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# Anatomical Comparison of Roots, Leaves, and Stomata of *Rhizophora stylosa* Griff. under Various Salinity Levels

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**Abstract** This study compares the root, leaf, and stomata anatomy of *Rhizophora stylosa* Griff. under various salinity levels and identifies anatomical parameters as indicators of salinity change. The experiment lasted for three months using a Completely Randomized Design (CRD) with five salinity treatments (15, 20, 25, 30, and 35 ppt), and three replications. The parameters observed included root structure (hypodermis and cortex thickness, density, and aerenchyma area), leaf anatomy (total thickness, hypodermis and palisade layers), and stomata characteristics (size, pore width, and density). Data were analyzed using ANOVA followed by DMRT. The results of the study show clear anatomical differences between low and high salinity levels. The most prominent adaptations occur at medium salinity levels (25–30 ppt), which are characterized by a thicker hypodermis layer, wider aerenchyma spaces, and larger stomata pores. These structural modifications indicate physiological strategies for maintaining water balance and reducing osmotic stress. These findings suggest that specific root, leaf, and stomata characteristics may serve as early biological indicators of salinity changes in coastal ecosystems. By providing anatomical references for assessing mangrove tolerance, this study contributes to an evidence-based approach for monitoring resilience and guiding conservation actions in the face of climate change-induced salinity increases.

**Keywords** Aerenchyma, Conservation, Hypodermis, Mangrove, Palisade

## 1. Introduction

Mangrove forests are a crucial component of coastal ecosystems, particularly in tropical and subtropical regions [1]. Mangroves consist of various shrubs and woody trees that have adapted to the extreme conditions of the tidal zone with muddy sediments [2]. Muddy substrate conditions are ideal for *Rhizophora* spp. due to their high adaptability and survival capabilities. One notable species is *Rhizophora stylosa* Griff., known for its salinity tolerance [3, 4]. This adaptability is crucial given the ever-changing dynamics of coastal environments.

Environmental quality in mangrove habitats is significantly influenced by salinity. Salinity fluctuations can be caused by internal factors, such as water depth and seabed topography [5]. Additionally, global warming through “thermal expansion” of seawater contributes to rising sea levels, which indirectly affects salinity dynamics in coastal areas [6]. Extreme salinity is a significant challenge to mangrove survival and demands robust physiological and anatomical adaptations.

Previous research on *R. stylosa* responses to salinity has been extensive, but its focus has varied. Inoue et al.'s [7]

study has researched the morphology of its organs at different salinity levels. Miryeganeh and Saze [8] have reported the transcriptome of *R. stylosa* in adaptation to salinity stress. Hastuti et al. [9] investigated the chlorophyll content of this species at various salinity levels. Research related to the anatomy of *R. stylosa* is still limited. Several organs have been studied, including the anatomy of leaves [10, 11, 12], roots [13], and stems [14]. However, integrated anatomical studies of root, leaf, and stomata are rarely conducted for this species. Filling this knowledge gap is crucial for elucidating the structural basis of salinity tolerance mechanisms in mangroves.

Understanding anatomical plasticity in response to salinity stress has practical relevance for mangrove conservation and restoration strategies [15]. Mangrove forests are declining globally due to anthropogenic pressures and climate change-induced sea-level rise [16]. The Global Mangrove Alliance reports that around 35% of the world's mangrove forests have been lost over the last century. Southeast Asia has the highest rates of deforestation [1]. Knowledge of species-specific tolerance and anatomical plasticity, such as found in *R. stylosa* Griff., can inform site selection, species choice, and restoration techniques in degraded or vulnerable coastal areas [17].

This study aims to compare the root, leaf, and stomata anatomical structures of *R. stylosa* under various salinity treatments and to identify reliable anatomical markers indicative of salinity variation. This study provides a comprehensive anatomical comparison covering roots, leaves, and stomata under conditions of gradual salinity treatment. The findings are anticipated to advance fundamental understanding of mangrove adaptation mechanisms and to support evidence-based management and conservation of coastal ecosystems subject to increasing salinity stress.

