MANGROVE
Mangrove Watch
MANGROVE 3(1): 17–31
ISSN 3048-0000

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Species-specific nutrient utilization and photosynthetic responses in mangrove ecosystems

Baburaj Haripriya[1], Pullaikodi Sreeja[1,*]
[1] *Department of Botany, Sir Syed College, Taliparamba, affiliated to Kannur University, Kerala 670141, India.*
*Correspondence: sreeja@sirsyedcollege.ac.in

Received Date: November 30, 2025 Revised Date: February 21, 2026 Accepted Date: February 28, 2026

ABSTRACT

Background: Mangrove ecosystems exhibit remarkable physiological and ecological adaptability to fluctuating environmental conditions. However, the relationship between soil nutrient dynamics, species-specific nutrient utilization, and photosynthetic status remains insufficiently understood. These interactions are essential for evaluating nutrient-driven physiological responses and functional adaptations. **Methods:** The study investigated soil nutrient composition, species-specific nutrient accumulation, and chlorophyll responses in three estuarine mangrove habitats along the Kannur coast, Kerala, India. Soil macronutrients and trace elements, leaf nutrient concentrations, and chlorophyll pigments were analyzed. Statistical analyses included one-way ANOVA, Tukey's HSD, and correlation analysis. **Findings:** Significant spatial variation was observed in soil nutrient composition, with calcium and potassium as the dominant macronutrients and phosphorus comparatively limited. *Avicennia officinalis* L. showed the highest macronutrient accumulation, while *Bruguiera cylindrica* (L.) Blume showed the lowest nutrient assimilation. Variations in soil nutrient availability influenced species-specific nutrient uptake patterns, indicating physiological adjustments associated with differences in chlorophyll content under contrasting environmental conditions. Soil phosphorus showed highly significant spatial variation ($F_{2,6}$ = 1032.7, $p < 0.001$). **Conclusion:** The findings indicate a close relationship between soil nutrient availability, tissue nutrient accumulation, and chlorophyll responses. Species-specific nutrient utilization strategies may contribute to maintaining physiological functions under varying environmental conditions, emphasizing the importance of nutrient dynamics in sustaining mangrove productivity. **Novelty/Originality of this article:** This study provides a comprehensive assessment linking soil nutrient composition, species-specific nutrient utilization, and chlorophyll responses across multiple estuarine mangrove habitats. It integrates soil nutrient dynamics and physiological performance among coexisting species, offering insights into nutrient-mediated adaptation and ecological resilience and contributing to the understanding of ecosystem functioning and conservation management.

KEYWORDS: chlorophyll content; mangroves; nutrient uptake; soil nutrients; species-specific adaptation.

1. Introduction

Mangrove ecosystems are among the most productive coastal ecosystem, thriving in saline and waterlogged environments where specialised flora and fauna interact each other. Their ecological success largely depends on the availability of soil nutrients and the efficiency with which different species utilize these resources for physiological functions, especially photosynthesis. Nutrients such as nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and iron (Fe) play vital roles in plant metabolism, chlorophyll synthesis,

Cite This Article:
Haripriya, B., & Sreeja, P. (2026). Species-specific nutrient utilization and photosynthetic responses in mangrove ecosystems. *Mangrove Watch, 3*(1), 17-31. https://doi.org/10.61511/mangrove.v3i1.2026.4009

Copyright: © 2026 by the authors. This article is distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

and energy transfer processes (Twilley et al., 1992). However, nutrient distribution in mangrove soils is often heterogeneous, varying with tidal influence, salinity, and organic matter decomposition (Adame et al., 2025).

The nutritional status of mangrove plants is closely linked to soil nutrient availability and can be assessed through the analysis of nutrient accumulation in plant tissues. Leaf nutrient composition serves as an important indicator of nutrient uptake, utilization efficiency, and adaptive responses of mangrove species to varying environmental conditions (Ishfaq et al., 2025; Nie et al., 2025; Quadros et al., 2021). Furthermore, chlorophyll content is widely recognized as a reliable measure of photosynthetic capacity and physiological performance, as chlorophyll synthesis is directly influenced by the availability of essential nutrients, particularly nitrogen and magnesium (Lu et al., 2025; Tränkner et al., 2018). Evaluating the soil nutrient status, leaf nutrient composition, and chlorophyll content provides valuable information on nutrient-plant interactions and the ecological functioning of mangrove ecosystems (Peinado et al., 2026).

Although previous studies have documented nutrient dynamics and physiological responses in mangrove ecosystems, the relationships among site-specific soil nutrient availability, species-level nutrient accumulation, and photosynthetic performance remain insufficiently understood, particularly across mangrove habitats experiencing contrasting environmental conditions in the coastal region of Kerala. Comparative assessment of nutrient accumulation and chlorophyll content among mangrove species and sites is important because differences in nutrient availability and environmental conditions may influence species-specific nutrient acquisition, utilization, and photosynthetic pigment concentration, thereby contributing to their adaptation and ecological resilience. *Avicennia officinalis* L., *Rhizophora mucronata* Poir., and *Bruguiera cylindrica* (L.) Blume are common mangrove species in the coastal regions of Kerala and exhibit differences in growth form, root adaptations, and physiological characteristics that may influence nutrient acquisition and utilization. However, comparative information linking soil nutrient availability with species-specific nutrient accumulation and chlorophyll responses across different mangrove habitats in Kannur remains limited. Therefore, the present study aims to (i) assess soil nutrient availability across three ecologically distinct mangrove sites in Kannur district, Kerala; (ii) evaluate nutrient accumulation in the selected mangrove species; and (iii) compare chlorophyll content among species and sites to examine their photosynthetic responses under varying environmental conditions. By integrating soil nutrient availability, species-level nutrient accumulation, and chlorophyll responses, this study provides a comparative assessment of species-specific nutrient utilization strategies and their role in regulating nutrient and photosynthetic responses under varying environmental conditions.

2. Methods

The study area includes three distinct geographical zones of Kannur district, Kerala (Figure 1). Sites are selected according to the observed pollution conditions. Site selection was further guided by the river network map of the district to ensure maximum representation of riverine influence, particularly in areas where major rivers converge with estuarine backwaters. Such locations were chosen to capture variations in nutrient inputs, sediment deposition, and hydrological conditions associated with river–backwater interactions. It includes site 1) northern zone – Koduvally (KOD) (medium fringe and medium polluted site), site 2) middle zone – Valapattanam (VPN) (fringe zone and highly polluted site), and site 3) southern zone – Kunhimangalam (KUN) (landward zone and conserved site). The sites are chosen to represent the ecological diversity and spatial variation in nutrient status.

Sampling was carried out at three selected mangrove sites. For vegetation sampling, 10 quadrats were established at each site. Within each quadrat, five healthy, mature, and undamaged individual plants of the selected mangrove species were identified and selected for leaf sampling. Two adjacent quadrats were considered together as one sampling unit to account for local spatial variation. Thus, the individual plants within the quadrats

represented the biological sampling units, while the quadrats provided the spatial framework for vegetation sampling.

