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Eco-geographical variation in leaf functional traits of teak (*Tectona grandis* L.f.) across Bangladesh

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Abstract

Changes in plant functional characteristics over environmental gradients are important for explaining species' adaptation and aiding climate-resilient forest management. This study assessed the eco-geographical variation of leaf functional features of *Tectona grandis* L.f. in different climatic zones of Bangladesh. Leaf samples were collected from 120 mature teak trees from ten districts representing tropical, tropical monsoon and humid subtropical environment. A total of 600 leaves, collected from 120 trees across 60 sampling locations, were examined for Specific Leaf Area (SLA), Leaf Dry Matter Content (LDMC), Leaf Thickness, Leaf Area, Relative Water Content (RWC), Leaf Water Content (LWC) and chlorophyll content. Soils collected from the respective sites were analyzed for moisture (%), pH and electrical conductivity (EC). Results of the one-way ANOVA revealed highly significant regional variation ($p < 0.001$) in major leaf traits and soil parameters. Pearson correlation analysis identified considerable ecological trade-offs among the measured characteristics, with a particularly strong negative correlation between SLA and LWC ($r = -0.61$, $p < 0.001$). In contrast, positive correlations were observed between leaf thickness and LWC ($r = 0.33$, $p < 0.01$), as well as between RWC and LWC ($r = 0.31$, $p < 0.05$), indicating coordinated water-retention strategies. Climatic circumstances and soil heterogeneity were the main causes of phenotypic differentiation; while overlaps among climatic groups indicated a significant effect of micro-environmental variables, which was shown by Principal Component Analysis. Overall, the results suggested that teak has a high functional flexibility through coordinated changes in leaf structure, water balance and physiological features. These adaptive responses may increase resilience under different climatic conditions and give useful information for site-specific plantation management, maintenance of functional diversity and climate-resilient forestry in Bangladesh.

Keywords: Adaptation, climatic zone, leaf functional traits, soil properties.

Introduction

Traits are features and characteristics of organisms that can be anatomical, morphological, biochemical, physiological, or phenological (Kattge *et al*. 2011). Plant traits are measured, described, and standardized across species depending on their response to environmental factors and constraints, trophic levels, and survival or dispersal strategies (Pérez-Harguindeguy *et al*. 2013). These can be measured at all hierarchical organization levels of the vegetation from leaves (Kühn *et al*. 2004) to individual plants (Violle *et al*. 2007), to plant populations and communities (Cadotte *et al*. 2015), and thus at the landscape and biogeographical levels (Violle *et al*. 2014). Therefore, mapping species traits captures vegetation features and diversity at all levels, from a local to a global scale (Akter *et al*. 2021; Abelleira Martínez *et al*. 2016). Variation in leaf traits help us to understand, explain, and predict why organisms live where they do, how they will respond to environmental change (Sharmi *et al*. 2021; Green *et al*. 2008), and how they interact with different stressors, disturbances, or resource limitations (Akter *et al*. 2021). Furthermore, traits and their variation filter for status, environmental changes, land-use intensity, stress, or disturbances (Garnier *et al*. 2007; Gámez-Virués *et al*. 2015). Traits can indicate resource depletion (Kühn *et al*. 2006), define the state, presence (Kühn *et al*. 2006), and dispersal strategies (Díaz *et al*. 2016), or indicate functional disturbances and shifts in ecosystems (Lavorel and Garnier 2002; Reichstein *et al*. 2014).

Leaf functional properties are especially significant to explain plant adaptation because of their direct linkage with photosynthesis, transpiration, water use efficiency,

nutrient absorption and biomass output. Differences in leaf area, specific leaf area, leaf dry matter content, chlorophyll content and leaf thickness are examples of how plants adapt their resource use methods to changing environmental contexts (Hikosaka *et al*. 2025; Nong *et al*. 2025). In forest tree species, these traits are valuable for detecting whether a plant employs a resource-acquisitive strategy for rapid development or a resource-conservative strategy for survival under stress. Recently, leaf functional traits have been shown to be significantly linked with environmental gradients, and can explain adaptation responses to climate, soil fertility, moisture availability and variation at the site level (Díaz *et al.* 2016; Dong *et al.* 2020; Akram *et al.* 2023). Additionally, the leaf traits of teak are associated with its growth performance and site suitability, and therefore, are crucial indicators of the morpho-physiological adaptation of plants to a variety of plantation environments (Kenzo *et al.* 2024; Meinata *et al.* 2025). Studying phenotypic variation of the leaf traits of the different populations of teak may aid in understanding the adaptive strategies, ecological trade-offs, and production potential of the species in a range of changing environmental conditions.

Tectona grandis L.f. is a widely distributed tropical hardwood species in South Asian countries including Bangladesh and is well known for its economic value and ecological importance. It plays a key role in timber production, carbon sequestration and the maintenance of forest ecosystem (Pandey and Brown 2000). Though, teak is grown across a range of environmental conditions in the country, relatively little attention has been given to how its leaf functional traits vary within the species across different geographical regions. Most studies on teak conducted in Bangladesh have focused mainly on growth, yield, and wood quality, with far less emphasis on physiological traits and functional strategies of teak plants (Hossain *et al*. 2016; Uddin *et al*. 2025). Hence, there is a lack of understanding of how leaf characteristics; particularly those related to resource usage vary in response to environmental variation among teak populations. Filling this gap would improve our understanding of plant adaptation and could support better forest management and planning under changing environmental conditions. The objective of this research was to assess- variation in leaf functional characteristics across different geographical areas of Bangladesh to see whether those functional traits varied considerably across those regions and to explain the relationships among those characteristics in order to investigate potential ecological trade-offs. It was anticipated the leaf functional traits of *T. grandis* L.f. to be significantly distinct throughout many geographical locations due to environmental heterogeneity, which indicated the coordinated ecological trade-offs and adaptive strategies for further resource management.

