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Adaptive Leaf Structure and Anatomy in *Rhizophora mucronata* Lam.: The Effects of Salinity and Pollution on Foliar Characteristics

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Abstract

Mangroves are the only woody, facultative halophytes that grow at the ecotone between land and sea. Effective stress management is crucial for mangrove plant survival in the saline environment, leading to distinctive adaptations among species. The study aimed to examine the variation in leaf lamina characteristics of *Rhizophora mucronata* Lam., focusing on its saline thriving and the impact of water pollution and salinity on the foliar characteristics of species at selected sites in northern Kerala districts. *R. mucronata* plants with similar heights and diameters were chosen from each study site, and their mature leaves from the third node were taken away for foliar examination. The laminar characteristics of *R. mucronata* vary spatially and are influenced by salinity and water quality. Significant foliar modifications such as low density of stomata, thick waxy cuticles, corky warts, thick water storage tissue/ hypodermis, and thick lamina were developed by *R. mucronata* to adapt to the high saline and polluted environment. Water analysis revealed that the conserved sites are less polluted than others. Water quality parameters like turbidity, NTU, colour, Hazen, total Coliforms, CFU/100ml, and total dissolved solids (TDS), mg/l were lower at the conserved sites. Compared to less polluted and conserved sites, *R. mucronata* distributed in more saline and polluted sites exhibit low leaf chlorophyll content in mg/g tissue, which indicates high salinity and water pollution impact the photosynthesis and productivity of Rhizophora. Therefore, immediate conservation measures must be implemented to conserve these polluted mangrove habitats.

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Introduction

Mangroves are the only woody, facultative halophytes that grow at the ecotone between land and sea. Consequently, they acquired several morphological, physiological, biochemical, and molecular traits that support their ecological adaptation and persistence in extreme conditions, including fluctuating water levels and salinity.[1]

The anatomical features of mangrove species play two crucial roles: they serve as taxonomic identification tools[3-6] and as an adaptation in response to fluctuating environmental stresses[6,7] such as elevated salt levels,[8,9] pollution,[10] sea level rise,[11,12] inundation,[13,14] varying light intensities,[15] and high temperatures. Foliar adaptations of mangroves to various stresses include changes in the salt gland size and structure,[16] size, and density of stomata,[17] water storage tissues,[18] cuticle thickening, leaf thickness, the thickness of palisade tissue,[19] epidermal wax deposition,[20] Casparian strip and suberin lamellae flexibility, and variations in vessel architecture.[21,22] The plasticity of these structural alterations is a key element controlling mangrove survival and fitness. Research on the lamina characteristics of mangroves can help understand many aspects of plant life, including photosynthetic processes, production, sequestration of carbon dioxide, and stress tolerance.

Effective stress management is crucial for mangrove plant survival in the saline environment, leading to distinctive adaptations among species. Three types of true mangroves could be distinguished based on their resistance to salinities: species that are high, moderate, and less salt-tolerant. *Rhizophora mucronata* Lam. is a high salt-tolerant species but they don't have salt glands like in the Avicennia species; they are salt excluders. Nevertheless, *R. mucronata* can survive in high salinity by preventing salt absorption at the root and excluding heavy salt through root ultrafiltration mechanism.[32] Furthermore, *R. mucronata* accumulates salt in its older leaves, which are subsequently shed to remove the salt from the plant.[33] *Rhizophora mucronata* trees were also found to increase their vessel density in response to high salinity, enabling improved water transport in hypersaline environments.[34]

R. mucronata is one of the dominant true mangrove species distributed in northern Kerala and also one of the major species recommended for planting in mangrove restoration programs. To ensure the conservation and restoration of the mangrove ecosystems, it is essential to comprehend how mangroves respond to regional and local changes.

Salinity surges and tides are important ecological constraints that limit the growth and survival of mangroves. Although most mangrove plants can withstand a saline level of 35 ppt, they flourish best in a range of 5 to 20 ppt.[40-42] Water salinity in mangroves is influenced by both natural and anthropogenic activities. Precipitation, freshwater inflow, and sea level rise are major natural factors,[43] and aquaculture, urbanization, land use changes, agriculture, and industrial effluent runoff are human-made factors influencing salinity and water quality.[44] Anthropogenic activities lead to water pollution, which in turn alters the salinity.