# 2. Materials and Methods

The tools used are buckets, dipper, and stirring sticks as mangrove planting tools; a refractometer to measure salinity; scissors, plastic, label paper, and a storage box for sampling; glass objects and glass covers for sample preparation; a microscope and an Optilab camera microscope for anatomical observation of sample preparations; and a laptop with SPSS software for data analysis. The materials used were *R. stylosa* Griff. mangrove seedlings; sea mud and compost as planting media; water and salt as solution materials for treatment; root and leaf organs of *R. stylosa* Griff. as samples to be made into preparations; 70% alcohol, 1% safranin, and glycerin for sample preparation.

### 2.1. Mangrove Planting and Gardening

Mangrove planting was carried out by selecting healthy, equal-size, fresh green mangrove seedlings, then planted on a mixed planting medium of sea mud and compost (1:1). Seedlings were allowed to grow and adapt for seven days, then treated with a 15, 20, 25, 30, and 35 ppt salt solution. Gardening mangroves in the form of moss removal and monitoring mangrove growth is done every ten days for 12 weeks of treatment time.

### 2.2. Sampling

Root samples were taken ± 1 cm from the tip of the primary root *R. stylosa* Griff. Leaf samples were taken on the third leaf on each tree by cutting the leaves ± 2 cm from the tip of the leaf. Samples of roots and leaves that have been taken are then put in a sample bottle that has been filled with 70% alcohol. Stomata samples of *R. stylosa* Griff. were taken from leaves when still attached to the tree.

### 2.3. Making Anatomical Preparation and Observation Parameters

Preparation of anatomical roots and leaves is done by a semi-permanent free-hand preparation method carried out in the order of fixation stage (70% alcohol), slicing stage (razor tool, thickness ± 20–30 micrometers), staining stage (1% safranin), mounting stage (glycerin), and labeling stage.

Quantitative parameters of the root include root hypodermis thickness, cortex thickness, hypodermis and cortex ratio, aerenchyma density, and aerenchyma area. Quantitative parameters of the leaf consist of leaf thickness, hypodermis thickness, palisade thickness, the ratio of leaf and hypodermis thickness, also the ratio of hypodermis and palisade thickness.

Preparation of stomata anatomy is done by the replica method (nail polish method) at 08.00–09.00 am. Quantitative parameters of stomata consist of stomata width, pore width, and stomata density.

### 2.4. Analysis of Data

Qualitative data were obtained from a descriptive analysis of root, leaf, and stomata anatomy. Quantitative data were obtained from ANOVA statistical analysis (with a 95% confidence level) on quantitative parameters. This is followed by the DMRT (Duncan's Multiple Range Test).

# 3. Results and Discussion

### 3.1. Anatomy of *Rhizophora stylosa* Griff. Root

The cross-section of the *R. stylosa* root (Figure 1) shows a layered structure, which is consistent across all salinity treatments. The anatomy of the root from the outer surface to the inner part consists of the epidermis as a protective layer; the cortex as a place for storing food reserves; the endodermis, which regulates and controls the flow of water and nutrients; and the stele, which consists of xylem to transport water, and phloem that distributes the products of

photosynthesis. This is in line with Tatongjai et al.'s [18] study, which stated that *Sonneratia caseolaris* mangrove roots consist of an outer periderm layer, which replaces the epidermis in mature roots; a cortex with aerenchyma; an endodermis as the inner layer of the cortex; and a stele containing pericycle, phloem, and xylem. Qualitative observations note a well-defined hypodermal layer, consisting of large hollow cells, which indicate a significant capacity for water and ion storage, facilitating salt excretion. The presence of extensive aerenchyma throughout the root cortex further indicates adaptation to hypoxic and saline conditions by increasing internal aeration. The aerenchyma forms interconnecting gas spaces within the root cortex, effectively reducing metabolic demands by decreasing the volume of living tissue requiring oxygen, as well as supporting oxygen transport from the stem to the roots [19].

