



MICROCLIMATE VARIATION AMONG FOUR COMMON URBAN TREE SPECIES IN CALABAR, NIGERIA

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ABSTRACT

Rapid urbanization in Calabar is increasing heat stress, but detailed evidence on how urban trees control microclimate remains scarce. This study measured temperature and relative humidity (RH) beneath four common urban tree species in Calabar using a temperature and relative humidity meter. Data were collected from *Azadirachta indica*, *Albizia lebeck*, *Delonix regia*, and *Terminalia mantaly* canopies, as well as from nearby open areas, during morning and afternoon periods. Linear mixed-effects models revealed strong daily fluctuations: afternoon temperatures were 3.22°C higher than in the morning (SE = 0.20; $p < 0.001$), while RH decreased by 9.36% (SE = 0.41; $p < 0.001$). Canopy shading consistently moderated these effects, lowering temperature by 0.81°C (SE = 0.20; $p < 0.001$) and raising RH by 2.52% (SE = 0.41; $p < 0.001$). Differences between species were generally minor: *Azadirachta indica* was slightly cooler than *Albizia lebeck* (−0.408°C; $p = 0.044$) and showed a smaller afternoon RH decrease (+1.52%; $p = 0.009$). Most interactions were not significant, suggesting microclimate effects were broadly similar across species. The models accounted for a large portion of variation (Temperature marginal $R^2 = 0.78$; RH marginal $R^2 = 0.91$). Although boundary (singular) fits and short-term sampling limit the broad applicability of species-specific results, diagnostics confirmed the reliability of key fixed effects. Overall, the findings show that canopy cover, more than species type, determined microclimate buffering in Calabar and emphasize the importance of expanding and preserving urban tree cover to reduce heat.

Keywords: Thermal regulation, Urban trees, Canopy shading, Tropics, Urban greening

INTRODUCTION

Urban areas across Nigeria are expanding rapidly, driven by population growth, infrastructure development, and accelerating land-use change (Oyeniyi *et al.*, 2025). As vegetation is replaced with impervious surfaces, cities such as Calabar may be exposed to elevated daytime temperatures, reduced atmospheric humidity, and diminished human thermal comfort (Seun *et al.*, 2022). These warming trends, intensified by climate change, lead to more heat-related illnesses and a greater risk for the elderly and children (Olawade *et al.*, 2025). In this context, urban heat stress poses both environmental and public health challenges that require immediate and evidence-based interventions. Urban trees are among the most effective and low-cost nature-based solutions for mitigating urban heat and improving human comfort (Morakinyo *et al.*, 2013). Through shading, evapotranspiration, and modification of wind and radiation fluxes, trees significantly influence microclimatic variables such as air temperature and relative humidity (Meili *et al.*, 2020). Microclimate, defined as the set of atmospheric conditions in a small, localized area, is strongly shaped by vegetation structure and landscape configuration (De Frenne *et al.*, 2021; Kempainen *et al.*, 2024). Numerous studies show trees buffer extreme temperatures and increase humidity beneath their crowns, creating cooler, more comfortable microenvironments in urban areas (De Frenne *et al.*, 2021; Feng *et al.*, 2023). However, the microclimatic benefits provided by trees are not uniform. They vary markedly among species due to differences in canopy architecture, leaf area, transpiration rates, stomatal conductance, and other morphological or physiological traits (Sanusi *et al.*, 2016; Zhao *et al.*, 2020; Richter *et al.*, 2022). Recent work shows that within the same climate, individual species create distinct microclimatic niches affecting human comfort, ecosystem processes, and urban biodiversity (Feng *et al.*, 2023). These effects are crucial for climate-responsive urban planning, yet they are often overlooked in greening programmes across

developing countries, including Nigeria. Understanding how microclimate varies among commonly planted tree species is essential for informed species selection and effective urban forestry planning. Species offering better cooling and humidity regulation improve thermal comfort, cut heat-related health risks, reduce cooling energy, and support biodiversity by creating favorable microhabitats (Zhang *et al.*, 2022). Despite recognition of the cooling and humidifying benefits of urban trees (Mohammed & Mustapha, 2026; Pattnaik *et al.*, 2024), empirical data on species microclimate regulation in Calabar remain limited. In Calabar, available research has largely examined carbon storage, floristic composition, or general urban forest structure (Ononyume & Edu, 2025), with little attention given to thermal and humidity variation beneath different tree species. As a result, urban greening initiatives commonly assume all trees provide similar microclimatic benefits. This leads to planting decisions that may be suboptimal for mitigating heat stress or enhancing urban resilience. To address this gap, this study aimed to quantify microclimate variation, specifically temperature and relative humidity, around four widely planted urban tree species in Calabar. The objectives are to assess diurnal patterns in temperature and relative humidity under and outside tree shade, to compare the microclimatic effects of the four selected species, and to identify species-level differences.

MATERIALS AND METHODS

Study Design

The study was carried out in February 2025 in Calabar, located at 4.9757° N, 8.3417° E. Four locations were randomly selected from the OpenStreetMap layer in QGIS version 3.44.4, Solothurn, including Atimbo, Etta Agbor, Ekpo Abasi, and Ikot Effanga. A preliminary reconnaissance survey was conducted to delineate major roads with substantial tree cover within the study areas. This assessment revealed that four species were consistently the most

prevalent across these locations. Consequently, these species were selected for detailed sampling. The total number of eligible trees per species was counted along each road. For each species, a random starting point was generated (using a random number between 1 and k), and every k -th tree of that species was chosen for sampling until five trees per species were selected. If a selected tree was inaccessible due to obstructions, restricted access, or unsafe conditions, the next eligible tree of the same species was selected.