Materials and methods

Description of study area and sampling: Leaf samples of teak (*T. grandis* L.f.) were collected from 10 districts of Bangladesh which covers almost the entire geographical coverage of Bangladesh (Fig.1). The selected sampling sites represented three different climatic regions such as tropical, tropical monsoon and humid sub-tropical regions (Mahmud *et al*. 2018; Peel *et al*. 2007). Among the sampling sites, Dhaka, Cumilla, Barishal, and Khulna represented the tropical region; Sylhet, Chattogram, Bandarban, and Rangamati represented the tropical monsoon region; and Dinajpur and Mymensingh represented the humid subtropical region (Fig. 1). The latitude of the sampling sites ranged from 22° 11′ 07.69″ N in Bandarban to 25° 25′ 13.19″ N in Dinajpur, while the longitude ranged from 88° 38′ 15.72″ E in Dinajpur to 92° 13′ 25.97″ E in Bandarban.

The tropical zone is with warm temperatures and rainfall in the seasons. The tropical monsoon area experiences more monsoon rain and has a more humid climate. The humid subtropical area has more seasonal differences such as colder dry seasons and hot wet summers. In each district, six random sampling sites were selected, based on the availability of patches of teak vegetation. From each of the sites, two adult teak trees were selected and five fully expanded young leaves were collected from each tree. Therefore, 60 leaves were sampled from each district, resulting in a grand total of 600 leaf samples collected from 120 teak trees across 60 sampling locations in Bangladesh. Only healthy, mature teak trees of comparable developmental stage (approximately 16-20 years old) were selected at each sampling site to minimize the influence of tree age on leaf functional trait variation.

Leaf and soil samples were collected into separate plastic bags right away and labeled with sites. The height and DBH (Diameter at Breast Height) of the sampling trees were determined immediately by using measuring tape. Also, total numbers of teak tree at the sampling site were also counted. Geographical locations of the sampling sites were tracked by GPS. After collection, the leaf samples were cleaned, labelled, and stored at −20°C until further analysis.

Leaf trait measurement: Leaf morphological and physiological traits were measured using standardized approaches and instruments. At first, images of leaf were taken using a DSLR camera (Canon EOS 80D). Then, ImageJ software (v. 1.8) was used to ensure that the digital measurement of leaf length, breadth and area were accurate (Schneider et al. 2012). SLA was calculated as the ratio of leaf area to leaf dry mass (SLA = leaf area / dry mass of the leaf). Dry mass of the leaf was taken after

