

Article

The Effect of Green Areas on Urban Microclimate: A University Campus Model Case

Gülçay Ercan Oğuztürk ^{1,*}, Sude Sünbül ¹ and Cem Alparslan ² 

¹ Department of Landscape Architecture, Faculty of Engineering and Architecture, Recep Tayyip Erdoğan University, Rize 53020, Türkiye; sude_sunbul22@erdogan.edu.tr

² Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdoğan University, Rize 53100, Türkiye; cem.alparslan@erdogan.edu.tr

* Correspondence: gulcay.ercanoguzturk@erdogan.edu.tr; Tel.: +90-0546-648-04-94

Abstract: Urbanization and the reduction of green spaces have significantly contributed to problems such as rising temperatures and declining air quality in urban areas. This study examines the impact of different types of green areas—broadleaved trees, coniferous trees, shrubs, and vines—on urban temperature regulation at the Recep Tayyip Erdoğan University Zihni Derin Campus. Surface temperature, humidity, ambient temperature, and wind speed measurements were collected using an infrared thermometer over a one-year period under various climatic conditions (August, October, January, and April) and at different times of the day (09:00 AM, 01:00 PM, and 05:00 PM). To quantitatively assess the cooling effect of each type of green area, a Response Surface Methodology (RSM) was applied, and a predictive formula was developed to estimate the cooling impact of various green areas under different environmental conditions. These formulated models enable the estimation of the temperature reduction provided by these four plant types based on different input parameters, achieving an accuracy of approximately 92% or higher without requiring direct measurements. The findings of this study provide a robust methodological framework and a practical tool for optimizing green space designs, mitigating urban heat island effects, and enhancing urban living comfort under various climatic conditions.

Keywords: broadleaved trees; coniferous trees; green areas; RSM; urban temperature



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1. Introduction

The rapid urbanization occurring worldwide has led to a significant reduction in green areas [1–3] and the destruction of natural habitats, particularly in large cities [4–7]. This process has resulted in various environmental and social issues, such as increasing urban temperatures, declining air quality, and deteriorating living comfort [8–12]. The preservation and expansion of green areas [13–15] in urban spaces are crucial for sustainable urban planning [16–18]. In particular, the presence of green areas in highly urbanized regions contributes to balancing [19–21] urban ecosystems and directly impacts human health and quality of life. Furthermore, green areas play a critical role in regulating the urban microclimate [5,22–25]. Broadleaved trees, coniferous trees, shrubs, and vines not only provide aesthetic value but also reduce surface temperatures [26,27], mitigating the urban heat island effect [28–31]. The literature emphasizes that landscape areas designed with appropriate plant species can lower temperatures, improve microclimate conditions [23,32–35], and enable users to enjoy these spaces more comfortably for extended periods [9,36–38]. Additionally, green areas support ecosystem services by reducing carbon emissions, improving air quality, and contributing to rainwater management [39]. In addition to its

ecological and climatic relevance, the role of green spaces in promoting landscape sustainability has gained increasing attention in recent studies. Green infrastructure contributes not only to environmental resilience but also to long-term sustainable urban development by integrating ecosystem services into land use planning [40–42].

Ensuring the sufficient presence of green areas in the physical structure of cities is essential for making urban life healthier and more sustainable. In this context, one of the critical urban spaces that should have extensive green areas is university campuses [43–45]. Universities are dynamic environments that cater to a broad range of users from different age groups, including students, academics, and other campus residents who spend a significant portion of their time in these spaces. The presence of green areas on campuses offers substantial advantages in terms of both environmental sustainability and the psychological and physical well-being of users [30,46,47]. The optimization of plant-based designs on university campuses should be carried out not only for aesthetic concerns but also by considering functional benefits. Selecting plant species suitable for climatic conditions, implementing shading strategies, and incorporating ecological landscaping arrangements improve the microclimate while enhancing the quality of life for campus users [48–51]. These spaces are vital urban components that enhance individuals' interaction with nature, supporting their academic and social lives. Therefore, in today's rapidly urbanizing world, preserving and effectively planning green areas on university campuses should be regarded as an integral part of the sustainable urbanization approach.

While numerous studies have explored the role of urban green spaces in mitigating surface temperature and reducing the Urban Heat Island (UHI) effect, most have primarily relied on remote sensing indicators such as NDVI or land cover classifications without differentiating among plant species or accounting for their biophysical traits. For instance, refs. [52,53] reported strong inverse relationships between vegetation cover and surface temperature in cities like Chicago and Tel Aviv, yet they did not assess the differential cooling effects of individual plant types. Similarly, ref. [54] demonstrated the efficiency of green roofs in Bangkok's tropical climate but without reference to species-specific physiological properties.

In contrast, this study contributes a more nuanced analysis by incorporating species-level variation (broadleaf, conifers, shrubs, and ivy) and focusing on functional traits such as Leaf Area Index (LAI), canopy density, and surface albedo. Refs. [55,56] emphasized the role of vertical canopy gradients and leaf-sapwood ratios in regulating plant respiration and energy exchange, while ref. [57] highlighted how spatial variation in LAI correlates with thermal performance in urban parks. Furthermore, studies by [58,59] stressed the importance of vegetation morphology and structure in seasonal temperature variation yet lacked species-level field assessments across varying microclimatic conditions.

By integrating in situ surface temperature measurements and plant-specific morphological data, this study offers a localized yet transferable model for understanding vegetation–climate interactions in humid subtropical zones. In doing so, it addresses a significant gap in the literature by moving beyond generalized vegetation classifications and emphasizing the need for plant-specific, trait-based approaches in designing effective urban greening strategies [60–62]. This study aims to examine the impact of different types of green areas (broadleaved trees, coniferous trees, shrubs, and vines) on urban temperature regulation at Recep Tayyip Erdoğan University Zihni Derin Campus, located in Rize. Surface temperature, humidity, ambient temperature, and wind speed measurements were conducted over a one-year period under various climatic conditions (August, October, January, and April) and at different times of the day (09:00 AM, 01:00 PM, and 05:00 PM). Surface and ambient temperature measurements were taken using an infrared thermometer, humidity measurements were conducted with a hygrometer, and wind speed measure-

ments were taken with an anemometer. Within the scope of the study, the temperature regulation effect of each type of green area was quantitatively assessed, and a regression analysis was conducted to develop a predictive model capable of estimating the cooling impact of these areas under different environmental conditions. This model highlights the strong cooling effects of broadleaved and coniferous trees while also demonstrating the complementary roles of shrubs and vines. These findings provide a scientific foundation for mitigating urban heat island effects, improving urban living comfort, and supporting sustainable urban design. By emphasizing the importance of green areas in urban planning, this study encourages the enhancement of plant-based designs with the potential to improve the microclimate.

Thus, this study fills a critical knowledge gap by providing a trait-based, species-specific approach to urban microclimate regulation, particularly in humid subtropical contexts.

2. Materials and Methods

This study was conducted within the boundaries of Recep Tayyip Erdoğan University Zihni Derin Campus, located in Rize, Turkey (Figure 1). The campus provides a suitable environment for examining surface temperature variations due to its diverse topographic structure, varying levels of land use intensity, and the presence of different types of vegetative areas. Within the scope of the study, locations dominated by different types of green spaces, including broad-leaved trees, coniferous trees, shrubs, and ivy, were selected. The locations had broad-leaved plants (*Salix babylonica*—*Prunus serrulata*—*Cercis siliquastrum*), Coniferous Plants (*Thuja occidentalis*—*Cedrus deodora*—*Juniperus chinensis*), shrubs (*Nandina domestica*—*Elaeagnus pungens*—*Grevilla rosmarinifolia*), and ivies, (*Hedera helix*—*Hedera hibernica*—*Hedera helix*).

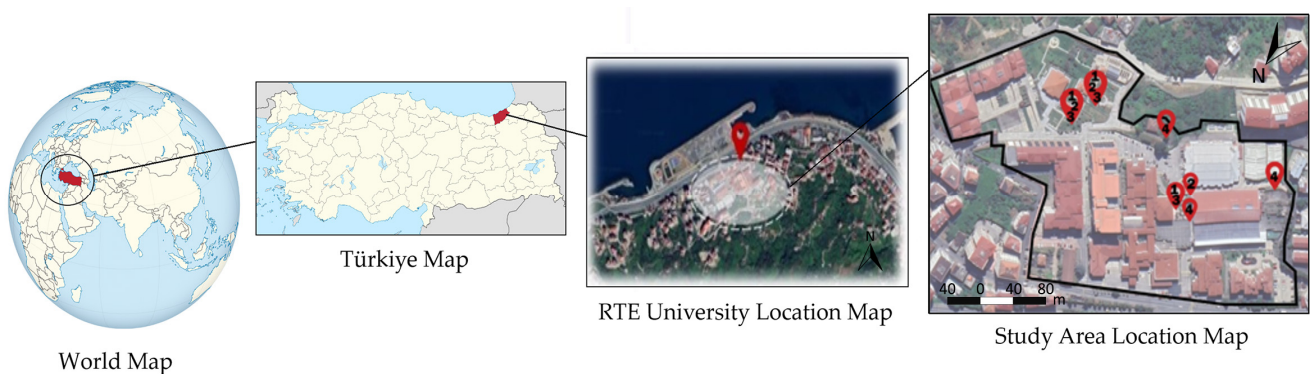


Figure 1. Location map of the study area.