Tree Measurements

For each tree, paired measurements (under-canopy and open reference) were taken twice daily (between 8-10 am and 12 noon to 2 pm) using a digital temperature and relative humidity meter (Sper Scientific, USA). At each measurement, the sensor was allowed to stabilize for at least 60 seconds before recording. The order of measurements on each tree was randomized daily to reduce time-of-day bias. Sampling occurred over five nonconsecutive days, resulting in approximately 20 paired observations per tree. All measurements were taken at a consistent height of 1.5 meters above ground. The under-canopy measurement was taken 0.5 meters from the trunk. The open reference site was located outside the canopy dripline (>5 meters) and was not shaded by nearby trees or structures. All data were recorded to the nearest ± 1 °C for temperature and $\pm 5\%$ for relative humidity.

Data Analysis

All analyses were performed in R (version 4.4.3). Linear mixed-effects models (LMMs) were used to investigate the

effects of location (open space vs. under canopy), species, and time of day on temperature and relative humidity. The overall model structure was:

$$\text{Response}_{ijk} = \beta_0 + \beta_1\text{Location}_i + \beta_2\text{Species}_j + \beta_3\text{Time}_k + (1|\text{Tree ID}) + \epsilon_{(ijk)}$$

Where Tree ID was included as a random effect to account for repeated measurements on the same individual tree, the models were fitted using the *lme4* package, and p-values for the fixed effects were obtained using the *lmerTest* package. Model assumptions, including normality and homoscedasticity of residuals, were visually assessed using residual-versus-fitted and Q-Q plots. Estimated marginal means (EMMs) were obtained using the *emmeans* package, and pairwise comparisons among species and locations were adjusted using the Tukey method. Data visualization was conducted with *ggplot2*.

RESULTS AND DISCUSSION

The raw distributions of temperature and relative humidity (RH) were plotted to visualize unadjusted patterns across species, canopy position (Open vs Under), and time of day (Morning vs Afternoon) (Figures 1 and 2). The plots reveal apparent diurnal differences, with afternoon temperatures generally higher and relative humidity lower than in the morning. Additionally, measurements taken under the canopy tend to be cooler and more humid than those in open areas. These patterns provided a clear rationale for applying mixed-effects models to formally quantify the effects of species, time, and canopy position on microclimate conditions.