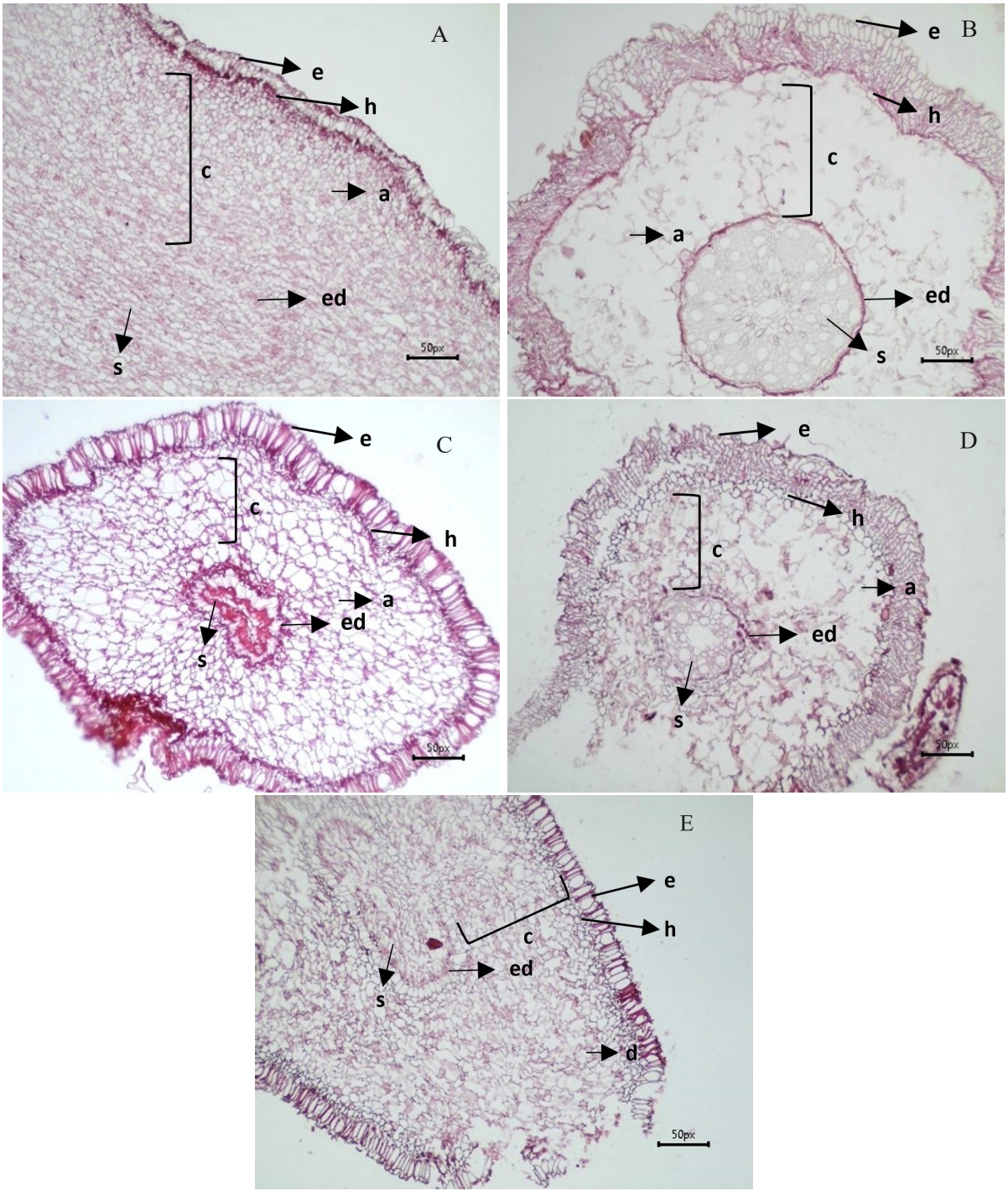



**Figure 1.** Cross-sections of *Rhizophora stylosa* Griff. roots exposed for 3 months to different salinity treatments: (A) 15 ppt, (B) 20 ppt, (C) 25 ppt, (D) 30 ppt, (E) 35 ppt. e) epidermis, h) hypodermis, c) cortex, a) aerenchyma, ed) endodermis, s) stele. Magnification 10x; scale bar = 50 px

