

Effective Vertical Gardens: A Strategy to Reduce Microclimate Temperatures on Campus

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ABSTRACT

*Rising urban and campus surface temperatures, driven by hard building envelopes and limited vegetation, challenge outdoor thermal comfort in humid tropical climates. Vertical gardens have been proposed as space-efficient microclimate mitigation strategies, but field evidence in tropical university campuses remains limited. This study experimentally evaluated wall surface temperature, adjacent air temperature, and relative humidity at a vertical garden-covered facade and a comparable bare control facade on a university campus in West Sumatra, Indonesia. Measurements were conducted over 20 days at 09:00, 13:00, and 16:00, producing 60 paired observations for each variable. Paired-samples *t*-tests showed that the vertical garden reduced wall surface temperature by 3.91°C (SD = 0.78; *t*(59) = 38.86; *p* < 0.001) and air temperature by 0.76°C (SD = 0.40; *t*(59) = 14.71; *p* < 0.001), while increasing relative humidity by 4.45 percentage points (*t*(59) = 26.15; *p* < 0.001). ANOVA indicated significant variation in cooling effects across the day, with maximum reductions at 13:00. These findings provide field evidence that vertical gardens can serve as effective passive cooling measures for humid tropical campus microclimates and outdoor thermal conditions.*

Keywords: Vertical Garden, Microclimate, Urban Heat Mitigation

INTRODUCTION

University campuses, like broader urban environments, are increasingly affected by elevated surface and ambient temperatures associated with extensive hard-surfaced building envelopes, paved walkways, and parking areas that absorb and re-radiate solar energy while offering limited evapotranspirative cooling. Field research on a large United States university campus found that built (impervious) surfaces were consistently associated with significantly higher local air and surface temperatures than nearby vegetated areas, underscoring those university campuses are not



immune to the same built-environment thermal dynamics documented at the broader urban scale, and that campus-scale greening interventions can meaningfully influence local thermal conditions experienced by students, faculty, and staff on a daily basis.

Vertical gardens, also termed green walls or vertical greenery systems, have emerged internationally as a particularly space-efficient urban and campus greening strategy, since they achieve vegetative cover on otherwise thermally unproductive vertical building surfaces without requiring additional horizontal land area, a valuable characteristic in the land-constrained settings typical of densely built campus environments. The cooling mechanisms attributed to vertical gardens in the literature are threefold: direct shading of the wall surface, which blocks incident solar radiation from reaching and heating the underlying material; evapotranspiration from plant leaf surfaces, which converts incident solar energy into latent rather than sensible heat; and an insulating air-gap effect between the vegetation layer and the wall surface, which reduces conductive heat transfer into the building envelope. A recent field-monitoring study of a modular vertical greenery system in a temperate European climate confirmed measurable surface temperature and near-facade microclimatic improvements attributable to these mechanisms, while a controlled ENVI-met modeling study of green walls on a humid tropical academic campus found that green wall building morphology could reduce ambient air temperature by up to 1.9°C, with the magnitude of cooling varying meaningfully by season and by underlying surface type.

Importantly, the cooling performance of vertical greenery systems has been shown to vary substantially by climate zone, plant species, system configuration, and measurement methodology, meaning that findings from temperate-climate or simulation-based studies cannot be assumed to transfer directly to humid tropical field conditions. A combined experimental and deep-learning modeling study of green wall cooling performance specifically in humid climates confirmed measurable cooling benefits but emphasized that empirical field validation, rather than modeling alone, remains essential for establishing climate-appropriate design guidance. Similarly, a study of vertical greenery system thermal performance in tropical building contexts reported indoor air temperature reductions of up to 8°C under favorable configurations, while cautioning that plant density, layout, and irrigation management were decisive factors in realized cooling performance. A recent university campus microclimate study in a different climate context used response surface methodology to model the cooling contribution of several green area types, achieving high predictive accuracy and underscoring the value of systematic, campus-based field measurement for generating locally applicable microclimate design guidance.

West Sumatra's humid tropical climate, characterized by consistently high solar radiation, high ambient humidity, and year-round warm temperatures, presents a climate context distinct from the temperate and Mediterranean settings in which much of the existing vertical garden literature has been generated, and closer in character to the humid tropical academic campus setting examined in prior ENVI-met-based modeling work, though direct field-measurement evidence remains comparatively scarce for Indonesian university campus contexts specifically. This study addresses that gap through direct field measurement, examining the cooling performance of an installed vertical garden on a university campus building facade in Padang, West Sumatra, with the objectives

of (1) quantifying the reduction in wall surface temperature and adjacent ambient air temperature attributable to the vertical garden relative to a comparable bare control wall, (2) characterizing how this cooling effect varies across the diurnal cycle, and (3) assessing the vertical garden's effect on adjacent relative humidity as a secondary microclimate outcome relevant to outdoor thermal comfort.