Although the study area, Recep Tayyip Erdoğan University Zihni Derin Campus, may appear geographically specific, its selection is methodologically and climatically justified. Located in Rize, the campus resides within a humid subtropical climate zone characterized by high precipitation, moderate temperatures, and rich vegetation diversity—conditions comparable to other urban settings that experience thermal stress due to climate change. Moreover, the campus includes a range of green typologies (broadleaved trees, conifers, shrubs, ivy), topographic variability, and user activity patterns, which provide a suitable context for investigating vegetation–climate interactions under realistic conditions [63,64]. Previous studies have shown that green infrastructure implementations in diverse climate zones, such as Bangkok and Addis Ababa, can significantly reduce surface temperatures and improve urban comfort, highlighting the transferability of such research findings [54,65]. University campuses, widely used in landscape and ecological

planning studies, serve as controlled yet dynamic urban environments, offering valuable data on vegetation–climate interactions [66,67]. Hence, the selected study area provides both accessibility and ecological relevance, making it an appropriate model for broader applications in urban green infrastructure planning. To ensure methodological consistency and environmental representativeness, a purposive sampling strategy was adopted to select the vegetated areas within the campus. Each green area type (broadleaved trees, conifers, shrubs, and ivy) was chosen based on distinct structural and physiological features, such as canopy density, height, and coverage area. The measurement locations were selected to capture a range of microclimatic conditions, including shaded, semi-shaded, and sun-exposed zones, thereby enabling comparative evaluation of their thermal regulation effects. Additionally, sampling sites were distributed across varying elevations and orientations to reflect the topographical diversity of the campus. This stratified approach allowed the study to assess how specific plant groups influence AT under different spatial and temporal contexts. The repeated measurement design and standardized device calibration ensured data reliability and reproducibility across all sampling periods.

The effects of different types of green spaces, including broad-leaved trees, conifers, shrubs, and ivy, on surface temperatures are being examined. The selected areas were determined in a way that ensures consistency in environmental variables such as shading, wind effects, and distance from buildings. An infrared thermometer (Testo 830-T2 (Testo, Titisee-Neustadt, Germany) and accuracy: ± 1.5 °C (between 0 and 500 °C)) was used to measure surface and ambient temperatures. This device utilizes infrared (IR) sensing technology to perform non-contact measurements, accurately determining surface temperature. A hygrometer (Extech 445815 Humidity Meter (Extech Instruments, Nashua, NH, USA), and accuracy: $\pm 3\%$ RH (relative humidity)) was used to determine humidity levels, providing precise data by measuring the relative humidity in the environment. To measure wind speed, an anemometer (Kestrel 3000 Pocket Weather Meter (Kestrel Instruments, Boothwyn, PA, USA), accuracy: $\pm 3\%$ of reading, and range: 0.4 to 40 m/s) was employed, offering reliable data by assessing airflow velocity. To ensure measurement accuracy, all devices were calibrated and compared with reference values. Within the campus, locations with broad-leaved trees, conifers, shrubs, and ivy in sun-exposed areas were identified. Measurement points were systematically determined in these areas and recorded by marking each point on a map. This step was crucial for ensuring the continuity and consistency of the measurements (Figure 2). All instruments were inspected prior to each data collection session to ensure battery levels and sensor cleanliness. Measurements were conducted under stable atmospheric conditions to minimize data variability. Potential measurement errors due to human handling were minimized by holding each device at a consistent height (150 cm) and angle during the fieldwork.

The selection of the months (January, April, August, and October) was based on the representation of four distinct seasons in the humid subtropical climate of Rize, which allowed for capturing seasonal variation in microclimatic parameters. Similarly, the chosen time points (09:00, 13:00, and 17:00) represent the morning, midday, and late afternoon periods, respectively—each with different levels of solar radiation and thermal exposure. This temporal structure is consistent with prior studies investigating the thermal performance of green spaces across diurnal cycles [68,69] and is further supported by recent findings that highlight the importance of time-based variation in vegetation–climate interactions [70,71]. These time intervals help assess the dynamic thermal behavior of different vegetation types throughout the day under varying atmospheric conditions.

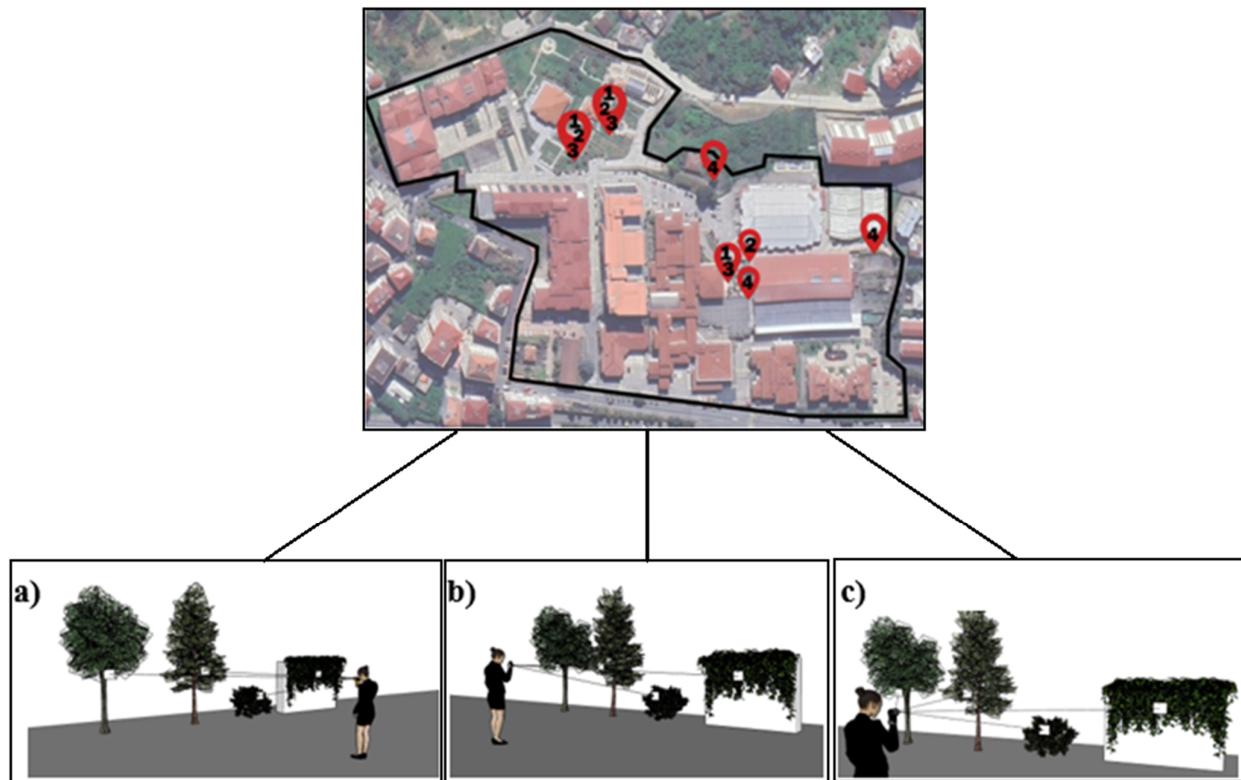


Figure 2. Images captured during the measurement process, (a) infrared thermometer, (b) hygrometer, and (c) anemometer.

Measurements were conducted in January (winter), April (spring), August (summer), and October (autumn). Data collection took place at three different times of the day: 09:00 (morning), 13:00 (noon), and 17:00 (evening). To better evaluate temperature variations throughout the day, three repeated measurements were taken at each measurement point, and the average values were used. Before starting the measurement process, the calibration of the measurement devices and the condition of their batteries were checked. Upon arrival at the designated measurement locations, any accumulated dust, leaves, or water puddles on the surface were cleared. During the measurement process, the infrared thermometer was held at approximately 150 cm height and positioned perpendicular to the surface (Figure 2a). Three repeated measurements were taken at each point, and the averages were recorded. For humidity measurements, the hygrometer was held at approximately 150 cm height to ensure a representative assessment of ambient conditions (Figure 2b). Three repeated measurements were taken at each measurement point, and the average values were recorded. The humidity levels in different areas (e.g., shaded and sun-exposed regions) were compared. For wind speed measurements, the anemometer was held at approximately 150 cm height and exposed directly to the airflow for the most accurate readings (Figure 2c). Three repeated measurements were taken at each measurement point, and the average values were recorded. The variations in wind speed across different areas were analyzed.

