

A study on the impact of courtyard vegetation on its thermal comfort performance in an educational building of warm and humid climates

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ABSTRACT

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Received: 16 June 2023
Revised: 29 April 2024
Accepted: 17 May 2024
Published: 31 December 2024

Citation:
Peter, A., and Kaushik, S. A. S. (2024). A study on the impact of courtyard vegetation on its thermal comfort performance in an educational building of warm and humid climates. *Science, Engineering and Health Studies*, 18, 24040011.

Courtyards are a popular design element that often focus on aesthetics while neglecting their potential functionality. Homogenous courtyard designs persist across climates, overlooking their ability to improve thermal performance. This research addresses this critical gap by conducting a quantitative study on the functional benefits of courtyards in an educational building. A case study approach was used to compare two similar courtyards at the NIT Trichy campus: one with and one without vegetation. This method allows for the isolation and quantification of the influence of courtyard vegetation on thermal performance. Field measurements of relevant thermal factors were conducted, complemented by simulations utilizing the Ladybug tool within Rhino software. The results revealed a compelling case for the integration of vegetation within courtyards. Significant variations in thermal factors were observed, particularly during mornings and noon. The vegetated courtyard had a 5–7°C lower mean radiant temperature than its non-vegetated counterpart. Furthermore, the simulations suggested that strategically placed trees can mitigate heat stress, potentially reducing the area subjected to strong heat stress by 50–70%, as measured using the universal thermal climate index. These findings highlight the importance of strategically designed courtyards with vegetation for promoting thermal comfort in educational buildings.

Keywords: outdoor thermal comfort; courtyard design parameters; universal thermal climate index; mean radiant temperature; warm-humid climate

1. INTRODUCTION

As an architectural passive design method, courtyards have proven to be effective in enhancing the thermal conditions of buildings (Salameh et al., 2020). They have been utilized in both public and private structures for countless years. According to Edwards et al. (2006), courtyards are created as a result of a building's interaction with its surroundings to provide thermal

comfort and natural ventilation without using energy, especially in hot, arid locations. Nowadays, courtyards have become a popular feature in modern homes across different countries and climates, serving as beautiful outdoor gardens. However, only a limited number of designers are exploring beyond the superficial esthetic aspects of courtyards and instead considering their potential as a passive design strategy to improve thermal comfort, energy efficiency, and overall sustainability of

buildings (Abdallah, 2022). Without considering the varying climatic variables from one place to another, many nations adopt courtyard prototype models in building designs (Elgheznawy and Eltarabily, 2021). This is a problem that needs to be investigated because a poorly planned courtyard may have unfavorable effects, such as overheating of the courtyard and adjacent indoor spaces, increased cooling load, and less usage of the courtyard for leisure and other activities.

Koch-Nielsen (2013), defined a courtyard building as a structure that features an open-to-sky interior space. Edwards et al. (2006) noted that this design approach has been in use since Neolithic times and has been widely adopted from China to Morocco. The provisions of environmental services, including natural lighting and ventilation, as well as protection from harsh external elements, are among the main functions of courtyard spaces (Woods and Hyde, 2013). Al-Hafith et al. (2017) demonstrated the effect of courtyard characteristics on its shading performance, wherein the aspect ratio, a measure of the courtyard's width to its height, was found to affect shading most effectively, yet courtyard orientation had the opposite impact. Ghaffarianhoseini et al. (2015) aimed to identify architectural features that can effectively enhance outdoor thermal comfort in hot and humid regions, focusing on the potential of courtyards; they investigated the impact of various design elements, including direction, height, albedo, and vegetation, on outdoor thermal comfort and found that reducing the albedo and increasing the vegetation in courtyards, along with other design factors, created more shaded areas and maintained suitable thermal comfort levels for tropical regions. Another investigation on residential courtyards by Lopez-Cabeza et al. (2022) examined the effect of albedo on thermal performance and user comfort. They found that the albedo of walls had a greater impact on the outdoor comfort index physiological equivalent temperature (PET) than that of floors, due to the significant influence of the mean radiant temperature (t_r). The study also revealed that light-colored walls led to the highest PET values during the day, whereas dark walls resulted in the highest PET values at night. However, the scenario with beige walls had the lowest mean values and performed the best throughout the day.