**Table 1.** Quantitative Data of *Rhizophora stylosa* Griff. Roots on Different Salinity Treatment

| Parameter | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ |
|---|---|---|---|---|---|
| Thickness of root hypodermis [H] (µm) | 67.17 | 111.21 | 88.24 | 105.74 | 78.98 |
| Thickness of root cortex [C] (µm) | 444.62 | 370.14 | 330.11 | 309.74 | 527.03 |
| Ratio H/ C | $0.16^{b}$ | $0.30^{ab}$ | $0.27^{ab}$ | $0.34^{a}$ | $0.16^{b}$ |
| Aerenchyma area (µm$^2$) | $539.47^{d}$ | $1348.05^{cd}$ | $1233.42^{cd}$ | $1900.56^{c}$ | $2022.10^{c}$ |
| Aerenchyma density (× $10^{-4}$/µm$^2$) | 13.11 | 6.96 | 8.69 | 7.54 | 5.90 |

*The numbers are followed by a different superscript alphabet on the same line, indicating a significant difference in the 95% confidence level ($p<0.05$). S1: 15 ppt; S2: 20 ppt; S3: 25 ppt; S4: 30 ppt; S5: 35 ppt*

Quantitatively, the thickness of the individual hypodermis and cortex did not show statistically significant differences between salinity (Table 1). The ratio of hypodermis thickness to cortex thickness (H/C) increased significantly at a salinity of 30 ppt compared to 15 ppt. This reflects a relative increase in hypodermis tissue under increased salinity stress. These findings are consistent with Parida et al.'s [20] study on *Salvadora persica*. The ratio of hypodermis thickness to cortex thickness (H/C) increased because the hypodermis thickened significantly, while the cortex relatively thinned or increased slightly. These structural modifications likely function as a barrier that limits salt entry and reduces osmotic stress on deeper tissues.

Similarly, a significant increase in aerenchyma area at higher salinity levels indicates the formation of more gas-filled spaces, as a result of programmed cell wall degradation. This is thought to be mediated by ethylene signaling under saline and flooded conditions. Consistent with Yuan et al.'s [21] study, Bermuda grass roots exposed to submerged and saline conditions developed a larger aerenchyma area compared to the control group, with an increase in root cavity levels from around 22% to more than 40% in the stress treatment. Maize plants exposed to salinity stress also showed a significant increase in the number and size of root cortex aerenchyma. This increase improved root oxygen supply, which is crucial for maintaining metabolic activity in submerged and saline substrates [22].

Aerenchyma density tends to decrease as the increasing salinity levels. The inverse relationship between density and size is consistent with the presence of larger aerenchyma at high salinity concentrations and represents adaptive plasticity to environmental stress. For example, research on root anatomical plasticity under salinity stress reports that an increase in aerenchyma size coincides with changes in density and wall thickness to maintain mechanical stability while facilitating gas exchange. In aquatic halophytes, larger aerenchyma stores excess water and gas, increasing salinity tolerance through structural adaptations involving changes in the density and size of these spaces [23, 24].

### 3.2. Anatomy of *Rhizophora stylosa* Griff. Leaf

The anatomy of a mangrove leaf from top to bottom consists of the upper epidermis, which protects the inner tissues of the leaf from excessive transpiration; the hypodermis to store water; the mesophyll palisade, which is the main center of photosynthesis; the mesophyll sponge, contributing to some photosynthetic activities; stomata as a place for gas exchange; and the lower epidermis. Leaf anatomy consistently shows a thick cuticle and well-developed hypodermis beneath the upper epidermis (Figure 2). This is a characteristic feature of the xeromorphic nature of mangroves. This is in accordance with Wijaya et al.'s [25] study that the anatomy of *Rhizophora mucronata* mangrove leaves consists of an epidermal layer, where the lower epidermis is smaller than the upper epidermis; several layers of hypodermis with rectangular-polygonal in shape; the mesophyll palisade; the mesophyll sponge with air cavities, irregular round cells. The hypodermis thickens at a salinity of 30 ppt, which is supported by quantitative data (Table 2). This is in line with Goldin's [26] research findings. At a salinity level of 30 ppt, there was significant thickening of the hypodermis of *Avicennia marina*, particularly in the water storage tissue. This thickening serves as an adaptation to salinity stress by increasing water storage capacity and providing a protective layer that shields palisade cells from excessive salt and light exposure.

