

Microclimate and User Perception in Vegetated and Non-Vegetated Educational Courtyards: A Paired Field Study in Visakhapatnam, India

K Sai Sri Laasya¹, Sai Gautham Kumar Gujjula²

¹ M.Arch (Sustainable Architecture) Student, School of Architecture, GITAM, Visakhapatnam, India

² Assistant Professor, School of Architecture, GITAM, Visakhapatnam, India

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ABSTRACT

Courtyards can moderate heat in dense educational settings, yet field evidence from warm-humid Indian campuses remains limited and is rarely integrated with user perception. This study compared a vegetated courtyard (GSB) and a non-vegetated courtyard (SACB) in Visakhapatnam through repeated air-temperature and relative-humidity measurements and an aggregate post-occupancy survey. Four spatial points were monitored at 09:00 am and 12:00 pm on ten dates between 23 July and 8 August 2026. Point readings were averaged for each courtyard-session and paired by date and time to avoid pseudo-replication. GSB was cooler on every date, with mean differences of -0.72°C at 09:00 am (95% CI -1.03 to -0.41 ; $p=0.0005$) and -1.20°C at 12:00 pm (95% CI -1.76 to -0.65 ; $p=0.0009$). Relative humidity was higher at GSB by 3.52 and 3.39 percentage points, respectively. Positive ratings for comfort during stays of at least 30 minutes and suitability for activities were both 90.9% at GSB and 20.0% at SACB. Physical and perceptual evidence therefore converged on a cooler, more usable microclimate at GSB. However, the observational design cannot separate vegetation from geometry, materials, shade and airflow. The study offers a transparent paired-analysis framework for small campus microclimate datasets and identifies priorities for stronger causal and thermal-comfort assessment.

Keywords: Courtyard microclimate, Outdoor thermal comfort, Post-occupancy evaluation, Warm-humid climate

INTRODUCTION

Courtyards allow circulation, waiting, informal learning, and social interaction in educational buildings. Exposed surfaces can increase short-wave and long-wave radiant loads in hot weather, while enclosure can provide self-shading but restrict airflow and delay heat release. Courtyard performance depends on the relation between geometry and orientation, as well as materials, vegetation, and weather (Al-Hafith et al., 2017; Diz-Mellado et al., 2023; Marchi et al., 2023). Planting is a valid strategy, as tree canopies can block incoming solar radiation and evapotranspiration can lower surrounding surface temperatures when enough water is present. Poorly positioned vegetation, however, can result in increased humidity or reduced airflow. Wind speed and mean radiant temperature have a significant influence on human heat exchange and the air temperature alone is not sufficient to estimate thermal comfort in hot humid conditions. Either PET or UTCI and measurements of the mean radiant temperature and wind speed would be needed (Karimi et al., 2023; Sun et al., 2021; Unal & Middel, 2025). The benefits of combined tree-and-shade interventions reported from hot-arid and Mediterranean climates cannot be directly generalized to coastal India.

(Peter & Kaushik, 2024) reported reductions of $5\text{--}7^{\circ}\text{C}$ in mean radiant temperature (MRT) within the vegetated courtyard of an educational institution in the warm-humid city of Tiruchirappalli, demonstrating

contextual relevance to coastal cities of India, while highlighting the importance of incorporating radiant metrics into outdoor thermal studies. Matched comparative field studies and measurements linking environmental conditions with user perceptions remain limited. This study compared air temperature and relative humidity in the GSB and SACB courtyards at 09:00 and 12:00, assessed differences in morning-to-noon warming, and examined whether the environmental patterns were consistent with aggregate user perceptions. The four measurement points were treated as spatial subsamples and averaged within each session; comparisons used sessions matched by date and time to avoid inflating the sample size.

LITERATURE REVIEW

Courtyard Microclimate as a Coupled Design Problem

The courtyard microclimate depends on the air movement, radiation, convection, evapotranspiration and thermal storage. Geometry determines how much sunlight can enter and the duration of shading. The width-to-height ratio determines annual shading (Al-Hafith et al., 2017) and aspect ratio is related to thermally comfortable hours found across 20 courtyards in Spain (Diz-Mellado et al., 2023).

(Marchi et al., 2023) found that perimeter openings altered the ambient air temperature by 1°C and the tree density by up to 2°C (highest increase in daytime PET as shading from tree is highest). Vegetation effects should therefore be interpreted in relation to both radiant exposure and airflow within the courtyard.

Materials also alter exposure levels; high reflectance may reduce the air temperature and increase the PET level of pedestrians due to radiation (Lopez-Cabeza et al., 2022). Trees have a substantial influence on outdoor thermal comfort in terms of reflected radiation level and shade (Karimi et al., 2020; Mohammad et al., 2021). Research in Phoenix has found that shade can lower the MRT value as much as 10°C. Trees and ground cover can also influence the incident radiation and the directions of airflow (Unal & Middel, 2025). Air temperature alone does not fully describe outdoor thermal comfort.