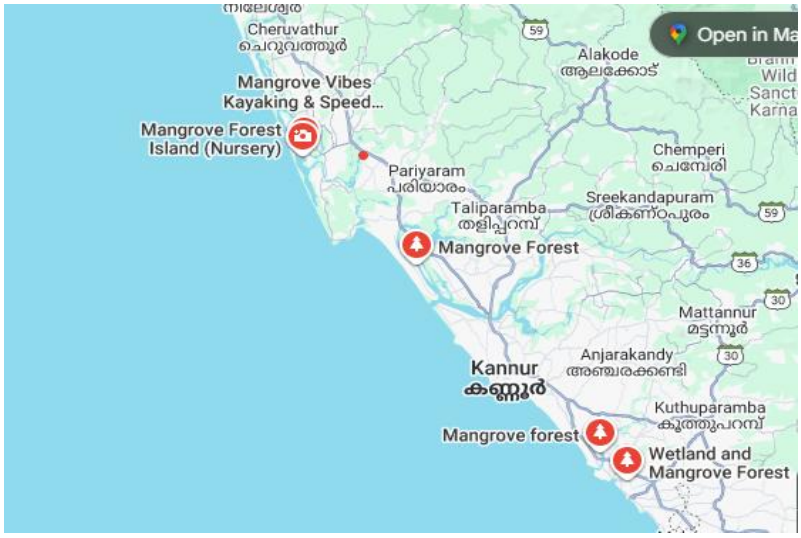


Fig. 1. Mangrove sampling sites at Kannur coast, Kerala

For soil nutrient analysis, rhizosphere soil samples were collected from a depth of 0–30 cm using a soil core sampler. Three soil subsamples were collected from each site and analysed separately. The mean of the three subsamples was calculated and used to represent the soil nutrient status of each site. For chlorophyll analysis, five healthy and mature individual plants were selected from each site. Leaf samples were collected separately from the selected plants and analysed for chlorophyll a, chlorophyll b, and total chlorophyll content. The values obtained from the five individual plants were averaged to obtain the representative chlorophyll value for each species at each site. The same sampling procedure was followed consistently across all study sites. For plant nutrient analysis, leaf samples were collected from the selected individual plants of *Avicennia officinalis*, *Rhizophora mucronata*, and *Bruguiera cylindrica*. Samples were maintained separately according to species and site, and the resulting measurements were used to determine species-specific nutrient concentrations. The sampling design was kept consistent across sites to facilitate comparisons of soil nutrient availability, plant nutrient composition, and chlorophyll content.

The same sampling procedure was followed consistently across all three sites. The sampling design was intended to capture both spatial variation among sampling units and biological variation among individual mangrove plants. Soil was collected at 30 cm depth from three geographical sites using soil core sampler. Three replicates were taken from each site and average is taken to calculate the actual concentration of nutrients. It is kept for shade dry, powdered, sieved and make air tight for analysing the samples. For quantification of nutrients in plant, leaf tissues were analysed. Plant analysis is based on the principle that the concentration of a nutrient within the plant is an integral value of all the factors that have interacted to affect it (Estefan et al., 2013). Mature and healthy leaves were collected from mangroves species of the ten quadrats in each site and kept for shade dry, powdered, then it is ready for nutrient quantification.

The major macronutrients like nitrogen, phosphorous, potassium, magnesium, sulphur and calcium was analysed. The concentration of nitrogen was measured by standard Kjeldahl method (Baethgen et. al., 1989). Soil and plant samples (0.5 - 1 g) were transferred to 100 ml Kjeldahl flask and acid digestion is done. Add 10 ml Conc. Sulphuric acid and digestion mixture (100 g Potassium sulphate + 10 g Copper sulphate + 1 g selenium powder) to it and kept it for overnight. Digest the sample until a white or clear precipitate obtained. Cool the flask and transfer the content of flask to 50 ml volumetric flask and makeup with

distilled water. Pipette out 10 ml of acid digest, then transfer to microkjeldahl distillation assembly, and titrate quantify the nitrogen content.

The analysis of most of the macronutrients are done by using wet digestion method or diacid digestion (Blanchar et. al., 1965). Wet digestion is done by treating the sample with diacid mixture of HNO_3 and $HClO_4$ in the ratio 9:3. Phosphorous and Sulphur is measured by using spectrophotometer, Potassium by flame photometry and Magnesium and Calcium through Atomic absorption spectroscopy. Phosphorus content was determined by the wet digestion method. Dried and finely ground samples (0.25 – 0.50 g) were digested with concentrated H_2SO_4 in the presence of a catalyst mixture until a clear digest was obtained. The digestion was carried out at controlled temperatures to ensure complete oxidation of the organic matter. After cooling, the digest was diluted to a known volume with deionized water and filtered. An aliquot of the digest was reacted with ammonium vanadomolybdate reagent to develop a yellow colour complex. The absorbance was measured at 410 nm using a UV–Visible spectrophotometer after 30 min of colour development. Standard phosphorus solutions were used to prepare a calibration curve, and phosphorus concentration in the samples was calculated from the curve and expressed on a dry weight basis. Reagent blanks and standard reference materials were included for quality control during analysis.

Potassium content was determined by the wet digestion method following Rashid (1986). Finely ground and dried samples (1 g) were digested using a nitric acid–perchloric acid mixture (HNO_3:$HClO_4$; 2:1) until a clear digest was obtained. The digest was cooled, diluted to a known volume with deionized water and filtered. Potassium concentration was measured using a Flame Photometer against standard potassium solutions. The concentration of potassium was calculated from the calibration curve and expressed on a dry weight basis. Calcium content was determined from the nitric acid–perchloric acid (HNO_3:$HClO_4$; 2:1) digest prepared from dried and finely ground samples.

After digestion and dilution to a known volume, calcium concentration was estimated by Ethylenediaminetetraacetic acid (EDTA) titration. Standard solutions were used for calibration, and the calcium content was calculated and expressed on a dry weight basis. Magnesium content was determined by the wet digestion method following Rashid (1986). Finely ground and dried samples (1 g) were digested using a nitric acid–perchloric acid mixture (HNO_3:$HClO_4$; 2:1) until a clear digest was obtained. After cooling, the digest was diluted to a known volume with deionized water and allowed to settle. Magnesium concentration in the digest was measured using an atomic absorption spectrophotometer (AAS). The concentration was calculated from the calibration curve prepared using standard magnesium solutions and expressed on a dry weight basis.

Available sulfur in soil was determined by the calcium chloride extraction method followed by turbidimetric measurement (Ryan et al., 2001; Williams & Steinbergs, 1959). Air-dried soil samples (5 g) were extracted with 25 ml of 0.15% $CaCl_2 \cdot 2H_2O$ solution by shaking for 30 min and filtering through Whatman No. 42 filter paper. An aliquot of the extract was treated with 6 M HCl, 70% sorbitol solution, and $BaCl_2 \cdot 2H_2O$ crystals to develop turbidity due to the formation of barium sulfate. The absorbance was measured at 470 nm using a UV–Visible spectrophotometer. Sulfate-sulfur concentration was determined from a standard calibration curve and expressed as mg kg^{-1} soil. The major micronutrients analysed include Iron, Manganese, Zinc, Copper and Boron.

