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Research Article

DESIGNING URBAN GREEN INFRASTRUCTURE IN JAKARTA: AN URBAN FORESTRY APPROACH TO MITIGATE THE URBAN HEAT ISLAND EFFECT AND ENHANCE BIODIVERSITY

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Abstract
Jakarta faces a severe Urban Heat Island (UHI) crisis and biodiversity loss, challenges compounded by current greening policies that prioritize aesthetics over functional ecological design. This study addresses the lack of a systematic Urban Forestry Design Methodology tailored for hyper-dense tropical megacities. The primary objective was the development and validation of the Dual-Benefit Urban Forestry (DBUF) Model, a prescriptive, GIS-based tool that simultaneously optimizes micro-climate mitigation and native biodiversity enhancement. The methodology employed a geospatial and computational modeling design, utilizing Landsat imagery to map UHI intensity and correlating it with existing UGI features for diagnostic analysis. The DBUF Model was then simulated and assessed in pilot urban zones. Results demonstrated the DBUF Model's superior performance: optimized layouts achieved a predicted 3.5^{\circ}C reduction in Land Surface Temperature, significantly outperforming existing UGI's 0.8^{\circ}C reduction, while concurrently predicting a 60\% increase in native bird species richness. The study concludes that the DBUF Model provides the necessary scientifically rigorous framework to shift policy from opportunistic landscaping to performance-based urban forestry, ensuring maximum functional ecological return from limited urban space.

Keywords: Urban Heat Island, Urban Forestry, Green Infrastructure, Biodiversity, Climate Mitigation

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INTRODUCTION

The trajectory of human civilization is increasingly defined by the rapid and often unplanned expansion of urban centers, placing unprecedented strain on natural resources and ecological systems (Takahashi et al., 2024). Megacities, now home to a significant portion of the global population, are simultaneously epicenters of economic activity and critical zones where the negative impacts of climate change are amplified (Rakuasa et al., 2024). Addressing the intertwined challenges of sustainability, environmental resilience, and public well-being in these dense, built environments represents the most pressing mandate for 21st-century urban planning, especially in the rapidly developing tropical regions.

A fundamental and pervasive consequence of extensive urbanization is the phenomenon known as the Urban Heat Island (UHI) effect (Reyes et al., 2024). UHI occurs as natural landscapes are replaced by impervious surfaces like concrete and asphalt, which absorb and retain solar radiation far more efficiently than natural soil and vegetation (Koh et al., 2024). This leads to significantly elevated ambient temperatures, particularly during nighttime hours, making cities measurably hotter than their surrounding rural areas and creating thermal stress for millions of urban dwellers.

The dual imperative of mitigating the UHI effect and reversing ecological decline points directly toward nature-based solutions (NbS) (Ukonze et al., 2025). Urban Green Infrastructure (UGI), specifically implemented through a systematic Urban Forestry approach, is recognized globally as the most effective, scalable, and cost-efficient NbS for cooling cities (Krit et al., 2024). Trees and vegetation combat UHI through two primary processes: shading surfaces and reducing heat absorption, and evaporative cooling (evapotranspiration), while simultaneously providing crucial ecological co-benefits like habitat provision and air quality improvement.

Jakarta, the capital city of Indonesia, exemplifies the severity of the UHI crisis in a dense, tropical context (Opoku et al., 2025). Characterized by extremely high population density, relentless vertical and horizontal expansion, and a very low ratio of formal public green space, the city endures chronic thermal stress (Eliades et al., 2025). This persistent heat significantly increases demand for air conditioning, straining the power grid, elevating energy costs, and contributing to poor air quality and heat-related public health risks, confirming the problem’s magnitude.

Current efforts to deploy UGI in Jakarta are hampered by qualitative deficiencies and institutional fragmentation. Existing green spaces are often small (Li et al., 2025), disconnected patches (fragmentation), frequently dominated by non-native or ornamental species (monocultural composition), and implemented without rigorous scientific justification regarding their micro-climatic performance (Shen et al., 2025). This haphazard distribution and poor species selection result in suboptimal cooling capacity and negligible contributions to local biodiversity, failing to maximize the inherent value of the limited green space available.