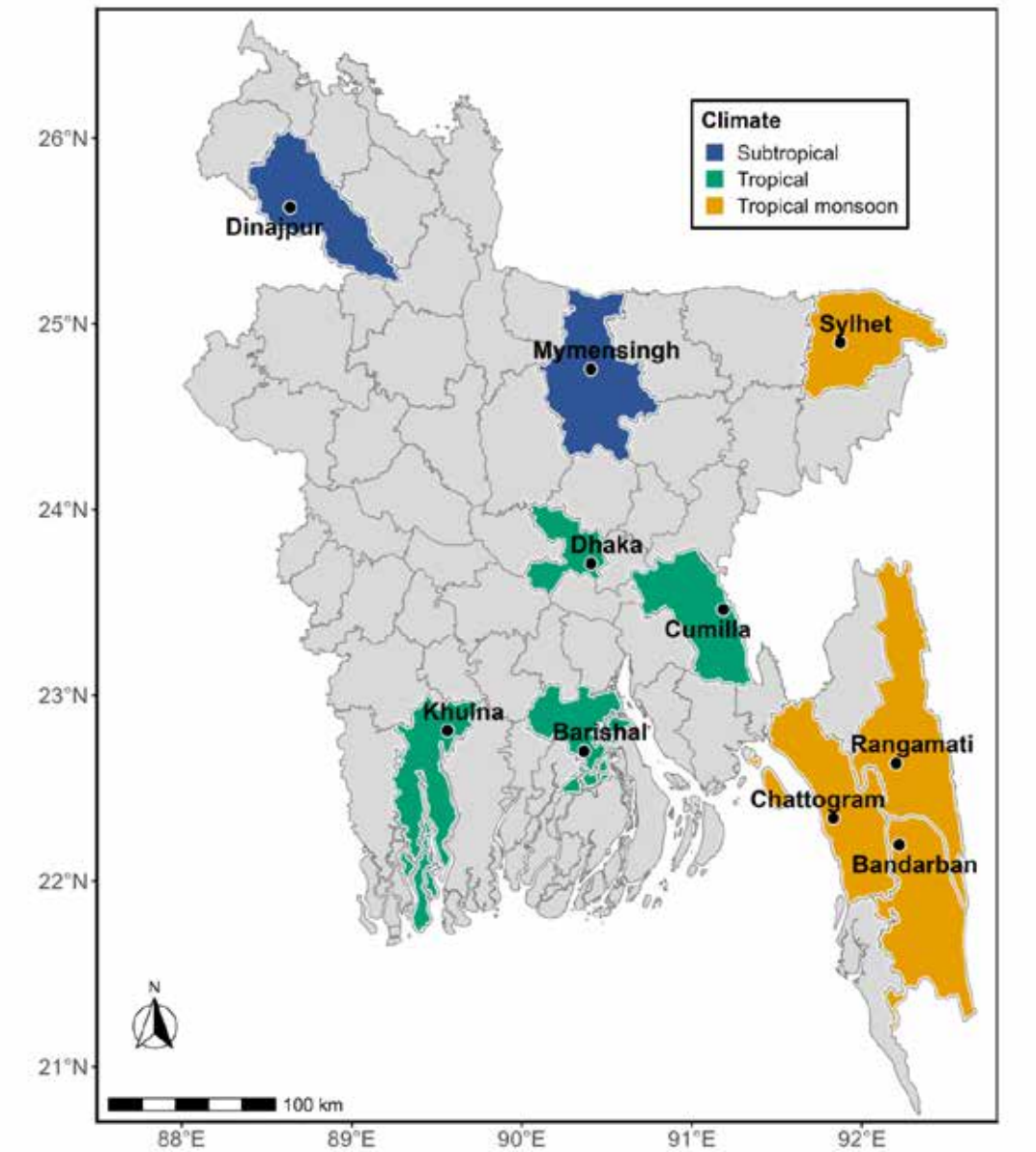


Figure 1. Map showing the geographic distribution of the sampling sites of *Tectona grandis* L.f. across different climatic regions of Bangladesh.

drying leaves in an oven at 80° C for 24 hours. RWC was determined following the standard gravimetric method using the formula, RWC = [(fresh weight − dry weight) / (turgid weight − dry weight)] × 100 (Hossain 2022). Leaf dry matter content (LDMC) was calculated as the ratio of leaf dry mass to fresh mass (LDMC = leaf dry mass / leaf fresh mass), indicating leaf structural investment. Furthermore, leaf water content (LWC) was determined as the differences between fresh mass and dry mass in relation to leaf area [LWC = (leaf fresh mass − leaf dry mass) / leaf area]. Leaf thickness was measured using a digital slide caliper (Vernier caliper) and leaf chlorophyll content was measured non-destructively by using a portable chlorophyll meter (SPAD-502 Plus, Konica Minolta, Japan).

Measurements of soil properties: Ten grams of soil was kept in an oven at 100° C for 24 hours. The soil moisture content was calculated using the formula, Soil moisture (%) = [(soil fresh weight − soil dry weight) / soil fresh weight] × 100, which represents the amount of water present in the soil. Within six hours of sample collection, soil pH values were measured using a pH meter (Hanna pH meter, pHeP). Additionally, an electrical conductivity (EC) meter (Hanna HI98331 Soil Test) was used to measure the soil EC.

Statistical analysis: One-way analysis of variance (ANOVA) was performed using Microsoft Excel 2019 to estimate differences in leaf functional traits among the studied geographical regions (Sokal and Rohlf 1981). To determine the correlations between those characteristics, to illustrate the characteristic distributions within the research areas, boxplots were created using the R programming language (Version 4.6.0). Heatmap was prepared following Pearson's correlation analysis among the measured variables using the same software.

To investigate multivariate relationships among leaf traits and soil variables, Principal Component Analysis (PCA) was conducted using R (Version 4.6.0) as well. PCA was performed on the "prcomp" function and the first two principal components (PC1 and PC2) were used for interpretation (Jolliffe 2002). The results were visualized as a biplot using ggplot2 (Wickham 2016) and factoextra (Kassambara and Mundt 2020). Samples were grouped by climatic zones and 95% confidence ellipses were drawn to show clustering patterns.

Results

The height of the sampled trees ranged from 4.5 m to 22 m whereas the maximum height was observed in Mymensingh and minimum in Chattogram respectively. Moreover the maximum Diameter at Breast Height (DBH) was observed in Dhaka and minimum in Chattogram respectively (Table 1).

ANOVA results revealed significant effects of sites on all of the leaf functional traits of *T. grandis* L.f. and soil properties across all the regions of Bangladesh (Table 2).

ANOVA results revealed a highly significant effect of geographical regions on SLA ($F= 6.20$, $p < 0.001$). Mean values of the leaf traits of the 10 sites are shown in Fig. 2. Mean SLA values varied substantially among districts, with the highest values observed in Mymensingh (51.83 ± 6.53) and Chattogram (51.61 ± 12.55), while the lowest values were recorded in Bandarban (24.06 ± 10.79) and Dhaka (26.53 ± 5.03). Intermediate values were observed in districts such as Dinajpur, Cumilla, and Khulna. Results clearly indicated geographical variation of SLA in Bangladesh. There was also a significant variation in LDMC ($F = 6.65$, $p < 0.001$) with Dinajpur and Dhaka having the highest values and Mymensingh and Khulna having the lowest values. Moderate and significant variation was observed in leaf thickness ($F = 3.92$, $p < 0.001$) and comparatively high in Bandarban, Rangamati and Sylhet. Significant geographical differences in leaf area ($F = 8.04$, $p < 0.001$) were found with the largest leaves in Sylhet and Dhaka and the smallest in Khulna and Rangamati. RWC showed the highest variation among all the traits ($F= 12.38$, $p < 0.001$) with the highest values in Barishal and Sylhet and the lowest in Dinajpur. There were significant differences in leaf water content (LWC) across districts ($F = 3.96$, $p < .001$). Although the amount of variability was moderate compared to traits such as RWC and leaf area, the data indicated that water content of leaves was affected by local environmental conditions. The boxplot distribution showed additional variability of median values and spread across regions, suggesting differences in plant water balance strategies. Furthermore, chlorophyll content also significantly differed among the