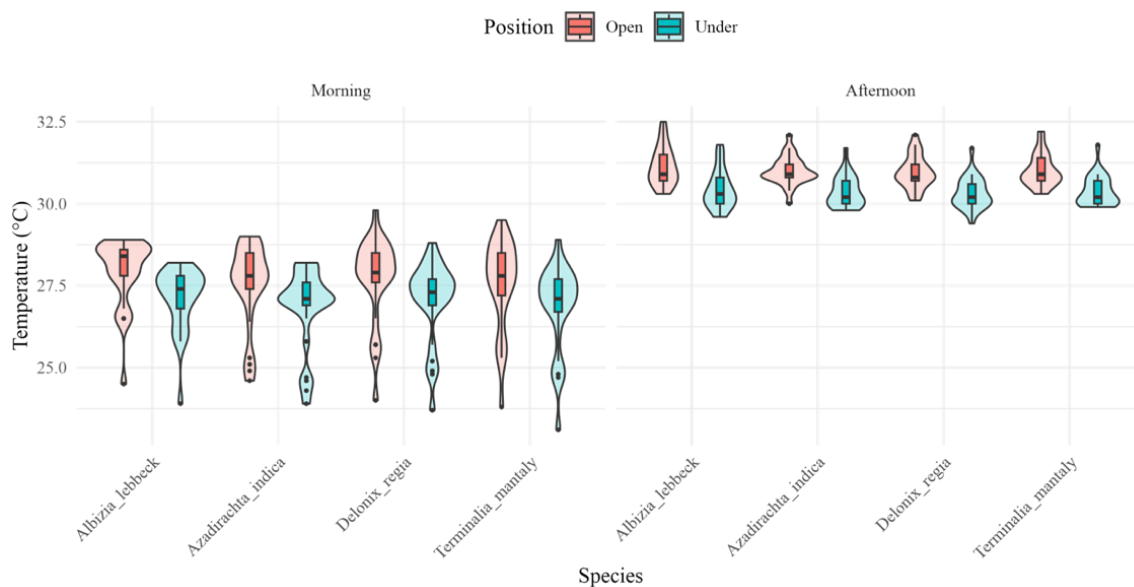


Figure 1: Temperature Distributions by Species, Position, and Time

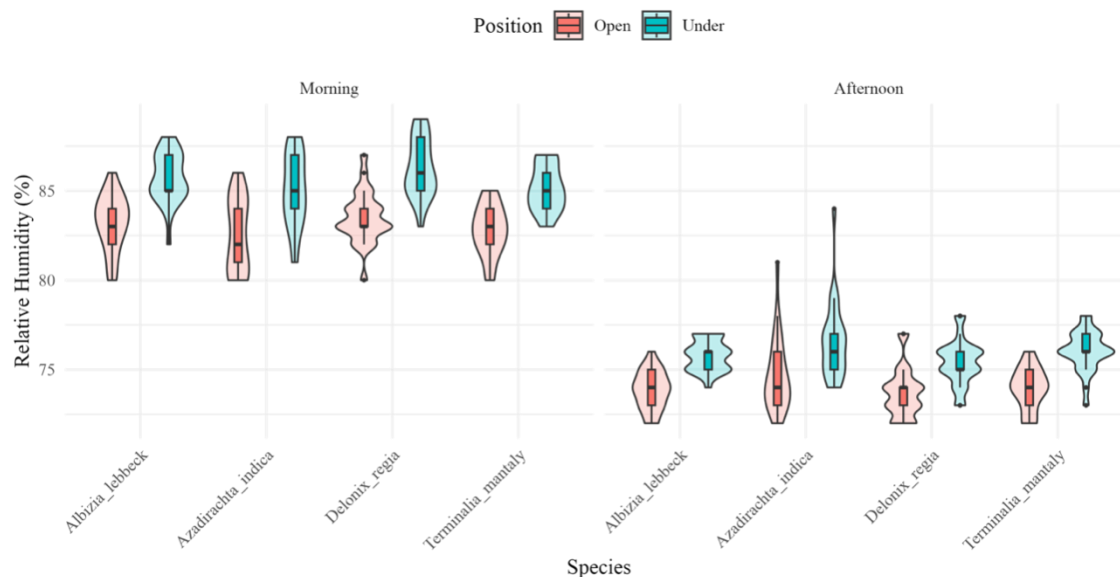


Figure 2: Relative Humidity Distributions by Species, Position, and Time

The temperature model indicated that measurements taken in the afternoon were considerably warmer than those in the morning, with temperatures rising by an average of 3.22°C (SE = 0.20; $t = 15.91$; $p < 0.001$; 95% CI approximately 2.82–3.61) after controlling for species and position. Temperatures recorded under the canopy were significantly cooler than in nearby open areas, showing an average decrease of 0.81°C (SE = 0.20; $t = -4.00$; $p < 0.001$; 95% CI approximately -1.21 to -0.41). Compared to *Albizia lebbbeck*, *Azadirachta indica* displayed slightly lower temperatures (Estimate = -0.41°C, SE = 0.20; $t = -2.02$; $p = 0.044$), while *Delonix regia* and *Terminalia mantaly* did not significantly differ (*D. regia*: $p =$

0.29; *T. mantaly*: $p = 0.07$). None of the two-way or three-way interactions (Species × Time, Species × Position, Time × Position, or Species × Time × Position) was significant (all $p > 0.10$), indicating consistent effects of time of day and canopy position across species. (Table 1). In the relative humidity model, humidity was markedly lower in the afternoon, decreasing by an average of 9.36 percentage points (SE = 0.41; $t = -22.86$; $p < 0.001$; 95% CI approximately -10.16 to -8.56). Canopy measurements showed significantly higher relative humidity than open areas, with a difference of 2.52 percentage points

Table 1: Estimated Effects, Test Statistics, and 95% Confidence Intervals for Temperature Model Terms

Effect	Term	Estimate	Std.error	Statistic	df	p.value	Conf.low	Conf.high
fixed	(Intercept)	27.93	0.3	93.01	8.05	0	27.24	28.62
fixed	Tree_speciesAzadirachta_indica	-0.41	0.2	-2.02	395	0.04	-0.81	-0.01
fixed	Tree_speciesDelonix_regia	-0.21	0.2	-1.05	395	0.29	-0.61	0.18
fixed	Tree_speciesTerminalia_mantaly	-0.37	0.2	-1.84	395	0.07	-0.77	0.02
fixed	TimeAfternoon	3.22	0.2	15.91	395	0	2.82	3.61
fixed	PositionUnder	-0.81	0.2	-4	395	0	-1.21	-0.41
fixed	Tree_speciesAzadirachta_indica:TimeAfternoon	0.27	0.29	0.94	395	0.35	-0.29	0.83
fixed	Tree_speciesDelonix_regia:TimeAfternoon	0.03	0.29	0.11	395	0.91	-0.53	0.59
fixed	Tree_speciesTerminalia_mantaly:TimeAfternoon	0.24	0.29	0.86	395	0.39	-0.32	0.81
fixed	Tree_speciesAzadirachta_indica:PositionUnder	0.12	0.29	0.41	395	0.68	-0.45	0.68
fixed	Tree_speciesDelonix_regia:PositionUnder	0.14	0.29	0.51	395	0.61	-0.42	0.71
fixed	Tree_speciesTerminalia_mantaly:PositionUnder	0.1	0.29	0.34	395	0.74	-0.47	0.66
fixed	TimeAfternoon:PositionUnder	0.1	0.29	0.34	395	0.74	-0.47	0.66
fixed	Tree_speciesAzadirachta_indica:TimeAfternoon:PositionUnder	-0.04	0.4	-0.1	395	0.92	-0.84	0.75
fixed	Tree_speciesDelonix_regia:TimeAfternoon:PositionUnder	-0.08	0.4	-0.19	395	0.85	-0.87	0.72
fixed	Tree_speciesTerminalia_mantaly:TimeAfternoon:PositionUnder	-0.02	0.4	-0.05	395	0.96	-0.82	0.77