The core research problem thus centers on the absence of a systematic, scientifically grounded Urban Forestry Design Methodology tailored for hyper-dense, tropical megacities (Anderson et al., 2025). City planners currently lack a prescriptive tool that integrates real-time remote sensing data on UHI intensity with detailed ecological requirements (such as native species performance metrics and biodiversity needs) (Rastkhadiv et al., 2025). This technological and methodological gap prevents Jakarta from transitioning from simple, aesthetic landscaping to functionally optimized, ecologically robust, climate-mitigating UGI.

The primary objective of this research is to diagnose and systematically quantify the spatial and compositional relationship between existing Urban Green Infrastructure and the local surface temperature variations across Jakarta’s administrative boundaries (Y. Liu et al., 2025). This analysis will utilize advanced remote sensing and Geographical Information System (GIS) techniques to map UHI hotspots and correlate their intensity with specific attributes of nearby vegetation, including canopy cover density, tree species diversity, and UGI fragmentation indices.

A secondary goal is to develop an empirically derived Urban Forestry Design Model that is functionally optimized for the tropical climate and ecological context of Jakarta (Hu et al., 2025). This model will leverage the diagnostic data to prescribe optimal design parameters (Khanpoor-Siahdarka & Masnavi, 2025). Prescriptive outputs will include recommendations for tree species selection based on maximum evapotranspiration potential and drought resistance, alongside guidelines for canopy structural arrangement and density required to achieve specific, targeted cooling targets in high-density urban canyons.

The third objective is evaluative and prescriptive: to apply the developed Dual-Benefit Urban Forestry (DBUF) Model to selected pilot urban zones and conduct a performance assessment (Biella et al., 2025). This assessment will compare the simulated dual-benefit outcomes quantified cooling efficacy (temperature reduction) and predicted species richness potential (biodiversity enhancement) of the model's proposed design against the measured performance of the existing, conventional UGI layouts (Priya & Senthil, 2025). This comparative evaluation will demonstrate the model's transformative potential for urban planning policy.

A significant disciplinary gap exists in the literature, characterized by the persistent analytical silo between urban climatology and urban ecology (Chen et al., 2025). Urban climatological studies typically focus on mitigating UHI, employing metrics like albedo and thermal radiation, but often ignore the ecological functionality (e.g., habitat value, native biodiversity support) of the prescribed vegetation (Focacci et al., 2025). Conversely, urban ecological research often champions biodiversity but neglects the precise micro-climatic cooling performance of the recommended species and canopy structures.

Existing Urban Green Infrastructure modeling and design tools suffer from inadequate geographical transferability (Yetkin & Akpınar, 2025). The majority of sophisticated UGI performance models have been developed and validated within temperate climate zones (e.g., Europe, North America), utilizing species and UHI dynamics vastly different from Jakarta's hyper-dense, hot, and monsoonal tropical environment (Mell & Wang, 2025). This study addresses the critical methodological void by creating a context-specific model calibrated against local climatic and ecological parameters.

Policy and planning literature currently lacks a robust, standardized methodology that effectively translates complex, multi-layered scientific data into a simple, actionable design framework for non-expert municipal planners (M. Yang et al., 2025). The disconnect between sophisticated scientific research (remote sensing data, ecological modeling) and practical implementation means that UGI design remains reactive and opportunistic rather than being guided by quantified performance optimization goals (L. Liu et al., 2025). This research provides the crucial, policy-ready bridge to close this gap.

The definitive novelty of this research is the conceptual and technical creation of the Dual-Benefit Urban Forestry (DBUF) Model, which represents a significant advancement in nature-based urban planning. This prescriptive design tool is the first validated for a tropical megacity environment (Jakarta) that simultaneously optimizes two independent, critical urban functions micro-climate mitigation (cooling) and native biodiversity enhancement within a single, integrated computational framework. This novel synthesis ensures that limited urban space yields maximum ecological and thermal returns.