Vegetation Configuration, Coverage and Mechanisms

Vegetation changes tree shade, evapotranspiration and aerodynamic roughness depending on canopy size, density, species, irrigation needs and vertical stratification. The CFD model was validated to assess the effects of planting coverage, height and covered area in the courtyards and the adjoining rooms (Sun et al., 2021). In a hot-humid courtyard, trees provided strong morning and midday cooling and humidification, however mixed vegetation changed flow regime dynamically during the day (Qin & Zhou, 2025; Zheng et al., 2024) reported similar results, with seasonally differentiated outcomes of mixing evergreen and deciduous trees, warning against a uniform greening strategy. Moreover, (Li et al., 2019) discussed the value of horizontal and vertical greening in existing buildings.

On the question of how best to shade educational courtyards and open spaces, several studies support combining vegetation and shading. In the study of some schools' courtyards (Mahmoud & Abdallah, 2022) found the most effective method of PET reduction was by a combination of vegetation and shading. On a campus at Assiut University, measurements, questionnaires and modelling studies showed that planting trees to achieve 50% semi-shading outperformed individual interventions, reducing the PET by 2°C (Abdallah, 2022). Also, from campus in hot-arid Egypt, (Gomaa et al., 2024) found energy savings under 60% vegetation coverage using modelling. The study also reported a significant reduction in PET and mean radiant temperature at this vegetation coverage. These findings support considering vegetation coverage and shade provision together, although their applicability to other climates requires further evaluation (Gomaa et al., 2024)

Field Measurement and User Perception

Field monitoring determines whether modelled benefits occur under actual weather and occupancy conditions. (Melas et al., 2021) found greater cooling during warm periods, with smaller differences

between vegetated and non-vegetated spaces in Athens compared to non-vegetated locations. Surface roughness increases, leading to more turbulent than laminar flow. and enhances convective heat transfer. Vegetated surfaces remained cooler during warmer periods. relatively stable leaf and air temperatures, radiation interception and shading effects. These processes can reduce mean radiant temperature. (Peter & Kaushik, 2024) provide a relevant climatic comparison: a pair of adjacent educational courtyards in the warm-humid climate of Tiruchirappalli. They reported a substantially greater reduction in mean radiant temperature due to vegetation. They also emphasized that season, shade and reference selection are important in determining the observed magnitude of the benefit. Nevertheless, the study demonstrates the potential benefit of vegetation under climatically comparable conditions.

User perception cannot be inferred from air temperature. (Karimi et al., 2023), combining 680 surveys with measurements, found that standard indices did not fully reproduce local thermal sensation at high temperatures. (Salameh et al., 2020) linked school-courtyard design with student satisfaction, highlighting psychological and functional dimensions. The present study adopts this objective-subjective approach but does not claim adaptive comfort modelling because only aggregate survey data were available.

METHODOLOGY

Study Setting and Comparative Design

Comparative observations were made in two courtyards of an educational campus in Visakhapatnam. Figure 1 summarises the study framework, including the matched monitoring programme and the environmental and post-occupancy comparisons. GSB represented the vegetated condition and SACB represented the non-vegetated condition. Figure 2 presents the site layouts and photographs illustrating the courtyard configurations and vegetation conditions at GSB and SACB. Verified information was unavailable for dimensions, orientation, aspect ratio, sky-view factor, surface fractions and tree species, canopy coverage and irrigation schedule. Thus, these characteristics were neither inferred nor statistically adjusted. The study assessed site-level microclimatic differences without isolating the independent effect of vegetation from other courtyard characteristics.

