Simulation-Based Optimisation of External Plant Placement and Leaf Area Index for Building Indoor Thermal Comfort

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Abstract. In hot, humid regions like Nigeria, sustainable alternatives to energy-intensive air conditioning are crucial for achieving indoor thermal comfort. This research investigates the impact of external planter placement and Leaf Area Index (LAI) on enhancing comfort within a lecture room through simulation. The researchers employed a quantitative methodology using EnergyPlus in DesignBuilder to compare a base case without plants against four experimental cases, where planters were placed at varying distances of 300 mm to 1200 mm from the building's exterior wall. The researchers simulated each case across three LAI values (3, 4, and 5) and conducted a comparative analysis of thermal comfort metrics — operative temperature, Predicted Mean Vote (PMV), and Predicted Percentage Dissatisfied (PPD). The findings indicate that incorporating external planters consistently improved indoor thermal comfort relative to the base model. Planters situated closest to the exterior wall (300mm) yielded the most significant reduction in operative temperature and the lowest PMV and PPD values. While increasing LAI generally resulted in minor improvements, the distance of the planters exhibited a more pronounced influence on thermal performance. This study highlights the efficacy of strategically positioning external vegetation to enhance indoor thermal comfort in hot-humid climates. Simulation-based optimisation provides valuable insights for architects and urban planners in designing effective passive cooling strategies, considering both plant distance and plant density, thereby promoting sustainable building design and energy conservation.

Keywords: Indoor Thermal Comfort; External Plant Placement; Leaf Area Index (LAI); Simulation-Based Optimisation; Hot-Humid Climate.

INTRODUCTION

In hot-humid climates, achieving indoor thermal comfort is a pressing challenge due to high temperatures and humidity levels that increase cooling demands in buildings [1–3]. Traditional air conditioning systems significantly contribute to energy consumption and greenhouse gas emissions, further exacerbating the climate change problem, making sustainable alternatives imperative [4–6]. One promising solution is the strategic integration of external vegetation to regulate heat transfer, optimise airflow, and enhance indoor comfort passively [6, 7]. Plants provide shading, reduce solar heat gain, and improve microclimatic conditions around buildings, all of which contribute to thermal regulation [8–10]. According to authors [11], the effectiveness of this strategy depends mainly on the placement of vegetation and the Mean Leaf Area Index (LAI). This key parameter quantifies foliage density and its interaction with solar radiation.

Simulation-based optimisation is emerging as a powerful tool for evaluating and refining plant placement strategies to maximise thermal benefits [9, 11–13]. According to authors [14], utilising computational models, researchers can assess the impact of external greenery on indoor temperature modulation, airflow patterns, and humidity control in different building configurations. These simulations enable precise adjustments of planters, species selection, and foliage density, thus enhancing the efficiency of vegetation in reducing heat loads. In the Nigerian context, where hot-humid conditions prevail in many regions, incorporating simulation techniques to optimise vegetation strategies is particularly valuable for sustainable architectural practices [15].

Despite the potential benefits of external plant placement in mitigating indoor heat stress, standardised guidelines on plant selection and arrangement remain limited. Existing studies emphasise the role of urban greenery in outdoor thermal comfort but often overlook its impact on indoor environments [16]. Simulation models help bridge this gap by providing data-driven insights into the effectiveness of different vegetation configurations. In the study by the author [17], which analyses variations in LAI and plant positioning, architects and urban planners can develop evidence-based strategies that reduce cooling loads and enhance occupant comfort without excessive reliance on mechanical cooling.

Recent research has investigated various aspects of optimising plant integration for indoor thermal comfort. However, a direct replication of "Simulation-Based Optimisation of External Plant Placement and Leaf Area Index for Indoor Thermal Comfort" appears to be limited [18]. However, several studies address similar themes using computational methods. Authors [19] investigated the impact of indoor living walls with varying leaf-to-floor area ratios on occupant thermal comfort, finding significant improvements and potential HVAC energy savings, highlighting the importance of LAI. Similarly, researchers in China examined the effects of indoor plants with different characteristics (colour, odour, size) on human comfort using physiological measurements and surveys, indicating a preference for green, slightly scented, and small plants; this suggests that plant selection beyond LAI is crucial [18, 20, 21]. Furthermore, authors [22] demonstrated, through a four-month quasi-experiment, a significant positive impact of a substantial quantity of indoor plants on the thermal comfort of office workers across different seasons, suggesting that the amount and distribution of plants are key factors [22].