Data Recording and Preliminary Analysis

The field data collected during the study were systematically recorded and prepared for the analysis process. Measurement results were stored using Excel spreadsheets or standardized data collection forms to minimize error rates and ensure data consistency. To enhance data reliability, environmental factors encountered during the measurement process (e.g., rainfall, wind speed variations, and solar radiation intensity) were docu-

mented in detail. Preliminary analysis was conducted to assess the validity of the collected data. In this context, abnormal values observed for specific variables (e.g., measurements significantly deviating from the average) were identified and excluded from the analysis to improve statistical reliability. To assess data quality prior to analysis, potential outliers were examined for all key variables used in the model, including AT, M, WS, A, and T. Outlier detection was based on the interquartile range (IQR) method, where any data points falling below $Q1 - 1.5 \times IQR$ or above $Q3 + 1.5 \times IQR$ were flagged as potential outliers. These thresholds were applied separately for each vegetation type and variable. Although outliers were identified, no data points were excluded from the model unless supported by clear evidence of measurement error (e.g., sensor malfunction). Additionally, preprocessing steps were applied, considering calibration processes of measurement devices and potential recording errors.

For detailed statistical analysis, RSM Regression Analysis was performed. RSM is a statistical approach based on mathematical models used in experimental designs to determine the relationship between input and output variables. In this technique, the Central Composite Design (CCD) was used as the experimental design approach, allowing for the evaluation of linear effects resulting from second-order interactions between different input variables [4,7]. A second-degree mathematical model was used to calculate the response resulting from interactions (Equation (1)).

$$Y = a_0 + \sum_{i=1}^k b_i X_i + \sum_{ij} b_{ij} X_{ij} + \sum_{i=1}^k b_{ii} X_i^2 + \dots n \quad (1)$$

In this analysis process, T was used as the dependent variable, while measurement A, WS, AT, and M were used as independent variables. This analysis aimed to determine the effects of independent variables on surface temperature and develop a predictive model. The model was designed to estimate surface temperatures based on different surface types and environmental conditions. The obtained regression model was subjected to validation tests using field data to assess the agreement between predicted and actual surface temperature measurements. This validation process was conducted to test the reliability of the model and improve its accuracy against varying environmental factors.

3. Results and Discussion

3.1. Seasonal Variations, the Impact of Green Areas, and Microclimate Improvement Potential

The study has identified that vegetative areas (broadleaved trees, coniferous trees, shrubs, and vines) play a crucial role in regulating [72,73] the urban microclimate [23,33,34,74].

January (winter season): During winter, surface temperatures in vegetative areas were measured between 2 and 5 °C, demonstrating that green areas maintain their thermal regulation effect throughout the year.

April (spring season): In spring, surface temperatures in vegetative areas ranged between 20 and 30 °C. The shading effect of broadleaved trees was particularly evident in this period.

August (summer season): In summer, surface temperatures in green areas were recorded between 20 and 30 °C. Broadleaved trees and shrubs stood out for their strong shading properties.

October (autumn season): During autumn, surface temperatures in vegetative areas ranged between 15 and 25 °C, further confirming that green areas have a year-round temperature-regulating potential. It has been determined that green areas exhibit temperature regulation functions in all seasons [75–77], particularly mitigating rising temperatures in summer [36,78,79] and reducing the urban heat island effect [80–82]. This finding under-

scores the necessity of prioritizing the preservation and expansion of green areas in urban planning processes.

3.2. Regression Model and Applicability

The ANOVA results presented in Table 1 indicate that the RSM model developed in this study is statistically significant. The model's high F-value (519.917) and low *p*-value confirm that the independent variables have a strong influence on the response variable. The linear terms explain 85.59% of the total variance, with the AT factor contributing 70.14%, followed by the M factor (7.96%). Quadratic terms account for 4.46%, while two-factor interactions contribute 3.48%. Among these, the interaction between M and AT ($F = 227.222$, 2.91%) emerges as the most significant. The low error rate (6.49%, Adj SS = 505.21) further supports the reliability of the model.

Table 1. Analysis of Variance for Leafy Plants.

Source	DF	Contribution	Adj SS	Adj MS	F-Value	<i>p</i> -Value	VIF
Model	14	93.51%	7278.84	519.917	95.71	0.0000	
Linear	4	85.59%	1193.49	298.374	54.92	0.0000	
A (m ²)	1	1.69%	125.56	125.561	23.11	0.0000	1.17
M (%)	1	7.76%	224.17	224.170	41.27	0.0000	3.47
WS (m/s)	1	6.01%	1.14	1.143	0.21	0.6475	4.63
AT (°C)	1	70.14%	859.27	859.268	158.17	0.0000	4.02
Square	4	4.44%	250.21	62.553	11.51	0.0000	
A × A	1	1.53%	118.82	118.815	21.87	0.0000	1.00
M × M	1	1.25%	7.94	7.938	1.46	0.2298	7.65
WS × WS	1	0.18%	65.16	65.159	11.99	0.0008	5.41
AT × AT	1	1.48%	67.85	67.854	12.49	0.0006	1.79
2-Way Interaction	6	3.48%	270.55	45.092	8.30	0.0000	
A × M	1	0.18%	11.93	11.928	2.20	0.1418	1.13
A × WS	1	0.00%	0.00	0.001	0.00	0.9881	1.25
A × AT	1	0.05%	4.11	4.115	0.76	0.3864	1.06
M × WS	1	0.20%	0.85	0.850	0.16	0.6934	3.79
M × AT	1	2.91%	227.22	227.223	41.83	0.0000	2.11
WS × AT	1	0.13%	9.81	9.808	1.81	0.1823	4.18
Error	93	6.49%	505.21	5.432			
Total	107	100.00%					
Model Summary							
		S	R-sq		R-sq (adj)		R-sq (pred)
		2.33075	93.51%		92.53%		91.12%

In conclusion, the ANOVA analysis indicates that AT and M are the most decisive factors affecting the response variable. The model demonstrates a strong fit in predicting the dependent variable. To enhance the reliability and robustness of the regression model developed in this study, a five-fold cross-validation technique was employed. The dataset was randomly partitioned into five equal subsets. In each iteration, four subsets were used to train the model, while the remaining subset served as the validation set. This process was repeated five times, ensuring that each subset was used for validation once. The average performance metrics—including R^2 , RMSE (Root Mean Square Error), and MAE (Mean Absolute Error)—were computed across all folds to evaluate model accuracy and generalizability. The use of cross-validation not only mitigated overfitting but also provided a comprehensive assessment of the model's predictive power under varying environmental conditions. The results indicated high consistency across folds, confirming the robustness of the model in estimating surface temperature responses to different vegetation types.

Regression Equation in Uncoded Units

$$T = 50.3 + 0.1284 A + 0.187 M - 64.4 WS - 0.984 AT - 0.000222 A \times A - 0.00640 M \times M + 26.43 WS \times WS - 0.01974 AT \times AT - 0.000407 A \times M - 0.00015 A \times WS + 0.000342 A \times AT + 0.041 M \times WS + 0.03551 M \times AT - 0.264 WS \times AT \quad (2)$$

Table 1, Analysis of Variance (ANOVA) for Leafy Plants, showing the influence of four independent variables—surface area (A), humidity (M), wind speed (WS), and ambient temperature (AT)—on surface temperature (T). The model explains 93.51% of the total variance, with AT being the dominant factor (70.14%), followed by M (7.76%) and A (1.69%). Significant quadratic and two-way interactions were also observed, especially between M and AT ($F = 227.22$). The low p -values (<0.05) indicate the model's strong statistical significance, while the low error contribution (6.49%) confirms the robustness of the model.

In Figures 3 and 4, the effect of the plant's measurement area, ambient humidity, wind speed, and temperature on the leafy plant is illustrated using a Pareto chart and contour plot. Upon examining the figure, it is observed that ambient temperature has a significant impact on the temperature of the leafy plant while also notably influencing humidity levels.