This study aimed to examine the variation in leaf lamina characteristics of *Rhizophora mucronata* Lam. and investigate how it aids the species in thriving in a saline environment. Another objective is to determine whether variations in the water salinity and the water pollution in different sites selected from north Kerala impact the foliar properties of *R. mucronata*. The current investigation on environmental factors influencing the morphology and leaf lamina characteristics of *Rhizophora* species may give insight to improve management techniques and establish conservation plans at local sites, especially in areas where water pollution or salinity levels are increasing.

Materials and Methods

The genus *Rhizophora* includes seven species and three hybrids. All species of this pantropical genus are true mangroves, and their distribution is limited to the intertidal zone.[24]

Sampling Sites

Mangroves cover an area of 19.531 km² in Kerala. Out of this, 50.05% is distributed in the northern districts of Kerala, including Kasaragod, Kozhikode, and Kannur.[2]

Seven different sampling sites (Table 1) were selected within the three northern districts of Kerala based on specific criteria such as population density and the distribution pattern of *Rhizophora mucronata*.

Sample Leaf Collection

R. mucronata plants with similar heights and diameters were chosen from each study site, and their mature leaves from the third node were taken away for foliar examination.[45] Intact mature leaves were collected in the morning and immediately taken to the laboratory after being sealed in plastic bags.[46]

Table 1: latitude, longitude, and degree of pollution of selected study stations from north Kerala districts

Study stations	Latitude and longitude	Panchayat/ Village/ Municipality	Pollution
C_1: Kadalundi	N11º07.618' E075º49.969'	Kadalundi and Vallikunnu Village	Conserved area
K_1: Kumbala	N12º35.919' E074º56.626'	Kumbala Grama Panchayat	Medium Pollution
K_2: Mogral	N12º33.669' E074º57.360'	MogralPuthur Panchayat	High Pollution
K_3: Thalankara	N12º29.336' E074º59.235'	Kasaragod Municipality	Medium Pollution
N_1: Kunjimangalam	N12º05.646' E075º13.410'	Kunjimangalam Panchayat	Conserved area
N_2: Pazhayangadi	N12°01'37.7" E75°16'11.3"	Ezhome Panchayat	Medium Pollution
N_3: Valapatanam	N11º56.078' E075º21.075'	Valapatanam Grama Panchayat	High Pollution

Morpho Anatomical Traits of Leaf Lamina

Laminar traits of *R. mucronata* studied include, Leaf area (LA) (cm²), Dry mass of leaf (DM) (g), Specific leaf area (SLA) = LA/DM (m²/Kg), Leaf mass per area (LMA) = 1/SLA (kg/m²), Lamina thickness (LTH) (µm), Leaf density (LD) = LMA/ Leaf thickness (LTH) (kg/m³), Leaf Fresh weight (FW) (g), Leaf Dry weight (DW), Moisture Content (MC%), mg Chlorophyll a/ g tissue, mg Chlorophyll b/ g tissue, Stomatal index (SI), Length of Stomata (SL) (µm), Width of Stomata (SW) (µm), Thickness of water storage/ non-assimilatory zone/colorless zone/ hypodermis (WST) (µm), Upper Palisade length (UPL) (µm), Lower spongy parenchyma thickness (SPT) (µm), UPL/SPT Ratio, Thickness of Upper Cuticle (UCT) (µm) and Thickness of Lower Cuticle (LCT) (µm).

Anatomic hand sections were taken at a point about halfway between the base and apex of the leaf lamina. The microscopic leaf anatomy slide preparations were analyzed using an Almicro Trinocular Microscope, and images were taken using a Magcam DC 5 microscope digital camera. Micrometric measurements were made using Magvision image analysis software.

Calculation of the stomatal index refers to research by Lestari (2006) using the formula that follows.