The thickness of the palisade tissue tends to decrease with increasing salinity. However, the suppression of palisade tissue development under high salinity conditions likely limits the exposure of photosynthetic tissue, reduces photo-oxidative damage, and conserves water. Several species show a clear reduction in palisade tissue thickness as the increasing salinity as part of anatomical adaptation or damage caused by salinity stress [27]. This is in accordance with Yao et al.'s [28] study that shows an increase in the thickness of the palisade tissue in *Lycium barbarum* under salinity stress. The palisade tissue underwent significant thickening at moderate salinity levels (100-200 mmol/L NaCl). However, at very high salinity levels (750 mM NaCl), the palisade layer may disappear, indicating a reduction or loss of this layer at extreme salinity concentrations [28].

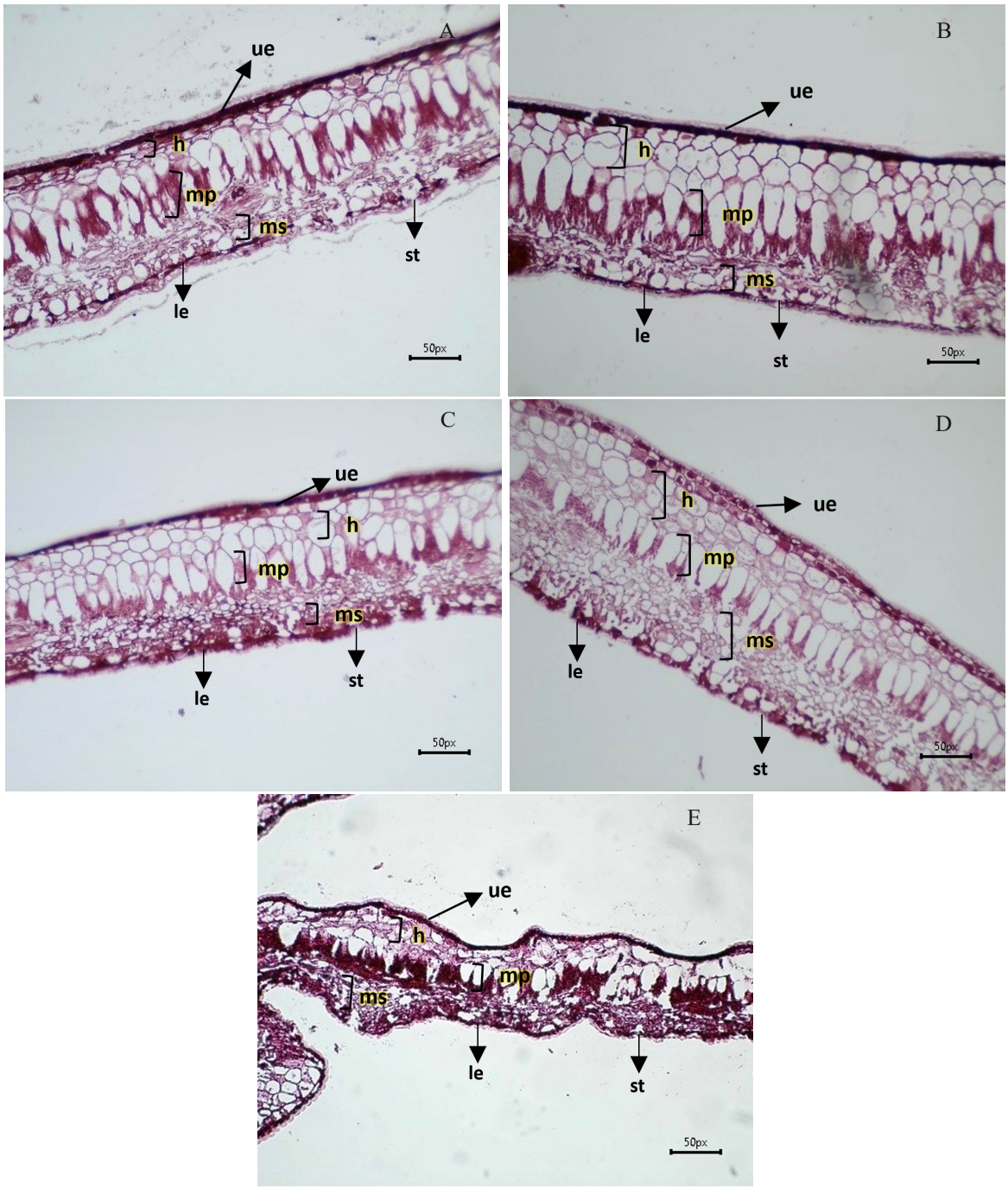



**Figure 2.** Cross-sections of *Rhizophora stylosa* Griff. leaves exposed for 3 months to different salinity treatments: (A) 15 ppt, (B) 20 ppt, (C) 25 ppt, (D) 30 ppt, (E) 35 ppt. ue) upper epidermis, h) hypodermis, mp) mesophyll palisade, ms) mesophyll sponge, st) stomata, le) lower epidermis. Magnification 10x; scale bar = 50 *px*