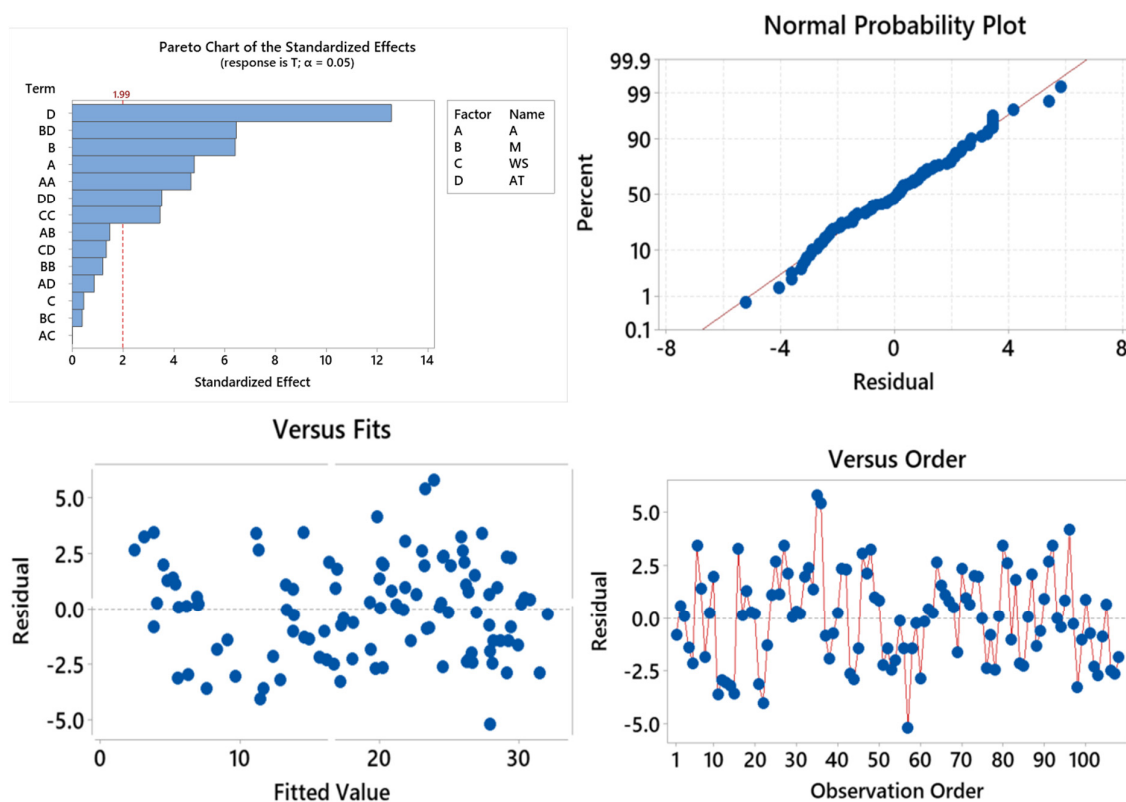


Figure 3. Residual analysis and Pareto chart of standardized effects, evaluating factor significance, normality, homoscedasticity, and independence for Leafy Plants.

Figure 3, Pareto chart and residual analysis for Leafy Plants. The Pareto chart identifies the standardized effects of main and interaction terms, with AT, M, and the interaction $M \times AT$ being the most influential. The normal probability plot shows residuals aligning closely along the diagonal, indicating normality. The residuals vs. fitted values and residuals vs. order plots confirm randomness and independence, supporting the model's homoscedasticity and predictive validity.

Figure 4, Contour plots showing the interaction effects between independent variables on T for Leafy Plants. AT and M interactions yield the most distinct thermal gradients, especially in the $AT \times M$ and $M \times AT$ plots, where red and yellow zones indicate optimal cooling potential. Hold values used in plots are $A = 200$, $M = 73.9$, $WS = 1.25$, $AT = 15$. These visualizations confirm that T response varies depending on the combination of

microclimatic conditions and plant characteristics, offering guidance for targeted landscape interventions.

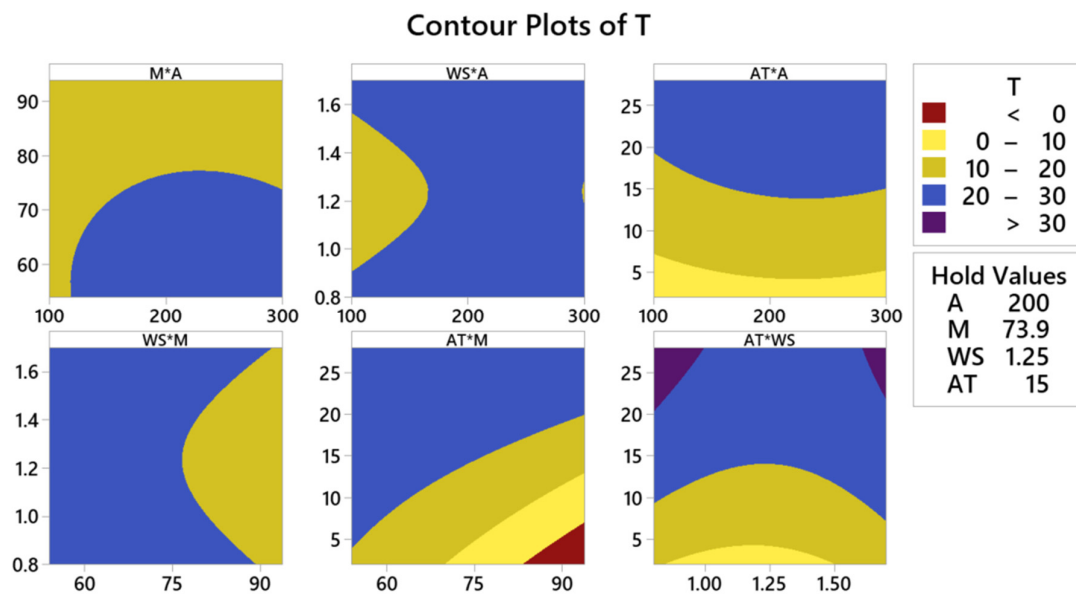


Figure 4. Contour plots of T, illustrating the interaction effects of variables on the response, with specific hold values for parameters A, M, WS, and AT for Leaf Plants.

The experimental results indicate that the AT, M×AT, M, and A factors have the highest impact. Residual analysis confirms that the model follows a normal distribution and exhibits high predictive power due to the randomly distributed residuals. The Pareto chart reveals that some interactions, such as M×AT and A×A, may be more influential than individual factors. Contour plots show that optimal results are achieved in the red and yellow regions. Overall, the model is reliable, and the identified factors and interactions are critically important for optimization.

According to Table 2, the RSM model is statistically significant ($F = 70.58$, $p < 0.001$). Linear terms play a substantial role in explaining the model (10.89%), with AT being the most prominent factor (7.52%), followed by M (2.21%). Quadratic terms account for 2.87% of the total variance, while two-factor interactions contribute 4.88%. Among these, the AT×M interaction ($F = 38.54$, 3.56%) emerges as the most significant. The low error rate (8.6%, Adj SS = 726.67) further supports the reliability of the model.

Regression Equation in Uncoded Units

$$T = 91.7 + 0.0376 A - 0.955 M - 54.1 WS - 1.208 AT - 0.000093 A \times A + 0.00159 M \times M + 29.83 WS \times WS - 0.01107 AT \times AT + 0.000228 A \times M - 0.0094 A \times WS + 0.000802 A \times AT - 0.088 M \times WS + 0.04088 M \times AT - 0.772 WS \times AT \quad (3)$$

Table 2, ANOVA results for Coniferous Plants. The model explains 91.40% of the total variance in T. The most influential variable is AT, with A 69.82% contribution, followed by M at 4.65% and A at 2.94%. While WS alone is statistically insignificant ($p = 0.799$), its interaction with AT (WS×AT) and the M×AT interaction is highly significant, with F-values of 10.71 and 38.54, respectively. These interactions suggest that combined microclimatic conditions are more impactful than individual variables. The low error rate (8.60%) supports the robustness and reliability of the RSM model.

The graphical analyses in Figures 5 and 6 indicate that the model follows a normal distribution and that the residuals are randomly distributed. The Pareto chart has identified AT, M×AT, M, and A as the most influential factors. Contour plots show that the optimal response variable is obtained in the red and yellow regions, with AT and M factors being the

key determinants. In conclusion, the AT factor is the strongest variable, and its interaction with M enhances the predictive power of the model.

Table 2. Analysis of Variance for Coniferous Plants.

Source	DF	Contribution	Adj SS	Adj MS	F-Value	p-Value	VIF
Model	14	91.40%	7720.51	551.465	70.58	0.000	
Linear	4	82.96%	919.53	229.883	29.42	0.000	
A (m ²)	1	2.94%	187.16	187.164	23.95	0.000	1.17
M (%)	1	4.65%	99.35	99.350	12.72	0.001	3.47
WS (m/s)	1	5.55%	0.51	0.510	0.07	0.799	4.63
AT (°C)	1	69.82%	635.11	635.111	81.28	0.000	4.02
Square	4	3.56%	242.56	60.641	7.76	0.000	
A×A	1	0.25%	20.84	20.844	2.67	0.106	1.00
M×M	1	2.41%	0.49	0.492	0.06	0.802	7.65
WS×WS	1	0.29%	82.98	82.979	10.62	0.002	5.41
AT×AT	1	0.62%	21.36	21.358	2.73	0.102	1.79
2-Way Interaction	6	4.88%	411.90	68.649	8.79	0.000	
A×M	1	0.01%	3.74	3.743	0.48	0.491	1.13
A×WS	1	0.02%	5.00	4.998	0.64	0.426	1.25
A×AT	1	0.27%	22.67	22.665	2.90	0.092	1.06
M×WS	1	0.05%	3.90	3.897	0.50	0.482	3.79
M×AT	1	3.54%	301.16	301.160	38.54	0.000	2.11
WS×AT	1	0.99%	83.65	83.647	10.71	0.001	4.18
Error	93	8.60%	726.67	7.814			
Total	107	100.00%	8447.17				