All the micronutrients undergo wet digestion Rashid (1986) with a diacid mixture of HNO_3 and $HClO_4$ in the ratio 9:3. Finely ground and dried samples (1 g) was digested with a nitric acid–perchloric acid mixture (HNO_3:$HClO_4$; 2:1) in a digestion tube. The samples were allowed to predigest overnight and then heated gradually in a block digester at 150 °C, followed by further digestion at 235 °C until a clear solution was obtained. After cooling, the digest was diluted to a known volume with deionized water and allowed to settle. The supernatant solution was analyzed for zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) using an Atomic Absorption Spectrophotometer. Standard solutions were used to prepare calibration curves, and micronutrient concentrations were calculated from the corresponding calibration curves and expressed on a dry weight basis. Reagent blanks were included during digestion and analysis to ensure analytical accuracy.

Weigh 0.2 g of fresh leaf tissue and ground in 6 ml 80% acetone and centrifuge it for 5 minutes at 5000 rpm. The supernatant was collected and add 4 ml 80% acetone and centrifuge again. Repeat the centrifugation until it becomes colourless and finally collect the supernatant and make up to a known volume with 80% acetone. Read the absorbance of the solution at 645 nm,663 nm against the solvent (80% acetone) as blank. The chlorophyll content is calculated by using standard allometric equations.

$$\text{Chlorophyll a (mg g}^{-1}) = [12.7 \times A663 - 2.69 \times A645] \times V / (1000 \times W) \quad \text{(Eq. 1)}$$

$$\text{Chlorophyll b (mg g}^{-1}) = [22.9 \times A645 - 4.68 \times A663] \times V / (1000 \times W) \quad \text{(Eq. 2)}$$

$$\text{Total Chlorophyll (mg g}^{-1}) = [20.2 \times A645 + 8.02 \times A663] \times V / (1000 \times W) \quad \text{(Eq. 3)}$$

[A663 = Absorbance at 663 nm, A645 = Absorbance at 645 nm, V = Final volume of extract (mL), W = Fresh weight of leaf sample (g)]

Results were statistically analysed to compare species -specific and site – specific variations. Correlation is done between soil nutrient and plant nutrient, Plant nutrient and chlorophyll content to interpret the results between the soil nutrient availability, plant nutrient utilization and productivity. Analysis of variance (ANOVA) is performed to analyse the variation in photosynthetic efficiency between sites and nutrient concentrations of leaf and soil samples. Differences in soil and plant nutrient concentrations were assessed using ANOVA to determine overall statistical significance ($p < 0.05$). When significant effects were detected, Tukey's honestly significant difference (HSD) post hoc test was applied to identify pairwise differences among sites and mangrove species.

3. Results and Discussion

3.1 Soil nutrient analysis

Distinct macro- and micronutrient analyses were observed among the sites, clearly indicating that there is a site-specific difference in nutrient availability of mangroves. These variations may be attributed to differences in soil characteristics, tidal inundation patterns, organic matter content, sediment deposition, and anthropogenic influences. The observed nutrient distribution suggests that environmental conditions play a significant role in regulating nutrient dynamics and availability in mangrove soils. Such differences in soil nutrient status can directly influence nutrient uptake, growth, and productivity of mangrove species.

3.1.1 Variation in macronutrient levels

The nitrogen content differs significantly among sites ($F_{2,6} = 835.4$, $P < 0.001$). Site 3 (KUN) recorded the highest mean nitrogen value (156.69 ± 2.01 mg kg^{-1}), followed by site 2 (VPN) (135.65 ± 5.16 mg kg^{-1}), while site 1 (KOD) exhibited the lowest (35.79 ± 0.30 mg kg^{-1}). A marked difference in phosphorus concentration was observed ($F_{2,6} = 1032.7$, $P < 0.001$). Site 2 (VPN) (40.15 ± 1.63 mg kg^{-1}) showed significantly higher phosphorus levels compared to site 3 (KUN) (6.05 ± 0.07 mg kg^{-1}) and site 1 (KOD) (5.17 ± 0.09 mg kg^{-1}). Potassium concentration varied significantly among sites ($F_{2,6} = 674.2$, $P < 0.001$). The highest mean value occurred at Valapattanam (421.7 ± 2.40 mg kg^{-1}), followed by Kunhimangalam (189.4 ± 10.49 mg kg^{-1}) and Koduvally (111.4 ± 3.40 mg kg^{-1}). Significant variation was found in calcium concentration ($F_{2,6} = 918.6$, $P < 0.001$). Site 3 (KUN) exhibited a remarkably higher calcium level (2891 ± 1.41 mg kg^{-1}) compared to site 2 (VPN) (340.65 ± 1.91 mg kg^{-1}) and site 1 (KOD) (1127.5 ± 2.12 mg kg^{-1}). Magnesium content also differed significantly among the sites ($F_{2,6} = 211.5$, $P < 0.001$), with site 3 (KUN) showing the maximum value (683.4 ± 18.96 mg kg^{-1}), followed by site 1 (KOD) (475.2 ± 5.37 mg kg^{-1}) and site 2 (VPN) (211.95 ± 4.31 mg kg^{-1}).

Site 3 (KUN) recorded the highest macronutrient content for calcium, nitrogen and magnesium compared to the other sites whereas site 2 (VPN) has elevated levels of potassium and phosphorus. Site 1 (KOD) recorded the medium levels of concentration of all macronutrients. Among macronutrients, Calcium shows the highest value of soil nutrient present, while phosphorus is the limiting factor in all ecosystems.

Table 1. Concentration of macronutrients in soil among three wetlands

Macronutrients	VPN (mean ± SD)	KUN (mean ± SD)	KOD (mean ± SD)	$F(df_1,df_2)$	P-value
Nitrogen	135.65 ± 5.16	156.69 ± 2.01	35.79 ± 0.30	835.4 (2,6)	< 0.001
Phosphorus	40.15 ± 1.63	6.05 ± 0.07	5.17 ± 0.09	1032.7 (2,6)	< 0.001
Potassium	421.7 ± 2.40	189.4 ± 10.49	111.4 ± 3.40	674.2 (2,6)	< 0.001
Calcium	340.65 ± 1.91	2891 ± 1.41	1127.5 ± 2.12	918.6 (2,6)	< 0.001
Magnesium	211.95 ± 4.31	683.4 ± 18.96	475.2 ± 5.37	211.5 (2,6)	< 0.001

Note: Values are mean ± SD, n = 3. There are significant differences at $P < 0.05$ according to Tukey's HSD test. VPN -Valapattanam (site 2); KUN- Kunhimangalam (site 3); KOD- Koduvally (site 1).

The results demonstrate considerable spatial heterogeneity in soil nutrient status among the studied wetlands. The elevated concentrations of specific nutrients at certain sites suggest differences in nutrient inputs, retention capacity, and biogeochemical cycling processes. From the table, it is clear that the concentration of soil macronutrients varied significantly among the three wetland sites. Nitrogen content was highest in VPN (135.65 ± 5.16) and KUN (156.69 ± 2.01), while the lowest concentration was recorded in KOD (35.79 ± 0.30). Similarly, phosphorus concentration was markedly higher in VPN (40.15 ± 1.63) compared to KUN (6.05 ± 0.07) and KOD (5.17 ± 0.09). Potassium also exhibited a declining trend from VPN (421.7 ± 2.40) to KUN (189.4 ± 10.49) and KOD (111.4 ± 3.40).