**Table 2.** Quantitative Data of *Rhizophora stylosa* Griff. Leaf on Different Salinity Treatment

| Parameter | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ |
|---|---|---|---|---|---|
| Thickness of leaf [L](µm) | $357.47^{b}$ | $370.03^{ab}$ | $378.13^{ab}$ | $456.29^{a}$ | $241.43^{b}$ |
| Thickness of leaf hypodermis [H] (µm) | $68.06^{e}$ | $75.07^{ed}$ | $94.05^{ed}$ | $138.50^{c}$ | $99.61^{d}$ |
| Thickness of palisade [P] (µm) | 128.56 | 122.39 | 122.77 | 112.00 | 78.61 |
| Ratio L/H | $5.31^{i}$ | $5.09^{ig}$ | $4.02^{igh}$ | $3.37^{gh}$ | $2.43^{h}$ |
| Ratio H/P | $0.54^{j}$ | $0.61^{j}$ | $0.78^{j}$ | $1.25^{i}$ | $1.31^{i}$ |

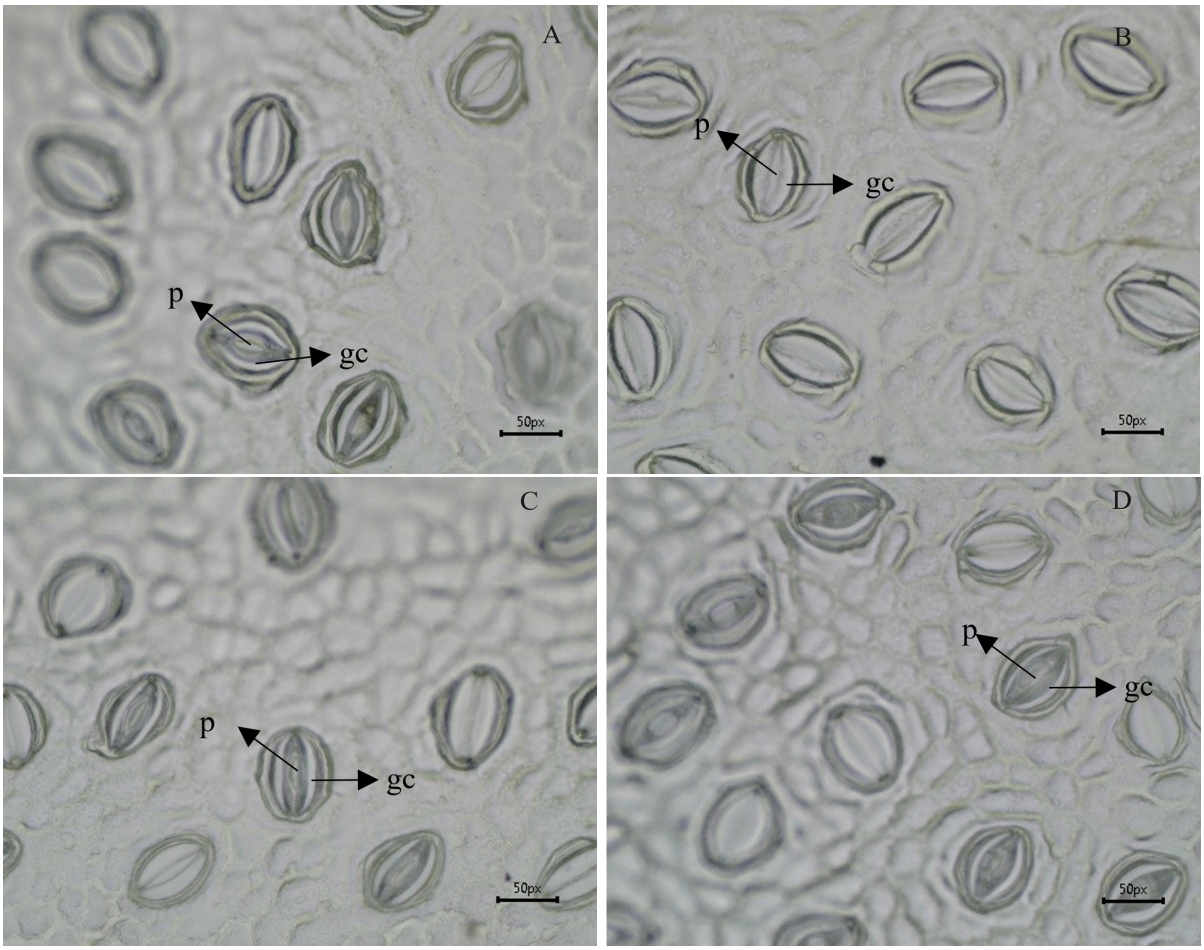
*The number's followed by a different superscript alphabet on the same line, indicating a significant difference in the 95% confidence level ($p<0.05$). S1: 15 ppt; S2: 20 ppt; S3: 25 ppt; S4: 30 ppt; S5: 35 ppt*