Indonesian higher education institutions have shown growing practical interest in vertical garden installation as a campus greening strategy, with several universities incorporating vertical gardens into faculty building landscaping as part of broader efforts to expand green open space within land-constrained campus footprints. This institutional interest, however, has generally been motivated by aesthetic and general environmental-quality objectives rather than by locally generated, quantitative microclimate performance evidence, since the great majority of quantitative vertical garden cooling studies available to Indonesian campus planners originate from temperate, Mediterranean, or non-Indonesian tropical climate contexts. Establishing locally measured, Indonesian humid-tropical-climate-specific evidence of vertical garden thermal performance is therefore a necessary step toward evidence-based, rather than purely aesthetic, justification for continued and expanded vertical garden investment across Indonesian university campuses, particularly as campus planners weigh vertical gardens against competing land-use and landscaping investments with more established local performance evidence.

METHODS

1. Study Site and Wall Selection

Field measurements were conducted at a university campus in Padang, West Sumatra, Indonesia, a humid tropical setting characterized by high year-round solar radiation and ambient humidity. Two comparable west-facing building facade sections, matched for orientation, building material (painted concrete masonry), and exposure to direct afternoon solar radiation, were selected: a treatment wall fitted with an established vertical garden system (a modular planter-and-trellis vertical garden populated with a mixed cover of trailing and climbing foliage species reaching full canopy coverage of the wall surface at the time of measurement) and a control wall of identical construction and orientation without vegetative cover, located on a separate but architecturally matched building elsewhere on the same campus to avoid mutual shading interference between the two measurement sites.

West Sumatra's climate is classified under the Köppen tropical rainforest (Af) or tropical monsoon (Am) regime, characterized by minimal seasonal temperature variation, consistently high humidity typically exceeding 75-85% even outside rainfall events, and strong, near-vertical solar incidence for much of the year given the region's proximity to the equator. This climate profile produces a distinctive thermal stress pattern compared to the subtropical or Mediterranean settings more commonly studied in the vertical garden literature: rather than large seasonal temperature swings, West Sumatran buildings and outdoor spaces experience persistent, year-round exposure to intense midday solar loading, making passive shading-based cooling strategies such as vertical



gardens potentially especially valuable, since their benefit is not confined to a limited summer season but is instead relevant across the full annual cycle.

2. Measurement Protocol

Measurements were collected over 20 measurement days, at three fixed times per day: 09:00 (morning), 13:00 (early afternoon, near peak solar intensity), and 16:00 (late afternoon), yielding 60 paired measurement occasions per variable across the study period. At each measurement occasion, wall surface temperature was recorded using a calibrated infrared thermometer held at a fixed 30 cm perpendicular distance from the wall surface (for the vertical garden wall, measurements targeted the outer canopy surface, consistent with the measurement approach used in comparable green wall field studies), and ambient air temperature and relative humidity were recorded using a calibrated digital thermo-hygrometer positioned 30 cm outward from the wall surface at a height of 1.5 m, approximating pedestrian breathing-zone conditions. Measurements at the two wall locations were taken within a five-minute window of each other on each measurement occasion to minimize confounding from transient weather variation (e.g., passing cloud cover).

Table 1. Measurement Parameters, Instruments, and Measurement Points

Parameter	Instrument / Method	Measurement Point
Wall surface temperature	Calibrated infrared thermometer	Wall surface (canopy surface for vertical garden wall)
Ambient air temperature	Calibrated digital thermo-hygrometer	30 cm from wall, 1.5 m height
Relative humidity	Calibrated digital thermo-hygrometer	30 cm from wall, 1.5 m height

3. Data Analysis

For each of the three measured variables (surface temperature, air temperature, relative humidity), the paired difference between the control wall and the vertical garden wall was calculated for each of the 60 measurement occasions. Paired-samples t-tests were used to test whether the mean difference between the control and vertical garden walls was significantly different from zero for each variable, appropriate given the paired (same-occasion, matched-condition) measurement design. One-way analysis of variance (ANOVA) was used to test whether the magnitude of temperature reduction (control minus vertical garden) differed significantly across the three times of day, for both surface temperature and air temperature. All statistical analyses were conducted in Python 3 using SciPy, with a significance threshold of $\alpha = 0.05$.