Calcium was the dominant macronutrient among all sites, with the highest concentration observed in KUN (2891 ± 1.41), followed by KOD (1127.5 ± 2.12) and VPN (340.65 ± 1.91). Magnesium concentration was also significantly higher in KUN (683.4 ± 18.96) compared to KOD (475.2 ± 5.37) and VPN (211.95 ± 4.31). The analysis of variance revealed highly significant differences ($P < 0.001$) for all macronutrients among the study sites, indicating substantial spatial variation in nutrient availability across the mangrove wetlands. These differences may reflect variations in sediment characteristics, tidal influence, nutrient cycling processes, and local environmental conditions.

3.1.2 Variation in micronutrient levels

There is significant spatial variation observed in micronutrient levels across three wetlands. Site 3 (KUN) recorded the highest value, followed by site 1 (KOD) and site 2 (VPN). The ANOVA results revealed highly significant differences ($P < 0.001$) for all tested micronutrients (Fe, Cu, Mn, and Zn). Among all three sites showed similar decreasing patterns of nutrients ie; Fe > Mn > Zn > Cu (Table 2). Iron content varied significantly between sites ($F_{2,6} = 218.4$; $P < 0.001$). The highest Fe concentration was recorded in site 3 (KUN) (92.8 ± 1.1 mg kg^{-1}), followed by site 1 (KOD) (73.1 ± 5.7 mg kg^{-1}), while the lowest value was observed in site 2 (VPN) (49.1 ± 3.0 mg kg^{-1}). Copper concentrations also differed significantly ($F_{2,6} = 156.2$; $P < 0.001$), with the maximum level at site 2 (VPN) (3.04 ± 0.20 mg kg^{-1}) and the minimum at site 1 (KOD) (0.17 ± 0.09 mg kg^{-1}). Site 3 (KUN) recorded an intermediate value (1.28 ± 0.11 mg kg^{-1}). Manganese content also shows a significant variation ($F_{2,6} = 254.8$; $P < 0.001$) among the three sites. The highest Mn concentration was observed in site 3 (KUN) (21.35 ± 0.49 mg kg^{-1}), while site 2 (VPN) had the lowest (6.36 ± 0.06 mg kg^{-1}), and site 1 (KOD) showed a moderate value (11.6 ± 2.26 mg kg^{-1}). Zinc concentrations also varied significantly among the three sites ($F_{2,6} = 173.7$; $P < 0.001$). The Zn level was maximum at site 3 (KUN) (14.95 ± 2.76 mg kg^{-1}), moderate at site 1 (KOD) (8.15 ± 0.35 mg kg^{-1}), and minimum at site 2 (VPN) (1.79 ± 0.86 mg kg^{-1}).

Table 2. Variation in micronutrient levels across three wetlands

Micronutrients	VPN (mean ± SD)	KUN (mean ± SD)	KOD (mean ± SD)	F (2,6)	P-value
Iron	49.1 ± 3.0	92.8 ± 1.1	73.1 ± 5.7	218.4	< 0.001
Copper	3.04 ± 0.20	1.28 ± 0.11	0.17 ± 0.09	156.2	< 0.001
Manganese	6.36 ± 0.06	21.35 ± 0.49	11.6 ± 2.26	254.8	< 0.001
Zinc	1.79 ± 0.86	14.95 ± 2.76	8.15 ± 0.35	173.7	< 0.001

Note: F-values give strong inter-site variation seen among replicates; all significant at P < 0.001 level. VPN -Valapattanam (site 2); KUN- Kunhimangalam (site 3); KOD- Koduvally (site 1).

Significant differences in soil micronutrient concentrations were observed among the three wetland sites (Table 2). Iron concentration ranged from 49.1 ± 3.0 to 92.8 ± 1.1, with the highest value recorded at KUN and the lowest at VPN. Copper concentration was greatest at VPN (3.04 ± 0.20), followed by KUN (1.28 ± 0.11) and KOD (0.17 ± 0.09). Manganese concentration was significantly higher at KUN (21.35 ± 0.49) compared to KOD (11.6 ± 2.26) and VPN (6.36 ± 0.06). Similarly, zinc concentration was highest at KUN (14.95 ± 2.76), followed by KOD (8.15 ± 0.35), while the lowest value was observed at VPN (1.79 ± 0.86).

Analysis of variance indicated highly significant differences (P < 0.001) among sites for all micronutrients. Overall, KUN exhibited higher concentrations of Fe, Mn, and Zn, whereas VPN showed relatively higher Cu levels. These findings indicate substantial spatial variation in soil micronutrient availability among the wetlands, reflecting differences in local environmental conditions and nutrient dynamics. Such variations may influence nutrient uptake and the ecological functioning of mangrove ecosystems.

3.2 Leaf nutrient analysis

There is species- specific nutrient utilization in both macro- and micronutrients. It clearly shows the relation between nutrient availability and species-specific nutrient utilization of mangroves. Variations were observed in both macro- and micronutrient concentrations, indicating differential nutrient acquisition and utilization strategies among the mangroves. The nutrient content of leaves provides an important indicator of the nutritional status of plants and their ability to adapt to prevailing environmental conditions. Differences in leaf nutrient concentrations may be attributed to variations in soil nutrient availability, species physiology, nutrient-use efficiency, and site-specific ecological factors (Liu et al., 2026; Whynot, 1989). These findings indicate species-specific responses to nutrient availability and demonstrate the role of environmental factors in regulating nutrient accumulation in mangrove leaves.

3.2.1 Variation in macronutrient levels

There is a significant variation in the utilization of nutrients by different species (Table 3). *A. officinalis* showed the highest nutrient uptake, *R. mucronata* has the oderate uptake and the least utilization capacity is for *B. cylindrica*. Among the nutrients utilized Ca and N is the major macronutrients absorbed, and P is the limiting factor in mangrove ecosystems. Calcium and nitrogen are absorbed in greater quantities due to their higher availability in estuarine sediments and their essential roles in structural stability and metabolic processes. Nitrogen supports chlorophyll synthesis and protein formation, while calcium contributes to cell wall integrity and ionic balance under saline conditions. In contrast, phosphorus remains limiting because it is readily immobilized in sediments through binding with iron, aluminium, or calcium compounds, reducing its bioavailability to mangrove plants.

Nitrogen, potassium, sulphur, magnesium, and calcium showed highly significant variation among species (P < 0.001), whereas phosphorus exhibited a moderate difference (P = 0.028) (Table 3). *A. officinalis* recorded the highest concentrations of nitrogen (2.50%), potassium (2.24%), sulphur (0.399%), and magnesium (1.31%), whereas *B. cylindrica*

exhibited the highest calcium content (1.33%). *R. mucronata* showed intermediate nutrient levels across most macronutrients.