Stomatal index[23] = number of stomata/ (number of stomata + number of epidermal cells) × 100

Chlorophyll Estimation

Chlorophyll content was estimated following Arnon's method (1949), with absorbance measured at 663 nm and 645 nm to determine chlorophyll a, chlorophyll b, and total chlorophyll content.

$$\text{mg Chl. a/g tissue} = 12.7(A_{663}) - 2.69(A_{645}) \times V \div (100 \times W)$$

$$\text{mg Chl. b/g tissue} = 22.9(A_{663}) - 4.68(A_{645}) \times V \div (100 \times W)$$

$$\text{mg total Chl. / g tissue} = 20.2\ (A_{645}) + 8.02\ (A_{663}) \times V \div (10 \times W)$$

where W is the fresh weight (g) of the tissue extracted, V is the total volume (ml) of chlorophyll extracted in 80% acetone, and A_{663} and A_{645} are the absorbance at particular wavelengths (nm).

Analysis of the water sample was also conducted according to the APHA method (2017)[31] to compare and study the effects of salinity and pollution on the foliar characters of *R. mucronata*. The parameters including pH (APHA, 2017 (Part 4500 H+)), Colour (APHA,2017 (Part 2120)), Hazen,[30] Turbidity, NTU (APHA,2017 (Part 2130)), Total Dissolved Solids, mg/l (APHA,2017 (Part 2540)), Salinity, ppt (APHA,2017 (Part 2520B)), and Total Coliforms, CFU/100ml (APHA,2017 (Part 9222B)) from all the selected study sites were measured.

Table 2: Water quality parameters (mean ± standard deviation) measured at all sampling sites throughout the study period, including pH, Color (Hazen), Total Dissolved Solids (mg/L), Turbidity (NTU), Salinity (ppt), and Total Coliforms (CFU/100 mL)

Sl No.	Parameters	K_1	K_2	K_3	N_1	N_2	N_3	C_1
1	pH	7.04± 0.02	6.51± 0.04	7.1± 0.03	7.05± 0.03	6.87± 0.02	7.74± 0.04	7.02± 0.02
2	Colour, Hazen	15	>20	10	5	15	>20	15
3	Total Dissolved Solids, mg/l	13300± 169	37204± 235	17960± 278	10030± 306	15550± 148	40328± 107	21426± 239
4	Turbidity, NTU	16.8± 5.78	40.52± 4.96	27.36± 7.34	2.60± 6.49	33.48± 7.46	100.3± 7.89	15.7± 7.52
5	Salinity, ppt	29.42± 3.46	36.05± 2.06	26.93± 2.47	18.37± 3.44	25.21± 2.51	38.42± 3.29	30.27± 2.48
6	Total Coliforms, CFU/100ml	1100	1100	400	400	1100	2400	400

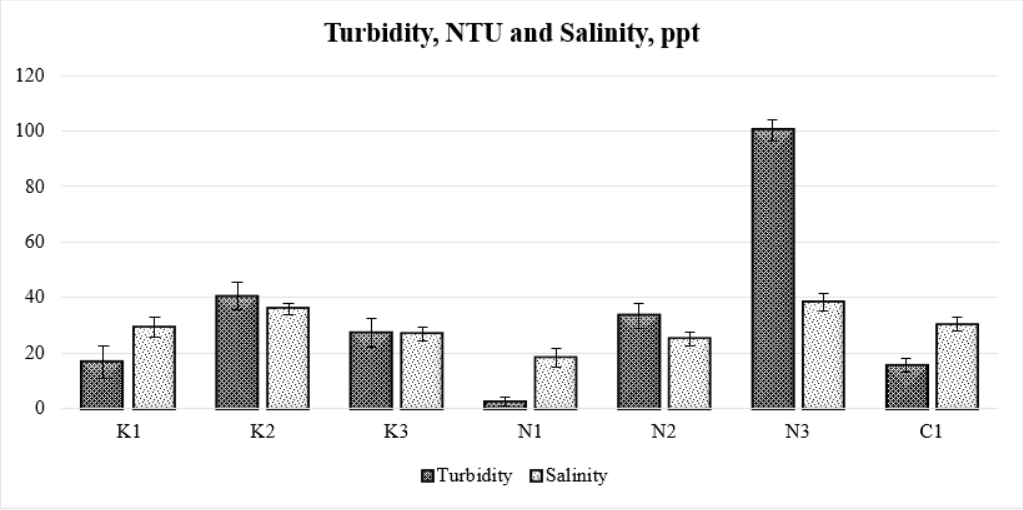

Fig. 1: Turbidity (NTU) and salinity (ppt) of water samples measured at all sampling sites throughout the study period. Data represent mean values ± standard deviation