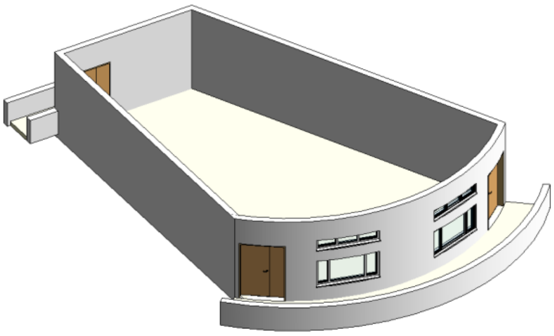
While these studies underscore the benefits of indoor plants on thermal comfort, they often focus on specific plant types (e.g., living walls) or general plant presence rather than a detailed optimisation of external plant placement influencing indoor conditions. Research on green facades has investigated the impact of Leaf Area Index (LAI) on the thermal performance of external green walls, revealing that increased LAI enhances cooling through shading and latent heat [23]. However, this focuses on the building envelope rather than direct outdoor placement. Therefore, a research gap exists in studies that specifically employ simulation-based optimisation to determine the ideal placement of external plants and their corresponding leaf area index, directly enhancing indoor thermal comfort, while considering factors such as solar radiation penetration, shading patterns, and the interplay with indoor environmental conditions. Therefore, this research has bridged this gap by adapting external plant optimisation techniques used in urban microclimate studies to the specific context of influencing indoor thermal environments.

This *study aims* to investigate a simulation-based optimisation of external plant placement and LAI for improving indoor thermal comfort in buildings. Computational modelling seeks to establish best practices for vegetation integration in tropical buildings. By demonstrating the thermal efficiency of strategically positioned greenery, this research contributes to sustainable design approaches that promote Indoor thermal comfort and, by extension, energy conservation and environmental resilience.

METHOD

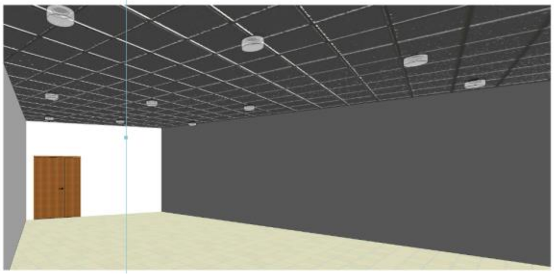
The study employed a quantitative research approach to evaluate the impact of external plant integration on indoor thermal comfort within a lecture room at the Faculty of Architecture, Bingham University, Karu. The study involved creating a base model (BM) that represents the existing scenario without plant integration, as shown in Figure 1. This BM was then compared against four cases (C1, C2, C3, and C4), each featuring planters at varying distances (300 mm, 600 mm, 900 mm, and 1200 mm, respectively) from the exterior wall. For each case, simulations were conducted across three different mean leaf area index (LAI) values (3, 4, and 5) to assess the influence of plant density on thermal performance.

Description of the Case Study Building. The single-sided, south-oriented lecture room located on the first floor of the Faculty of Architecture Building at Bingham University Karu (FAB) served as the case study room. The interior finishes included cream-coloured walls, cream-coloured vitrified tiles, a suspended ceiling, and brown metal doors. Existing windows consist of two aluminium frames with single-pane glass panels, accompanied by a clerestory window each, as shown in Figure 1.



Sectional aerial view

Interior view facing south windows



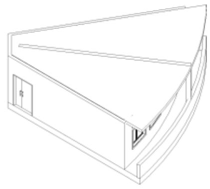
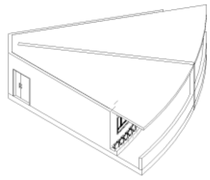
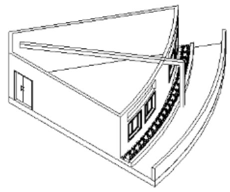
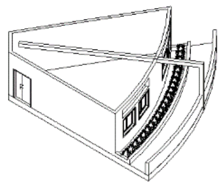
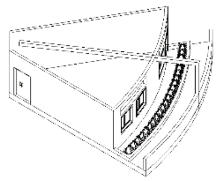
Interior view facing the north door

Pictorial view of the FAB

Figure 1 – Case study: Lecture Room in the FAB

Test Cases. The configuration for the experiment involved five cases: BM. C1, C2, C3, and C4 as shown in Table 1.