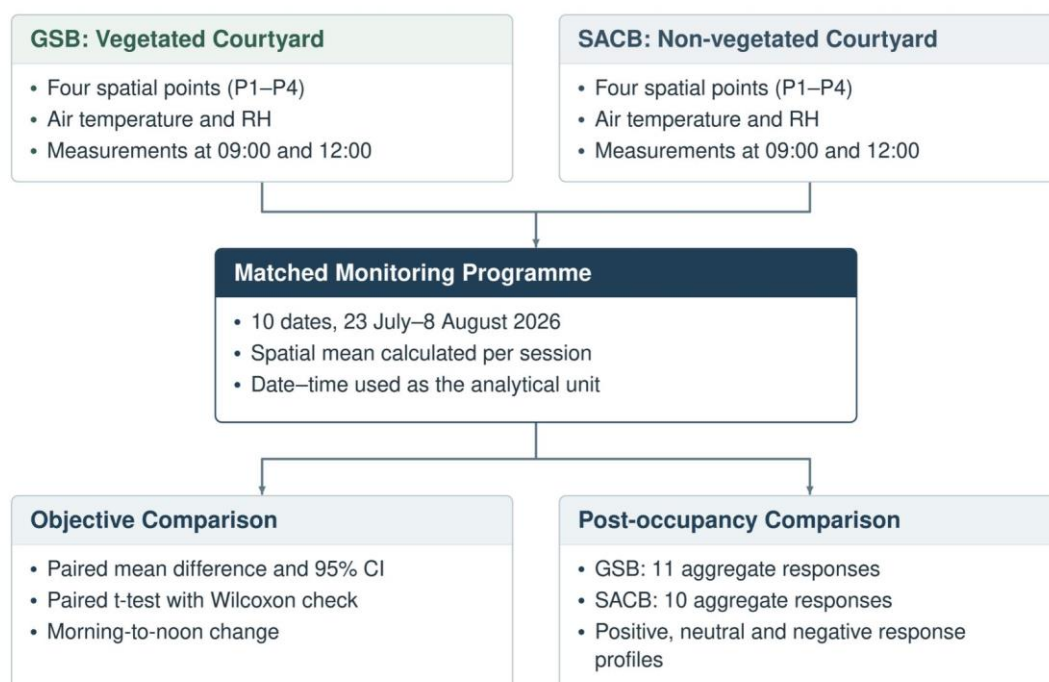


Figure 1: Field-monitoring and analytical framework for the comparative assessment of the GSB and SACB courtyards

Environmental Monitoring

Measurements were made on ten monitoring dates: 23, 24, 27 and 31 July and 3-8 August 2026. Air temperature and relative humidity at P1-P4 in both courtyards were measured at 09:00 am and 12:00 pm on each date, yielding 20 sessions and 80-point readings per variable were collected at each site. Outdoor extrema recorded were between 26 and 29 °C for minimum temperature, 31 and 35 °C for maximum temperature, 67 and 86% for minimum RH and 74 and 93% for maximum RH. As these were daily extrema and not simultaneous readings, they provided contextual weather information and were not utilized in calculating courtyard cooling intensity.

The records did not include information on the model, accuracy, calibration, response time, sensor height, shielding, stabilization period and simultaneous measurement status of the instruments. Such details, in particular shielding and height, should be obtained from the field log prior to submission.

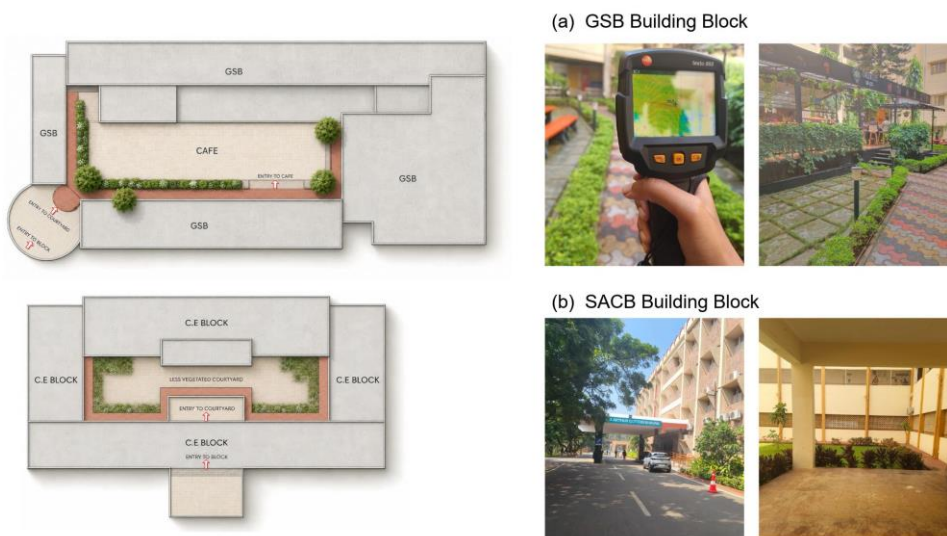


Figure 2: Comparative site layouts and field conditions of the vegetated GSB and Non-vegetated SACB courtyards

Post-occupancy survey

Aggregated survey results were available for 11 GSB and 10 SACB users (approximately 90% students). GSB had a higher proportion of frequent users than SACB (30.0% vs. 70.0% were infrequent or first-time visitors). The five-point survey items assessed thermal sensation, humidity, shade, comfort for at least 30-minute stays, suitability for activity, perceived influence of vegetation or hardscape, and overall quality. Ratings of 4–5 were classified as positive, 3 as neutral and 1–2 as negative. The survey results were analyzed descriptively and no inferential tests or adjustments were made as only aggregate charts were available and question wording differed between sites.