Table 3. Macronutrient concentrations (%) in three mangrove species with one-way ANOVA results

Macro -nutrient	*A. officinalis* (mean ± SD)	*R. mucronata* (mean ± SD)	*B. cylindrica* (mean ± SD)	F (2,6)	P-value	Significance
Nitrogen	2.50 ± 0.23	0.77 ± 0.10	0.91 ± 0.01	142.6	<0.001	***
Phosphorus	0.175 ± 0.008	0.139 ± 0.008	0.164 ± 0.003	6.72	0.028	*
Potassium	2.24 ± 0.09	0.401 ± 0.01	0.324 ± 0.007	389.4	<0.001	***
Sulphur	0.399 ± 0.001	0.251 ± 0.004	0.211 ± 0.016	178.3	<0.001	***
Calcium	0.75 ± 0.07	1.115 ± 0.007	1.33 ± 0.04	38.5	<0.001	***
Magnesium	1.31 ± 0.04	0.582 ± 0.009	0.23 ± 0.01	302.1	<0.001	***

Values are means ± SD (n = 3). One-way ANOVA tested differences among species (df = 2, 6). Significance: *** (Highly significant), * (moderately significant).

3.2.2 Variation in micronutrient levels

Significant variations were observed in the micronutrient concentrations (Fe, Cu, Mn, Zn) plant tissues of different species (Table 4). Iron, manganese, copper, and zinc differed significantly ($P < 0.001$), with *A. officinalis* again exhibiting the highest values for all four elements. Boron did not differ significantly among species ($P = 0.095$*). The consistently higher micronutrient concentrations in *A. officinalis* indicate its superior capacity for trace element accumulation, reflecting adaptive differences in nutrient uptake and retention across mangrove taxa.

Table 4. Micronutrient concentrations (ppm) in three mangrove species with one-way ANOVA results

Micronutrients	*A. officinalis* (mean ± SD)	*R. mucronata* (mean ± SD)	*B. cylindrica* (mean ± SD)	F (2,6)	P-value	Significance
Boron	10.37 ± 0.69	8.07 ± 1.23	9.02 ± 1.43	3.26	0.095	ns
Iron	1245 ± 21.2	657 ± 4.2	875 ± 35.4	229.6	<0.001	***
Manganese	89 ± 1.4	68.5 ± 2.1	51 ± 4.2	168.9	<0.001	***
Copper	79.3 ± 0.4	49.1 ± 1.4	41.7 ± 2.8	454.8	<0.001	***
Zinc	51.16 ± 1.64	23.7 ± 5.23	27.6 ± 3.54	35.2	<0.001	***

Note: Values are means ± SD (n = 3). One-way ANOVA tested species differences (df = 2, 6). Significance; *** (highly significant), ns (not significant).

3.3 Chlorophyll content analysis

There is a significant variation in chlorophyll content among species and sites (Figure 2). The findings emphasize that chlorophyll content in mangroves is not solely dependent on nutrient abundance, but also on site quality and species-specific physiological responses.

3.3.1 Comparative chlorophyll profiles of mangrove species among wetlands

The total chlorophyll content exhibited noticeable variation among the three mangrove wetlands. Highest value for total chlorophyll content was observed in site 1 (KOD), moderate for site 3 (KUN) and least observed in site 2 (VPN). Among the mangrove species, *Rhizophora mucronata*, *Avicennia officinalis*, and *Bruguiera cylindrica* were commonly distributed across all three sites. Chlorophyll pigment concentration varied among species and locations. *Kandelia candel* exhibited the highest total chlorophyll content in site 1 (KOD), whereas *Avicennia officinalis* recorded the highest value in Site 2 (VPN). In site 3 (KUN), *Bruguiera cylindrica* showed the greatest chlorophyll concentration among the species examined.

The observed inter-site and interspecific variations in chlorophyll content indicate differences in photosynthetic pigment accumulation among mangrove species and sites. Such variation may be associated with differences in nutrient uptake, species-specific responses to environmental conditions, and habitat characteristics. Overall, the higher chlorophyll content recorded in KOD indicates greater accumulation of photosynthetic pigments at this site, while the lower values in VPN suggest relatively reduced photosynthetic pigment accumulation. These findings show the influence of site conditions on chlorophyll production and the physiological performance of mangrove species.

3.3.2 Total chlorophyll content of mangrove species

When combining the pigment concentrations of the three sites, the total photosynthetic efficiency differs among the species (Figure 3). *R. mucronata* recorded the highest total chlorophyll content among the species examined, followed by *A. officinalis*, whereas *K. candel* recorded the lowest value. The highest chlorophyll content was recorded in *Rhizophora mucronata* (1.96 mg g^{-1} tissue), followed closely by *Avicennia officinalis* (1.89 mg g^{-1} tissue) and *Rhizophora apiculata* (1.75 mg g^{-1} tissue). Moderate chlorophyll concentrations were observed in *Sonneratia alba* (1.18 mg g^{-1} tissue) and *Bruguiera cylindrica* (1.26 mg g^{-1} tissue). In contrast, relatively lower chlorophyll contents were recorded in *Bruguiera gymnorhiza* (0.56 mg g^{-1} tissue), *Aegiceras corniculatum* (0.54 mg g^{-1} tissue), *Avicennia marina* (0.41 mg g^{-1} tissue), and *Kandelia candel* (0.39 mg g^{-1} tissue).

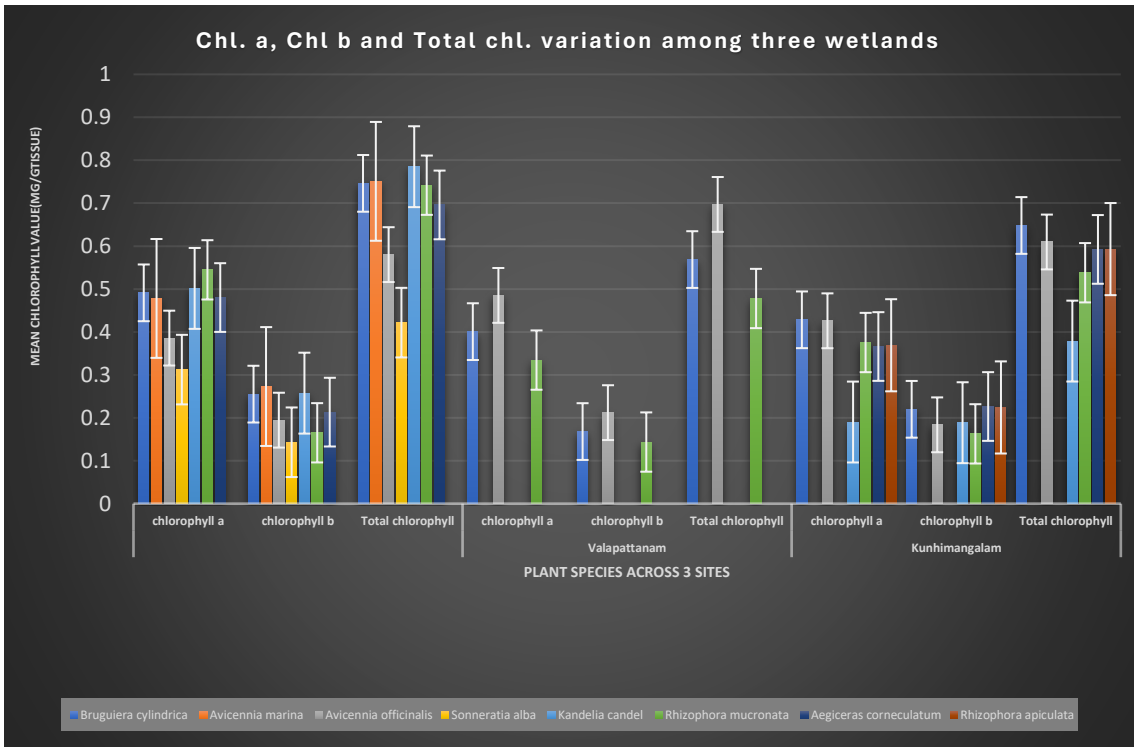


Fig. 2. Chlorophyll (Chl.) a, chlorophyll b & total chlorophyll among three wetlands

The observed differences in chlorophyll content indicate species-specific variation in photosynthetic pigment accumulation among mangroves. Species exhibiting higher chlorophyll concentrations may have a greater capacity for light harvesting; however, chlorophyll content alone does not directly indicate photosynthetic efficiency, whereas lower chlorophyll levels may reflect differences in physiological adaptation and resource allocation. The findings demonstrate that there is substantial variation in chlorophyll content among mangrove species, reflecting differences in pigment accumulation and species-specific physiological responses.