The decrease in leaf thickness and hypodermis thickness ratio (L/H), and the increase in hypodermis and palisade thickness ratio (H/P), further reinforce the shift in tissue allocation that prioritizes water-retaining tissues under salinity stress. Leaf thickness may initially increase due to the expansion of palisade tissue and cell size, especially at moderate salinity levels, which can promote leaf growth and reduce salinity damage [28]. This is in line with Sanchez et al.'s finding [29], that is the hypodermis layer thickens in *R. mangle* in response to higher salinity as a protective measure, but this depends on the species and does not always lead to an increase in the L/H ratio.

### 3.3. Anatomy of *Rhizophora stylosa* Griff. Stomata

Qualitative analysis showed that *R. stylosa* had an anomocytic type with kidney-shaped guard cells (Figure 3). Stomata had undulating or wavy to rounded anticlinal edges [30]. The length and width of stomata tend to decrease as salinity levels increase. Meanwhile, pore dimensions (length, width, area) were significantly larger at higher salinity levels (Table 3). This is in line with Tang et al.'s [31] study, which shows that salinity concentration increases parameters related to leaf porosity and the looseness of leaf structure in Walnut (*Juglans major* × *Juglans regia*). This can be attributed to an increase in leaf pore dimensions at higher salinity. This looseness can facilitate better $CO_2$ diffusion despite stomata limitations under salinity stress.

This counterintuitive stomata behavior, whereby pores remain more open under high salinity conditions, may reflect a balancing act between minimizing water loss and ensuring sufficient $CO_2$ uptake for photosynthesis. The water reservoir in the thickened hypodermis likely maintains guard cell turgor, facilitating stomata aperture opening despite osmotic stress. Studies show that salinity stress initially causes partial closure of stomata to limit water loss, but leaves can also develop adaptations that loosen leaf structure and increase pore dimensions, allowing better $CO_2$ diffusion into the mesophyll despite stomata limitations. This facilitates sustained photosynthesis under salinity stress while managing water conservation [31].



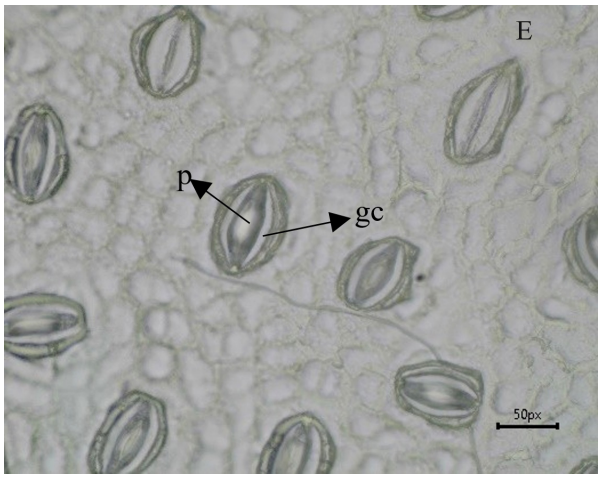



**Figure 3.** Stomata of *Rhizophora stylosa* Griff. exposed for 3 months to different salinity treatments: (A) 15 ppt, (B) 20 ppt, (C) 25 ppt, (D) 30 ppt, (E) 35 ppt. p) porous, gc) guard cell. Magnification 40x; scale bar = *50px*