Data quality control and statistical analysis

The data were checked for completeness, for consistent units and plausibility of single readings. SACB RH at P1 was measured at 09:00 am on 23 July as 31% while P2-P4 were 72.0, 72.0 and 71.9% and the outdoor daily RH range was 72–74%. The probable error was excluded without imputation and the other three points defined the mean for the session. No temperature values were removed.

The exclusion affected one of the 80 SACB RH observations, and the recorded value remains to be verified against the original field log. The courtyard session mean was calculated by averaging the available P1–P4

readings by site, date, and time. GSB and SACB were then paired by date and time. The analysis included means, standard deviations, paired differences (GSB minus SACB), two-sided 95% confidence intervals, paired t-tests and Cohen's d_z . For non-parametric sensitivity checks, we used Wilcoxon signed-rank tests, with 10 matched pairs at each observation time. Table 1 summarises the monitoring design, analytical units and data quality-control procedures.

Table 1: Monitoring design, analytical approach and quality-control procedures

Component	Specification	Analytical implication
Sites	GSB vegetated; SACB non-vegetated	Two-site observational comparison
Repeated dates	10 dates between 23 July and 8 August 2026	Date used for matched pairing
Times	09:00 am and 12:00 pm	Time-stratified primary analysis
Spatial points	P1-P4 per site/session	Averaged; not treated as independent replicates
Environmental variables	Air temperature and relative humidity	No PET/UTCI because wind and radiant data were absent
RH quality control	SACB P1, 23 July 09:00 = 31% excluded	Three-point mean used for that RH session
Survey	GSB $n=11$; SACB $n=10$; aggregate charts	Descriptive comparison only

RESULTS

Air-Temperature Differences

Mean air temperature at GSB was 29.27°C (SD 0.79) at 09:00 am and at SACB was 29.98°C (SD 0.88), a paired difference of -0.72°C (95% CI -1.03 to -0.41; $p=0.0005$; Cohen's $d_z=-1.67$). At 12:00, respective means were 29.43°C (SD 0.61) and 30.63°C (SD 0.80), giving a paired difference of -1.20°C (95% CI -1.76 to -0.65; $p=0.0009$; $d_z=-1.55$). GSB was cooler at both times on all ten dates.

The Wilcoxon tests supported the conclusions of the paired t-tests, with $p=0.002$ at each time. On each monitoring date, GSB was cooler than SACB. Figure 3 shows the date-wise air-temperature profiles of GSB and SACB at 09:00 and 12:00.