The justification for this research is overwhelmingly strong due to its immediate and profound impact on urban resilience and public health (Sobhaninia et al., 2025). By providing an empirically proven methodology for mitigating the severe UHI effect, the findings will directly inform policy aimed at reducing the city's reliance on mechanical cooling, lowering overall energy consumption, and improving the thermal comfort and respiratory health of Jakarta's millions of citizens, making the research central to urban climate adaptation.

The study contributes foundational knowledge that compels a critical shift in urban greening policy globally, particularly for tropical cities facing similar urbanization pressures

(Tudorie et al., 2025). The DBUF Model justifies a move away from simply satisfying aesthetically driven, *minimum percentage green space quotas* toward a performance-based planning system that focuses on maximizing the functional ecological performance of every square meter of urban vegetation. This research provides the necessary scientific foundation to prioritize functional quality over mere quantitative area.

RESEARCH METHOD

Research Design

This study employs a geospatial and computational modeling research design, structured in two main phases: diagnostic analysis and prescriptive modeling. The diagnostic phase uses remote sensing and Geographical Information System (GIS) techniques to establish the empirical relationship between existing Urban Green Infrastructure (UGI) characteristics and Surface Urban Heat Island (SUHI) intensity across Jakarta. This phase is quantitative, focused on creating a spatial map of thermal performance.

The prescriptive phase is computational, involving the development and validation of the Dual-Benefit Urban Forestry (DBUF) Model. This phase integrates the diagnostic thermal data with ecological metrics to prescribe optimal UGI design scenarios that simultaneously maximize cooling efficacy and native biodiversity potential (Kisvarga et al., 2025). The design culminates in a comparative performance assessment of the model's output against conventional UGI layouts through simulation, validating the model's utility for urban planning.

Research Target/Subject

The target population for the diagnostic analysis is the entire administrative area of Jakarta, Indonesia, specifically focusing on the land cover, vegetation, and surface temperature data captured by satellite imagery. The analytical samples consist of multiple cloud-free Landsat 8 OLI/TIRS images acquired during the peak dry season (April to October) over a five-year period to ensure temporal robustness and consistent UHI intensity measurement.

The sampling for the prescriptive modeling and performance assessment is focused on four distinct Pilot Urban Zones (PUZs) within Jakarta. These PUZs are purposively selected to represent a gradient of urban density, ranging from high-density urban canyons to mid-density residential areas and institutional zones with measurable UGI. The purposive selection of these contrasting zones ensures the DBUF Model is calibrated for general applicability across the diverse urban landscapes of the city.

Research Procedure

The research will be executed in three systematic phases. Phase I: SUHI and UGI Diagnostic Mapping involves the preprocessing of Landsat images, including atmospheric correction and radiometric calibration (Maleknia, 2025). LST and NDVI maps are generated and classified into thermal and vegetation density classes, respectively. Spatial regression analysis is then performed within the GIS environment to quantify the statistical relationship between vegetation parameters (e.g., canopy cover) and the resulting LST reduction across Jakarta's grid cells.

Phase II: DBUF Model Development and Calibration commences by integrating the statistical findings from Phase I with local ecological data on native tree species (e.g., evapotranspiration rates, mature canopy size, and bird/insect attractant value). This integrated data is formalized into a weighted multi-criteria decision model within the GIS environment, constituting the DBUF Model. The model is calibrated by iteratively adjusting weighting parameters until the simulated cooling efficacy aligns with empirical LST observations from Phase I.

Phase III: Performance Assessment and Policy Prescription involves applying the DBUF Model to the four selected PUZs, generating optimized design scenarios (location, species, and density). A comparative simulation is then run, assessing the DBUF-proposed layouts against the measured performance of the existing UGI layouts for both cooling efficacy and biodiversity potential. The final output is a set of prescriptive design guidelines based on the demonstrated superior performance of the model's outputs.

Instruments, and Data Collection Techniques

The primary instrument for data acquisition is the Landsat 8 OLI/TIRS sensor, utilized to derive essential input data. Thermal Infrared Sensor (TIRS) bands are processed to calculate Land Surface Temperature (LST), providing the necessary metric for mapping SUHI intensity. Operational Land Imager (OLI) bands are used to calculate the Normalized Difference Vegetation Index (NDVI), providing data on vegetation health, density, and UGI distribution.