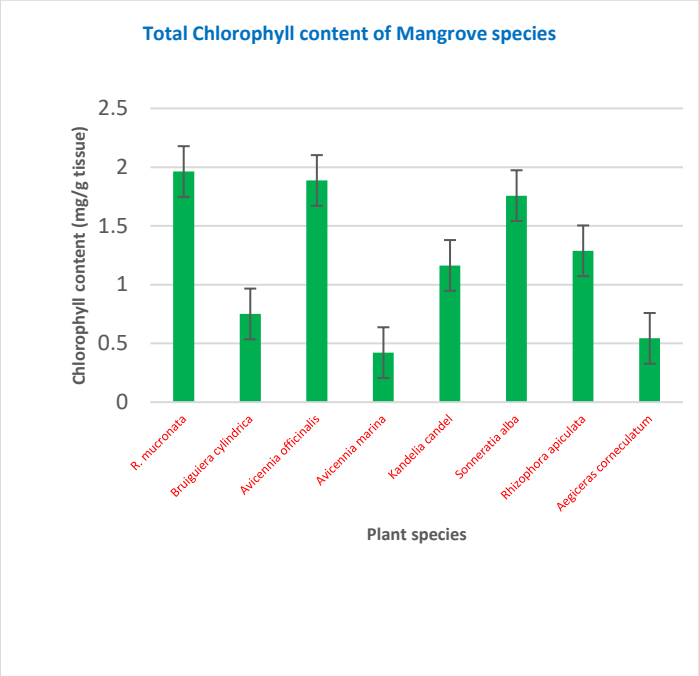


Fig. 3. Total chlorophyll of Mangrove species in the three wetlands

3.4 Correlation between soil nutrient availability, nutrient utilization and photosynthetic efficiency

Mangrove productivity is determined not only by soil nutrient concentration but also by the species' intrinsic capacity to acquire and utilize nutrients effectively. The present study highlights the complex relationship between soil nutrient availability, species-specific nutrient uptake, and chlorophyll content in mangrove ecosystems along the Kannur coast. Mangrove soils exhibited spatial heterogeneity in macronutrient and micronutrient distribution, consistent with tidal influence, sediment characteristics, and organic matter input (Alongi, 2009; Reef et al., 2010). Variability in calcium, potassium, and phosphorus concentrations across sites reflects both geochemical and biological controls, as nutrient mobilization in mangrove sediments is governed by redox potential, microbial mineralization, and tidal flushing (Holguin et al., 2001; Kristensen et al., 2008).

The positive correlations between soil nutrient concentrations and plant tissue nutrient content across all three mangrove species indicate an association between soil nutrient availability and foliar nutrient accumulation (Figure 4). *Avicennia officinalis* exhibited the highest correlation coefficients for most nutrients (Figure 4) (r = 0.82 for N, 0.79 for K, and 0.75 for Fe), suggesting superior nutrient absorption efficiency compared to *Rhizophora mucronata* and *Bruguiera cylindrica*. This pattern aligns with previous studies reporting that *A. officinalis* effectively utilizes available nutrients due to its well-developed pneumatophore system and efficient root-rhizosphere interactions (Alongi, 2018; Ball, 1996; Naidoo, 2006; Reef et al., 2010). The moderate correlations in *R. mucronata* and B. cylindrica may reflect their more conservative nutrient uptake strategies or species-specific adaptations to fluctuating salinity and anoxic sediment conditions (Ball, 1996; Clough, 1984; Kathiresan & Bingham, 2001; Medina et al., 2015; Reef et al., 2010). The slightly weaker or missing correlation values for sulphur in Rhizophora suggest possible species-specific variations in sulphur assimilation or sediment-derived availability. Therefore, these correlations suggest that soil nutrient status is associated with foliar nutrient accumulation and may contribute to interspecific differences in nutrient-use strategies.

Correlations between leaf nutrient utilization and chlorophyll content further emphasize the importance of nutrient balance for maintaining physiological performance (Figure 5). Nitrogen, potassium, magnesium, and iron showed the strongest positive relationships with chlorophyll content, with r > 0.75 in *A. officinalis* (Figure 5), indicating

their critical role in photosynthetic metabolism. Nitrogen and magnesium are essential for chlorophyll synthesis, while potassium and iron facilitate stomatal regulation and electron transport (Lovelock et al., 2007; Reef et al., 2010; Twilley & Day, 2019). The relatively weaker correlations for micronutrients such as Cu and B suggest that, although these elements are important cofactors in enzymatic processes, their influence on photosynthetic performance is secondary compared to macronutrients (Chen & Ye, 2014; Feller et al., 2003). These findings are consistent with observations from mangrove ecosystems in India and Southeast Asia, where nutrient-enriched soils were linked to enhanced photosynthetic capacity and biomass production (Ahmed et al., 2025; Kathiresan & Bingham, 2001).

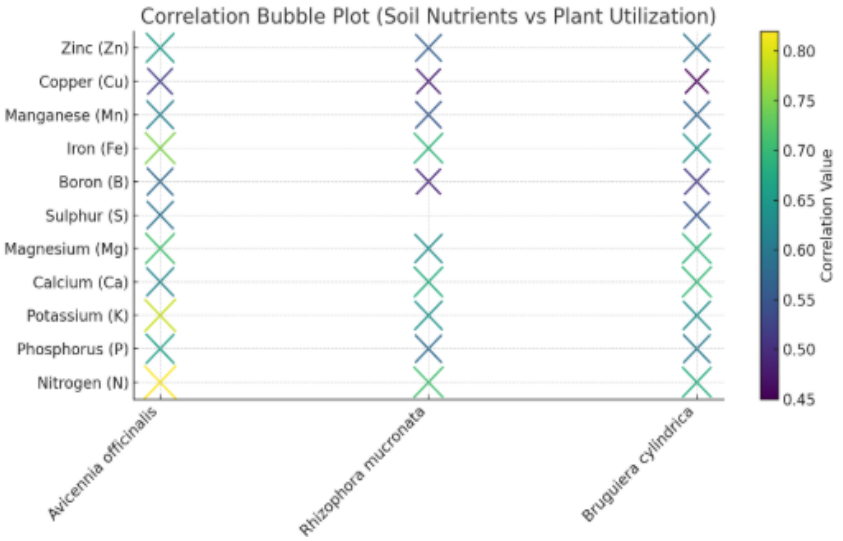


Fig. 4. Correlation plot between soil nutrient availability and plant utilization

Integrating both correlation patterns indicates that soil nutrient availability, foliar nutrient accumulation, and chlorophyll content are interrelated in the studied mangrove species. Species like *A. officinalis* and *R. mucronata* with strong soil–plant nutrient coupling (Figure 4), maintain higher chlorophyll content (Figure 5), reflecting greater physiological adaptability under variable coastal conditions. The association between macronutrient, particularly N and K, availability and chlorophyll content highlights the potential role of nutrient status in influencing photosynthetic pigment accumulation in mangrove species. In contrast, the relatively weaker relationships in *B. cylindrica* may indicate differences in nutrient allocation and species- specific physiological responses.