Table 1 – Test Cases

Case	Case Description	Diagram
BM	Without plant integration	
C1	Planter at a distance of 300mm from the exterior wall	
C2	Planter at a distance of 600mm from the exterior wall	
C3	Planter at a distance of 900mm from the exterior wall	
C4	Planter at a distance of 1200mm from the exterior wall	

Simulation. The simulation tool for this investigation was EnergyPlus in the DesignBuilder, a building performance simulation software. This software enabled the modelling of the lecture room geometry and the configuration of various planning scenarios. The researchers populated Karu's weather file in the software, configured the cases, and initiated the simulation. The simulations generated data on key thermal comfort metrics, including operative temperature, Predicted Mean Vote (PMV), and Predicted Percentage Dissatisfied (PPD). Operative temperature provided a measure of the average temperature experienced by occupants. At the same time, PMV and PPD quantified the occupants' perceived thermal sensation and the percentage of occupants likely to feel discomfort, respectively.

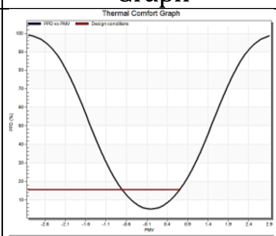
These metrics were crucial for evaluating the effectiveness of planter integration in enhancing indoor thermal comfort.

Data analysis involved a comparative assessment of the simulation results across the different cases and LAI values. The operative temperature, PMV, and PPD values for each scenario were compared to the baseline model to determine the extent to which planter integration improved thermal comfort. Furthermore, trends in thermal performance were analysed as a function of planter distance and LAI. This analysis is to identify the optimal planter placement and plant density for maximising cooling benefits and minimising thermal discomfort within the lecture room.

RESULTS AND DISCUSSION

Thermal Comfort Level of the Cases. The base model (BM), derived from simulations, represents a lecture room without any plant integration, as presented in **Помилка! Джерело посилання не знайдено.**. The simulation shows an operative temperature of 25.0°C, with a Predicted Mean Vote (PMV) of 0.71, suggesting that occupants would likely experience a slightly warm environment. The Predicted Percentage Dissatisfied (PPD) is 15.53%, indicating that a small percentage of occupants may find the thermal conditions uncomfortable. This baseline scenario establishes a reference point for evaluating how introducing planters, with varying leaf area indices and distances, impacts the indoor thermal comfort.

Table 2 – Thermal performance in the Base Model (BM)

	Plants Mean Leaf Area Index	Thermal Comfort Graph	Operative temperature (°C)	PMV	PPD (%)
Base Model (BM)	Without plant integration		25.0	0.71	15.53

The thermal performance data in Table 3 highlight the impact of plant density on indoor comfort within the C1 planter, positioned 300mm from the exterior wall. As the LAI increases from three to five, the operative temperature slightly decreases from 24.10°C to 24.00°C, suggesting a minor cooling effect. Concurrently, the predicted mean vote (PMV) decreases from 0.21 to 0.18, indicating a marginal improvement in thermal comfort. The expected percentage of dissatisfied (PPD) also shows a slight reduction, moving from 5.93% to 5.69%, which implies better occupant satisfaction with thermal conditions. These results suggest that a higher plant density may contribute to improved thermal comfort, albeit with relatively slight variations in environmental parameters.

Table 4 details the thermal performance of a building with a planter positioned 600mm from the exterior wall (C2), examining different plant mean leaf area indices. Regardless of whether the leaf area index is 3, 4, or 5, the operative temperature remains constant at 24.50°C. This consistent temperature results in a Predicted Mean Vote (PMV) of approximately 0.39, indicating that occupants would likely feel slightly warm but generally comfortable. As a result, the Predicted Percentage Dissatisfied (PPD) is relatively low, ranging from 7.98% to 8.24%, indicating that most occupants are likely to be thermally satisfied.

Even though the operative temperature remains constant, increasing the leaf area index results in a slight improvement in thermal comfort. When the mean leaf area index increases from 3 to 5, the PMV decreases slightly from 0.39 to 0.38, moving closer to the neutral comfort zone (PMV = 0). Similarly, the PPD decreases somewhat from 8.24% to 7.98%; this suggests that, while the operative temperature remains unchanged, the increased evapotranspiration from the larger leaf area subtly improves perceived thermal comfort and reduces the percentage of dissatisfied occupants by a slight amount.