Model Summary		S	R-sq	R-sq (adj)	R-sq (pred)
		2.79528	91.40%	90.10%	88.76%

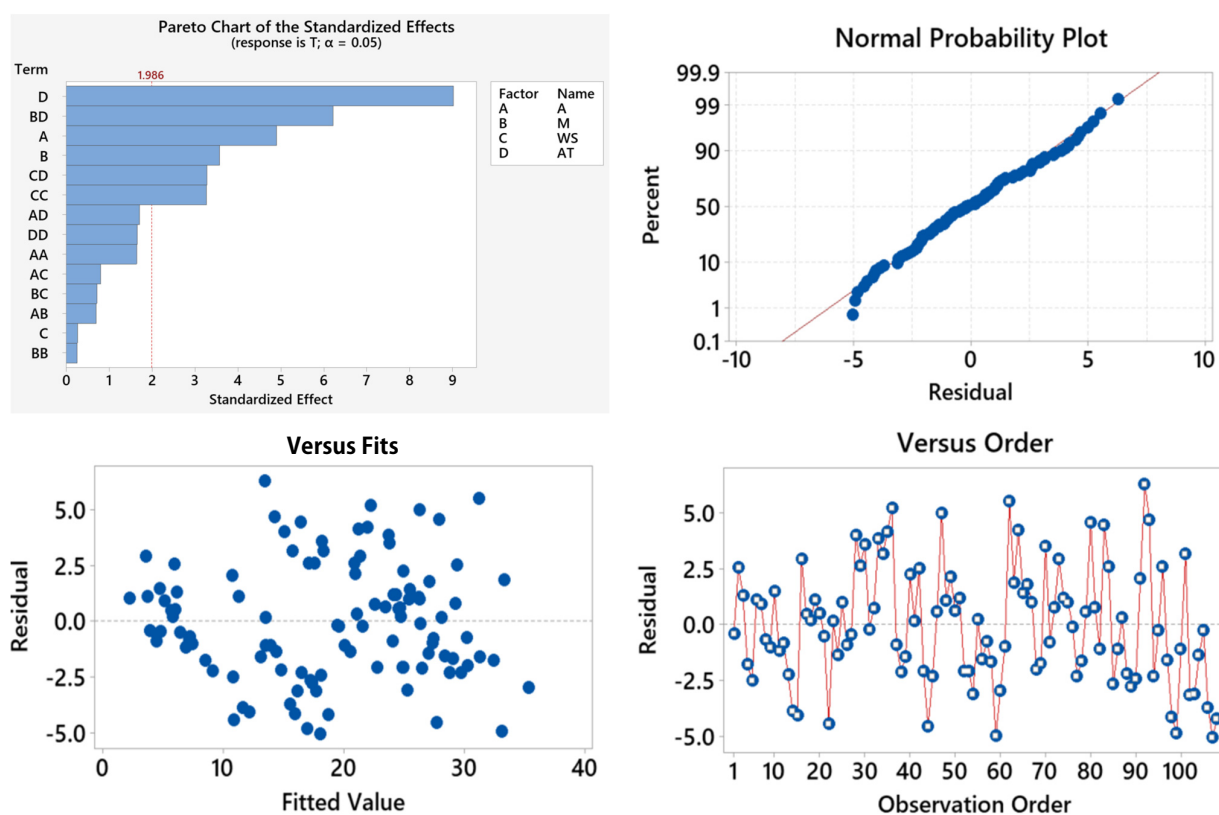


Figure 5. Residual analysis and Pareto chart of standardized effects, evaluating factor significance, normality, homoscedasticity, and independence for Coniferous Plants.

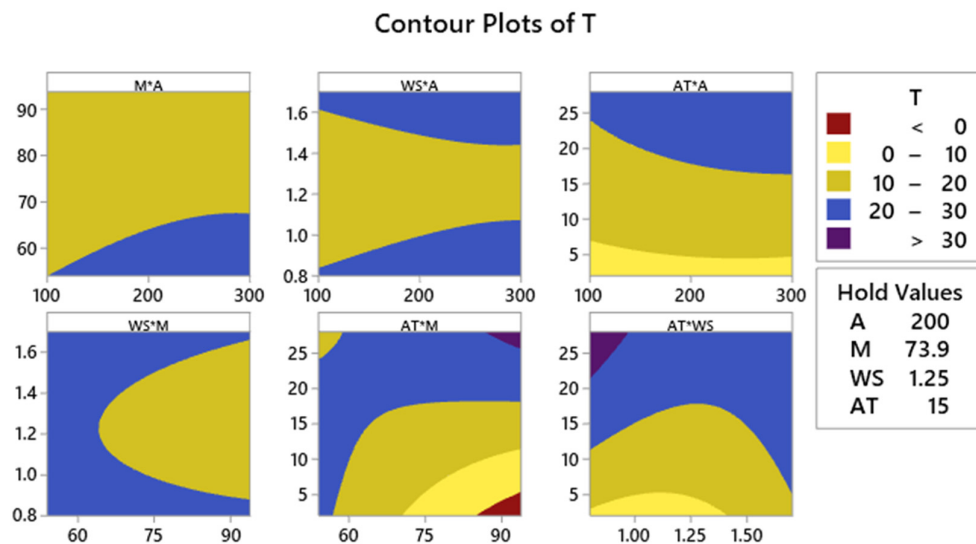


Figure 6. Contour plots of T, illustrating the interaction effects of variables on the response, with specific hold values for parameters A, M, WS, and AT for Coniferous Plants.

Figure 5, Pareto chart and residual diagnostics for Coniferous Plants. The Pareto chart highlights AT, M, and the interaction term $M \times AT$ as the most significant predictors of T variation. The normal probability plot shows a close alignment to the theoretical distribution, indicating normality. The Versus Fits and Versus Order plots exhibit randomly scattered residuals without obvious patterns, confirming the assumptions of independence and constant variance (homoscedasticity) and validating the statistical reliability of the model.

Figure 6, Contour plots of T for Coniferous Plants, illustrating interaction effects among A, M, WS, and AT. The most prominent interactions appear in the $AT \times M$ and $M \times AT$ plots, where red and yellow zones indicate stronger cooling effects. The $AT \times WS$ plot also shows notable gradients, indicating how AT modulates the influence of WS. These plots provide visual evidence for the nonlinear and interactive behavior of environmental variables, underscoring the importance of multivariate considerations in green infrastructure planning.

According to Table 3, the RSM model is statistically significant ($F = 69.34$, $p < 0.001$). Linear terms explain a significant portion of the model's variance (9.96%), with AT being the strongest variable (7.98%), followed by M (1.93%). Quadratic terms account for 1.96% of the total variance, while two-factor interactions contribute 4.82%. The $M \times AT$ interaction ($F = 41.35$, 3.88%) has been identified as the most significant interaction. The model exhibits a low error rate (8.74%, Adj SS = 592.22) and is considered reliable.

Regression Equation in Uncoded Units

$$T = 86.6 + 0.0162 A - 0.887 M - 43.9 WS - 1.281 AT - 0.000070 A \times A + 0.00101 M \times M + 22.36 WS \times WS - 0.00620 AT \times AT + 0.000046 A \times M + 0.0062 A \times WS + 0.000152 A \times AT - 0.032 M \times WS + 0.03822 M \times AT - 0.612 WS \times AT \quad (4)$$

Table 3, ANOVA results for shrubs. The model explains 91.26% of the total variance in T. Among the linear factors, AT is the most dominant (70.34%), followed by M (5.50%) and WS (7.75%). However, A has a negligible effect (0.02%, $p = 0.559$). Significant interactions include $M \times AT$ ($F = 41.35$) and $WS \times AT$ ($F = 8.26$), confirming the importance of combined climatic effects. The model's reliability is supported by a low error contribution (8.74%) and statistically significant interaction terms.

According to Figures 7 and 8, the model conforms to a normal distribution, and the residuals are randomly distributed. The Pareto chart identifies AT, $M \times AT$, and M as the most influential factors. Contour plots indicate that the optimal response variable is

achieved in the red and yellow regions, with AT and M factors being the key determinants. In conclusion, AT is the most significant independent variable, and its interaction with M enhances the predictive power of the model.

Table 3. Analysis of Variance for shrubs.