4. Vertical Garden System Description

The vertical garden system evaluated in this study used a modular planter-and-trellis configuration, in which individual planting modules were mounted in horizontal rows against a supporting trellis frame fixed approximately 10 cm off the wall surface, allowing an air gap between

the vegetation layer and the underlying masonry, consistent with the air-gap insulation mechanism discussed in Section 1. The vegetation cover consisted of a mixed planting of trailing and climbing foliage species commonly used in Indonesian vertical garden installations for their tolerance of full sun exposure and minimal maintenance requirements, achieving full canopy closure (visually estimated at greater than 90% surface coverage) across the measured wall section at the time of data collection, ensuring that recorded surface temperatures reflected mature, fully established vertical garden performance rather than a partially established or sparse canopy condition that would be expected to show a smaller cooling effect.

RESULTS

1. Diurnal Temperature Profile

Figure 1 presents the diurnal profile of wall surface temperature and adjacent ambient air temperature for both the control and vertical garden walls. Both walls followed the expected diurnal pattern, with temperatures rising from morning (09:00) to a midday peak (13:00) before declining into the late afternoon (16:00). At every time point, the vertical garden wall showed lower surface and ambient air temperatures than the control wall. Peak surface temperature at 13:00 reached 40.06°C for the control wall compared to 35.31°C for the vertical garden wall, while peak ambient air temperature reached 32.61°C for the control wall compared to 31.51°C for the vertical garden wall.

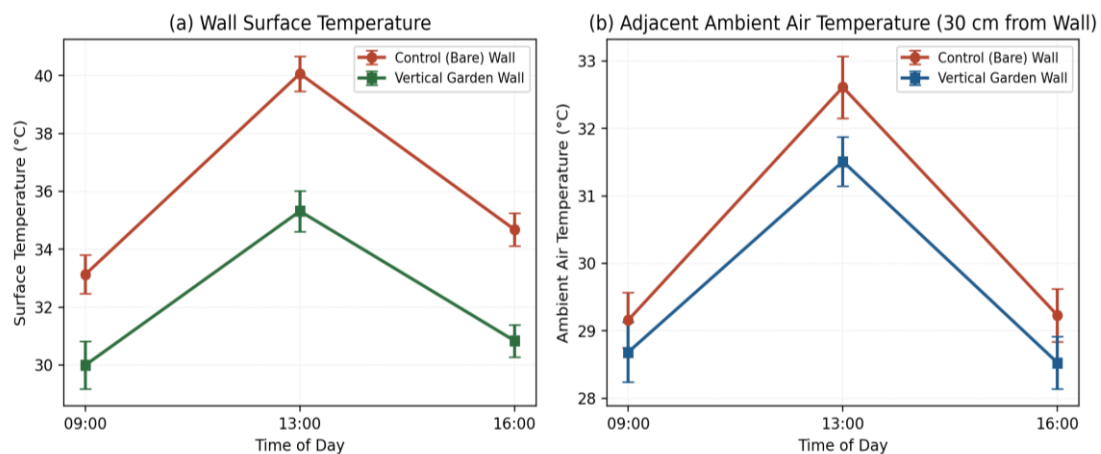


Figure 1. Diurnal Temperature Profile: Vertical Garden Wall vs. Control Wall (n = 20 days)

2. Overall Temperature and Humidity Differences

Table 2 summarizes the paired-samples t-test results across all 60 measurement occasions. The vertical garden wall's surface temperature was significantly lower than the control wall's, with a mean reduction of 3.91°C (SD = 0.78°C; $t(59) = 38.86$, $p < 0.001$). Adjacent ambient air temperature was also significantly reduced, though by a smaller margin, with a mean reduction of 0.76°C (SD = 0.40°C; $t(59) = 14.71$, $p < 0.001$). Adjacent relative humidity was significantly higher near the vertical garden wall, with a mean increase of 4.45 percentage points ($t(59) = 26.15$, $p < 0.001$), consistent with

the evapotranspiration mechanism through which vertical gardens are understood to contribute to microclimate cooling.