**Table 3.** Quantitative Data of *Rhizophora stylosa* Griff. Stomata on Different Salinity Treatment

| Parameter | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ |
|---|---|---|---|---|---|
| Length of stomata (µm) | 43.21 | 44.35 | 43.60 | 40.68 | 38.41 |
| Width of stomata (µm) | 26.41 | 26.30 | 24.28 | 25.24 | 24.51 |
| Length of porous (µm) | $24.12^{b}$ | $29.71^{ab}$ | $30.98^{ab}$ | $31.26^{ab}$ | $32.26^{a}$ |
| Width of porous (µm) | $7.80^{d}$ | $7.47^{d}$ | $14.09^{c}$ | $14.14^{c}$ | $14.84^{c}$ |
| Porous area ($\mu m^2$) | $186.32^{f}$ | $221.03^{f}$ | $441.60^{e}$ | $442.04^{e}$ | $474.56^{e}$ |
| Stomata density ($10^{-5}/\mu m^2$) | 13.75 | 11.57 | 10.67 | 11.81 | 14.60 |

*The numbers are followed by a different superscript alphabet on the same line, indicating a significant difference in the 95% confidence level (p<0.05). S1: 15 ppt; S2: 20 ppt; S3: 25 ppt; S4: 30 ppt; S5: 35 ppt*

Environmental conditions within the experimental garden, particularly controlled temperatures and light exposure limited by the roof, likely alleviate additional abiotic stress that typically causes stomata closure in natural habitats with high salinity. This highlights the importance of microhabitat context when interpreting physiological adaptations. Plant microhabitats refer to the small-scale abiotic and biotic conditions that plants experience directly, which often differ significantly from broader population or regional conditions. These small-scale differences include variations in water availability, temperature, soil composition, light exposure, and salinity that create unique microhabitats [32].

The trend of increased stomata density at the highest salinity levels is inversely correlated with stomata size. Plants experiencing salinity stress often show an increase in stomata density, which is believed to compensate for reduced stomata size. Smaller stomata tend to open and close more quickly, allowing for more efficient regulation of gas exchange under stress, including improved water use efficiency and maintenance of photosynthesis [33]. This trade-off enables plants to optimize carbon dioxide uptake while minimizing water loss, which is particularly crucial under stressful conditions, such as high salinity [33, 34].

### 3.4. Implications for Mangrove Conservation

The anatomical plasticity observed in *R. stylosa* along the salinity gradient, characterized by hypodermis expansion, aerenchyma enlargement, and stomata pore adjustment, highlights the species' inherent resistance mechanisms to osmotic and oxidative stress in saline environments.

These anatomical parameters have the potential to serve as practical bioindicators for early detection of salinity stress. Monitoring changes in specific anatomical parameters offers a sensitive and early method for detecting salinity stress, enabling proactive management before visible growth or phenotypic symptoms appear [35, 36].

This study used three replications. This number is the minimum amount of replications often used as a requirement for ANOVA analysis to estimate the mean and variance. However, a larger number of replications will increase statistical power and population representation, so further research with a larger sample size is highly recommended to prevent non-significant data.

# 4. Conclusions

This study shows that *R. stylosa* exhibits significant anatomical plasticity in response to various salinity levels, which is mainly reflected in the thickening of the root and leaf hypodermis, enlargement of the root aerenchyma, and adjustment of stomata pore dimensions. These anatomical changes, which were particularly evident at salinity levels of 25 to 30 ppt, suggest adaptive strategies to reduce osmotic stress, enhance gas exchange, and maintain physiological function under saline conditions. These findings provide valuable insights into the anatomical basis of salinity tolerance in *R. stylosa* and identify measurable traits as early bioindicators of environmental stress caused by salinity. Further research with a larger sample size is needed to obtain more accurate results.

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# Conflicts of Interest

The authors declare that there are no conflicts of interest related to the publication of this manuscript. This research was conducted independently, without any commercial or financial relationships that could be considered a potential conflict that could influence the results or interpretations presented.

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