Source	DF	Contribution	Adj SS	Adj MS	F-Value	p-Value	VIF
Model	14	91.26%	6182.65	441.618	69.34	0.000	
Linear	4	83.62%	674.25	168.561	26.47	0.000	
A (m ²)	1	0.02%	2.19	2.188	0.34	0.559	1.17
M (%)	1	5.50%	131.09	131.093	20.58	0.000	3.47
WS (m/s)	1	7.75%	6.13	6.133	0.96	0.329	4.63
AT (°C)	1	70.34%	540.83	540.835	84.92	0.000	4.02
Square	4	2.81%	132.96	33.239	5.22	0.001	
A×A	1	0.17%	11.64	11.639	1.83	0.180	1.00
M×M	1	2.11%	0.20	0.196	0.03	0.861	7.65
WS×WS	1	0.15%	46.62	46.619	7.32	0.008	5.41
AT×AT	1	0.38%	6.70	6.698	1.05	0.308	1.79
2-Way Interaction	6	4.83%	327.20	54.534	8.56	0.000	
A×M	1	0.01%	0.15	0.155	0.02	0.876	1.13
A×WS	1	0.04%	2.19	2.191	0.34	0.559	1.25
A×AT	1	0.01%	0.81	0.814	0.13	0.722	1.06
M×WS	1	0.12%	0.52	0.518	0.08	0.776	3.79
M×AT	1	3.86%	263.35	263.346	41.35	0.000	2.11
WS×AT	1	0.78%	52.59	52.587	8.26	0.005	4.18
Error	93	8.74%	592.28	6.369			
Total	107	100.00%	6774.93				

Model Summary				S	R-sq	R-sq (adj)	R-sq (pred)
				2.52360	91.26%	89.94%	88.58%

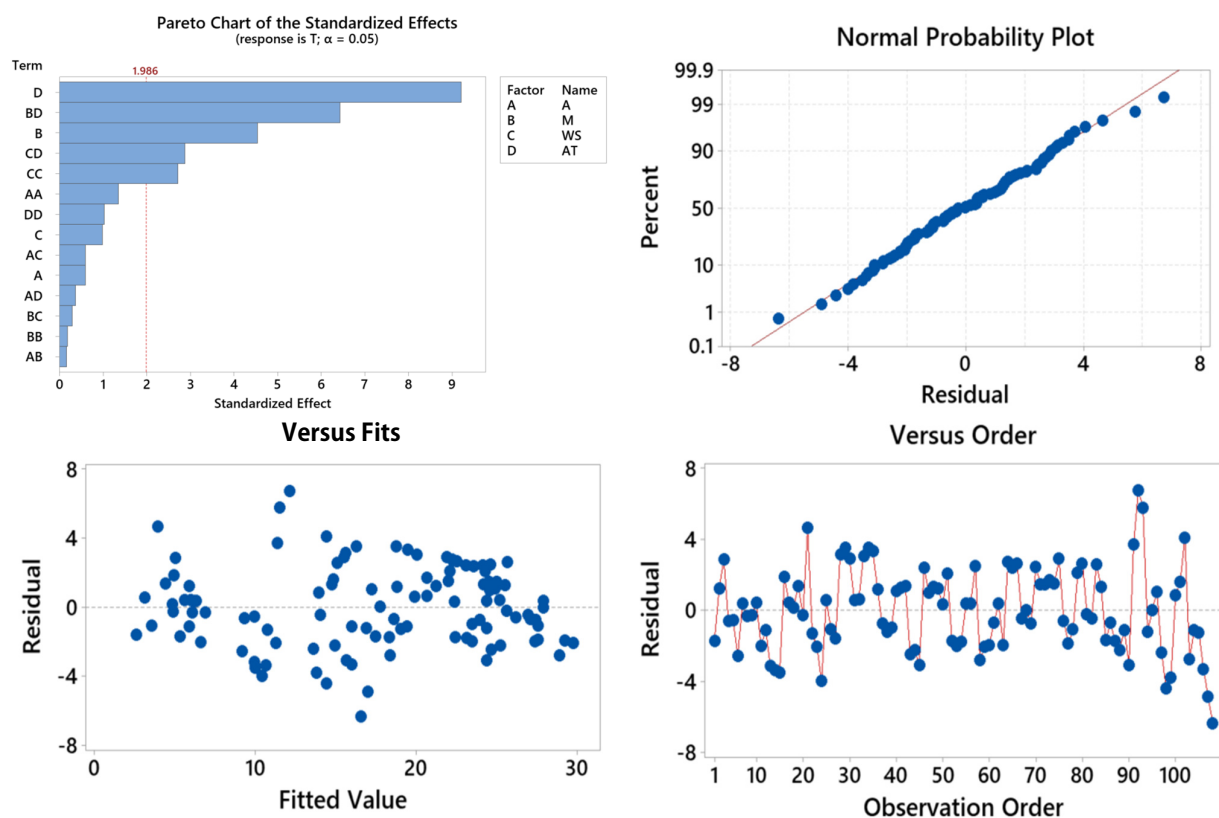


Figure 7. Residual analysis and Pareto chart of standardized effects, evaluating factor significance, normality, homoscedasticity, and independence for shrubs.

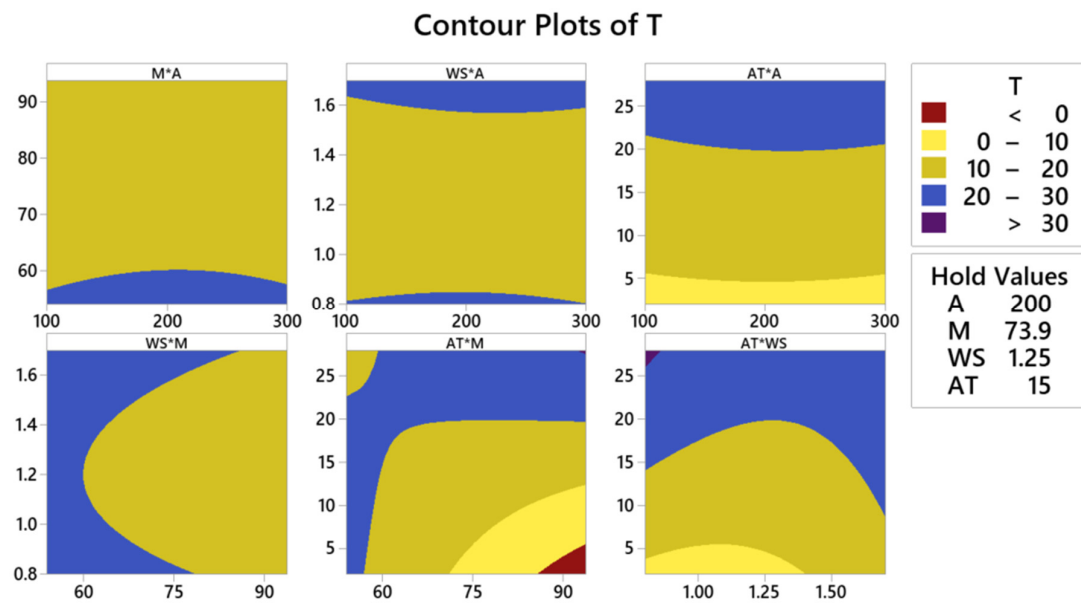


Figure 8. Contour plots of T, illustrating the interaction effects of variables on the response, with specific hold values for parameters A, M, WS, and AT for shrubs.

Figure 7, Pareto chart and residual analysis for shrubs. The ambient AT and its interaction with M ($M \times AT$) are identified as the most impactful predictors of T. The normal probability plot confirms the normality of residuals, while the Versus Fits and Versus Order plots show randomly scattered residuals, verifying the assumptions of homoscedasticity and independence. These diagnostics validate the statistical robustness and predictive performance of the model.

Figure 8, Contour plots of T for shrubs, showing how the T varies with the interaction of environmental factors. The most significant interactions— $AT \times M$ and $M \times AT$ —demonstrate strong gradients with visible red and yellow zones, indicating higher cooling effects. The influence of WS is also observable in the $WS \times AT$ and $WS \times WS$ plots. These graphical representations reinforce the model's findings by visually depicting how different variables synergistically regulate microclimate conditions in shrub-covered areas.

According to Table 4, the RSM model is statistically significant ($F = 81.76, p < 0.001$). Linear terms explain a large portion of the model's variance (12.48%), with AT being the strongest variable (9.68%), followed by M (2.83%). Quadratic terms account for 2.34% of the total variance, while two-factor interactions contribute 4.00%. The $M \times AT$ interaction ($F = 41.04, 3.31\%$) has been identified as the most significant interaction. The model exhibits a low error rate (7.51%, Adj SS = 591.98) and is considered reliable.

Regression Equation in Uncoded Units

$$T = 108.7 - 0.0521 A - 1.185 M - 47.7 WS - 1.575 AT + 0.000114 A \times A + 0.00225 M \times M + 21.48 WS \times WS + 0.00587 AT \times AT + 0.000076 A \times M + 0.0040 A \times WS - 0.000579 A \times AT + 0.009 M \times WS + 0.03806 M \times AT - 0.446 WS \times AT \quad (5)$$

Table 4, ANOVA results for Vines. The model explains 92.49% of the total variance in T. Among the linear factors, AT shows the highest contribution (71.45%, $p < 0.001$), followed by M (7.87%). A and WS are statistically insignificant on their own. The $M \times AT$ interaction ($F = 41.00, p < 0.001$) and $WS \times AT$ interaction ($F = 4.38, p = 0.039$) are the most prominent two-way effects. The model demonstrates high reliability with a low error rate (7.51%), indicating a strong fit between observed and predicted values.

When analyzing the graphs in Figures 9 and 10, it is observed that the model conforms to a normal distribution and that the residuals are randomly distributed. The Pareto chart reveals that the AT, $M \times AT$, and M factors have the highest impact. The contour plots indicate that the optimal response variable is obtained in the red and yellow regions,

highlighting the determining influence of the AT and M factors. In conclusion, the AT factor is the most significant independent variable, and its interaction with M enhances the predictive power of the model.

Table 4. Analysis of Variance for Vines.