Table 3 – Thermal performance in C1

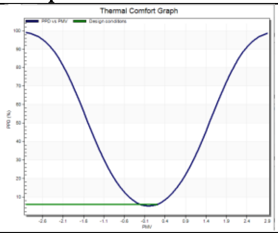
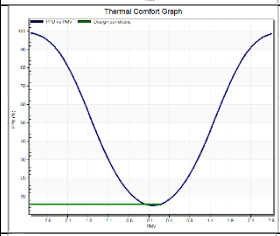
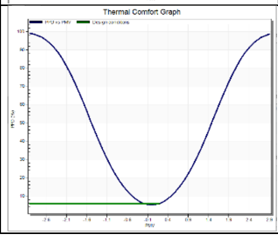
	Plants Mean Leaf Area Index	Thermal Comfort Graph	Operative temperature (°C)	PMV	PPD (%)
C1 Planter at a distance of 300mm from the exterior wall	3		24.10	0.21	5.93
	4		24,10	0.2	5.80
	5		24.00	0.18	5.69

Table 4 – Thermal performance in C2

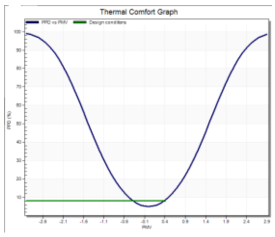
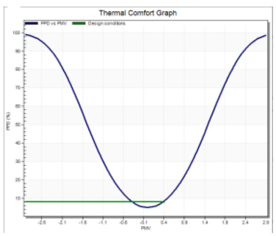
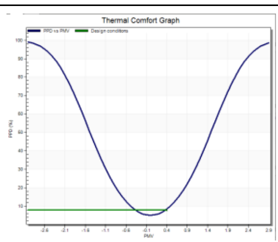
	Plants Mean Leaf Area Index	Thermal Comfort Graph	Operative temperature (°C)	PMV	PPD (%)
C2 Planter at a distance of 600mm from the exterior wall	3		24.50	0.39	8.24
	4		24.50	0.39	8.11
	5		24.50	0.38	7.98

Table 5 presents the thermal performance within a building integrated with a planter located 900mm from the exterior wall (Case C3) under varying plant mean leaf area index values. Notably, the operative temperature remains constant at 24.75°C across all three leaf area index values (3, 4, and 5); this suggests that for a planter at this specific distance, changes in the density of the plant foliage, as represented by the mean leaf area index, do not significantly influence the overall operative temperature within the space. However, while the operative temperature remains stable, the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) show a slight improvement with increasing leaf area index. As the mean leaf area index increases from 3 to 5, the PMV shifts from 0.49 to 0.45, moving closer to the neutral comfort zone (PMV = 0). Similarly, the PPD decreases from 9.95% to 9.30%, indicating a marginal reduction in the percentage of occupants likely to feel thermally uncomfortable; this suggests that, although the plants at this distance don't significantly alter the air temperature, the increased foliage may be subtly influencing other factors that contribute to thermal comfort, such as humidity levels or radiant temperature distribution within the space. The higher leaf area index likely leads to increased evapotranspiration, which can slightly raise humidity and potentially have a minor cooling effect on surrounding surfaces, contributing to the observed slight improvement in PMV and PPD despite the constant operative temperature.

In the case of C4, as presented in Table 6, where planters are 1200 mm from the exterior wall, the operative temperature remains steady at 24.90°C, regardless of changes in the plants' leaf area index (LAI). However, as the LAI increases from 3 to 5, there's a slight improvement in thermal comfort: the Predicted Mean Vote (PMV) decreases marginally, moving closer to the neutral comfort zone, and the Predicted Percentage Dissatisfied (PPD) also sees a slight reduction; this indicates that while air temperature is unaffected, denser planting slightly enhances occupants' perceived comfort.

Table 5 – Thermal performance in C3

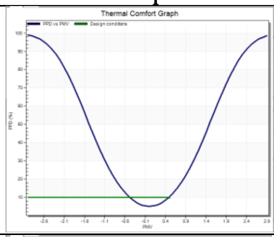
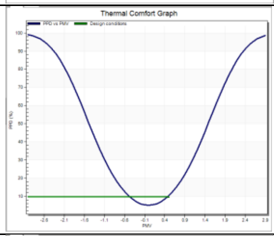
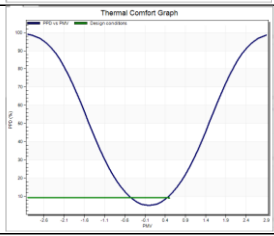
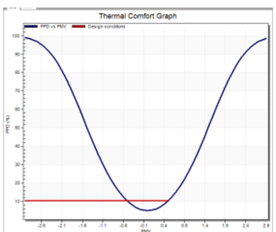
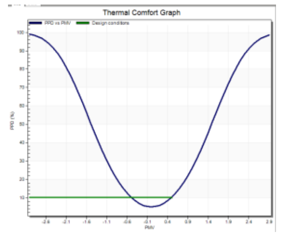
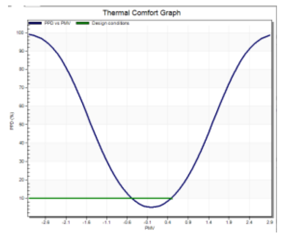
	Plants Mean Leaf Area Index	Thermal Comfort Graph	Operative temperature (°C)	PMV	PPD (%)
C3 Planter at a distance of 900mm from the exterior wall	3		24.75	0.49	9.95
	4		24.75	0.47	9.70
	5		24.75	0.45	9.30