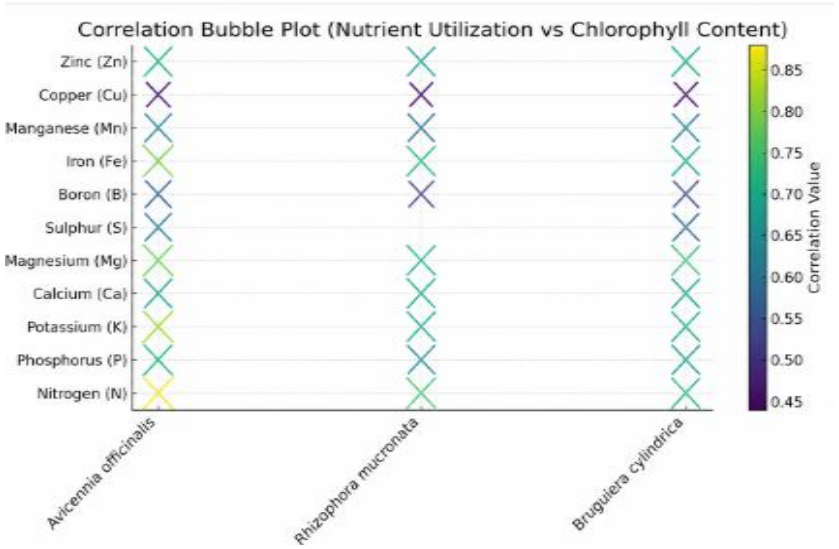


Fig. 5. Correlation plot between plant nutrient utilization and photosynthetic efficiency

4. Conclusions

The present study highlights the linkages between site- and species-specific variation in soil nutrient availability, leaf nutrient accumulation, and chlorophyll content in mangrove ecosystems. Variations in soil nutrient status were reflected in leaf nutrient composition and chlorophyll content, indicating species-specific patterns of nutrient accumulation and utilization under different site conditions. The observed differences among species and sites emphasize the role of nutrient dynamics in regulating the physiological functioning and adaptive responses of mangrove vegetation. Understanding these nutrient–plant interactions is essential for evaluating mangrove productivity, ecosystem functioning, and the ecological sustainability of coastal wetland environments.

Marked variations in both macro- and micronutrient concentrations among the sites indicate that nutrient availability is strongly influenced by local environmental conditions, sediment characteristics, tidal inundation regimes, and nutrient cycling processes. The differential distribution of nutrients highlights the dynamic nature of mangrove ecosystems and their capacity to regulate nutrient storage and transformation. Leaf nutrient analysis revealed considerable variation in nutrient accumulation among mangrove species, reflecting differences in nutrient uptake efficiency, utilization patterns, and physiological adaptations. The observed species-specific nutrient profiles suggest that mangroves employ distinct nutrient acquisition strategies to cope with varying environmental conditions and resource availability. Such differences may contribute to variations in growth performance, metabolic activity, and ecological fitness within mangrove habitats.

Chlorophyll content also varied among species and sites, with the highest overall values recorded at site 1 (KOD) and the lowest at site 2 (VPN). *Rhizophora mucronata* recorded the highest overall chlorophyll content among the species examined, whereas *Kandelia candel* showed the lowest value. The observed relationships between soil nutrient availability, leaf nutrient accumulation, and chlorophyll content suggest an association between nutrient status and photosynthetic pigment accumulation, rather than directly demonstrating differences in photosynthetic efficiency. Nutrient uptake efficiency directly influences the chlorophyll content among mangrove species. *Rhizophora mucronata* emerges as the most photosynthetically efficient species due to its balanced nutrient assimilation, while *A. officinalis* shows strong nutrient accumulation ability. *Bruguiera cylindrica*, however, exhibits nutrient limitation effects on photosynthetic function. Efficient phosphorus conservation across species indicates physiological adaptation to nutrient-limited environments. These results emphasize that mangrove functioning depends not only on nutrient supply but also on the species' adaptive mechanisms that optimize resource use under fluctuating environmental conditions. Understanding such species-specific strategies is essential for effective mangrove conservation and restoration planning in coastal ecosystems.

The correlation patterns further indicate species-specific relationships between soil nutrients and leaf nutrient accumulation, with *Avicennia officinalis* showing relatively stronger associations for several nutrients. These findings suggest that mangrove species may differ in their nutrient-use strategies under variable environmental conditions. However, the present study was limited by the assessment of nutrient and chlorophyll characteristics at a limited number of sites and the use of chlorophyll content as an indicator of photosynthetic status. Future studies should include long-term seasonal monitoring, direct measurements of photosynthetic parameters, and controlled nutrient-manipulation experiments to better understand the mechanisms linking nutrient availability, nutrient utilization, and mangrove physiological responses. Such information can contribute to improved understanding of species-specific responses and support mangrove conservation and restoration planning.

Acknowledgement

The authors gratefully acknowledge the support and facilities provided by the Department of Botany and Sir Syed College, Taliparamba, affiliated to Kannur University, Kerala, for carrying out this research. We also thank all contributors and colleagues for their valuable assistance and encouragement during the study. The authors also sincerely acknowledge the CSIR-UGC Fellowship for the financial support provided.

Author Contribution

Conceptualization, H.B.; Methodology, H.B. and S.P.; Validation, H.B. and S.P.; Formal Analysis, H.B.; Investigation, H.B.; Data Curation, H.B.; Writing – Original Draft Preparation, H.B.; Writing – Review & Editing, S.P.; Supervision, S.P.; and Project Administration, H.B. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding. The study was independently conducted by the author based on work experience.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this manuscript, the authors used OpenAI to improve the language, grammar, and readability of the manuscript. The authors carefully reviewed and edited the AI-generated content as necessary and take full responsibility for the accuracy, originality, and integrity of the manuscript.