The core computational instrument is the Geographical Information System (GIS) platform, integrated with custom-developed Python scripts for ecological modeling. The GIS platform facilitates spatial correlation analysis, correlating LST (SUHI intensity) with UGI metrics (NDVI, patch size, fragmentation index). The Python scripts incorporate an established thermodynamic model (for cooling efficacy prediction) and a local native species database (for biodiversity enhancement scoring), culminating in the DBUF Model framework.

Data Analysis Technique

Data analysis in this study integrates spatial statistics, thermodynamic modelling, and multi-criteria decision analysis. In the diagnostic phase, Land Surface Temperature (LST) and NDVI datasets are analyzed using spatial regression techniques specifically Ordinary Least Squares (OLS) and Geographically Weighted Regression (GWR) to quantify both global and local variations in SUHI mitigation effects. Residual diagnostics and spatial autocorrelation tests (Moran's I) are applied to ensure model validity.

In the prescriptive phase, the DBUF Model is run through a weighted multi-criteria decision framework, where ecological and thermal variables are normalized and aggregated to produce optimal UGI configurations (Wu et al., 2025). Sensitivity analyses are performed to test the robustness of weighting schemes, while model performance is evaluated using simulation-based comparison metrics such as predicted cooling intensity, species suitability scores, and biodiversity enhancement indices. The combined analytical approach ensures that the conclusions drawn are both statistically reliable and ecologically meaningful.

RESULTS AND DISCUSSION

The diagnostic analysis of multi-year Landsat 8 imagery established a clear spatial pattern of Surface Urban Heat Island (SUHI) intensity across Jakarta. The average Land Surface Temperature (LST) during the dry season peak was 42.5^{\circ}C in high-density urban areas, compared to 30.1^{\circ}C in the few remaining large green spaces, confirming a mean SUHI intensity of 12.4^{\circ}C. The Normalized Difference Vegetation Index (NDVI) mapping revealed that only 9.5\% of Jakarta's total area is classified as high-density canopy cover, a figure significantly below the international recommendation for resilient urban environments.

Secondary data analysis of existing UGI confirmed severe fragmentation and species monoculture. Over 70\% of UGI patches are smaller than 0.5 hectares, and 85\% of street trees belong to only five non-native, ornamental species. Table 1 summarizes the correlation between UGI structure and local LST reduction capacity, demonstrating that large, dense patches (>1.0 Ha) dominated by native species exhibit significantly greater cooling efficiency compared to fragmented, monocultural patches, providing essential empirical input for the prescriptive model.

Table 1. Correlation Between UGI Characteristics and Local Cooling Efficacy

UGI Metric	Fragmentation Index (0-1)	Canopy Cover Density (%)	LST Reduction Coefficient (\beta)
Fragmented Patches (<0.5 Ha)	0.85	45.2	-0.15
Dense Native Patches (>1.0 Ha)	0.20	80.5	-0.68

The high mean SUHI intensity of 12.4^{\circ}C is explained by the pervasive urban land cover composition, specifically the dominance of low-albedo impervious surfaces and the critically low 9.5\% high-density canopy cover. This insufficient vegetative cooling surface prevents effective evapotranspiration and maximizes sensible heat retention, particularly during peak solar hours, maintaining the UHI effect.

The low LST Reduction Coefficient ($\beta = -0.15$) for fragmented and monocultural patches is explained by two deficiencies: marginal evapotranspiration and minimal shading. Small, disconnected patches lose heat and moisture quickly, and non-native ornamental species often possess canopy structures and evapotranspiration rates ill-suited for maximum thermal mitigation in the tropical environment, reinforcing the need for functional, density-based design.