Table 3: Laminar traits of Rhizophora mucronata at all sampling sites (mean ± standard deviation)

Laminar traits of *R. mucronata*	Study Sites						
	K_1	K_2	K_3	N_1	N_2	N_3	C_1
LA (cm^2)	81.94± 3.07	68.14± 2.50	88.18± 3.14	94.39± 3.19	78.93± 3.04	70.7± 4.56	93.93± 4.06
FW (g)	4.08± 0.04	6.79± 0.06	5.39± 0.07	3.86± 0.09	4.36± 0.11	6.28± 0.13	4.49± 0.21
DM (g)	1.74± 0.07	2.09± 0.13	1.91± 0.28	1.39± 0.06	1.71± 0.08	1.93± 0.06	1.82± 0.08
Moisture content %	57.35 ± 0.02	69.20 ± 0.02	64.58 ± 0.05	64.04 ± 0.03	60.73± 0.03	69.32 ± 0.02	59.53 ± 0.05
SLA (m^2/Kg)	4.712± 0.260	3.259± 0.239	4.618± 0.687	6.788± 0.375	4.613± 0.283	3.661± 0.267	5.160± 0.319
LMA (kg/m^2)	0.212± 0.014	0.307± 0.018	0.216± 0.043	0.147± 0.021	0.217± 0.017	0.273± 0.020	0.194± 0.020
LD (kg/m^3)	304.79± 20.08	415.96± 24.33	330.0± 65.79	230.47± 32.89	295.94± 23.13	360.06± 26.38	300.03± 30.96
mg Chl. a/ g tissue	0.819± 0.012	0.438± 0.021	0.766± 0.005	0.983± 0.014	0.794± 0.025	0.379± 0.017	0.913± 0.024
mg Chl. b/g tissue	0.586± 0.009	0.284± 0.004	0.589± 0.014	0.699± 0.025	0.521± 0.016	0.284± 0.007	0.672± 0.026
Total Chl. mg/g	1.405± 0.035	0.722± 0.032	1.355± 0.029	1.682± 0.041	1.315± 0.024	0.663± 0.016	1.585± 0.035

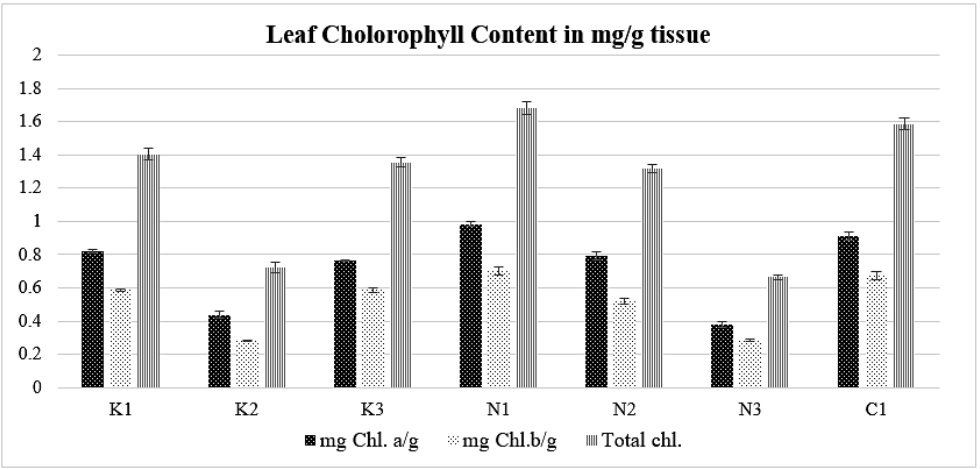

Fig. 2: Leaf chlorophyll content (mg/g tissue) of *Rhizophora mucronata* (mg Chl. a, mg Chl. b, and total chlorophyll) at all sampling sites. Data represent mean values ± standard deviation