Open Access

©2026. The authors. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original authors and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

References

Adame, M. F., Iram, N., Gamboa-Cutz, J. N., & Masque, P. (2025). Nitrogen processes within tropical mangroves in Australia. *Journal of Geophysical Research: Biogeosciences, 130*(4), Article e2024JG008335. https://doi.org/10.1029/2024JG008335

Ahmed, S., Sarker, S. K., Kamruzzaman, M., Perri, S., Hilmers, T., Uhl, E., Hossain, M. R., Tasnim, N., Naabeh, C. S. S., Anika, T. T., Rahman, M. M., & Pretzsch, H. (2025). Soil

nutrients and leaf area index interact with species and structural diversity to buffer mangrove productivity against salinity. Soil Ecology Letters, 7(2), Article 250299. https://doi.org/10.1007/s42832-025-0299-x

Alongi, D. M. (2009). *The energetics of mangrove forests*. Springer. https://link.springer.com/book/10.1007/978-94-007-2373-2

Alongi, D. M. (2018). Impact of global change on nutrient dynamics in mangrove forests. *Forests, 9*(10), Article 596. https://doi.org/10.3390/f9100596

Ball, M.C. (1996). *Comparative ecophysiology of mangrove forest and tropical lowland moist rainforest*. In: Mulkey, S.S., Chazdon, R.L., Smith, A.P. (eds), Tropical Forest Plant Ecophysiology. Springer, Boston, MA. https://doi.org/10.1007/978-1-4613-1163-8_16

Chen, Y., & Ye, Y. (2014). Effects of salinity and nutrient addition on mangrove *Excoecaria agallocha*. *PLoS ONE, 9*(4), Article e93337. https://doi.org/10.1371/journal.pone.0093337

Clough, B. F. (1984). Growth and salt balance of the mangroves *Avicennia marina* (Forsk.) Vierh. and *Rhizophora stylosa* Griff. in relation to salinity. *Australian Journal of Plant Physiology, 11*(5), 419–430. https://doi.org/10.1071/PP9840419

Estefan, G., Sommer, R., & Ryan, J. (2013). *Methods of soil, plant, and water analysis: A manual for the West Asia and North Africa region* (3rd ed.). International Center for Agricultural Research in the Dry Areas. https://hdl.handle.net/20.500.11766/7512

Feller, I. C., Whigham, D. F., McKee, K. L., & Lovelock, C. E. (2003). Nitrogen limitation of growth and nutrient dynamics in a disturbed mangrove forest, Indian River Lagoon, Florida. *Oecologia, 134*(3), 405–414. https://doi.org/10.1007/s00442-002-1117-z

Holguin, G., Vázquez, P., & Bashan, Y. (2001). The role of sediment microorganisms in the productivity, conservation, and rehabilitation of mangrove ecosystems: An overview. *Biology and Fertility of Soils, 33*(4), 265–278. https://doi.org/10.1007/s003740000319

Ishfaq, M., Tam, N. F. Y., Lang, T., Hussain, M., & Zhou, H. (2025). Nitrogen-phosphorus conservation and trade-offs in mangroves. *Plant and Soil, 512*(1), 241–260. https://doi.org/10.1007/s11104-024-07130-7

Kathiresan, K., & Bingham, B. L. (2001). Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology, 40*, 81–251. https://doi.org/10.1016/S0065-2881(01)40003-4

Kristensen, E., Bouillon, S., Dittmar, T., & Marchand, C. (2008). Organic carbon dynamics in mangrove ecosystems: A review. *Aquatic Botany, 89*(2), 201–219. https://doi.org/10.1016/j.aquabot.2007.12.005

Liu, H., Cui, L., Li, W., Han, G., Wu, J., Li, B., & Nie, M. (2026). Plant functional traits: A key to understanding and restoring ecosystem structure and functioning in wetlands. *Journal of Plant Ecology, 19*(4), Article rtaf125. https://doi.org/10.1093/jpe/rtaf125

Lovelock, C. E., Ball, M. C., Martin, K. C., & Feller, I. C. (2007). Nutrient enrichment increases photosynthesis and growth in mangroves. *Tree Physiology, 27*(1), 85–92. https://doi.org/10.1093/treephys/27.1.85

Lu, Z., Ren, T., Li, Y., Cakmak, I., & Lu, J. (2025). Nutrient limitations on photosynthesis: From individual to combinational stresses. *Trends in Plant Science, 30*(8), 872–885. https://doi.org/10.1016/j.tplants.2025.03.006

Medina, E., Fernandez, W., & Barboza, F. (2015). Element uptake, accumulation, and resorption in leaves of mangrove species with different mechanisms of salt regulation. *Web Ecology, 15*(1), 3–13. https://doi.org/10.5194/we-15-3-2015

Naidoo, G. (2006). Factors contributing to dwarfing in the mangrove *Avicennia marina*. *Annals of Botany, 97*(1), 109–116. https://doi.org/10.1093/aob/mcj016

Nie, T., Xu, Z., He, Q., Feng, E., & [penulis lain]. (2025). Green leaf nutrients, not soil nutrients, mediate trace element resorption in mangrove plants across wet and dry seasons. *Tree Physiology, 45*(11), Article tpaf127. https://doi.org/10.1093/treephys/tpaf127

Peinado-Torrubia, P., Pons-Perpinyà, J., Clemente-Moreno, M. J., Gago, J., Colmenero-Flores, J. M., & López-Serrano, L. (2026). The role of the “overlooked” elements magnesium

and chloride for improving photosynthesis and crop water-use efficiency in plants. *Plant and Soil*. https://doi.org/10.1007/s11104-026-08384-z

Quadros, A. F., Helfer, V., Nordhaus, I., Reuter, H., & Zimmer, M. (2021). Functional traits of terrestrial plants in the intertidal: A review on mangrove trees. *The Biological Bulletin, 241*(2), 123–139. https://doi.org/10.1086/716510

Rashid, A. (1986). *Mapping zinc fertility of soils using indicator plants and soil analyses*. Pakistan Agricultural Research Council.

Reef, R., Feller, I. C., & Lovelock, C. E. (2010). Nutrition of mangroves. *Tree Physiology, 30*(9), 1148–1160. https://doi.org/10.1093/treephys/tpq048

Ryan, J., Estefan, G., & Rashid, A. (2001). *Soil and plant analysis laboratory manual* (2nd ed.). International Center for Agricultural Research in the Dry Areas.

Tränkner, M., Tavakol, E., & Jákli, B. (2018). Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. *Physiologia Plantarum, 163*(3), 414–431. https://doi.org/10.1111/ppl.12747

Twilley, R. R., Chen, R. H., & Hargis, T. (1992). Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. *Water, Air, and Soil Pollution, 64*, 265–288. https://doi.org/10.1007/BF00008234

Twilley, R. R., & Day, J. W. (2019). The productivity and nutrient dynamics of mangrove wetlands. *Wetlands Ecology and Management, 27*, 41–59. https://doi.org/10.1007/s11273-018-9635-8

Whynot, T. W. (1989). *Effects of repeated fertilization on nitrogen fluxes in a young lodgepole pine stand as measured by an in situ sequential coring technique* [Doctoral dissertation, University of British Columbia].

Williams, C. H., & Steinbergs, A. (1959). Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Australian Journal of Agricultural Research, 10*(3), 340–352. https://doi.org/10.1071/AR9590340

Biographies of Authors

Baburaj Haripriya, Department of Botany, Sir Syed College, Taliparamba, affiliated to Kannur University, Kerala 670141, India.

- Email: haripriyababurajphd@gmail.com
- ORCID: 0009-0000-5045-7605
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Pullaikodi Sreeja, Department of Botany, Sir Syed College, Taliparamba, affiliated to Kannur University, Kerala 670141, India.

- Email: sreeja@sirsyedcollege.ac.in
- ORCID: 0000-0002-8163-9994
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A