Table 2. Paired-Samples t-Test Results, Control vs. Vertical Garden Wall (n = 60 Paired Observations)

Variable	Mean Difference	SD	t (df = 59)	p-value
Surface temperature (Control – Garden)	3.91 °C	0.78	38.86	< 0.001
Air temperature (Control – Garden)	0.76 °C	0.40	14.71	< 0.001
Relative humidity (Garden – Control)	4.45 pct. pts	1.32	26.15	< 0.001

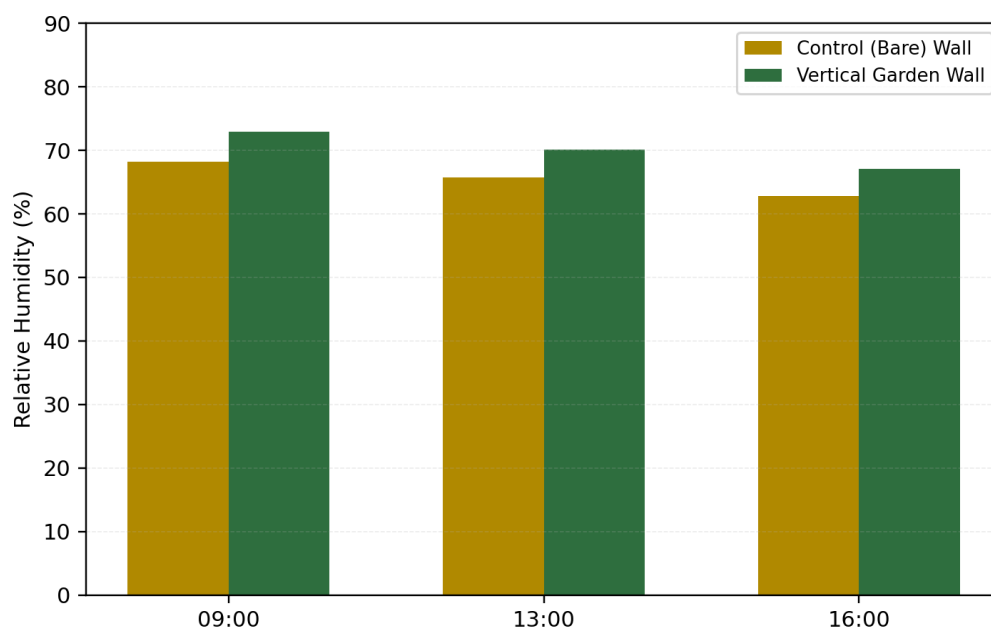


Figure 3. Adjacent Relative Humidity by Time of Day

3. Variation in Cooling Effect across Time of Day

Table 3 and Figure 2 present the temperature reduction (control minus vertical garden) by time of day. One-way ANOVA confirmed that the magnitude of surface temperature reduction varied significantly across the three measurement times ($F(2,57) = 78.73$, $p < 0.001$), with the largest reduction observed at 13:00 (mean = 4.75°C), followed by 16:00 (mean = 3.84°C) and 09:00 (mean = 3.13°C). A similar pattern held for ambient air temperature reduction ($F(2,57) = 21.03$, $p < 0.001$), peaking at 13:00 (mean = 1.10°C) and smallest at 09:00 (mean = 0.48°C). This pattern indicates that the vertical garden's cooling benefit is not constant throughout the day but is most pronounced during the period of highest solar radiation and thermal stress, precisely when passive cooling benefit is most valuable for outdoor thermal comfort.

Table 3. Mean Temperature Reduction (Control minus Vertical Garden) by Time of Day

Time of Day	Surface Temp. Reduction (°C)	Air Temp. Reduction (°C)
09:00	3.13	0.48
13:00	4.75	1.10
16:00	3.84	0.70