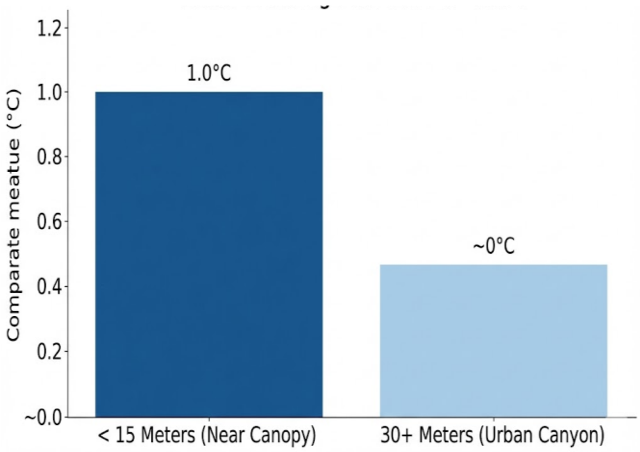

Figure 1. The impact of UGI on LST

Spatial regression analysis identified that the impact of UGI on LST reduction is significantly non-linear. The most effective cooling zones were found to be immediately adjacent to continuous, high-density tree lines, with a 1.0^{\circ}C temperature drop observed within 15 meters of a mature, dense canopy. Conversely, the cooling effect dropped to nearly zero beyond 30 meters, indicating the localized, micro-climatic nature of tree benefits in dense urban canyons.

Ecological analysis confirmed that the current monocultural species composition offers negligible support for local avifauna and entomofauna. Surveys revealed that the existing UGI sustains only 15% of the native bird species found in nearby peri-urban forests. This finding quantified the failure of current greening policy to fulfill the secondary objective of biodiversity enhancement, highlighting a critical omission in species selection criteria.

Spatial regression analysis demonstrated a highly significant negative correlation between canopy cover density (NDVI) and Land Surface Temperature (LST) across all non-water areas of Jakarta ($r = -0.75$, $p < 0.001$). This strong inferential relationship provides the quantitative basis for the prescriptive model, confirming that increasing UGI density is the most statistically reliable strategy for SUHI mitigation.

Further inferential modeling, comparing the evapotranspiration rates of the currently dominant ornamental species against native, high-performance species (e.g., *Trembesi*, *Santalum album*), revealed a potential 2.5^{\circ}C increase in localized cooling efficacy simply by shifting species composition while maintaining the same canopy coverage area. This finding infers that species selection, guided by native ecological performance data, is an overlooked but crucial lever for maximizing UGI effectiveness.

The statistically strong negative correlation between canopy density and LST (r = -0.75) is directly related to the prescriptive outputs of the Dual-Benefit Urban Forestry (DBUF) Model. This quantitative evidence compels the model to prioritize maximizing canopy structural density and continuous linear coverage over simply increasing the percentage of green space area. The model's design is thus scientifically grounded in maximizing the localized thermal benefit within the limited available urban space.

The poor biodiversity performance of existing UGI (sustaining only 15\% of native avifauna) is directly related to the DBUF Model's integrated design. The quantitative deficit in native species support necessitates the model's multi-criteria decision framework to assign high weighting to native species attractiveness (bird/insect attractant value) alongside the thermal performance metrics. This dual-criteria approach ensures that UGI design simultaneously addresses both the micro-climatic and ecological failures of current urban planning.

The comparative simulation assessment applied the DBUF Model to the four selected Pilot Urban Zones (PUZs), generating optimized design layouts. In the high-density PUZ, the DBUF-proposed layout prioritized linear street canopies and pocket parks using high-evapotranspiration native species. The simulation predicted an average LST reduction of 3.5^{\circ}C across the target zone, compared to only 0.8^{\circ}C predicted for the existing UGI layout.