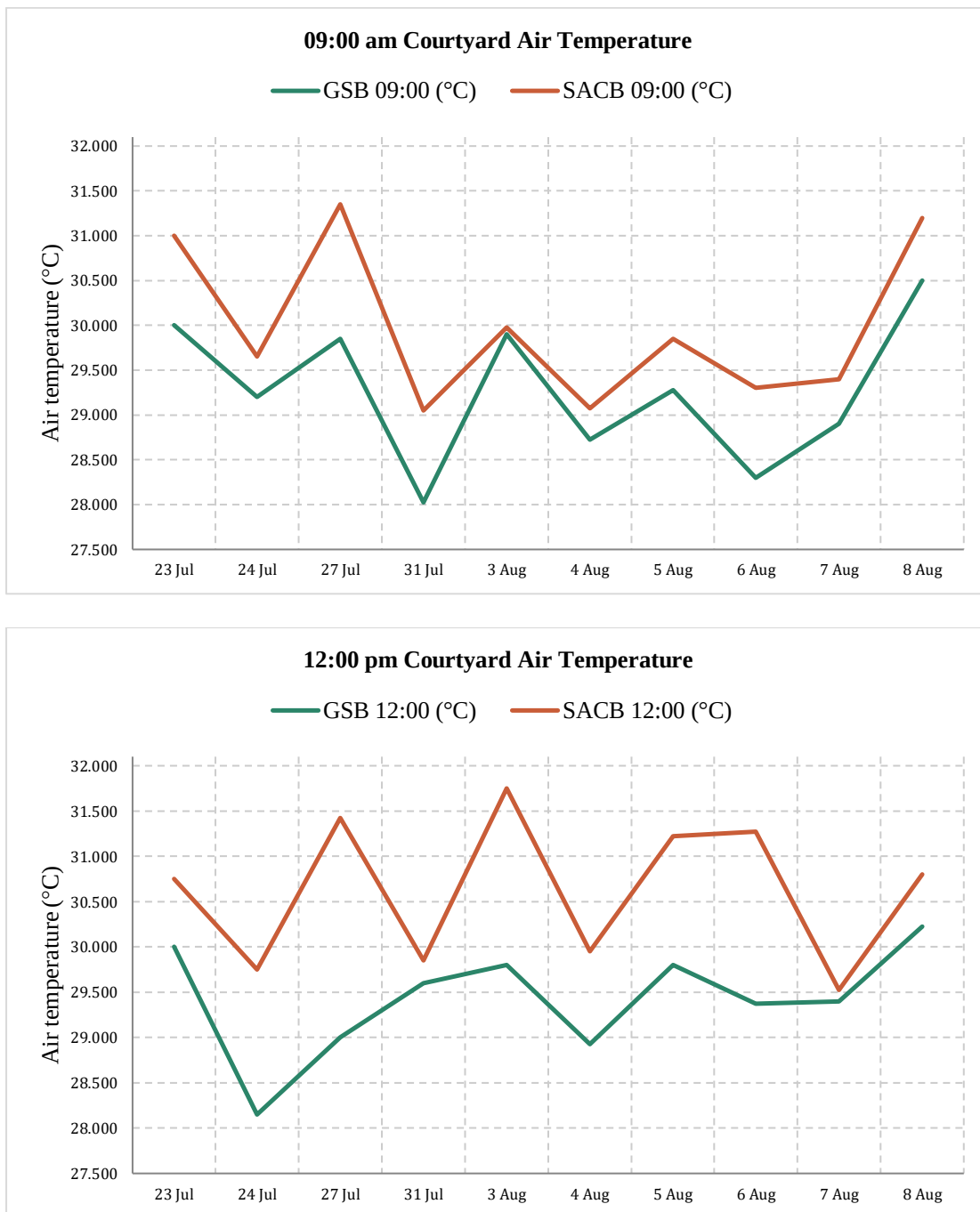


Figure 3: Date-wise courtyard air temperature (°C) at 09:00 am and 12:00 pm

Relative-humidity differences

At 09:00 am, mean RH was 79.58% (SD 4.46) at GSB and 76.06% (SD 4.52) at SACB, a difference of +3.52 percentage points (95% CI +0.83 to +6.20; $p=0.0159$; $dz=0.94$). At 12:00, means were 79.20% (SD 4.50) and 75.81% (SD 4.02), respectively, giving a difference of +3.39 percentage points (95% CI +1.24 to +5.55; $p=0.0061$; $dz=1.13$).

Signed-rank tests were also significant ($p=0.014$ and $p=0.012$). Table 2 reports the courtyard means, standard deviations, paired mean differences, 95% confidence intervals, p -values and effect sizes for both observation times. GSB was more humid on eight of ten dates at each time, indicating a general shift with day-to-day overlap. Figure 4 illustrates the date-wise variation in quality-controlled relative humidity at 09:00 and 12:00 for both courtyards