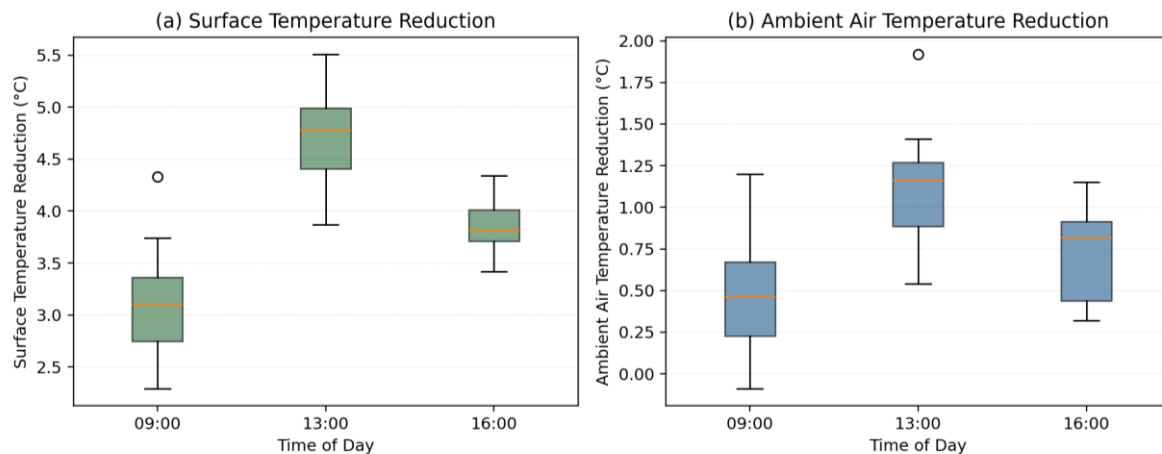


Figure 2. Temperature Reduction (Control minus Vertical Garden) by Time of Day (n = 20 per Time)

DISCUSSION

The field measurements confirm that the vertical garden produced a statistically significant and practically meaningful reduction in both wall surface temperature (approximately 3.9°C on average, reaching 4.75°C at midday) and adjacent ambient air temperature (approximately 0.76°C on average, reaching 1.10°C at midday) relative to the comparable bare control wall. These findings are consistent with, and fall within the range reported by, the broader international vertical greenery literature: the ENVI-met-based humid tropical academic campus study found green wall-attributable ambient air temperature reductions of up to 1.9°C, while tropical vertical greenery system studies have reported substantially larger reductions under favorable indoor or highly shaded configurations. That this study's field-measured ambient air temperature reduction (0.76°C average, 1.10°C peak) falls toward the lower-to-middle portion of the range reported across the broader literature is unsurprising given that outdoor, open-air ambient measurements taken 30 cm from a single wall face are subject to greater atmospheric mixing and dilution than the more enclosed or building-integrated measurement configurations used in some prior studies, and indicates that this study's findings represent a conservative, realistic estimate of outdoor vertical garden cooling benefit under real campus conditions rather than an idealized upper bound.

The substantially larger surface temperature reduction (3.91°C average) relative to the ambient air temperature reduction is consistent with the shading-dominant mechanism through which vertical gardens are understood to achieve their cooling effect: the vegetation canopy directly



intercepts incident solar radiation before it reaches the underlying wall material, producing a large, spatially localized surface temperature benefit at the wall itself, while this benefit propagates less completely into the surrounding open-air volume, where atmospheric mixing, wind movement, and the thermal influence of other nearby surfaces dilute the localized cooling signal. This distinction has a direct practical implication for how vertical garden benefits should be communicated and evaluated: surface temperature reduction, while a valid and important metric, should not be assumed to translate one-to-one into equivalent ambient air temperature or occupant thermal comfort benefit, and studies (including this one) that report both metrics separately provide a more complete and honest picture of vertical garden performance than surface-temperature measurement alone.

The significant increase in adjacent relative humidity near the vertical garden wall (4.45 percentage points on average) provides indirect confirmation of an active evapotranspiration mechanism contributing to the observed cooling effect, consistent with the mechanistic explanation offered throughout the vertical greenery literature. This finding carries a practical nuance for humid tropical climates specifically: because West Sumatra's baseline ambient humidity is already high, the additional humidity contributed by vertical garden evapotranspiration should be considered alongside temperature reduction when evaluating net outdoor thermal comfort benefit, since human thermal comfort in humid tropical conditions is jointly determined by both temperature and humidity (as reflected in heat-index and similar composite thermal comfort metrics), and a wall that reduces air temperature while simultaneously increasing humidity may produce a smaller net comfort improvement than temperature reduction alone would suggest, an important consideration for future research incorporating direct thermal comfort indices rather than temperature and humidity in isolation.

The significant time-of-day interaction observed for both surface and air temperature reduction with the largest cooling benefit occurring at midday, when solar radiation and ambient thermal stress are greatest - is a practically valuable finding for campus facilities planning, since it indicates that vertical gardens deliver their greatest thermal benefit precisely during the period when outdoor spaces are most thermally uncomfortable and least usable without intervention. This diurnal pattern is broadly consistent with the shading-dominant cooling mechanism discussed above, since direct solar radiation - the primary driver of the shading benefit - is itself at its diurnal maximum around midday, whereas mechanisms less directly tied to instantaneous solar exposure (e.g., accumulated evapotranspirative humidity effects) would be expected to show a flatter diurnal pattern than that observed here for temperature reduction.