Results

The leaves of *R. mucronata* are simple, oppositely arranged,[47] dark green to yellowish green, shiny, hairless,[47] leathery, and crammed towards the tips of branches. Lamina was broadly elliptic or ovate-oblong and cuneated at the base.[25] The margins are[47] smooth, with a pointed apex and a characteristic small needle-like tip. Midrib green

beneath. The lower surface of the lamina has scattered black dots. These leaf-based structures, called cork warts (figure 5), help remove surplus salt from foliage and prevent it from accumulating in plant tissues. Cork warts form during leaf initiation and are present on the abaxial surface. They serve as an airway from the atmosphere to plant tissue, specifically aerenchyma cells.[26,27]

Table 4: Anatomical traits of *Rhizophora mucronata* leaf samples (mean ± SD) at all sampling sites

Anatomical traits	Study Sites						
	K_1	K_2	K_3	N_1	N_2	N_3	C_1
WST (µm)	275.52 ±3.49	281.43 ±4.08	279.92 ±2.47	242.54 ±2.94	274.01 ±3.09	294.74 ±3.78	259.07 ±2.69
UPL (µm)	93.66 ±1.23	88.99 ±0.96	96.87 ±2.17	109.14 ±2.07	89.12± 1.02	85.38± 1.12	101.26± 1.12
SPT (µm)	287.09 ±0.92	300.55 ±1.24	270.35 ±1.26	276.02 ±1.13	295.89 ±1.01	354.40 ±2.01	286.77 ±1.35
UPL/SPT Ratio	0.326	0.296	0.358	0.396	0.301	0.241	0.353
UCT (µm)	0.77± 0.01	1.12± 0.03	0.67± 0.02	0.62± 0.02	0.85± 0.01	1.23± 0.03	0.63± 0.01
LCT (µm)	0.76± 0.01	1.12± 0.03	0.65± 0.02	0.61± 0.03	0.80± 0.01	1.21± 0.03	0.61± 0.01
LTH (µm)	696.26 ±1.25	738.94 ±0.94	653.03 ±1.34	638.5± 1.19	734.81 ±1.28	756.26 ±1.87	645.43 ±1.02
SI	7.45± 0.12	6.34± 0.11	8.22± 0.14	8.73± 0.11	7.26± 0.18	6.47± 0.11	8.54± 0.18
SL (µm)	11.23± 0.73	14.91± 2.05	10.88± 0.36	10.47± 0.0.81	13.77± 0.81	15.26± 0.44	11.45± 0.54
SW (µm)	8.08± 0.04	9.02± 0.08	8.14± 0.08	7.45± 0.05	8.23± 0.06	9.22± 0.084	7.14± 0.05

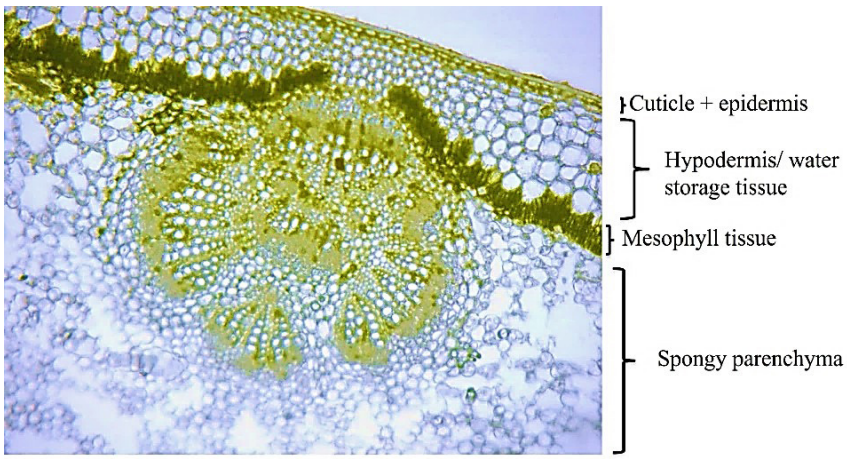

Fig. 3: Transverse section (T.S.) of *Rhizophora mucronata* leaf showing cuticle, epidermis, hypodermis/ water storage tissue, mesophyll tissue, and spongy parenchyma

