. Average leaf count of seedlings by salinity and silicon treatments. Error bars represent standard errors. Letters denote significant differences ($P < 0.05$).

showed a predictable decline, paralleling chlorophyll readings from SPAD and atLEAF+ sensors. Control and 10 ppt treatments exhibited no significant differences throughout the experiment, while 30 ppt and 50 ppt saline treatments experienced a sharp decline by month 9 ($P < 0.05$). By the final month, only low-silicon-dosage plants remained, with the highest average readings observed in nonsaline treatments with high silicon dosages (Fig. 5). The 10 ppt seedlings had significantly lower NDVI values by the end of the project, and low P value significance ($P < 0.05$) was noted between leaf count and NDVI values in months 2 and 3 (Table 2). Additionally, high dosages of silicon did not significantly increase seedling SPAD values independent of saline, as noted in Fig. 6.

Initially, there were no significant ($P < 0.05$) differences in atLEAF+ readings across all treatments during the first 3 months, regardless of salinity or silicon concentration. However, by month 3, the 30 ppt + 0.58 g treatment group showed a notable increase in atLEAF+ readings. From month 4 onward, higher silicon concentrations in S3 treatments were associated with significant interactions ($P < 0.05$) (Fig. 5). All plants in 50 ppt treatments without silicon died by month 5, although 50 ppt + 0.24 g and 50 ppt + 0.84 g treatments showed slightly higher survival rates, although not enough to persist through the experiment (Fig. 5). Similarly, 30 ppt treatments began experiencing losses during this period, with higher silicon levels associated with increased chlorophyll readings, plant heights, and leaf counts. However, by month 9, 30 ppt treatments began dying at a rapid rate, starting with low-silicon treatments; by month 10, all 30 ppt specimens had died. Survival rates were not significantly improved with silicon dosages of 0.24 through 0.84 g ($P < 0.05$). Chlorotic readings for control and 10 ppt + 0.84 g treatments showed no significant differences ($P < 0.05$) throughout the experiment. While plants with 10 ppt salinity experienced steady declines in height and leaf numbers, those treated with silicon exhibited physiological improvements. By the end of the experiment, there were no significant differences ($P < 0.05$) between the remaining seedlings in the 0 ppt and 10 ppt treatments, regardless of silicon dosage (Fig. 5). Significant P values were observed between atLEAF+, SPAD, and leaf count measurements in months 2, 3, and 10 ($P < 0.05$).

The SPAD readings followed trends similar to those of atLEAF+ results, as expected, because of the similarity of the measurements. No significant differences ($P < 0.05$) in SPAD P values were observed during the first month of treatment (Fig. 5), but significance was recorded between atLEAF+, chlorophyll content, and SPAD readings in months 2 and 3 ($P < 0.05$) (Table 2). No hypersaline plants survived beyond 6 months, including the 50 ppt + 0.58 g and 50 ppt + 0.84 g treatments (Fig. 5). A significant difference ($P < 0.05$) was observed between low salinity and 30 ppt treatments in month 8, with the latter group surviving until month 10. By month 4, all 50 ppt only treatment plants had died, with further significant declines observed in silicon-supplemented 50 ppt plants. By month 5, most 50 ppt seedlings had perished. During this same period, the 30 ppt