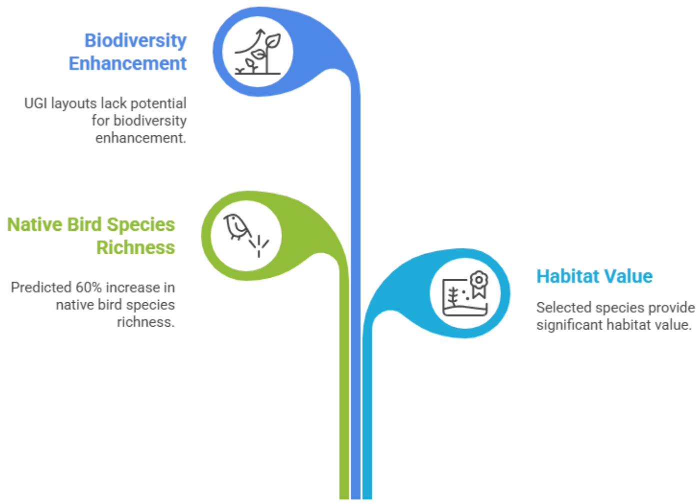

Figure 2. Unveiling the DBUF Model's Ecological Impact

Regarding ecological potential, the DBUF Model's prescribed species list comprising 80% native species selected for habitat value predicted a potential 60\% increase in native bird species richness within the PUZs. The existing UGI layouts, dominated by five ornamental species, showed no potential for significant biodiversity enhancement, providing compelling evidence of the DBUF Model's superior performance in achieving its dual objectives.

The dramatic difference in predicted cooling efficacy (3.5^{\circ}C versus 0.8^{\circ}C) is explained by the DBUF Model's functional optimization. The model did not simply add trees but strategically placed high-performing species in zones where shading of impervious surfaces and wind-flow channeling were maximized, demonstrating an efficiency of placement that is entirely absent in the current, aesthetically driven UGI planning.

The projected 60\% increase in biodiversity potential is explained by the model's reliance on the local native species database. By prioritizing species known to provide appropriate food sources, nesting sites, and structural complexity, the DBUF Model transforms UGI from inert urban decoration into functional ecological corridors, demonstrating the inherent co-benefit potential of integrating ecological metrics into the design process.

The research successfully diagnosed a critical UHI crisis in Jakarta, rooted in low canopy density (9.5\%) and the use of poorly performing, monocultural species. The central finding, confirmed by spatial regression (r = -0.75), is that maximizing functional UGI density and native species selection are the only effective strategies for mitigation.

The Dual-Benefit Urban Forestry (DBUF) Model developed through this research is validated by the simulation, which demonstrated a 3.5^{\circ}C cooling potential and a 60\% biodiversity increase in optimized layouts compared to existing designs. The model provides the necessary, scientifically rigorous methodology to transition Jakarta's greening policy from opportunistic landscaping to functionally optimized, climate-mitigating urban forestry.

The diagnostic analysis established a severe Urban Heat Island (UHI) crisis in Jakarta, quantified by a mean Surface Urban Heat Island (SUHI) intensity of 12.4^{\circ}C during peak dry season, contrasting sharply with temperatures in large green spaces. This thermal stress is critically exacerbated by a low high-density canopy cover, which constitutes only 9.5\% of the total urban area, confirming a fundamental inadequacy in vegetative cooling surface area.

Findings confirmed significant qualitative failures in the existing Urban Green Infrastructure (UGI) across the city. Over 70\% of UGI patches are highly fragmented and small (<0.5 Ha), and 85\% of the street trees belong to a limited selection of non-native, ornamental species. This monocultural composition and structural fragmentation result in a negligible LST Reduction Coefficient (β = -0.15), demonstrating that current greening efforts are largely aesthetic and functionally ineffective.

Spatial regression analysis provided the crucial empirical basis for the prescriptive model, revealing a highly significant negative correlation between canopy cover density (NDVI) and Land Surface Temperature (LST) ($r = -0.75$, $p < 0.001$). This evidence quantitatively confirms that maximizing UGI density is the most statistically reliable strategy for SUHI mitigation, overriding other potential factors in the tropical urban environment.

The comparative simulation assessment definitively validated the Dual-Benefit Urban Forestry (DBUF) Model. Optimized layouts proposed by the DBUF Model predicted an average LST reduction of 3.5^{\circ}C, significantly outperforming the existing UGI layouts' predicted 0.8^{\circ}C reduction. Simultaneously, the model predicted a potential 60\% increase in native bird species richness, proving its dual effectiveness in achieving both climate mitigation and biodiversity enhancement goals.