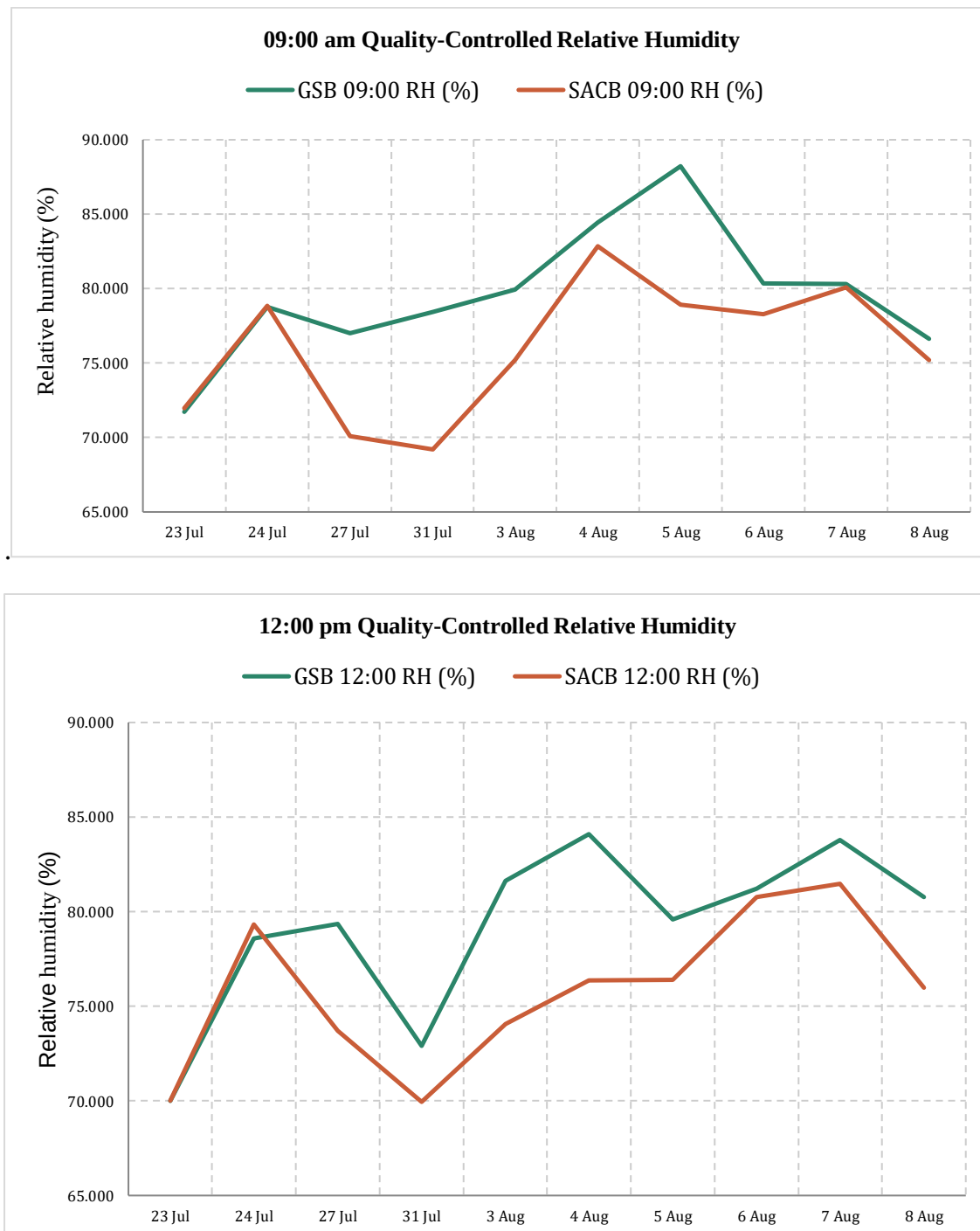


Figure 4: Date-wise Relative humidity (%) at 09:00 am and 12:00 pm

Table 2: Descriptive statistics and paired comparisons of courtyard air temperature and relative humidity

Outcome	GSB mean $\pm$ SD	SACB mean $\pm$ SD	Paired difference (95% CI)	p	Cohen's dz
Temperature, 09:00 am	29.27 $\pm$ 0.79°C	29.98 $\pm$ 0.88°C	-0.72 (-1.03, -0.41)	0.0005	-1.67
Temperature, 12:00 pm	29.43 $\pm$ 0.61°C	30.63 $\pm$ 0.80°C	-1.20 (-1.76, -0.65)	0.0009	-1.55

RH, 09:00 am	79.58 ± 4.46%	76.06 ± 4.52%	#ERROR!	0.0159	0.94
RH, 12:00 pm	79.20 ± 4.50%	75.81 ± 4.02%	#ERROR!	0.0061	1.13