Table 1. Description of sampling sites, sample size (number of plants sampled per site) and growth traits (plant height and diameter at breast height (DBH) of *Tectona grandis* L.f. in different sites (districts) of Bangladesh. Values correspond to minimum (Min), maximum (Max) and average (Avg) measurements at each sampling site

Sites	Climatic region	No. of plants per sites			Plant height (m)			DBH(cm)		
		Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
Mymensingh	Subtropical	20	75	39	10	22	16.33	71	110	97.7
Cumilla	Tropical	5	13	9	8	14	10.25	55	73	63.7
Dinajpur	Subtropical	10	85	48	11	21	15	33	70	48.7
Chattogram	Tropical Monsoon	12	110	43	4.5	13	7.7	25	76	49.6
Rangamati	Tropical Monsoon	50	200	113	9.1	15	12.13	82.3	164.6	118
Bandarban	Tropical Monsoon	12	80	35	5.5	12	9.3	42.7	180	94.7
Barishal	Tropical	10	18	13	9.1	18.3	12.99	85.3	176.8	114
Sylhet	Tropical Monsoon	5	11	7	12.2	16.77	14.15	88.4	158.5	114.4
Khulna	Tropical	7	15	10	7.6	15.85	11.88	53.3	76.2	65.4
Dhaka	Tropical	3	8	5	10.7	16.77	11.27	149.5	216.4	169.3

Table 2. One-way ANOVA results showing the effects of ten studied sites (df, Sites = 9 and Residual = 50) on the leaf functional traits of *Tectona grandis* L.f. and their corresponding soil properties in Bangladesh

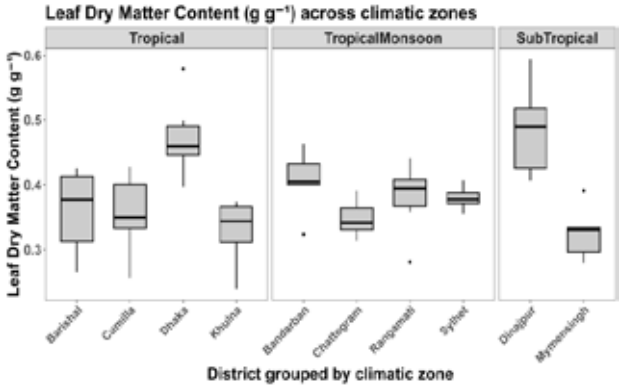
Traits	F-value	P-value
Leaf traits		
Specific leaf area	6.20	<0.001
Leaf dry matter content	6.65	<0.001
Thickness	3.92	<0.001
Leaf Area	8.04	<0.001
Relative water content	12.38	<0.001
Leaf water content	3.96	<0.001
Chlorophyll	3.76	<0.01
Soil properties		
Soil pH	12.26	<0.001
Electrical conductivity	4.09	<0.001
Soil moisture	17.08	<0.001

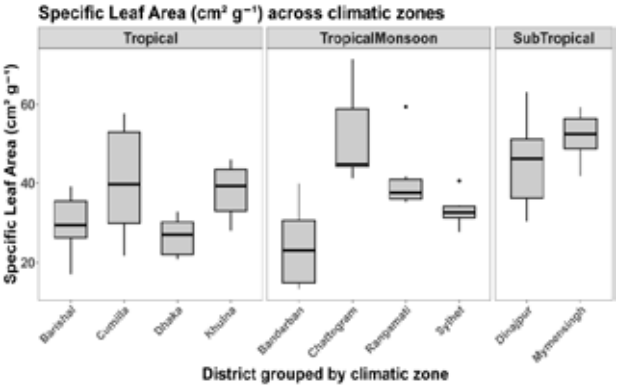
sites, but with a relatively low magnitude ($F= 3.76$, $p < 0.01$).

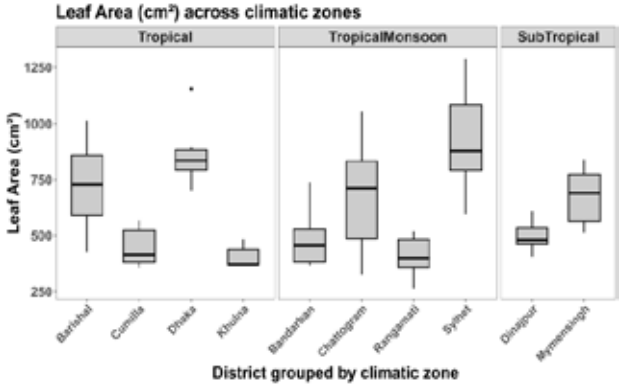
Soil pH differed significantly among the study sites ($F = 12.26$, $p < 0.001$), suggesting a large variation in soil chemical conditions across the studied districts. There were also significant differences in soil EC values, among sites ($F = 4.09$, $p < 0.001$). The soil moisture content had a very high level of variation ($F=17.08$, $p<0.001$) indicating that water availability might be highly heterogeneous across the sampling sites (Figure 2).