(SE = 0.41; $t = 6.15$; $p < 0.001$; 95% CI approximately 1.72–3.32). There were no significant differences among species compared to *Albizia lebbbeck* in the main effects (all $p > 0.17$),

but the *Azadirachta indica* × Afternoon interaction was substantial (Estimate = +1.52% relative humidity, SE = 0.579; $t = 2.63$; $p = 0.009$), suggesting the afternoon decrease in

humidity was smaller for *A. indica* (-7.84%). All other interactions were not significant (Table 2). The temperature model explained a significant amount of variation (marginal $R^2 = 0.78$; conditional $R^2 = 0.88$), with minimal variation between trees but notable variation across days (Table 2). The relative humidity model explained most of the variance (marginal $R^2 = 0.91$; conditional $R^2 = 0.92$), with the random effect of TreeID contributing modestly and an interclass correlation coefficient of approximately 0.081 (Table 3). The estimated marginal means revealed consistent microclimate patterns, driven mainly by time of day and canopy cover. Temperature was always lower under tree canopies than in open areas, with the strongest differences occurring in the afternoon. Morning temperatures ranged from 27.5–27.9°C in open areas and 26.8–27.1°C under canopies, while afternoon temperatures increased sharply to 30.96–31.14°C in the open but remained cooler under canopies (30.32–30.43°C). Species differences in temperature

were modest, with *Albizia lebbbeck* slightly warmer and *Azadirachta indica* and *Terminalia mantaly* slightly cooler across positions and times (Table 4). Relative humidity showed the opposite pattern: canopies consistently enhanced RH relative to open sites at both times of day. Morning relative humidity ranged from 82.5–83.5% in open areas but increased to 85.0–86.3% under canopies, representing a 2.5–3.0 percentage-point rise. Afternoon relative humidity declined overall yet remained higher beneath canopies (75.4–76.6%) than in open areas (73.7–74.7%). Species differences were again minor but consistent, with *Delonix regia* showing slightly higher relative humidity levels and *Azadirachta indica* and *Terminalia mantaly* exhibiting lower values. Collectively, these results demonstrate that tree canopies reliably buffer the microclimate by reducing temperatures and increasing moisture, with pronounced diurnal shifts but relatively minor species-level variation (Table 5)

Table 2: Estimated Effects, Test Statistics, and 95% Confidence Intervals for Relative Humidity Model Terms

Effect	Term	Estimate	Std.error	Statistic	df	p-value	Conf. low	Conf. high
fixed	(Intercept)	83.2	0.35	239.29	81.78	0.00	82.51	83.89
fixed	Tree_speciesAzadirachta_indica	-0.68	0.49	-1.38	81.78	0.17	-1.66	0.30
fixed	Tree_speciesDelonix_regia	0.28	0.49	0.57	81.78	0.57	-0.70	1.26
fixed	Tree_speciesTerminalia_mantaly	-0.4	0.49	-0.81	81.78	0.42	-1.38	0.58
fixed	TimeAfternoon	-9.36	0.41	-22.86	380.00	0.00	-10.17	-8.55
fixed	PositionUnder	2.52	0.41	6.15	380.00	0.00	1.71	3.33
fixed	Tree_speciesAzadirachta_indica:TimeAfternoon	1.52	0.58	2.62	380.00	0.01	0.38	2.66
fixed	Tree_speciesDelonix_regia:TimeAfternoon	-0.44	0.58	-0.76	380.00	0.45	-1.58	0.70
fixed	Tree_speciesTerminalia_mantaly:TimeAfternoon	0.52	0.58	0.90	380.00	0.37	-0.62	1.66
fixed	Tree_speciesAzadirachta_indica:PositionUnder	7E-14	0.58	0.00	380.00	1.00	-1.14	1.14
fixed	Tree_speciesDelonix_regia:PositionUnder	0.28	0.58	0.48	380.00	0.63	-0.86	1.42
fixed	Tree_speciesTerminalia_mantaly:PositionUnder	-0.2	0.58	-0.35	380.00	0.73	-1.34	0.94
fixed	TimeAfternoon:PositionUnder	-0.56	0.58	-0.97	380.00	0.33	-1.70	0.58
fixed	Tree_speciesAzadirachta_indica:TimeAfternoon:PositionUnder	-0.08	0.82	-0.10	380.00	0.92	-1.69	1.53
fixed	Tree_speciesDelonix_regia:TimeAfternoon:PositionUnder	-0.52	0.82	-0.63	380.00	0.53	-2.13	1.09
fixed	Tree_speciesTerminalia_mantaly:TimeAfternoon:PositionUnder	0.32	0.82	0.39	380.00	0.70	-1.29	1.93

Table 3: Marginal and Conditional R² Values and Tree-level Intraclass Correlation for each Response Variable

Response	Marginal R ²	Conditional R ²	ICC Tree
Temperature	0.78	0.88	0
Relative humidity	0.91	0.92	0.081

Table 4: Estimated Marginal Means (EMMs) of Temperature across Species, Position, and Time of Day