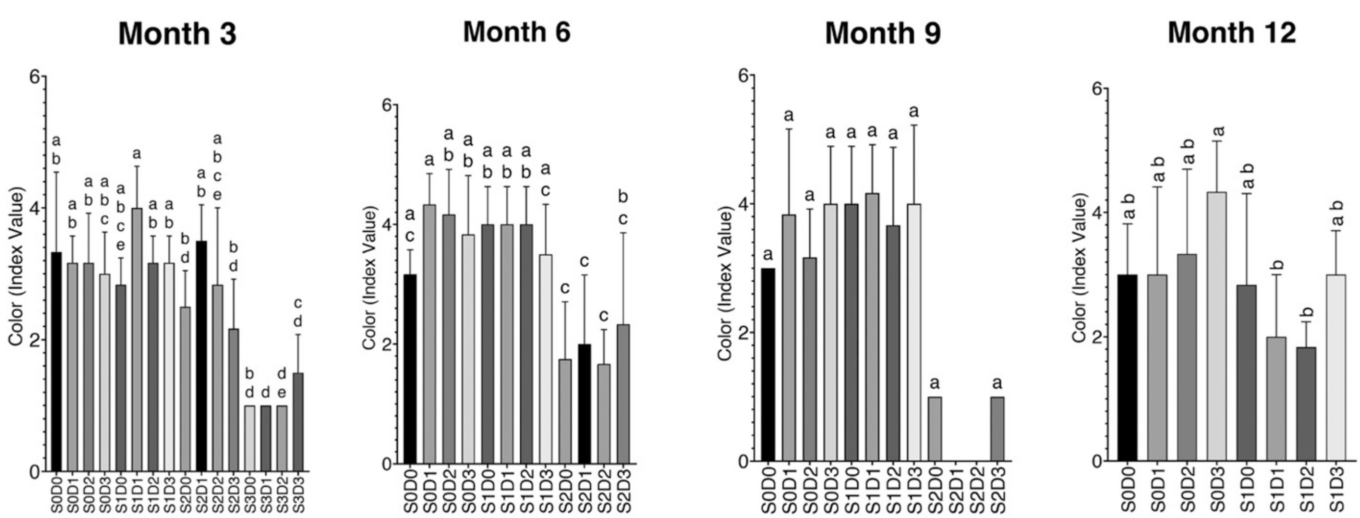

Fig. 3. Average chlorophyll content values by salinity and silicon treatments. Error bars represent standard errors. Letters denote significant differences ($P < 0.05$).

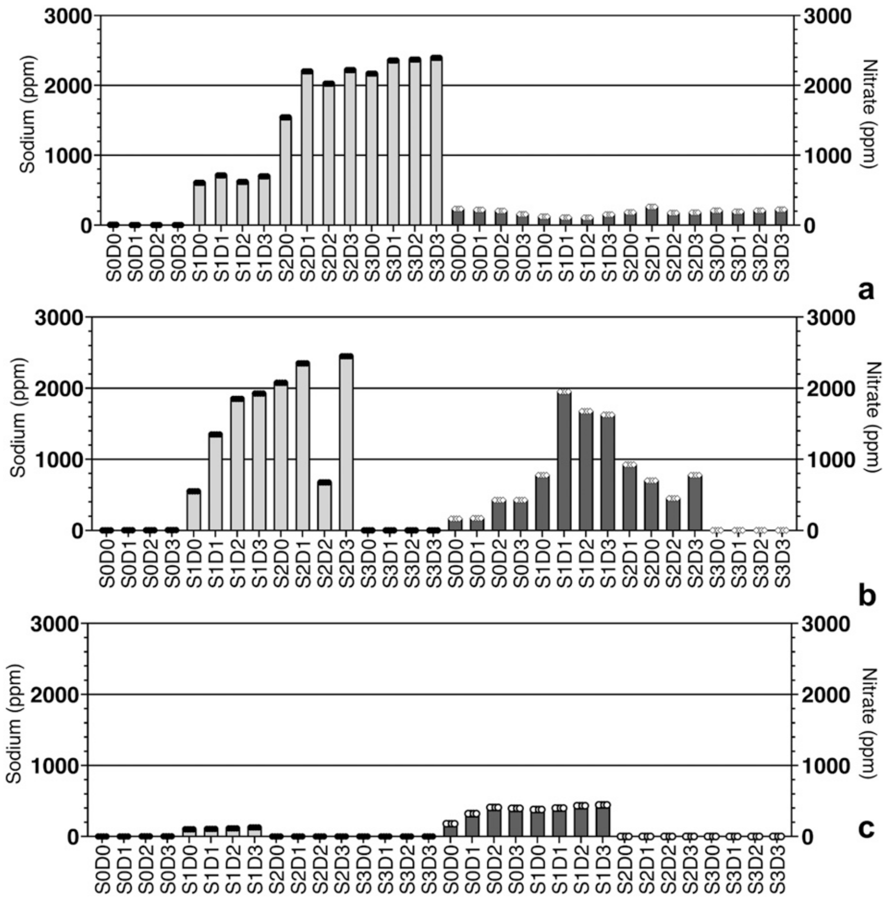

Fig. 4. Average sodium (left) and nitrate (right) readings by salinity and silicon treatments.

treatment plants began to decline, starting with the 30 ppt + 0.84 g group. A notable increase in SPAD values was observed at month 6 for the 0.84 g only and 30 ppt + 0.58 g treatments. By month 9, most 30 ppt plants had died; by the final month, SPAD values for control and 10 ppt treatments were not significantly different ($P < 0.05$). Only the control and brackish seedlings survived the entire experiment, with little to no variation in SPAD means, which ranged from 40 to 60 throughout the study (Fig. 5).