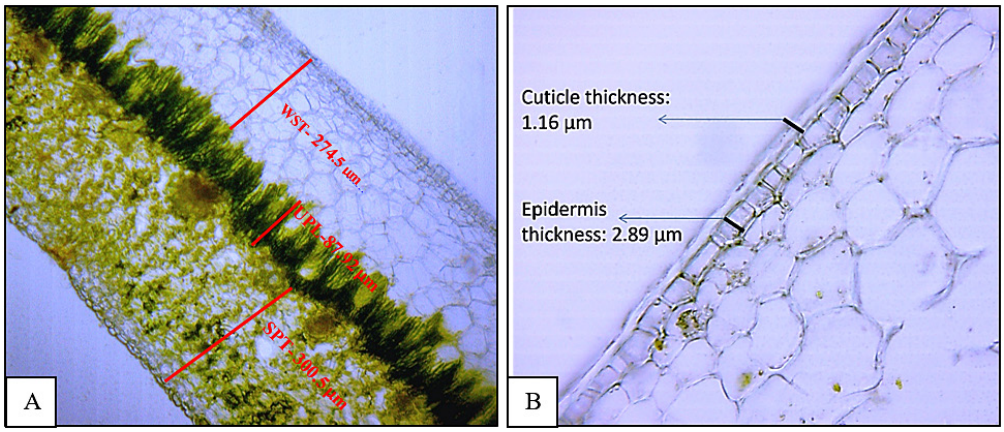

Fig. 4: Transverse section (T.S.) of *Rhizophora mucronata* leaf showing (A) thickness of WST, SPT, and length of palisade (UPL), and (B) thickness of cuticle and epidermal cells

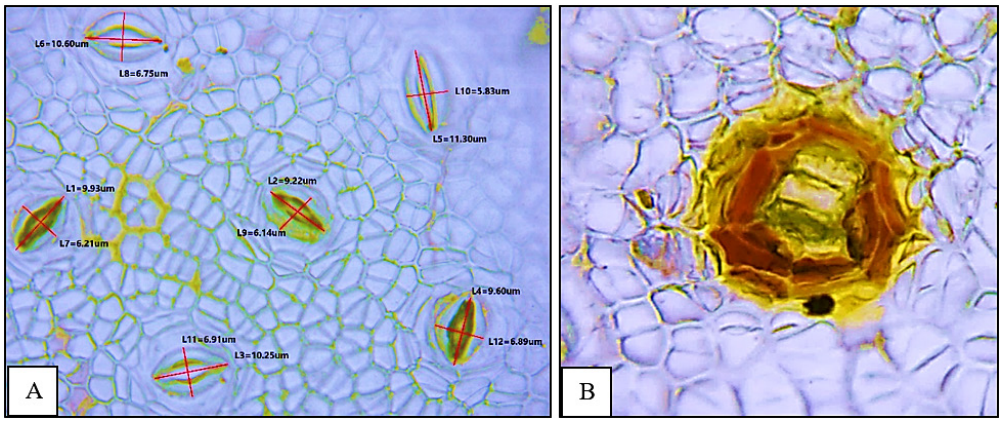

Fig. 5: Lower epidermal peel of *Rhizophora mucronata* leaf showing (A) stomata with length and width measurements and (B) cork warts

Discussion

R. mucronata distributed in sites like N3 (38.42 ppt) and K_2 (36.05 ppt) are exposed to more saline water, which can result in the plants experiencing more osmotic stress. Compared to other low salinity sites like K_1 (29.42±3.46 ppt), N1 (18.37±3.44 ppt), and N_2 (25.21±2.51 ppt), thick cuticles, smaller leaf lamina, thick WST, and less dense, larger stomata are observed in leaves of *R. mucronata* at K_2 and N_3. Water analysis from all the sites also shows that the quality parameters like color, Hazen, total dissolved solids, mg/l, turbidity, NTU, and total Coliforms, CFU/100ml were also observed to be higher at the sites N_3 and K_2 compared to the conserved sites like N1 and C1. Water quality parameters (Mean±SD) across the study sites are given in table 2. Basyuni *et al*. assessed[38] *Rhizophora mucronata* growth during the first year of the restoration of mangroves at[38] abandoned ponds in Langkat, North Sumatra, and discovered that the landward zone was ideal for mangrove restoration using *R. mucronata*, with a 96% growth rate and a salinity concentration of 30 ppt.