Source	DF	Contribution	Adj SS	Adj MS	F-Value	p-Value	VIF
Model	14	92.49%	7285.66	520.404	81.76	0.000	
Linear	4	84.67%	983.13	245.782	38.61	0.000	
A (m ²)	1	0.20%	13.00	12.997	2.04	0.156	1.17
M (%)	1	7.87%	222.51	222.509	34.96	0.000	3.47
WS (m/s)	1	5.15%	1.31	1.314	0.21	0.651	4.63
AT (°C)	1	71.45%	762.82	762.820	119.84	0.000	4.02
Square	4	3.82%	183.96	45.989	7.22	0.000	
A×A	1	0.40%	31.13	31.130	4.89	0.029	1.00
M×M	1	3.05%	0.98	0.977	0.15	0.696	7.65
WS×WS	1	0.38%	43.03	43.034	6.76	0.011	5.41
AT×AT	1	0.00%	6.01	6.010	0.94	0.334	1.79
2-Way Interaction	6	3.99%	314.28	52.380	8.23	0.000	
A×M	1	0.02%	0.41	0.412	0.06	0.800	1.13
A×WS	1	0.00%	0.92	0.919	0.14	0.705	1.25
A×AT	1	0.15%	11.82	11.818	1.86	0.176	1.06
M×WS	1	0.17%	0.04	0.039	0.01	0.938	3.79
M×AT	1	3.30%	261.09	261.094	41.02	0.000	2.11
WS×AT	1	0.35%	27.91	27.912	4.38	0.039	4.18
Error	93	7.51%	591.98	6.365			
Total	107	100.00%	7877.64				

Model Summary				S	R-sq	R-sq (adj)	R-sq (pred)
				2.52297	92.49%	91.35%	89.93%

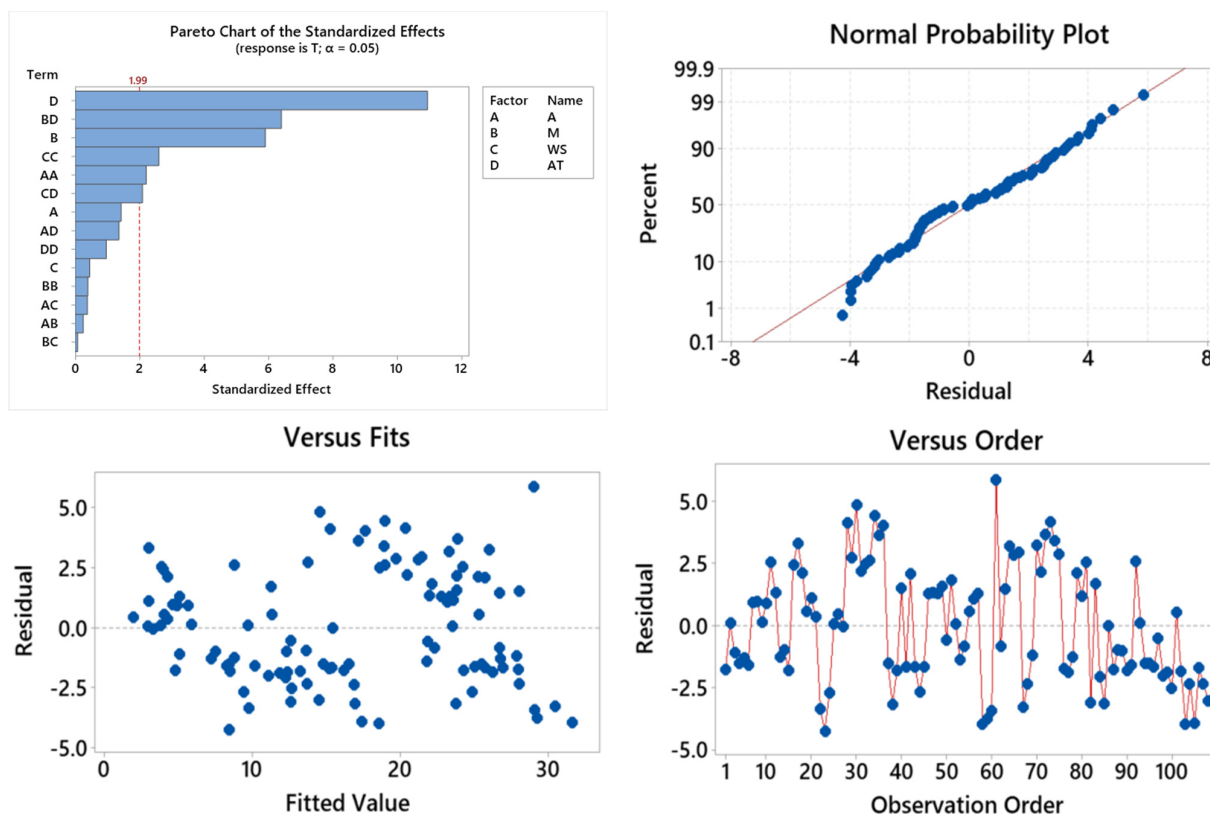


Figure 9. Residual analysis and Pareto chart of standardized effects, evaluating factor significance, normality, homoscedasticity, and independence for shrubs.

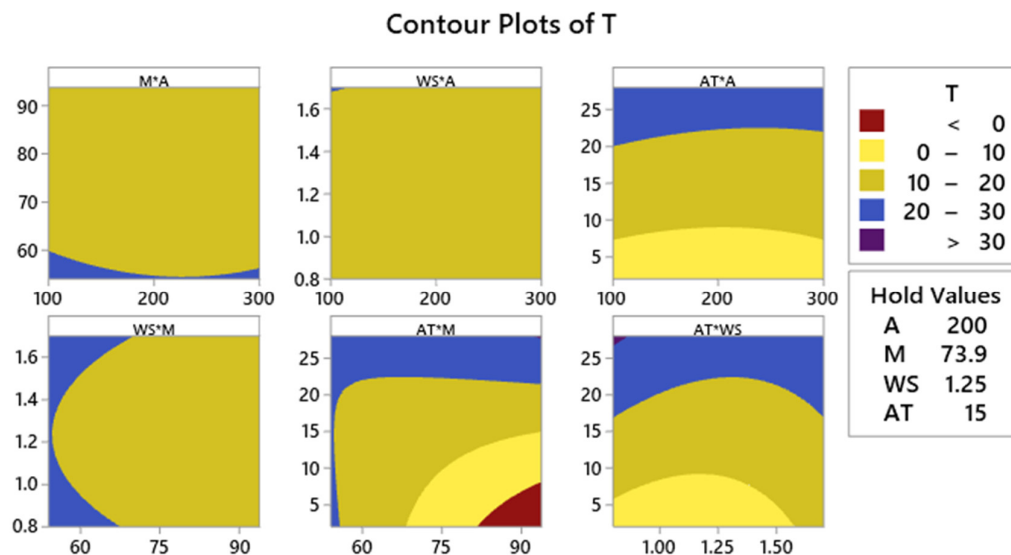


Figure 10. Contour plots of T, illustrating the interaction effects of variables on the response, with specific hold values for parameters A, M, WS, and AT for shrubs.

Figure 9, Residual diagnostics and Pareto chart for Vines. The Pareto chart reveals that AT, M, and the interaction term $M \times AT$ have the strongest standardized effects on T. The normal probability plot shows residuals closely following the expected trend, validating normal distribution. Additionally, the Versus Fits and Versus Order plots confirm the randomness and independence of residuals, supporting the assumption of homoscedasticity and enhancing the model's statistical credibility.

Figure 10, Contour plots for Vines, displaying the combined effects of environmental variables on T. The $M \times AT$ and $AT \times M$ plots show strong gradient shifts in color, indicating effective cooling performance through synergistic humidity–temperature interactions. Plots such as $WS \times AT$ also demonstrate localized thermal variations, especially in transitional zones. Red and yellow regions mark optimal microclimatic outcomes. These visual insights emphasize the importance of incorporating interactive variable effects into urban greening design strategies, particularly when using vine-based vertical vegetation.

In order to evaluate the generalizability of these findings, it is important to compare them with similar studies conducted in different climatic and urban contexts. The outcomes of this study are consistent with previous research in cities such as Chicago, Tel Aviv, and Bangkok, where green infrastructure significantly reduced urban temperatures. For instance, ref. [52] demonstrated a strong inverse relationship between vegetation cover and surface temperature in Chicago. Similarly, ref. [53] found that increasing green space coverage from 10% to 30% could eliminate the UHI effect in Tel Aviv. In tropical cities like Bangkok, ref. [54] showed that green roofs and passive cooling strategies were effective in lowering residential temperatures. Furthermore, studies in Addis Ababa and Beijing [65,83] revealed that the spatial connectivity and composition of green spaces are critical for achieving urban thermal comfort. These cross-regional findings support the idea that green infrastructure design must be adapted to specific climatic contexts and demonstrate that the strategies explored in this study have the potential for broader application.