Across all salinity treatments, silicon supplementation displayed diminishing returns beyond the initial increment of 1% $m \cdot v^{-1}$ (0.24 g/pot). As illustrated in Fig. 6, neither the 3% dose nor the 5% dose yielded statistically significant improvements in SPAD chlorophyll indices, relative to the 1% treatment. Accordingly, the growth response plateaued at ≥1% silicon, indicating that higher concentrations confer no additional measurable benefit.

Table 1. Correlation coefficients among leachate parameters (N = 6 per treatment) for months 1, 6, and 12.

	K	Ca	NO_3^-	pH	EC
Month 1					
Na	**0.946******	**0.973******	0.328	**−0.506***	0.261
K		**0.961******	0.445	**−0.636****	0.069
Ca			0.336	−0.478	0.183
NO_3^-				−0.373	−0.258
pH					−0.050
Month 6					
Na	**0.833******	**0.877******	**0.610***	**−0.762***	**0.823*****
K		**0.961******	**0.937******	**−0.903*****	**0.821*****
Ca			**0.883******	**−0.832*****	**0.795***
NO_3^-				**−0.807***	**0.644***
pH					**−0.907******
Month 12					
Na	**0.988******	**0.984******	−0.548	**−0.745***	**0.996******
K		**0.994******	−0.559	**−0.760***	**0.990******
Ca			−0.593	**−0.757***	**0.983******
NO_3^-				0.040	−0.537
pH					**−0.729***

Asterisks denote significance levels (****$P < 0.0001$, ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$).
Ca = calcium; EC = electrical conductivity; K = potassium; Na = sodium.

The experiment followed a randomized complete block design to minimize any unintended environmental effects, meaning each treatment group's replications were placed in a random order within each group. Sixteen combinations of salt and silicon amendment treatments were tested, with six replications per group. Treatment groups are denoted as "S" for saltwater and "D" for silicon treatments. The control group (S0D0) received no amendments, while other groups received varying levels of salt (S0 for no salt, S1 for 10 ppt, S2 for 30 ppt, and S3 for 50 ppt) and silicon (D1 for 0.24 g, D2 for 0.58 g, and D3 for 0.84 g). Pots were randomly arranged within a 5-m × 5-m area in the greenhouse.

Data analysis was conducted using GraphPad Prism 10 software. Sensor data collected each month was grouped into cohorts, with each cohort analyzed independently from the others. For each cohort, data from the different sensor suites were analyzed using a one-way analysis of variance, followed by a Tukey test for post hoc multiple comparisons. The means of each treatment group were compared against each other. Additionally, a correlation matrix was generated for each cohort by calculating the Pearson R values of the averages for each treatment group and comparing P values across sensor data for NDVI, SPAD, Light Flux, AtLEAF+, and leaf counts (N = 6 replicates at maximum).

Discussion

The present study provided a comprehensive, empirically grounded assessment of how chronic saline intrusion influences early developmental stages in Cabbage Palm and simultaneously demonstrated the mitigating effects conferred by silicon supplementation. Phenotypic data clearly delineated a salinity threshold because seedlings exposed to 30 ppt and 50 ppt experienced sharp declines in height, leaf initiation, and chlorophyll content, ultimately resulting in complete mortality within 8 months and 6 months, respectively. In contrast, seedlings subjected to 10 ppt maintained growth rates indistinguishable from those of controls, thereby identifying 10 ppt as a critical ecological limit for 1-year-old seedlings in this species. Crucially, silicon treatments, applied at concentrations ranging from 1% to 5%, provided measurable alleviation of salt stress, which was evident through improved chlorophyll retention, leaf production, and growth persistence. Although silicon supplementation significantly improved physiological performance at higher salinity levels, survival was prolonged rather than indefinite, suggesting that silicon's protective effects, while substantial, have upper bounds defined by salinity intensity and exposure duration. The low salinity tolerance of young Cabbage Palm seedlings underscores their vulnerability to saltwater infiltration, which could severely impact future populations of this ecologically and economically important species. Because these palms mature, their resistance to salinity increases (Chaerle and