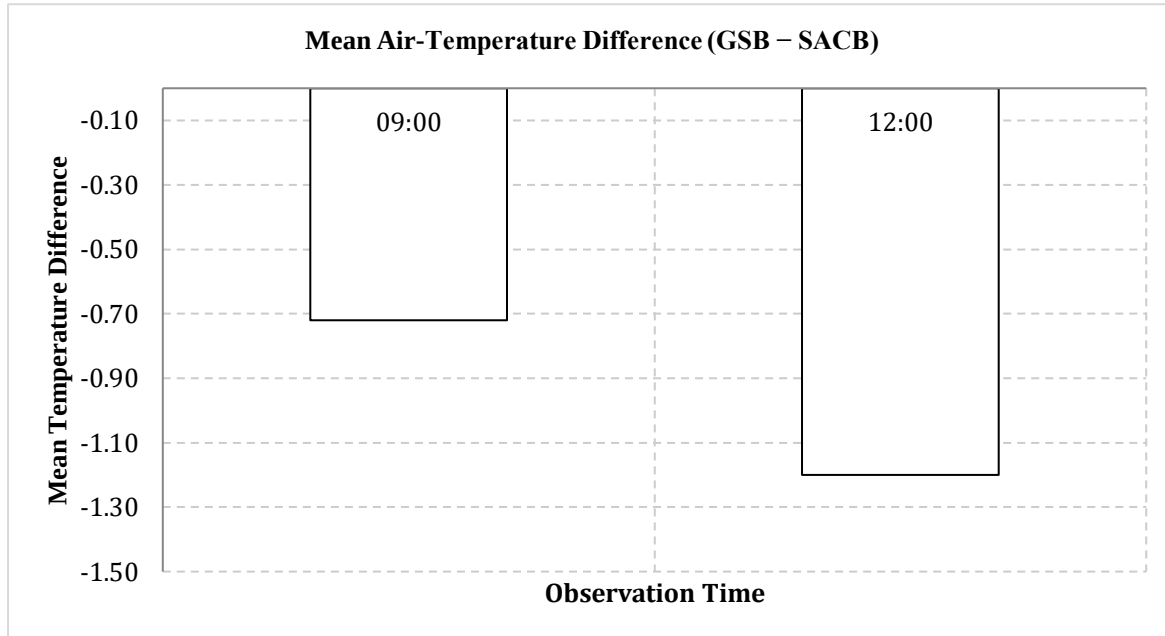
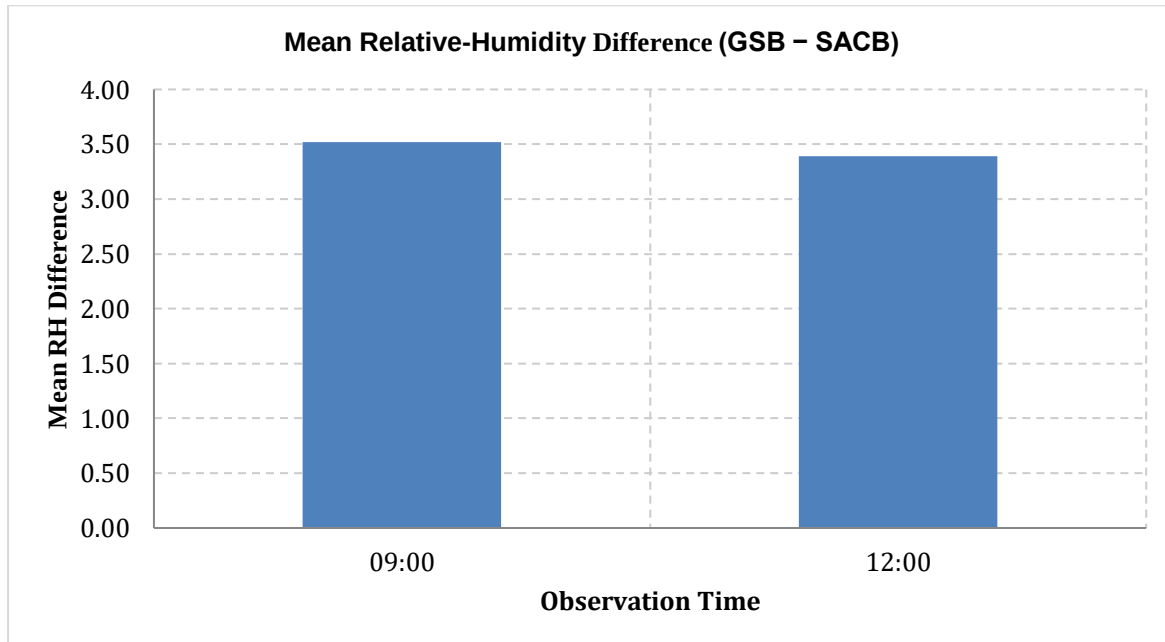


Figure 5: Paired mean differences in Air Temperature (°C) and Relative Humidity (%) between the GSB and SACB courtyards at 09:00 and 12:00

Late-morning change

From 09:00 am to 12:00 pm, GSB warmed by 0.16°C and SACB by 0.65°C. The difference-in-differences was -0.48°C (95% CI -1.08 to +0.11; $p=0.097$). Although the direction suggests lower late-morning heat accumulation at GSB, the interval crossed zero; the result is suggestive rather than conclusive. The mean noon temperature difference of 1.20°C was statistically significant.

Post-Occupancy Responses

The survey responses were generally consistent with the measurements. At GSB, 54.5% rated thermal conditions as comfortable and 45.5% as neutral; no respondents selected ‘uncomfortable’. SACB responses were 20.0% comfortable, 20.0% uncomfortable and 60.0% neutral. For both comfort during stays of at least 30 minutes and activity suitability, GSB received positive ratings of 90.9% and SACB received 20.0%.

At GSB, 81.8% rated vegetation shading as effective and an equal percentage perceived significant or very significant cooling from vegetation. At SACB, 30.0% thought available shade was effective, 50.0% thought it was ineffective or slightly effective, and 80.0% thought exposed hardscape contributed moderately or significantly to heat. The overall environmental quality was rated as good by 72.7 % at GSB and 30.0 % at SACB. Humidity comfort was also similar: positive ratings were 18.2% and 20.0% respectively. Humidity comfort ratings were predominantly neutral at both sites, despite higher measured RH at GSB. Figure 6 presents a descriptive comparison of positive response proportions across the six survey outcomes for GSB and SACB.