According to a study by Hoppe-Speer *et al*., *R. mucronata* seedlings exhibit stress symptoms such as increased leaf necrosis when salinity rises, resulting in an overall decrease in growth.[35] The freshwater treatment (0 PSU) had the maximum stomatal conductance and photosynthetic performance, and the[35] lowest salinity treatment (8 PSU) showed the highest growth.[35] The exact

tolerance range of *R. mucronata* to salinity has not been fully explored because Aziz and Khan demonstrated that *R. mucronata* seedlings had optimal development at 17.5 PSU,[35] while Jayatissa *et al*. discovered that *R. mucronata* seedlings were flourishing at 26 PSU. During the germination stage, *R. mucronata* exhibits a strong tolerance to salt. Low salinity greatly accelerated seedling growth, with 20.5 psu yielding the best growth. Furthermore, plant growth was negatively affected by greater salinities.[39]

The Hazen (1892) color, measures the intensity of the yellow color in a liquid on a scale from 0 to 500. High value of color Hazen in water indicates pollution and potential dissolved organic matter or contaminants. Water samples at K_2 and N_3 with a high Hazen color (>20) indicate higher levels of organic contamination. At K_1, N_2, and C_1, the Hazen color (15) is moderate, indicating a moderate degree of organic pollution. At K_3 (10) and N_1 (5), low Hazen color (10 and below) indicates less pollution.

Turbidity, NTU also measures the water quality. Turbidity increases with the amount of total suspended solids in the water. Urban runoff, garbage discharge, and soil erosion can all contribute to turbidity.[29] Anthropogenic activities might contribute to water pollution with significant suspended particulate matter, as indicated by a very high turbidity of more than 100 NTU at N_3. Total Coliforms were also detected to be higher at N_3 (2400 CFU/100ml). High levels of turbidity at K_2 (40.52 NTU) and N_2 (33.48 NTU) further indicate polluted conditions caused by industrial discharge, urban runoff, and waste disposal. At K_3 (27.36 NTU) and K_1 (16.8 NTU), moderate turbidity denotes moderate pollution, most likely from human or naturally occurring sources. N_1 shows low turbidity (2.60 NTU) and comparatively less total Coliform count (400 CFU/100 ml), indicating comparatively less pollution.

In *Rhizophora*, the most prevalent characteristic is an increase in leaf thickness to cope with the saline environment.[18] The thickness of the leaves increases when exposed to high saline conditions. To reduce the toxicity of salt to plant cells, high salinity induces increased leaf succulence.[27] The range of mean LTH values, from 638.5 cm^2 (N1) to 756.26 cm^2 (N_3), indicates that the LTH varies spatially. N_3 exhibits the highest LTH (756.26 cm^2±1.87), significantly thicker than all other samples, while N_1 has the lowest LTH (638.5 cm^2 ± 1.19). Table 4 shows the anatomical traits of *R. mucronata* leaf samples across the study sites.

R. mucronata leaf has a thick, multiseriate (2-6 layer) and well-developed hypodermis layer/ water storage tissue to retain water and shield the leaves from intense solar radiation. WST accommodates salt and water[3,8] and aids in controlling salt levels in *Rhizophora*, especially when the plant sheds leaves in response to saline stress. The thickest WST (294.74 ± 3.78) was identified at site N_3. At the sites, K_2 and K_3 also exhibit comparatively thick WST (281.43 ± 4.08 and 279.92 ± 2.47). Out of all the locations, C_1 (259.07 ± 2.69) had the thinnest WST. Samples from the sites show relatively small standard deviations, suggesting that the thickness of WST is consistent within each site.

The hypodermis is followed by a compactly arranged palisade and spongy mesophyll cells. The deep placement of chloroplasts within the elongated palisade cells may reduce the impact of photodamage on the plant.[18] Palisade cell length often correlates with the efficiency of the leaf to capture light and photosynthesize. The structure, shape, and size of palisade cells affect leaf photosynthesis.[28] There are significant variations in palisade cell length between the study sites, particularly when comparing sites N_1 and N_3. The leaf UPL ranges from 85.38µm to 109.14µm among the sites. The longest palisade cells can be observed at N_1 109.14 µm± 2.07, while the shortest ones are found at N_3 85.38 µm± 1.12.