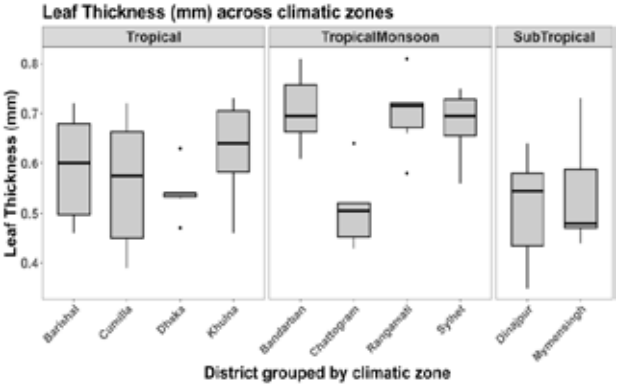
Pearson's correlation analysis showed several significant associations among leaf functional traits and selected soil properties (Figure 3). The correlation heatmap provided a clear visual summary of both the direction and strength of these relationships. Overall, most correlations were weak to moderate, while the strongest relationship was observed between SLA and LWC.

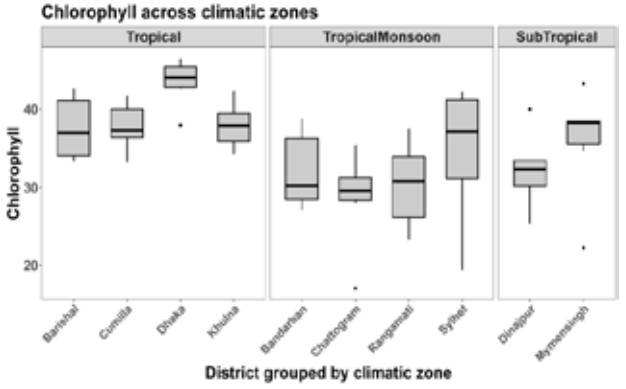
SLA showed a strong and highly significant negative correlation with LWC ($r = -0.61$, $p < 0.001$), indicating that samples with higher SLA tended to have lower leaf water content. SLA was also significantly and negatively correlated with LDMC ($r = -0.33$, $p < 0.01$), leaf thickness ($r = -0.31$, $p < 0.05$), RWC ($r = -0.26$, $p < 0.05$), and chlorophyll content ($r = -0.32$, $p < 0.05$). These results suggest that SLA was inversely associated with several structural and physiological leaf traits. LDMC showed a highly significant negative correlation with RWC (r =

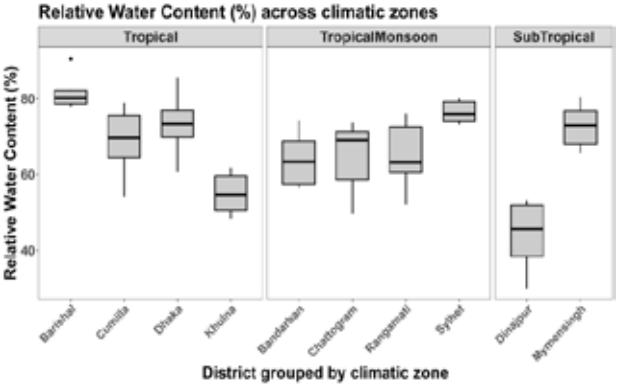

Leaf Dry Matter Content (g g⁻¹) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Leaf Dry Matter Content (g g⁻¹)
0.6
0.5
0.4
0.3
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone

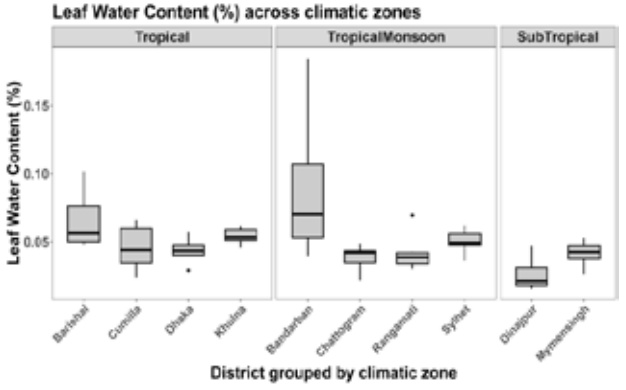

Specific Leaf Area (cm² g⁻¹) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Specific Leaf Area (cm² g⁻¹)
60
40
20
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone

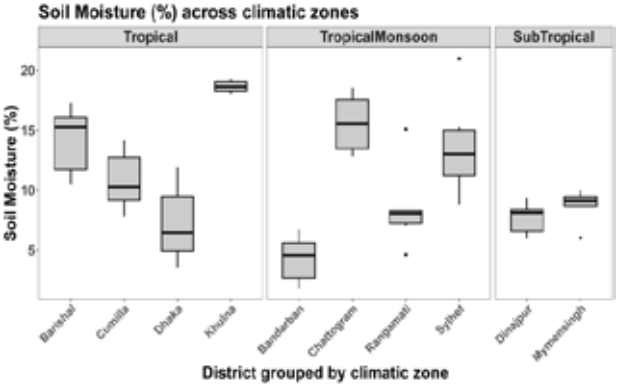

Leaf Area (cm²) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Leaf Area (cm²)
1250
1000
750
500
250
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone


Leaf Thickness (mm) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Leaf Thickness (mm)
0.8
0.7
0.6
0.5
0.4
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone


Chlorophyll across climatic zones
Tropical
TropicalMonsoon
SubTropical
Chlorophyll
40
30
20
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone


Relative Water Content (%) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Relative Water Content (%)
80
60
40
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone


Leaf Water Content (%) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Leaf Water Content (%)
0.15
0.10
0.05
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone


Soil Moisture (%) across climatic zones
Tropical
TropicalMonsoon
SubTropical
Soil Moisture (%)
20
15
10
5
Barishal
Cumilla
Dhaka
Khulna
Bandarban
Chattogram
Rangamati
Sylhet
Dinajpur
Mymensingh
District grouped by climatic zone

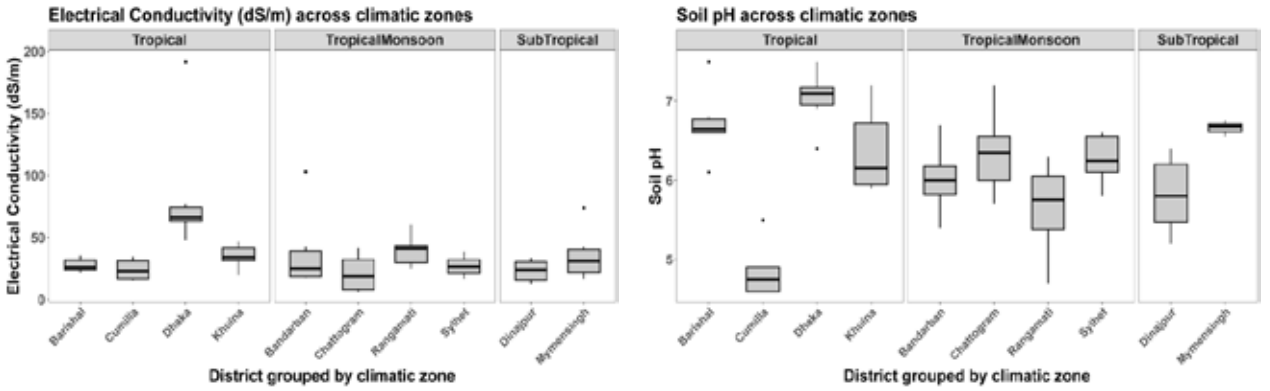


Figure 2. Boxplots showing the distribution of leaf functional traits (Specific leaf area, Leaf dry matter content, leaf thickness, leaf area, Relative water content, Leaf water content and leaf chlorophyll content) of *Tectona grandis* L.f. and corresponding soil properties (Moisture content, pH and Electrical conductivity) across different geographical regions of Bangladesh.

−0.42, $p < 0.001$) and a significant negative correlation with soil moisture ($r = -0.37$, $p < 0.01$). This indicates that higher LDMC was associated with lower RWC and reduced soil moisture conditions. Leaf thickness was positively correlated with LWC ($r = 0.33$, $p < 0.01$), suggesting that thicker leaves tended to contain higher water content. Leaf area showed significant positive correlations with RWC ($r = 0.41$, $p < 0.01$) and soil pH ($r = 0.42$, $p < 0.001$). This indicates that larger leaf area was associated with higher relative water content and relatively higher soil pH. In addition, RWC was positively correlated with LWC ($r = 0.31$, $p < 0.05$), reflecting a consistent relationship between plant water status indicators.

Among soil-related variables, soil pH was significantly correlated with leaf area, while soil electrical conductivity showed a significant positive correlation with chlorophyll content ($r = 0.36$, $p < 0.01$). However, most other relationships between soil properties and leaf traits were weak and statistically non-significant. Strong correlation was not observed among the studied variables, suggesting that the measured traits represented relatively distinct aspects of plant functional response and soil condition.

The first two principal components accounted 41.8% of the overall variance (22.7% for Dim1 and 19.1% for Dim2 of the variability). The PCA bi-plot demonstrated a clear contribution of the leaf characteristics and soil variables to the overall sample separation. The positive readings of Dim1 were mostly connected with leaf area, chlorophyll content, soil pH, electrical conductivity, RWC, LWC and leaf thickness along Dim1. In contrast, SLA and soil moisture were positioned negatively on Dim1, suggesting an opposite relationship to the variables that were positioned positively on the axis. This means that samples with greater chlorophyll content, larger leaf area, higher water-related leaf traits and higher soil pH and EC were different from those with higher SLA and soil moisture.

LWC, RWC, leaf thickness, and soil moisture were found in the negative direction along Dim2, while LDMC, leaf area, pH, EC, and chlorophyll were orientated in the positive way. The close proximity of leaf area, pH, EC, and chlorophyll indicates a positive relationship between these factors. In similar fashion, vectors containing the values of LWC, RWC, and leaf thickness all headed in the same direction, indicating a positive correlation between these attributes and the possibility of coordinated structural trait response and leaf water retention. SLA, on the other hand, was directed in the opposite direction of most leaf area, chlorophyll, pH, and EC vectors, indicating a negative correlation with them.

The distribution of the sample showed a minor separation of climatic groups but with much overlap. Samples from the subtropical region were mainly positioned on the negative side of Dim1 and the positive side of Dim2, indicating a much higher association with SLA and to some