Tree species	Time	Position	emmean	SE	df	lower.CL	upper.CL
<i>Albizia lebbbeck</i>	Morning	Open	27.93	0.33	10.05	27.19	28.66
<i>Azadirachta indica</i>	Morning	Open	27.52	0.33	10.05	26.79	28.25
<i>Delonix regia</i>	Morning	Open	27.72	0.33	10.05	26.98	28.45
<i>Terminalia mantaly</i>	Morning	Open	27.56	0.33	10.05	26.82	28.29
<i>Albizia lebbbeck</i>	Afternoon	Open	31.14	0.33	10.05	30.41	31.88
<i>Azadirachta indica</i>	Afternoon	Open	31.00	0.33	10.05	30.27	31.74
<i>Delonix regia</i>	Afternoon	Open	30.96	0.33	10.05	30.23	31.70
<i>Terminalia mantaly</i>	Afternoon	Open	31.02	0.33	10.05	30.28	31.75

Tree species	Time	Position	emmean	SE	df	lower.CL	upper.CL
<i>Albizia lebbbeck</i>	Morning	Under	27.12	0.33	10.05	26.39	27.85
<i>Azadirachta indica</i>	Morning	Under	26.83	0.33	10.05	26.09	27.56
<i>Delonix regia</i>	Morning	Under	27.05	0.33	10.05	26.32	27.79
<i>Terminalia mantaly</i>	Morning	Under	26.84	0.33	10.05	26.11	27.58
<i>Albizia lebbbeck</i>	Afternoon	Under	30.43	0.33	10.05	29.70	31.17
<i>Azadirachta indica</i>	Afternoon	Under	30.37	0.33	10.05	29.63	31.10
<i>Delonix regia</i>	Afternoon	Under	30.32	0.33	10.05	29.59	31.05
<i>Terminalia mantaly</i>	Afternoon	Under	30.38	0.33	10.05	29.65	31.11

Table 5: Estimated Marginal Means (EMMs) of Relative Humidity across Species, Position, and Time of Day

Tree Species	Time	Position	emmean	SE	df	Lower CL	Upper CL
<i>Albizia lebbbeck</i>	Morning	Open	83.2	0.371	99.625	82.464	83.936
<i>Azadirachta indica</i>	Morning	Open	82.52	0.371	99.625	81.784	83.256
<i>Delonix regia</i>	Morning	Open	83.48	0.371	99.625	82.744	84.216
<i>Terminalia mantaly</i>	Morning	Open	82.8	0.371	99.625	82.064	83.536
<i>Albizia lebbbeck</i>	Afternoon	Open	73.84	0.371	99.625	73.104	74.576
<i>Azadirachta indica</i>	Afternoon	Open	74.68	0.371	99.625	73.944	75.416
<i>Delonix regia</i>	Afternoon	Open	73.68	0.371	99.625	72.944	74.416
<i>Terminalia mantaly</i>	Afternoon	Open	73.96	0.371	99.625	73.224	74.696
<i>Albizia lebbbeck</i>	Morning	Under	85.72	0.371	99.625	84.984	86.456
<i>Azadirachta indica</i>	Morning	Under	85.04	0.371	99.625	84.304	85.776
<i>Delonix regia</i>	Morning	Under	86.28	0.371	99.625	85.544	87.016
<i>Terminalia mantaly</i>	Morning	Under	85.12	0.371	99.625	84.384	85.856
<i>Albizia lebbbeck</i>	Afternoon	Under	75.8	0.371	99.625	75.064	76.536
<i>Azadirachta indica</i>	Afternoon	Under	76.56	0.371	99.625	75.824	77.296
<i>Delonix regia</i>	Afternoon	Under	75.4	0.371	99.625	74.664	76.136
<i>Terminalia mantaly</i>	Afternoon	Under	76.04	0.371	99.625	75.304	76.776

Pairwise Tukey-adjusted contrasts between species within each Time × Position combination showed that most species pairs did not differ significantly under any microclimatic condition. Across all morning/afternoon and open/under-canopy combinations, adjusted comparisons mostly revealed non-significant differences, indicating broad similarity among species once time of day and position were accounted for. The only clear species-level differences aligned with the main-effect results: *Azadirachta indica* showed slightly cooler temperatures than the reference species *Albizia lebbbeck*, and its decline in relative humidity from morning to afternoon was slightly smaller. Aside from these effects, no additional species contrasts remained statistically significant after multiple-comparison adjustment (Tables 6 and 7). Model diagnostics indicated boundary (singular) fit warnings for both models, reflecting random-effect components that were not fully estimable. In the temperature model, the

TreeID random-intercept variance was effectively zero, suggesting that after accounting for species, time of day, and position, between-tree differences in temperature were negligible. However, day-to-day variation captured by the Date random effect remained evident. In contrast, the RH model retained a modest TreeID variance component (ICC ≈ 0.081), indicating a small but detectable contribution of between-tree differences to relative humidity variability. Given these warnings, random intercepts were retained. Still, fixed-effect interpretations were made cautiously, and all reported results derive from identifiable model components supported by diagnostic checks. Residual simulations and residual-versus-fitted plots (Figures 3 and 4) did not reveal significant violations of homoscedasticity or normality, suggesting that the primary fixed-effect estimates remain valid despite the singular fits.