Table 6 – Thermal performance in C4

	Plants Mean Leaf Area Index	Thermal Comfort Graph	Operative temperature (°C)	PMV	PPD (%)
C4 Planter at a distance of 1200mm from the exterior wall	3		24.90	0.51	10.48

	4		24.90	0.50	10.13
	5		24.90	0.49	10.06

Comparison of the thermal performance of the cases. Figure 2 illustrates the comparative thermal performance across the Base Model (BM) and Cases C1 through C4, highlighting the impact of planter integration and distance from the exterior wall on indoor thermal comfort. The Base Model, lacking plant integration, exhibits the highest operative temperature, leading to a slightly warm perception and a notable level of thermal discomfort among occupants. In contrast, introducing planters consistently lowers operative temperatures, with Case C1 (planters closest to the wall) demonstrating the most significant reduction. As the planter distance increases from C1 to C4, the operative temperature gradually rises, indicating a diminishing cooling effect.

The Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) follow similar trends. Case C1 exhibits the lowest PMV, corresponding to a neutral thermal sensation, and the lowest PPD, indicating high occupant satisfaction. As planter distance increases, both PMV and PPD rise, suggesting a shift towards warmer perception and increased discomfort. However, even at the most significant distance (C4), planter integration still improves thermal comfort compared to the BM. Overall, placing planters closer to the exterior wall yields the most substantial enhancement in thermal comfort, demonstrating the effectiveness of this passive cooling strategy in mitigating heat gain.

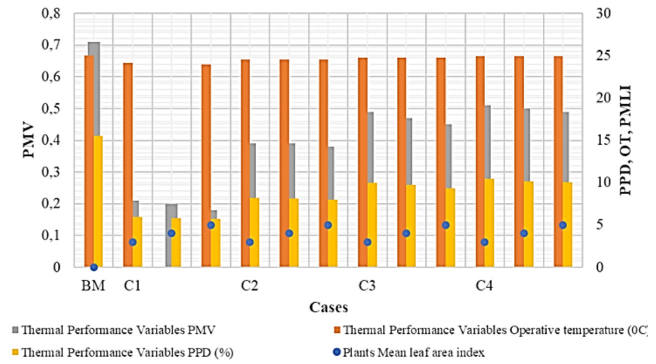


Figure 2 – Comparative Analysis of Thermal Comfort Performance

Notes: OT – Operative temperature, PMLI – Plants Mean leaf area index

CONCLUSIONS

The study confirms the effectiveness of integrating external planters as a passive cooling strategy to improve indoor thermal comfort in a hot-humid climate. The simulation results demonstrate that introducing planters, particularly when placed closer to the building's exterior, leads to a notable reduction in operative temperatures and enhances occupants' thermal comfort. This improvement is evident in lower Predicted Mean Vote (PMV) values, indicating a shift toward a more neutral thermal sensation, and reduced Predicted Percentage Dissatisfied (PPD) values, which signify greater occupant satisfaction. The findings align with the broader understanding that vegetation, through shading and evapotranspiration, can effectively mitigate heat gain and regulate the microclimate around buildings.

Furthermore, the research highlights the importance of optimising plant placement and Mean Leaf Area Index (LAI) to maximise these benefits. While increasing LAI generally contributes to improved thermal comfort, the study reveals that the distance of the planters from the exterior wall significantly influences their impact on indoor temperatures. Specifically, planters positioned closer to the building envelope exhibit a more pronounced cooling effect, highlighting the importance of evidence-based design strategies that consider both plant density and location to achieve optimal thermal performance.

In conclusion, this study contributes to the growing body of knowledge on sustainable architectural practices by demonstrating the efficacy of simulation-based optimisation in designing effective vegetation strategies. By providing quantitative data on the relationship between planter placement, LAI, and indoor thermal comfort, this research offers valuable insights for architects and urban planners seeking to reduce cooling loads and enhance occupant well-being in hot-humid climates like Nigeria. The findings support the adoption of external plant integration as a key component of sustainable building design, promoting both energy conservation and environmental resilience.

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