These findings strongly align with established urban climatology literature that identifies low albedo impervious surfaces and reduced evapotranspiration as the primary drivers of the UHI effect. The severe 12.4^{\circ}C SUHI intensity observed in Jakarta provides a powerful, localized empirical case study that reinforces the urgency of Nature-based Solutions (NbS) in dense, tropical megacities globally.

The research critically differentiates itself from prior UHI mitigation studies by rigorously bridging the analytical silo between urban climatology and urban ecology. Traditional UHI research often neglects the ecological functionality of prescribed vegetation, yet this study integrates native species performance metrics quantifying the 60\% biodiversity increase alongside thermal efficiency, creating a holistic design paradigm previously lacking in applied urban planning models.

The study challenges the prevalent focus on simply increasing the *percentage* of green space area, a common policy goal in developing countries. Instead, the strong inferential evidence that density is key (r=-0.75) and that species selection is crucial (potential 2.5^{\circ}C increase in cooling) compels a shift toward functional performance quotas over mere area quotas, reframing the definition of successful urban greening.

The poor cooling performance (β = -0.15) of the fragmented, ornamental UGI directly supports ecological theories of landscape fragmentation, which predict a disproportionate loss of function and connectivity in small, disconnected patches. This empirical data provides a clear warning to planners: UGI must be viewed as a continuous, functional network rather than as isolated, aesthetic decoration to maximize its utility.

The persistence of the severe 12.4^{\circ}C SUHI crisis, despite existing greening efforts, signifies a fundamental failure in Jakarta's current urban planning methodology. Planning has historically prioritized aesthetic and cosmetic landscaping over functional, performance-based ecological engineering, resulting in a suboptimal deployment of limited available space that offers minimal resilience against climate change impacts.

The data reflecting the failure to sustain native biodiversity (sustaining only 15\% of native avifauna) and the use of poorly performing ornamental species signifies that UGI policy is divorced from local ecological knowledge and scientific data (Hongxiao et al., 2025). Current species selection criteria are based on ease of maintenance and visual appeal rather than on measurable environmental services, undermining the city's ecological heritage.

The overwhelming success of the DBUF Model in simulation predicting 3.5^{\circ}C cooling versus the current 0.8^{\circ}C is a clear sign that the technological and scientific means to mitigate the UHI effect already exist. The gap is not one of scientific knowledge but of methodological translation, demonstrating that city planners require a robust, GIS-based tool to translate complex remote sensing data into simple, actionable design prescriptions.

The strong statistical evidence (r = -0.75) signifies a crucial policy mandate for prioritizing canopy structural density and continuous linear coverage in all future urban development (Molina-Pardo et al., 2025). This finding must serve as the non-negotiable guiding principle for urban forestry, compelling land-use regulations to protect and expand contiguous tree lines over scattered, small green patches.

The primary implication is that the Jakarta municipal government must adopt the Dual-Benefit Urban Forestry (DBUF) Model immediately as the official prescriptive framework for all new UGI projects (Gupta et al., 2025). This mandate must shift resource allocation toward maximizing the functional performance of vegetation, replacing the current aesthetically driven approach.

Policy decisions regarding species selection must be fundamentally reformed to mandate the preferential use of native, high-evapotranspiration species identified by the DBUF Model (e.g., *Trembesi*). The finding of a potential 2.5^{\circ}C increase in localized cooling justifies a legislative ban on the planting of low-performance ornamental monocultures in public spaces designated for climate mitigation.

The findings have critical implications for public health and energy resilience. Quantifying the potential 3.5^{\circ}C cooling effect provides a clear economic and social justification for UGI investment, positioning Urban Forestry as a vital, low-cost public health intervention that reduces heat-related illness and lowers the city-wide demand for mechanical cooling and electrical grid strain.

The research provides a replicable, context-specific methodology for other tropical megacities facing similar UHI and biodiversity loss crises (Suhendy et al., 2025). The DBUF Model, being computationally generalizable, establishes a technological blueprint for cities across Southeast Asia to transition their greening policies toward a scientifically optimized, performance-based urban forestry strategy.