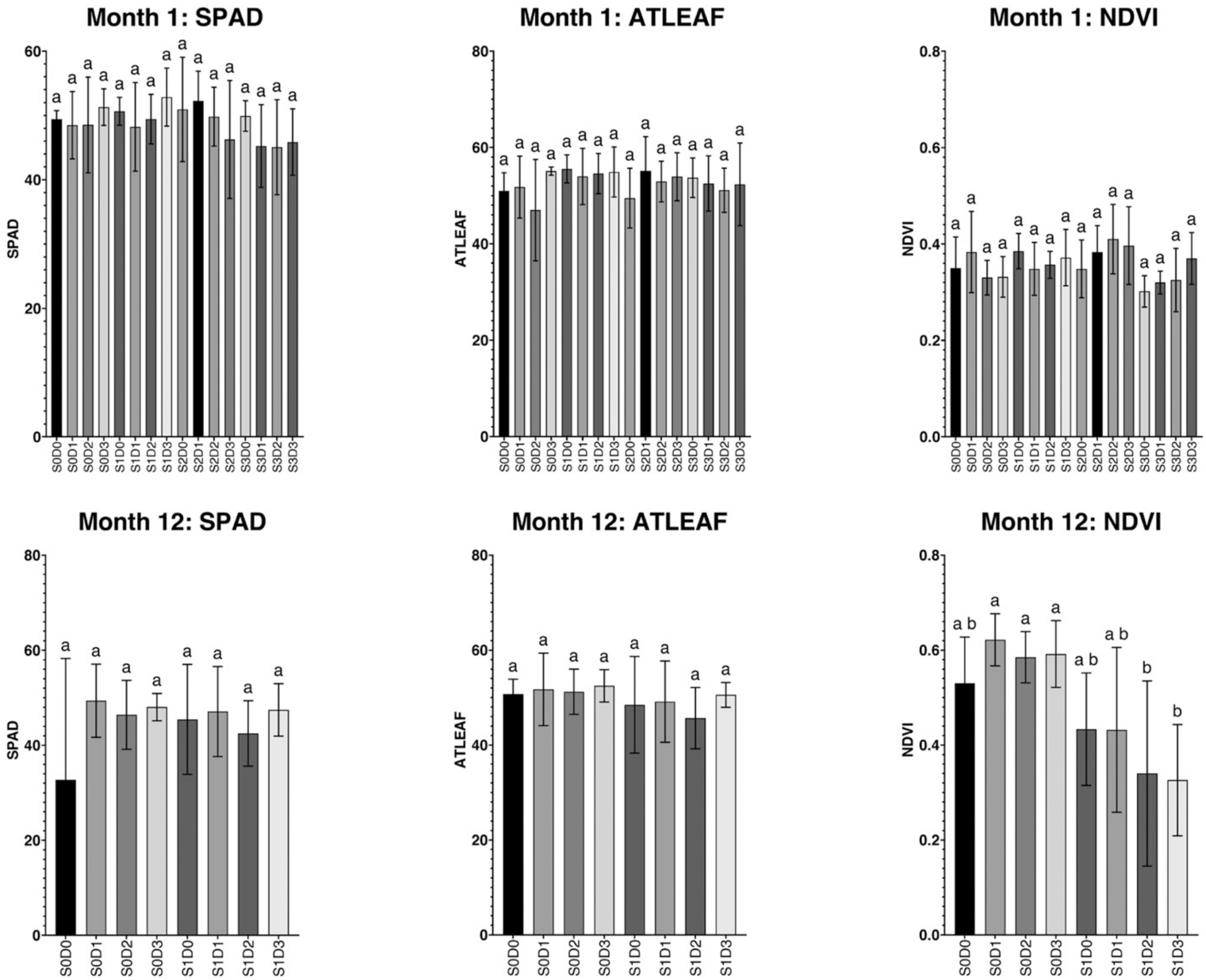

Fig. 5. Average soil plant analytical development (SPAD), atLEAF, and normalized difference vegetation index (NDVI) readings by salinity and silicon treatments. Error bars represent standard errors. Letters denote significant differences ($P < 0.05$).

Van Der Straeten 2000; Martin 2018), explaining their prevalence in naturally saline coastal soils.