Table 6: Pairwise Contrasts from the Linear Mixed-effects Temperature Model showing the Effects of Time and Position

Contrast	Time	Position	Estimate	SE	df	t.ratio	p.value
<i>Albizia lebbbeck</i> - <i>Azadirachta indica</i>	Morning	Open	0.41	0.21	198.20	1.98	0.20
<i>Albizia lebbbeck</i> - <i>Delonix regia</i>	Morning	Open	0.21	0.21	198.20	1.03	0.73
<i>Albizia lebbbeck</i> - <i>Terminalia mantaly</i>	Morning	Open	0.37	0.21	198.20	1.81	0.27
<i>Azadirachta indica</i> - <i>Delonix regia</i>	Morning	Open	-0.20	0.21	198.20	-0.95	0.78
<i>Azadirachta indica</i> - <i>Terminalia mantaly</i>	Morning	Open	-0.04	0.21	198.20	-0.17	1.00
<i>Delonix regia</i> - <i>Terminalia mantaly</i>	Morning	Open	0.16	0.21	198.20	0.78	0.87
<i>Albizia lebbbeck</i> - <i>Azadirachta indica</i>	Afternoon	Open	0.14	0.21	198.20	0.68	0.90
<i>Albizia lebbbeck</i> - <i>Delonix regia</i>	Afternoon	Open	0.18	0.21	198.20	0.87	0.82
<i>Albizia lebbbeck</i> - <i>Terminalia mantaly</i>	Afternoon	Open	0.13	0.21	198.20	0.62	0.93
<i>Azadirachta indica</i> - <i>Delonix regia</i>	Afternoon	Open	0.04	0.21	198.20	0.19	1.00
<i>Azadirachta indica</i> - <i>Terminalia mantaly</i>	Afternoon	Open	-0.01	0.21	198.20	-0.06	1.00
<i>Delonix regia</i> - <i>Terminalia mantaly</i>	Afternoon	Open	-0.05	0.21	198.20	-0.25	0.99

Contrast	Time	Position	Estimate	SE	df	t.ratio	p.value
<i>Albizia lebbek - Azadirachta indica</i>	Morning	Under	0.29	0.21	198.20	1.42	0.49
<i>Albizia lebbek - Delonix regia</i>	Morning	Under	0.07	0.21	198.20	0.33	0.99
<i>Albizia lebbek - Terminalia mantaly</i>	Morning	Under	0.28	0.21	198.20	1.34	0.54
<i>Azadirachta indica - Delonix regia</i>	Morning	Under	-0.22	0.21	198.20	-1.09	0.70
<i>Azadirachta indica - Terminalia mantaly</i>	Morning	Under	-0.02	0.21	198.20	-0.08	1.00
<i>Delonix regia - Terminalia mantaly</i>	Morning	Under	0.21	0.21	198.20	1.01	0.74
<i>Albizia lebbek - Azadirachta indica</i>	Afternoon	Under	0.06	0.21	198.20	0.31	0.99
<i>Albizia lebbek - Delonix regia</i>	Afternoon	Under	0.11	0.21	198.20	0.54	0.95
<i>Albizia lebbek - Terminalia mantaly</i>	Afternoon	Under	0.05	0.21	198.20	0.25	0.99
<i>Azadirachta indica - Delonix regia</i>	Afternoon	Under	0.05	0.21	198.20	0.23	1.00
<i>Azadirachta indica - Terminalia mantaly</i>	Afternoon	Under	-0.01	0.21	198.20	-0.06	1.00
<i>Delonix regia - Terminalia mantaly</i>	Afternoon	Under	-0.06	0.21	198.20	-0.29	0.99

Table 7: Pairwise Contrasts from the Linear Mixed-effects Relative Humidity Model showing the Effects of Time and Position