The low density of stomata and thick waxy cuticles are other important foliar characteristics observed in *R. mucronata* in high-saline sites. To minimize water loss through transpiration, leaves with thicker, waxy cuticles and fewer stomata are found.[27] Larger stomata are more sparsely distributed on the surface of the leaf, allowing for better adaptation to saline conditions. The study by Ashraf *et al*. demonstrated that as salinity increased, *Avicenna marina* and *Rhizophora mucronata* considerably decreased their stomatal conductance.

The largest stomata are found at site N_3, which has broader SW (9.22 µm) and longer SL (15.26 µm). The stomata of K_2 are comparatively large, measuring 14.91 µm in length and 9.02 µm in width.

N1 possesses the smallest stomata, measuring only 7.45 µm in width and 10.47 µm in length.

The leaf areas at seven study sites range from 68.14 cm^2 (K_2) to 94.39 cm^2 (N_1), with moderate variability within each site, as indicated by standard deviation values ranging from 2.50 to 4.56. Sites N_1 (94.39±3.19), K_3 (88.18±3.14), and C_1 (93.93±4.06) show the largest average leaf areas, while Sites K_2 (68.14±2.50) and N_3 (70.7±4.56) have the smallest average leaf areas. Laminar traits, Chlorophyll a, Chlorophyll b, and total Chlorophyll content in mg/g tissue in the leaves of *R. mucronata* across the study sites were given in table 3.

The average range of the moisture content is 57.35% (K_1) to 69.32% (N_3). The two sites with the highest moisture content are K2 (69.20%) and N_3 (69.32%). The lowest moisture content is found in K_1 (57.35%). The intermediate moisture content readings at Sites K_3, N_1, N_2, and C_1 range from 59.53% to 64.58%.

The measurement of leaf surface area per unit of dry mass of leaf is called Specific Leaf Area/ (SLA). The highest SLA (6.788±0.375) was found in N_1 and low SLA leaves at locations K_2 (3.259±0.239) and N_3 (3.661±0.267). Site K_2 exhibits the highest leaf density (415.96 ± 24.33), which may be a sign of stress adaptation. The lowest leaf density can be observed in N_1 (230.47 ± 32.89). The leaf densities are intermediate at K_1, K_3, N_2, N_3, and C_1.

The total chlorophyll content (mg/g tissue) in *R. mucronata* leaf tissue was quantitatively assessed to be higher in K_1 (1.405±0.035), N_1 (1.682±0.041), and C_1 (1.585±0.035). The leaves from locations K_2 (0.722±0.032) and N_3 (0.663±0.016) have relatively low levels of total chlorophyll. Other sites show relatively intermediate values (K_3=1.355±0.029, N_2= 1.315±0.024 and N_3= 0.663±0.016). leaf chlorophyll content (mg/g tissue) of *R. mucronata* across the study sites is shown in figure 2. There is relatively little variation within each site, as indicated by the low standard deviation values, which range from 0.016 to 0.041 among the samples.

Conclusion

Significant foliar modifications such as low density of stomata, thick waxy cuticles, corky warts, thick water storage tissue/ hypodermis, and thick lamina were developed by *R. mucronata* to adapt to the stressful environment including water pollution and high salinity.

The laminar characteristics of *R. mucronata*, such as LA, LTH, WST, UPL, SI, stomatal size, and chlorophyll content, vary spatially and are influenced by water quality parameters like salinity, turbidity, color, pH, and TDS. Compared to the conserved sites like N_1 and C_1, sites N_3 and K_2 are identified as more polluted showing high water turbidity, total Coliform count, total dissolved solids, and high salinity.

Compared to less polluted and conserved sites like Kadalundi(C_1) and Kunjimangalam(N_1), *R. mucronata* distributed in more saline and polluted sites (K_2 and N_3) show variation in foliar characteristics as an adaptation and show low chlorophyll content in mg/g tissue, which indicates high salinity and water pollution impact the photosynthesis and productivity of *Rhizophora*. Therefore, immediate conservation measures must be implemented to preserve these polluted mangrove habitats.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from other Sources

Not Applicable

Author Contributions

- **Swedha Madhavan M:** Conceptualization, Methodology, Sample collection, Writing – Original Draft.
- **Sreeja P:** Supervision, Review & Editing.
- **Silshalakshmanan P:** Assist in field sample collection
- **Aiswarya T:** Assist in field sample collection
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