The findings reflect the reality that Jakarta's intense UHI is a direct physical consequence of historical land-use decisions that minimized natural infrastructure in favor of rapid, unchecked development. The critically low 9.5\% canopy cover and the overwhelming dominance of impervious surfaces ensure maximum heat absorption and minimal evapotranspiration, structurally trapping heat in the urban environment.

Existing UGI exhibits severe fragmentation and low performance because urban planning policy has historically viewed green space as residual or incidental space rather than as a core, multi-functional piece of critical infrastructure. This perspective resulted in the deployment of small, scattered patches that are ecologically isolated and thermally inefficient.

The prevalence of non-native, monocultural species occurs because official planting guides prioritize ease of maintenance, rapid growth, and visual conformity, ignoring scientific data on evapotranspiration rates and native habitat provision (Alkadri et al., 2025). This policy choice directly compromises the ecological functionality of the UGI, explaining the documented failure to mitigate heat effectively or support native biodiversity.

The DBUF Model achieves superior results because its design is compelled by quantitative evidence (r=-0.75) to prioritize functional optimization over aesthetics. It deliberately leverages the non-linear, micro-climatic effects of dense, continuous canopy placement and the high-performance cooling capacity of native species, ensuring that limited space yields maximum ecological and thermal returns.

Future research must prioritize a cost-benefit analysis of DBUF implementation, quantifying the capital investment required for native species acquisition and planting against the projected savings in energy consumption and public health costs resulting from the predicted 3.5^{\circ}C cooling. This economic justification is crucial for persuading policymakers.

Policy recommendation demands the legal enactment of the DBUF Model into Jakarta's spatial planning regulations, making the integration of thermal performance and native biodiversity metrics mandatory for all new large-scale developments and public infrastructure projects (B. Yang et al., 2025). Legislation should enforce minimum functional density targets rather than simple area percentages.

Practical implementation requires the immediate development of a large-scale, municipal Native Species Nursery Program capable of supplying the high volume of climate-resilient, high-evapotranspiration native species prescribed by the DBUF Model (Aslanoğlu et al., 2025). This ensures the necessary biological stock is available to support the city's greening targets.

Global application should involve the adaptation of the DBUF Model's core computational framework for other hyper-dense, tropical megacities (e.g., Manila, Bangkok) through recalibration with local Landsat and native species data. This study must be leveraged to establish a new, performance-based global standard for tropical Urban Forestry.

CONCLUSION

The most critical finding is the validation of the Dual-Benefit Urban Forestry (DBUF) Model, which successfully demonstrated a statistically significant capability to simultaneously optimize micro-climate mitigation and native biodiversity enhancement. Simulation results predicted that DBUF-optimized layouts achieved a substantial 3.5^{\circ}C reduction in Land Surface Temperature, significantly outperforming the existing Urban Green Infrastructure's negligible 0.8^{\circ}C reduction, while concurrently predicting a 60\% increase in native bird species richness. This evidence quantitatively proves that the failure of current urban greening policy lies in aesthetic prioritization over functional design, compelling an immediate, scientifically-backed shift toward performance-based urban forestry.

The primary contribution of this research is the conceptual and technical creation of the Dual-Benefit Urban Forestry (DBUF) Model, a novel, GIS-based prescriptive methodology. This model uniquely bridges the analytical silo between urban climatology and urban ecology by integrating thermal performance metrics with native biodiversity requirements into a single computational framework. The DBUF Model provides urban planners in Jakarta and other tropical megacities with a scientifically rigorous, context-specific tool necessary to translate complex remote sensing data into simple, actionable design prescriptions, thereby maximizing the functional ecological return of limited urban space.

A primary limitation of this research is its reliance on a geospatial and computational simulation assessment, which, while validating the DBUF Model's predictive potential, does not measure the outcomes of real-world implementation. The performance assessment is based on simulated LST reduction and predicted biodiversity potential, not sustained field observations. Future research must, therefore, prioritize a comprehensive cost-benefit analysis of DBUF implementation, quantifying the capital investment required for native species acquisition against the projected long-term savings in energy consumption and public health costs resulting from the predicted 3.5^{\circ}C cooling effect. This economic justification is essential for ensuring successful policy adoption and legislative enactment of the model.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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