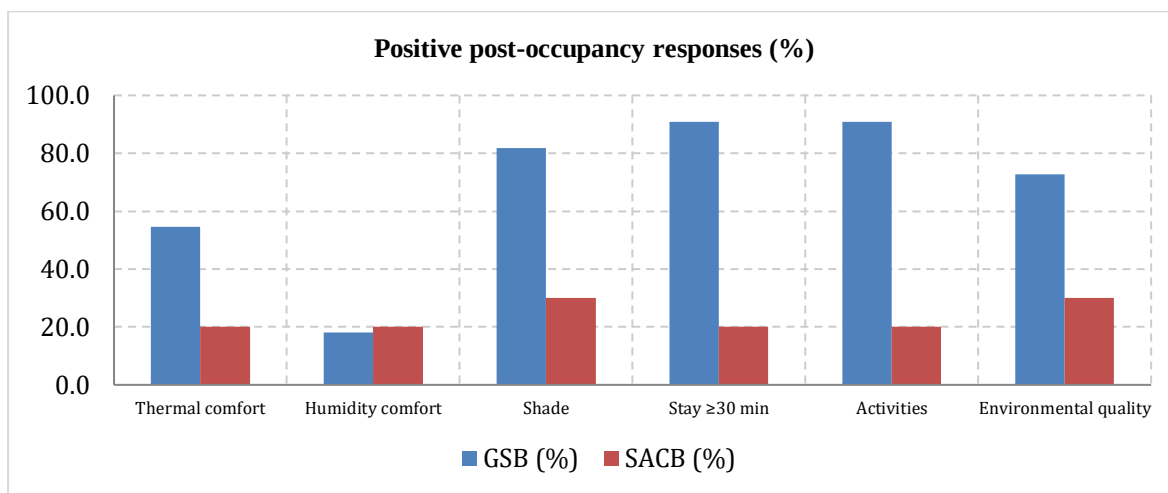


Figure 6: Post-occupancy responses across six comparable outcomes

DISCUSSION

Interpreting the Physical Contrast

GSB was cooler in all matched observations, and the advantage increased from about 0.7°C in the morning to 1.2°C at noon. This consistency, the confidence intervals, and the agreement between parametric and signed-rank tests indicate that the mean effect was not produced by a few unusual days. The direction is physically plausible: shade and cooler planted surfaces reduce short-wave and long-wave exposure; evapotranspiration can redistribute available energy. The same directional pattern is reported in similar studies on courtyard and urban spaces, but the magnitude varies depending on climate, geometry and the selected metric (Melas et al., 2021; Peter & Kaushik, 2024; Zheng et al., 2024).

The larger noon difference is consistent with a greater vegetation-associated benefit under increasing solar load. The effects of air temperature cannot be directly or numerically compared with the reductions in radiant temperature. (Peter & Kaushik, 2024) showed that warm-humid educational courtyards have 5–7 °C lower mean radiant temperature. (Unal & Middel, 2025); Middel reached reductions of up to 10°C in the shade in hot-arid cases. Potential benefits associated with reduced radiant exposure were not quantified in the present study. Higher RH at GSB is consistent with a cooler vegetated environment. However, this increase cannot be attributed solely to evapotranspiration because cooling alone can increase relative humidity, even without additional water vapor. The mechanisms underlying the 3.4–3.5 percentage-point RH difference remain uncertain without data on vapor pressure, specific humidity, leaf area or irrigation. It

is also relevant to humid climates, where additional moisture may restrict evaporative heat loss, hence comfort is more apparent in the shade. Predominantly neutral humidity ratings at both sites support a cautious interpretation.

Convergence Between Measurements and Perception

For 09:00 am and 12:00 pm observations, GSB was cooler than SACB on all ten matched dates. The average temperature advantage increased from 0.72°C to 1.20°C and neither confidence interval included zero. The RH was approximately 3.4–3.5 percentage points higher. Lower late-morning warming at GSB was suggestive, but not statistically conclusive. The post-occupancy survey results were in agreement with measurements. GSB was rated higher on shade, longer stays, activity suitability and overall environmental quality. Humidity comfort ratings were mainly neutral at both sites (Abdallah, 2022; Karimi et al., 2023; Salameh et al., 2020).

The respondents were independent, the sample sizes were small, the exposure histories varied and only aggregated responses were available. Most users of SACB were infrequent or first-time visitors while GSB had more frequent users; therefore, activity, clothing, familiarity and momentary weather may influence responses. Differences in question wording further limit comparability between the survey results.

CONCLUSION

For 09:00 am and 12:00 pm observations, GSB was cooler than SACB on all ten matched dates. The mean temperature advantage increased from 0.72°C to 1.20°C and neither confidence interval included zero. The RH was about 3.4–3.5 percentage points higher. Lower late-morning warming at GSB was suggestive, though not statistically conclusive. Measurements were in agreement with the results of the post-occupancy questionnaire. GSB received higher ratings for shade, length of stay, suitability for activity and overall environmental quality. Humidity comfort ratings were mostly neutral at both sites.

The findings indicate that GSB was cooler and received more favorable comfort ratings than SACB during the study period, although differences in geometry, materials and airflow may also have contributed. The findings support further evaluation of vegetation, shading and ventilation as complementary strategies for improving courtyard microclimates. To strengthen causal inference and thermal comfort assessment, replicated courtyard comparisons and a comfort survey at the respondent level are required, in addition to continuous time-matched monitoring of mean radiant temperature and wind speed.

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