Contrast	Time	Position	Estimate	SE	df	t.ratio	p.value
<i>Albizia lebbek - Azadirachta indica</i>	Morning	Open	0.68	0.52	100.91	1.30	0.57
<i>Albizia lebbek - Delonix regia</i>	Morning	Open	-0.28	0.52	100.91	-0.53	0.95
<i>Albizia lebbek - Terminalia mantaly</i>	Morning	Open	0.40	0.52	100.91	0.76	0.87
<i>Azadirachta indica - Delonix regia</i>	Morning	Open	-0.96	0.52	100.91	-1.83	0.26
<i>Azadirachta indica - Terminalia mantaly</i>	Morning	Open	-0.28	0.52	100.91	-0.53	0.95
<i>Delonix regia - Terminalia mantaly</i>	Morning	Open	0.68	0.52	100.91	1.30	0.57
<i>Albizia lebbek - Azadirachta indica</i>	Afternoon	Open	-0.84	0.52	100.91	-1.60	0.38
<i>Albizia lebbek - Delonix regia</i>	Afternoon	Open	0.16	0.52	100.91	0.31	0.99
<i>Albizia lebbek - Terminalia mantaly</i>	Afternoon	Open	-0.12	0.52	100.91	-0.23	1.00
<i>Azadirachta indica - Delonix regia</i>	Afternoon	Open	1.00	0.52	100.91	1.91	0.23
<i>Azadirachta indica - Terminalia mantaly</i>	Afternoon	Open	0.72	0.52	100.91	1.37	0.52
<i>Delonix regia - Terminalia mantaly</i>	Afternoon	Open	-0.28	0.52	100.91	-0.53	0.95
<i>Albizia lebbek - Azadirachta indica</i>	Morning	Under	0.68	0.52	100.91	1.30	0.57
<i>Albizia lebbek - Delonix regia</i>	Morning	Under	-0.56	0.52	100.91	-1.07	0.71
<i>Albizia lebbek - Terminalia mantaly</i>	Morning	Under	0.60	0.52	100.91	1.14	0.66
<i>Azadirachta indica - Delonix regia</i>	Morning	Under	-1.24	0.52	100.91	-2.36	0.09
<i>Azadirachta indica - Terminalia mantaly</i>	Morning	Under	-0.08	0.52	100.91	-0.15	1.00
<i>Delonix regia - Terminalia mantaly</i>	Morning	Under	1.16	0.52	100.91	2.21	0.13
<i>Albizia lebbek - Azadirachta indica</i>	Afternoon	Under	-0.76	0.52	100.91	-1.45	0.47
<i>Albizia lebbek - Delonix regia</i>	Afternoon	Under	0.40	0.52	100.91	0.76	0.87
<i>Albizia lebbek - Terminalia mantaly</i>	Afternoon	Under	-0.24	0.52	100.91	-0.46	0.97
<i>Azadirachta indica - Delonix regia</i>	Afternoon	Under	1.16	0.52	100.91	2.21	0.13
<i>Azadirachta indica - Terminalia mantaly</i>	Afternoon	Under	0.52	0.52	100.91	0.99	0.75
<i>Delonix regia - Terminalia mantaly</i>	Afternoon	Under	-0.64	0.52	100.91	-1.22	0.62