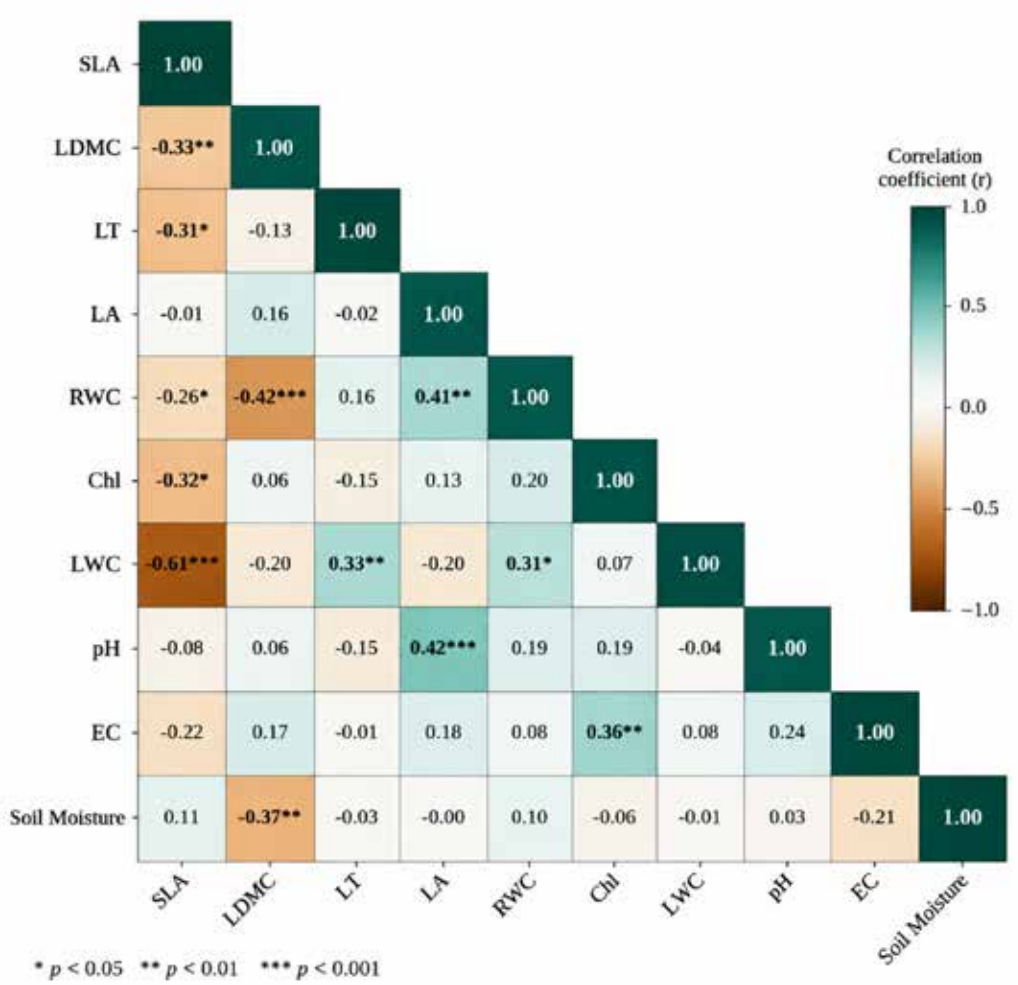


Figure 3. Pearson correlation heatmap illustrating the relationships between soil variables and leaf functional traits of *Tectona grandis* L.f. Darker shades represent stronger positive or negative correlations. SLA = Specific Leaf Area, LDMC = Leaf Dry Matter Content, LT = Leaf Thickness, LA = Leaf Area, RWC = Relative Water Content, Chl = Chlorophyll, LWC = Leaf Water Content, EC = Electrical Conductivity. The values represent Pearson's correlation coefficients (r). Asterisks indicate statistical significance: *p < 0.05, **p < 0.01, and ***p < 0.001.

extent with the features in the top part of the biplot. The biggest distribution of samples was in the tropical region from bottom left to top right quadrants, demonstrating more diversity in leaf features and soil conditions for this group. Some tropical samples were associated with higher leaf area, chlorophyll, pH, EC and LDMC, whilst others were found around the lower section of the biplot indicating the variations in water related leaf traits. The tropical-monsoon samples were mostly scattered on the middle and lower-right side of the biplot and were linked with RWC, LWC and leaf thickness, but there was a large overlap with the other groups.

As a whole, PCA showed that variation in teak leaf traits was influenced by both plant functional traits and soil properties. The strongest multivariate patterns were associated with coordinated changes in chlorophyll content, leaf area, soil pH, EC, LDMC and leaf water variables, whereas SLA and soil moisture were positioned at opposite sides of the ordination space. The overlap across climatic groups indicates that climatic area was not the sole factor driving trait variation, and that local soil conditions and site level variability also contributed significantly to structuring the observed leaf trait responses.