The underlying physiological mechanisms responsible for the observed responses involve complex ionic dynamics within the rhizosphere. Leachate analyses revealed marked elevations in sodium ion concentrations under saline conditions accompanied by significant correlations among sodium, potassium, and calcium ions. These ionic relationships highlight competitive and antagonistic interactions inherent to salt stress, potentially disrupting nutrient absorption, ion homeostasis, and overall metabolic stability in plant tissues. Additionally, a clear inverse relationship between sodium concentration and rhizosphere pH indicated acidification resulting from increased saline irrigation, a condition known to impair nitrogen availability. This was further supported by highly significant correlations observed between sodium and nitrate levels across multiple assessment intervals. Silicon supplementation appeared to mitigate these effects by reducing sodium uptake, stabilizing rhizosphere pH, and correcting nutrient imbalances. Consequently, seedlings that received silicon amendments demonstrated improved chlorophyll content and sustained photosynthetic activity, as quantified through established optical sensor indices such as SPAD, atLEAF+, and NDVI, consistent with findings reported by prior studies of silicon-enhanced salt tolerance in various plant species. This research underscores the value of optical sensors for efficient and nondestructive monitoring of plant health under saline stress conditions. Similar trends correlating improved NDVI and SPAD readings with reduced saline stress have been documented in related palm species, including *Pseudophoenix sargentii* and *Thrinax radiata* (Khoddamzadeh et al. 2023).

The ecological implications of saline intrusion on seedling recruitment and survival in natural environments are profound, especially for foundational species such as the Cabbage Palm, which play critical roles in coastal and subtropical ecosystems. While mature Cabbage Palms typically exhibit higher salinity tolerance, younger seedlings remain particularly vulnerable to environmental stressors. Consequently, chronic saline exposure initially manifests through reduced juvenile recruitment and regeneration capacities rather than immediate adult mortality. Over extended periods, this demographic shift threatens genetic diversity, compromises population structure, and diminishes resilience to additional stressors, including diseases and extreme weather events. Persistent reductions in seedling recruitment also risk altering community composition and ecosystem stability, thereby potentially diminishing overall biodiversity.

The current study indicated that silicon soil amendments can effectively address these conservation challenges by enhancing seedling resilience to saline conditions. Specifically, increased survivorship observed at moderate salinity levels (30 ppt) suggests that integrating silicon treatments into ecological restoration protocols could significantly improve establishment success rates. By supporting seedlings through critical early growth stages until deeper root penetration into freshwater

Table 2. Correlation coefficients among optical and phenotypic parameters (N = 6 per treatment) for months 1, 6, and 12.

	NDVI	AtLEAF+	Leaf count	Flux
Month 1				
SPAD	0.202	0.337	0.452	−0.137
NDVI		0.309	0.269	−0.101
AtLEAF+			0.291	−0.033
Leaf count				0.083
Light				
Month 6				
SPAD	0.954	0.989	0.968	**0.704****
NDVI		0.960	0.947	**0.651****
AtLEAF+			0.980	**0.705****
Leaf count				**0.586***
Light				
Month 12				
SPAD	0.964	1.000	0.919	**0.887******
NDVI		0.966	0.984	**0.818******
AtLEAF+			0.923	**0.883******
Leaf count				**0.724****
Light				0.02

Asterisks denote significance levels (****$P < 0.0001$, ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$). NDVI = normalized difference vegetation index; SPAD = soil plant analytical development.

strata occurs, silicon amendments offer a strategic approach to bolster reforestation efforts and assisted migration initiatives, particularly in coastal areas susceptible to fluctuating saline intrusion.

Moreover, enhancing seedling establishment via silicon treatments has extensive ecological benefits that extend beyond individual species conservation. Cabbage Palm serves as a foundational species in Florida's coastal ecosystems, providing structural habitat, nesting opportunities, and essential food resources for diverse fauna. Consequently, reduced seedling survival rates could trigger cascading ecological consequences, potentially resulting in biodiversity loss and altered community structures. By promoting seedling tolerance and survival, silicon amendments indirectly support broader ecological stability, facilitating sustained trophic interactions and overall ecosystem functionality. Furthermore, seedlings exhibiting enhanced physiological vigor contribute to maintaining primary productivity and carbon sequestration capabilities under saline conditions, underscoring the broader ecological value of silicon-based interventions in promoting ecosystem resilience and sustainability.

From a horticultural perspective, the findings of this research offer critical insights and practical benefits for commercial growers and landscape managers operating within Florida's economically significant green industry. Given the widespread commercial use of Cabbage Palm in ornamental landscaping and ecological restoration projects, optimizing nursery practices to enhance seedling resilience directly translates to substantial economic and environmental benefits. Experimental outcomes indicated that silicon amendments administered at an economically viable and physiologically optimal concentration of approximately 1% delivered maximal growth and physiological enhancements. Adoption of this optimized concentration is likely to reduce seedling mortality rates, improve transplant success, and enhance the overall quality of nursery stock. Additionally, leveraging nondestructive optical sensor technologies, such as SPAD, atLEAF+, and NDVI indices, enables real-time monitoring and adaptive management of nursery operations. This technological integration allows more precise resource allocation, lowers operational costs, and maximizes nursery productivity and profitability.