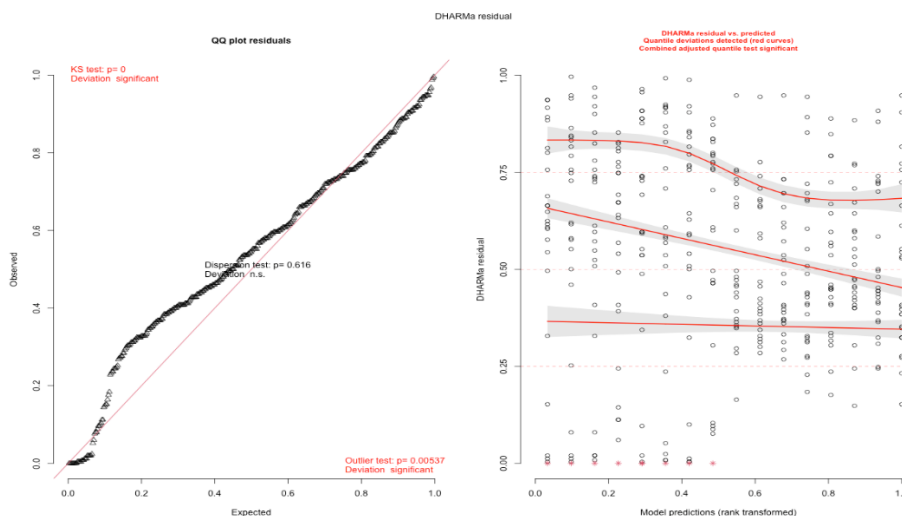


Figure 3: Residual-Versus-Fitted and Q-Q Plots for Temperature

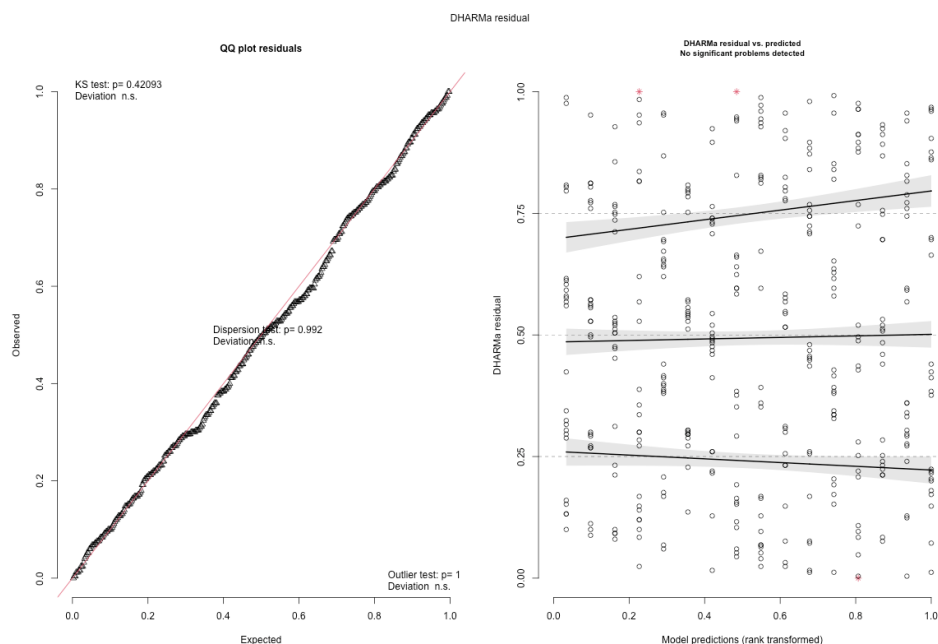


Figure 4: Residual-Versus-Fitted and Q-Q Plots for Relative Humidity

The combined temperature and humidity models reveal a consistent and ecologically coherent pattern of microclimate regulation in urban tree environments, with time of day and shading position exerting far stronger influences than interspecific differences (Feng *et al.*, 2023). The pronounced afternoon warming (+3.2°C) and concurrent decline in relative humidity (-9.4%) highlight the strong diurnal forcing characteristic of tropical urban climates, where high solar load and declining atmospheric moisture combine to amplify thermal stress (Lefevre *et al.*, 2025). In this context, even modest canopy-mediated buffering, cooling of ~0.8°C, and humidification of ~2.5 percentage points represent a meaningful microclimatic service, particularly given the compact scale of individual-tree environments. These results align with substantial literature showing that shading and evapotranspiration from urban vegetation produce measurable, localized cooling and humidity stabilization (Yu *et al.*, 2025). This suggests that even small canopy patches can contribute to thermal comfort and to moderating the microclimate in densely developed tropical cities (Zhou *et al.*, 2024).

Species-level differences were comparatively minor, indicating that the microclimatic benefits observed here were largely structural rather than taxon-specific. However, *Azadirachta indica* showed slightly cooler temperatures and a less sharp decline in relative humidity, likely due to its dense crown and ongoing transpiration during peak heat (Lin *et al.*, 2024). Similar reports by Huang *et al.* (2020) documented a substantial cooling effect in Wuhan, China, where sites with high tree canopy cover were up to 3.3 °C cooler at midday than open streets. While relative humidity differences were not quantified, the authors noted a clear improvement in overall thermal comfort, underscoring the importance of canopy cover in densely built environments. In Indonesia, Fadhlurrahman and Nasrullah (2020) found that canopy structure variations significantly affected microclimate. Among seven tree species, canopy temperatures ranged from 33.7–35.7 °C, lower than in open areas, with denser canopies cooling more. Relative humidity increased with canopy density, indicating a positive relationship between leaf area index and humidity ($y = 8.14x + 48.25$), highlighting how

canopy complexity influences local moisture. Evidence from South America supports these patterns. In Brazil, Pereira *et al.* (2021) found that lawns had a midday heat index of 43.9 °C, while tree-covered areas had lower thermal loads. Though humidity wasn't specified, the lower heat index suggests that shading, evapotranspiration, and moisture retention reduce heat. The high marginal R^2 values for both models underscore the dominance of environmental conditions, time of day, and canopy position in shaping microclimate. Also, the near-zero TreeID variance in the temperature model indicates that individual-tree differences contribute little beyond species and structural context. By contrast, the modest TreeID effect in the RH model ($ICC \approx 0.081$) suggests that the trees exert slightly greater individual influence on humidity than on temperature, plausibly through transpiration dynamics (Chen *et al.*, 2024). The presence of measurable but slight day-to-day variation also supports the idea that broader atmospheric conditions modulate the benefits of microclimate (J. Zhang *et al.*, 2022), underscoring that tree-driven cooling and humidification interact with, rather than replace, ambient climatic forces. Despite these findings, several limitations temper the strength of the inferences. First, the singular (boundary) fit warnings indicate that some random-effect components, particularly the TreeID intercept in the temperature model, were not fully estimable. Diagnostics showed no major violations, but boundary fits suggest a simplified model, warranting cautious interpretation, especially concerning subtle between-tree differences. Second, although measurements were taken under realistic field conditions, they reflect short-term snapshots rather than continuous monitoring, meaning that the results may not capture the full spectrum of microclimatic variability, such as cloud cover dynamics, wind patterns, or seasonal shifts, that could alter canopy effects. Third, the study assessed a limited set of species typical of the study area. In contrast, these species are operationally crucial in West African cities; they do not encompass the global diversity of urban trees, and thus the generalizability of species-level comparisons beyond similar tropical environments remains constrained. Finally, the spatial scale of measurement (individual-tree under-canopy and adjacent open points) captures fine-scale

microclimates but not neighborhood-scale thermal dynamics, which are increasingly recognized as critical for urban heat resilience planning. Taken together, the findings show that urban trees in tropical environments reliably reduce temperature and humidity at micro scales, with canopy presence consistently providing cooling and humidifying effects across species (Jayasooriya *et al.*, 2024). While differences between species were relatively minor, the clear benefit of *Azadirachta indica* highlights opportunities to include species with more stable transpiration patterns in targeted microclimate strategies. Future research using continuous microclimate loggers, broader species selections, and multi-seasonal observations will help refine these insights, improve their applicability, and support the development of a greener, more thermally resilient urban landscape in Calabar.

CONCLUSION

Urban trees in Calabar provide consistent microclimatic benefits by cooling the environment and slightly increasing humidity, with time of day and canopy position exerting the most significant influence on local conditions. While species differences were minimal, *Azadirachta indica* showed marginally better performance, suggesting that canopy structure drives microclimate regulation. The study provides evidence from Calabar, highlighting the importance of even small canopy patches for improving thermal comfort and supporting climate-resilient urban planning. However, limitations such as a short sampling duration, model boundary fits, and a limited species set mean that the findings should be interpreted cautiously. Broader, longer-term studies are needed to refine these insights and strengthen urban forestry strategies in Calabar.

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