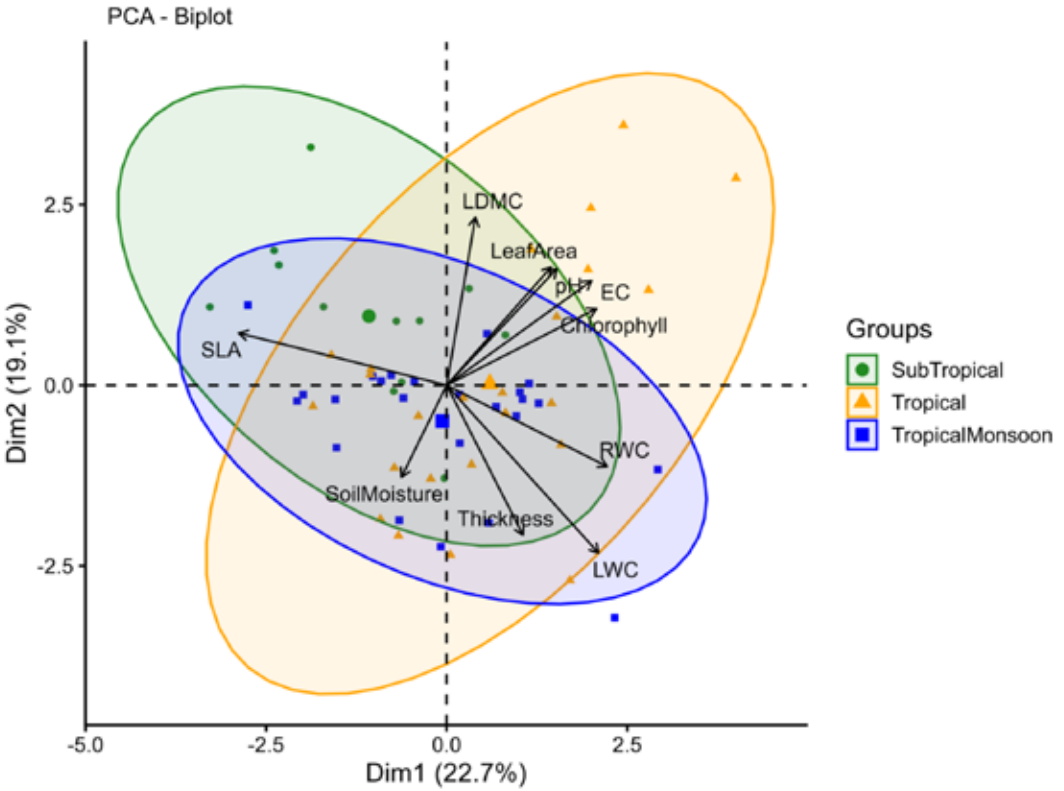


Figure 4. Principal Component Analysis (PCA) biplot illustrating the multivariate variation of leaf functional traits and soil properties among three climatic regions. SLA = Specific Leaf Area, LDMC = Leaf Dry Matter Content, RWC = Relative Water Content, LWC = Leaf Water Content, EC = Electrical Conductivity.

Discussion

The associations found between SLA, LDMC, leaf thickness and water related factors revealed that teak trees adapt their functional traits in response to environmental variability across Bangladesh. The negative association of SLA with LDMC reflected a trade-off between quick resource acquisitions against conservative stress-tolerant strategies, a pattern frequently reported in woody plant species developing under differing environmental circumstances (Reich 2014). In this study, populations characterized by higher LDMC and thicker leaves were also associated with better water-related features, suggesting more structural adaptability under somewhat stressful conditions. The correlated association between RWC, LWC and leaf thickness further suggested that the maintenance of leaf water balance is an essential adaptation mechanism in teak. Such structural and physiological adaptations may allow plants to maintain consistent performance despite the variation in soil moisture availability and seasonal weather fluctuation. Similar responses have been found to be key indicators of drought adaptation and environmental resilience in tropical tree species (Poorter *et al*. 2009; Pérez-Harguindeguy *et al*. 2013).

Correlations between leaf traits and soil parameters were found, indicating the importance of local soil in teak functional performance. Positive associations were found between chlorophyll content, leaf area and soil parameters suggesting that better soil conditions may improve photosynthetic activity and leaf growth. Other studies also reported a positive association between leaf chlorophyll content and leaf area (Rawat et al. 2021). However, the modest strength of most associations showed that teak responses are regulated by numerous interacting environmental variables rather than by a single ecological parameter.

The PCA patterns further suggested that climatic region alone could not explain the observed trait variance. There was considerable overlap among groups indicating that local site characteristics, soil heterogeneity and micro-environmental variation greatly influenced teak functional responses. This can partly explain the successful establishment and extensive adaptation of teak in environmentally varied regions of Bangladesh.

The results showed that populations of *T. grandis* L.f. developed unique forms of coping mechanisms to adjust to different climatic circumstances. Hence, selection of seed sources and planting stock should be guided by growth performance and site-specific climatic and edaphic conditions. The origin of seeds is of special importance in teak, since it affects development, stem quality and tolerance to stress (Keiding *et al*. 1986; Vishnu *et al*. 2022).

Populations with higher water-holding capacity, relative water content and structural stability may be more appropriate for planting and regeneration efforts in ecologically difficult sites. In more favorable conditions, however, when the constraints of water and nutrients are less severe, populations with better resource-acquisition features such as bigger leaf area and higher chlorophyll content may have an advantage. It is also important to protect teak populations from diverse geographical locations to maintain the genetic and functional variability required for long-term adaptation, breeding and climate-resilient plantation forestry (Alfaro *et al*. 2014).

Conclusion

The present study revealed that *T. grandis* L.f. is highly adaptable to different environmental conditions in Bangladesh. Variations in leaf traits were found which suggests teak adapts its growth, water use and structural characteristics in response to changes in climatic and soil conditions. Traits connected with water retention and leaf architecture were notably important for plant resistance to changing environmental conditions. The results also revealed that the functional ecology of teak in Bangladesh remains underexplored, especially in terms of leaf form, physiological adaptation and environmental-trait relationships across geographical regions. Previous studies in the country have focused on growth performance, wood quality and plantation productivity, but functional trait-based ecological studies are still few. This research thus provides an important basis for understanding the adaptive ecology of teak under local environmental conditions. The results suggested that variety of features at the regional level should be considered in forestry, for example in establishing plantations, selecting seed sources and planning restoration. Populations with better water use efficiency and stress tolerance traits would be more suitable for climate-resilient forestry management, particularly at sites prone to moisture stress and environmental variation. In addition, maintenance of genetic and functional diversity that may support long term plantation productivity and ecological resilience in Bangladesh is important for the conservation of regionally varied populations of teak.

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