Despite rigorous experimental control provided by greenhouse conditions, inherent limitations in replicating natural environmental variability must be acknowledged. Greenhouse experiments typically exclude important environmental variables such as periodic flooding, temperature fluctuations, and herbivore pressure. Therefore, future research should prioritize field-based trials to validate the effectiveness of silicon amendments under more realistic fluctuating environmental conditions. Moreover, examining the potential synergistic effects between silicon amendments and beneficial soil microorganisms, especially mycorrhizal fungi, represents an essential avenue for future investigation. Such studies could explore improvements in nutrient uptake efficiency and enhanced stress tolerance conferred by microbial interactions. Additionally, genomic analyses comparing silicon-treated and untreated seedlings would provide valuable insights into molecular mechanisms underpinning salt tolerance, potentially guiding future breeding initiatives aimed at developing genetically resilient palm cultivars.

Conclusion

This study underscored the practical efficacy and conservation significance of silicon amendments in enhancing resilience among Cabbage Palm seedlings exposed to saline stress, particularly at low to moderate salinity levels. While elevated salinity inevitably led to seedling mortality, silicon supplementation substantially delayed this outcome, maintained growth, and improved physiological parameters, thereby demonstrating silicon's capacity to mitigate abiotic stress. These findings hold considerable relevance for horticultural management and conservation efforts targeting the Cabbage Palm, a species of notable ecological value and economic value increasingly threatened by sea-level rise and saltwater intrusion. Additionally, unexpected mortality within control groups highlighted the complex interplay of factors that influence plant stress, including temperature fluctuations, pest pressures, and nutrient dynamics, emphasizing the need for integrated management strategies over isolated interventions. Silicon amendments thus present a robust component within broader land management frameworks, enhancing ecosystem resilience amid climate-driven challenges and offering potential broader applications for improving crop and ecosystem sustainability under prevalent saline conditions. Practically, the results advocate incorporating silicon amendments into nursery and landscape management protocols at an economically and ecologically optimized dosage of 1% because higher concentrations demonstrated diminishing returns. Despite these promising outcomes, inherent limitations from controlled greenhouse conditions necessitate field validations to address real-world variability, such as groundwater fluctuations, temperature extremes, and humidity variations. Future research should evaluate silicon interventions across broader developmental stages, genetic diversity, and environmental gradients to comprehensively harness silicon's strategic potential in bolstering plant stress resilience amid global climate change.

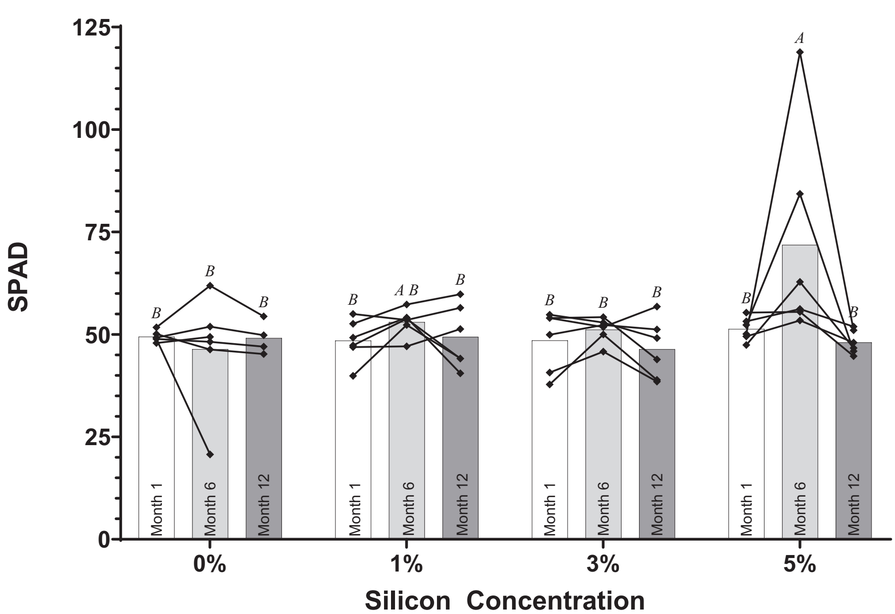

Fig. 6. Average soil plant analytical development (SPAD) readings by silicon treatments for months 1, 6, and 12. Letters denote significant differences ($P < 0.05$). Incongruous lines indicate that the cohort completely died. Saline is not a factor in this figure.

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