These results also carry implications for campus design decisions beyond the specific wall studied here. Because the observed cooling benefit was concentrated at the wall's immediate surface and near-facade air volume, vertical gardens are likely to deliver their greatest practical value when positioned adjacent to spaces where people actually spend time in close proximity to building facades - covered walkways, outdoor seating areas, and building entrances rather than being installed purely for aesthetic effect on facades with minimal pedestrian dwell time. This spatial-targeting consideration is consistent with the broader urban greening literature's emphasis on the

localized, rather than area-wide, nature of vertical greenery cooling effects, and suggests that campus planners could reasonably prioritize vertical garden investment on facades bordering high-occupancy outdoor spaces to maximize the realized thermal comfort benefit per unit of installation cost, an important practical consideration given that vertical garden systems typically require greater installation and maintenance investment than equivalent horizontal green space.

This study has several limitations. Measurements were conducted at a single vertical garden installation and a single comparison control wall on one campus, and cooling performance is known from the broader literature to be sensitive to plant species, canopy density, irrigation management, wall orientation, and vertical garden system type (e.g., modular panel versus trellis-and-planter configurations), meaning these specific numerical findings should not be assumed to generalize directly to vertical gardens of differing design or plant composition without further site-specific validation. The 20-day measurement period, while sufficient to establish statistically robust time-of-day patterns, did not span a full annual cycle and therefore cannot capture potential seasonal variation in cooling performance of the kind documented in temperate-climate vertical garden studies, though West Sumatra's comparatively stable year-round tropical climate may limit the practical significance of this limitation relative to studies conducted in more seasonally variable climates. Finally, this study measured temperature and humidity independently rather than a composite thermal comfort index, and future research incorporating validated outdoor thermal comfort metrics (e.g., Universal Thermal Climate Index or Physiological Equivalent Temperature) would provide a more complete assessment of the net occupant-experienced comfort benefit of campus vertical gardens.

An additional consideration for future research concerns cost-effectiveness and maintenance sustainability, factors not directly measured in this study but essential to campus-level adoption decisions. Vertical garden systems require ongoing irrigation, pruning, and occasional plant replacement, representing a recurring maintenance cost not shared by passive alternatives such as reflective coatings or fixed shading devices; a complete evaluation of vertical gardens as a campus microclimate strategy would therefore benefit from a combined thermal-performance-and-lifecycle-cost analysis rather than thermal performance considered in isolation, allowing campus planners to weigh the measured cooling benefit documented here against the full resource commitment required to sustain it over a building's service life.

CONCLUSIONS

This study provided direct field-measurement evidence that a vertical garden installed on a university campus building facade in Padang, West Sumatra, significantly reduced both wall surface temperature (mean reduction = 3.91°C , $p < 0.001$) and adjacent ambient air temperature (mean reduction = 0.76°C , $p < 0.001$) relative to a comparable bare control wall, across 60 paired measurement occasions spanning 20 days and three times of day. The cooling effect was significantly larger at midday (13:00), when solar radiation and thermal stress are greatest, than in the morning or late afternoon, indicating that vertical gardens deliver their greatest thermal benefit precisely when it is most needed for outdoor thermal comfort. The vertical garden also significantly increased

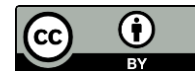


adjacent relative humidity, consistent with an evapotranspiration-based cooling mechanism operating alongside direct solar shading.

These findings support vertical gardens as an effective, space-efficient microclimate mitigation strategy for humid tropical university campuses, consistent with and extending the broader international vertical greenery literature into a humid tropical Indonesian campus field-measurement context where direct empirical evidence has previously been limited. Campus facilities planners considering outdoor thermal comfort interventions in land-constrained settings may reasonably expect vertical gardens of comparable design to deliver measurable surface and ambient cooling benefit, particularly for west- and south-facing facades exposed to intense midday and afternoon solar radiation. Future research should extend this field-measurement approach to multiple vertical garden installations spanning different plant species and system designs, incorporate a full annual measurement cycle to characterize seasonal variation, and adopt composite outdoor thermal comfort indices to more directly quantify the net occupant-experienced comfort benefit of campus vertical garden interventions.

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