3.3. Functional Plant Traits and Their Role in Microclimate Regulation

Plant species used in urban green spaces differ significantly in their ability to regulate temperature, largely due to physiological and structural traits such as LAI, canopy density, stomatal conductance, and specific leaf area (SLA). Broadleaved trees, for instance, generally exhibit higher LAI values (5–6), offering extensive canopy cover and effective shading,

which are critical for reducing solar radiation and surface temperatures [84,85]. Shrubs, although smaller in height, contribute significantly through dense branching and moderate LAI values (~2–3), playing a key role in blocking low-angle solar rays and enhancing localized evapotranspiration [57,62]. Groundcover plants and vines, while having lower vertical structures, increase surface cooling by modifying surface albedo and improving soil moisture retention through continuous, low-lying canopy layers [86,87].

Furthermore, vertical variations in LAI influence carbon assimilation, gas exchange, and the thermal buffering capacity of vegetated areas [55]. He et al., found that plant functional traits like the leaf-to-sapwood area ratio are highly responsive to seasonal water availability, suggesting that plant water use efficiency is closely linked to their cooling potential [56]. Additionally, recent studies using remote sensing techniques such as GEDI and GEE platforms have demonstrated that spatial variation in LAI and plant area index (PAI) strongly correlates with thermal regulation in forested and urban landscapes [57,61]. These findings reinforce that the effectiveness of green infrastructure in mitigating urban heat depends not only on species' presence but also on their functional characteristics. Therefore, incorporating plant-specific structural parameters into urban landscape design can enhance microclimatic performance and resilience, particularly in regions experiencing rapid urbanization and climate stress.

In recent years, the importance of plant-based microclimate regulation and green infrastructure design has been further emphasized in the context of climate change adaptation. For example, ref. [88] demonstrated that the morphological and seasonal traits of urban tree species significantly affect surface temperature modulation, highlighting the importance of species-specific strategies. Similarly, ref. [89] emphasized the role of green spaces in enhancing urban thermal comfort under heat stress, with a focus on their spatial distribution and connectivity. Additional findings by [90,91] confirmed that plant physiological traits, such as transpiration capacity and canopy density, play crucial roles in mitigating urban heat. Moreover, ref. [92] argued that the integration of vegetation in compact urban forms contributes positively to long-term urban resilience. These recent studies reinforce the relevance of the current research and support the notion that functionally diverse vegetation not only enhances urban sustainability but also improves adaptive capacity under climatic extremes.

The statistically significant interaction between M and AT observed across all vegetation types is underpinned by well-established microclimatic and plant physiological mechanisms. Humidity plays a critical role in regulating evapotranspiration, a key process in surface energy exchange, which is highly sensitive to ambient thermal conditions. Elevated temperatures tend to increase atmospheric demand for moisture, potentially accelerating transpiration rates; however, this response is modulated by ambient humidity levels, which influence vapor pressure gradients and stomatal behavior. Depending on the physiological characteristics of the plant species—such as leaf morphology, stomatal conductance, and canopy density—higher humidity under warm conditions may either amplify or suppress transpiration. This dynamic directly affects latent heat flux, thereby altering the surface energy balance and resultant temperature profiles. In urban green spaces, especially those characterized by dense or vertically structured vegetation, such interactions become particularly relevant as they determine the extent to which vegetative surfaces can buffer heat through evaporative cooling. Hence, the strong $M \times AT$ interaction not only validates the statistical robustness of the RSM model but also aligns with the biophysical principles governing plant–climate interactions in urban microclimates.

3.4. Practical Implications for Landscape Sustainability

The findings of this study offer valuable implications for climate-responsive urban landscape design, particularly on university campuses. Based on measured microclimatic differences among vegetation types, the following strategic recommendations are proposed:

3.4.1. Increasing Green Areas

Expanding the presence of green areas, especially in urban zones with dense built-up surfaces, is essential for mitigating the UHI effect. Broad-leaved shade trees should be strategically planted in areas with a high concentration of impervious surfaces, such as campus parking lots and roads, to reduce surface temperatures and improve user comfort [84,88].

3.4.2. Shading and Vertical Green Systems

The use of ivy and vertical garden systems on buildings, walls, and fences is encouraged to enhance shading and promote energy-efficient cooling for surrounding structures. These systems also provide additional ecological functions such as biodiversity support and air filtration [91,92].

3.4.3. Vegetative Design and Diversity

The study demonstrates that broad-leaved trees, conifers, and ivy are particularly effective in microclimate regulation. Therefore, they should be prioritized in landscape compositions. Shrubs and vines also contribute meaningfully to localized surface cooling and should not be overlooked in landscape planning [61,85,90].

3.4.4. User Comfort and Space Planning

Seasonal and diurnal variations in thermal comfort indicate the need for space-use planning. For example, relocating open-air campus activities to morning or evening hours during summer can significantly improve comfort. Moreover, integrating green areas into social and recreational zones can encourage longer and healthier outdoor engagement [56,66].

3.4.5. Future Studies and Data Monitoring

The modeling framework presented in this study can be applied in other climatic zones or scaled up using advanced technologies such as remote sensing (e.g., GEDI), GIS-based mapping, and drone thermography. These tools would enable detailed monitoring and strategic optimization of vegetation placement and composition [93,94].

In conclusion, this study emphasizes that functionally diverse vegetation, when designed with site-specific climatic and spatial conditions in mind, can offer scalable and transferable solutions for sustainable urban and campus environments.

These recommendations are not only derived from the empirical findings of the present study but are also supported by a broad range of recent literature that emphasizes the importance of species-specific vegetation design [55,56,89], microclimate-sensitive landscape planning [40,41,84], and climate-adaptive green infrastructure strategies [61,62,88,94]. Integrating these insights into urban and campus-scale planning can greatly enhance resilience to climate stressors while also improving human well-being and ecological sustainability.

Despite the model's strong predictive performance and the statistical robustness of the experimental design, several limitations should be acknowledged to ensure a comprehensive interpretation of the findings. Firstly, potential calibration drifts or environmental exposure effects on the sensors over time may have introduced minor inaccuracies in the recorded temperature and humidity data. Although all instruments were calibrated prior to field deployment, undetected deviations could have subtly influenced the measurement

accuracy. Secondly, seasonal irregularities—such as unanticipated precipitation events or abrupt wind fluctuations during data collection—may have acted as uncontrolled variables, potentially affecting the consistency of the microclimatic observations. Lastly, the study assumed uniformity in vegetation maturity and canopy density across all sampled areas; however, slight variations in plant growth stages or structural characteristics might have contributed to differential heat retention and evapotranspiration dynamics. Acknowledging these limitations provides critical context for interpreting the results and highlights the need for further research under controlled and long-term environmental conditions to enhance the generalizability and accuracy of future models.

4. Conclusions

This study, conducted within the scale of Recep Tayyip Erdoğan University Zihni Derin Campus, has revealed surface temperature variations across different seasons and plant species. The findings reaffirm the critical role of green spaces in mitigating the urban heat island effect and regulating the microclimate. The measurements indicate that ivy-covered surfaces are among the most effective plant types in temperature regulation.

The comparative evaluation of the four vegetation types—Deciduous Plants, Coniferous Plants, shrubs, and ivy—revealed consistent and statistically significant RSM models for each case ($p < 0.001$). Among them, ivy exhibited the highest model fit ($F = 81.76$), while Coniferous Plants had the lowest ($F = 69.34$). In terms of explained variance, ivy also achieved the strongest model performance (92.49%), whereas Coniferous Plants showed the lowest (91.40%). The AT emerged as the most dominant variable across all models, with its impact being particularly prominent in ivy (71.45%) and Deciduous Plants (70.14%). The M showed the greatest effect in ivy (7.87%) and the least in shrubs (5.50%). The most influential two-way interaction observed was $M \times AT$, especially in shrubs ($F = 41.35$) and ivy ($F = 41.04$). This interaction was consistently strong across all plant types, supporting the physiological relevance of combined thermal and humidity effects. The $WS \times AT$ interaction was statistically significant only for ivy and Coniferous Plants ($p < 0.05$). The models demonstrated low error rates overall, with ivy showing the highest predictive reliability (error = 7.51%) and Coniferous Plants the lowest (error = 8.60%). Residual diagnostics, including normal probability plots and versus-fit analyses, confirmed the assumptions of normality and homoscedasticity, validating the robustness of the models. Additionally, contour plots revealed that optimal surface temperature responses were typically concentrated in red and yellow regions, indicating effective thermal regulation. These optimal zones were broader for ivy and Deciduous Plants, whereas shrubs and Coniferous Plants exhibited more localized response regions. Overall, these findings reinforce the dominant influence of AT and M on surface temperature regulation and highlight the effectiveness of RSM in capturing species-specific microclimatic behavior.

Overall, the findings emphasize that species-specific physiological traits—such as canopy structure and transpiration efficiency—play a decisive role in microclimatic performance. The consistent dominance of AT and M across all models further reinforces their critical role in surface temperature regulation. Furthermore, the study demonstrates that data-driven modeling approaches like RSM are highly effective in capturing complex environmental interactions and can support the development of targeted climate-responsive green infrastructure strategies.

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Abbreviations

The following abbreviations are used in this manuscript:

IR	Utilizes infrared
RSM	Response surface methodology
AT	Ambient temperature
WS	Wind speed
A	Surface area
CCD	Central composite design
T	Surface temperature

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