The school courtyard serves as a secluded outdoor area for students to engage in programs and take breaks to play and relax (Salameh et al., 2020). Abdallah (2022) conducted a study to improve the thermal comfort of students in open areas of educational buildings. The findings revealed that using hybrid staggered shading with trees in wide canyons significantly reduced the PET values and that hybrid shading at a height of 4 m resulted in the best OTC improvement in school courtyards. The study by Abdallah (2022) included field measurements and student surveys to investigate the outdoor thermal comfort of courtyards. The use of a passive technique, such as hybrid shading with 50% semi-shading and trees, resulted in a substantial reduction in PET values for inner courtyard temperatures, with an average temperature difference of 6.5°C compared with the basic scenario. Elgheznawy and Eltarabily (2021), conducted a study on how sun sail shading impacted thermal comfort in school courtyards. They measured the predicted mean vote (PMV) and later simulated PET and provided scenarios with varying percentages of courtyard coverage. The findings showed that using 40% sun sail shading was ineffective in the

school courtyard, and a 60% court-covering ratio was necessary. In tropical regions like Tiruchirappalli, India, the primary factor influencing the thermal comfort of individuals is heating caused by the sun (Kaushik et al., 2022). The universal thermal climate index (UTCI) is a widely used outdoor thermal comfort index (Diz-Mellado et al., 2023). Halder et al. (2022) quantified the effect on urban heat islands using multi-temporal Landsat data. PMV, PET, and UTCI are other commonly used outdoor thermal indices (Karimi et al., 2020, 2022, 2023; Mohammad et al., 2021).

To improve the thermal conditions of both indoor and outdoor spaces in educational buildings and reduce heat stress on students during classes and outdoor activities, efforts have been made to provide thermal comfort (Mahmoud and Abdallah, 2022). Salameh et al., (2020) conducted a study to evaluate courtyard designs in the UAE with the aim of enhancing student happiness. The results showed that the courtyard design accounted for 29.2% of overall student happiness. Despite this, not much thought had gone into creating these courtyards to give students enough thermal comfort (Elgheznawy and Eltarabily, 2021). To improve both the comfort of students and energy efficiency of educational buildings, it is important to enhance the thermal conditions of courtyards. However, there is a lack of studies on student comfort evaluations in educational buildings, particularly in outdoor spaces like courtyards (Abdallah, 2022). Therefore, we conducted a quantitative research study to examine the influence of vegetation as a design parameter on the thermal performance of courtyards.

This study introduces innovative contributions to the field of environmental thermal comfort assessments in educational courtyard environments by focusing on the specific impact of courtyard vegetation on mean radiant temperature and heat stress reduction. Unlike previous research, which emphasizes general passive design strategies, our study offers nuanced insights into vegetation's microclimatic effects based on field measurements and computational simulations using an advanced tool (Ladybug plugin within Rhino software).

2. MATERIALS AND METHODS

2.1 Description of study context and climate

Tiruchirappalli is located in Tamil Nadu (10.7°N, 78.7°E) and is 81 m above sea level. The study area is inside the campus of the National Institute of Technology, Tiruchirappalli, which includes educational buildings with open courtyards. According to the Köppen-Geiger climate classification, Tiruchirappalli belongs to the tropical savannah climate, classified as Aw, with no major change in temperature between summer and winter. Summers are long (March to September) and characterized by lower humidity, with higher humidity from December to January. Based on the EPW file, the temperature range of Tiruchirappalli is between 15°C to 45°C, with the majority of hours falling between 25°C and 30°C and an average temperature of 29°C. The maximum monthly t_r occurs in April (31.6°C), and the minimum monthly occurs in December (25.2°C). The relative humidity (RH) range of Tiruchirappalli is between 20% to 100%, with most hours concentrated between 70% and 80%, and an average RH of 67.5%. The methodology employed in this study is illustrated in Figure 1.

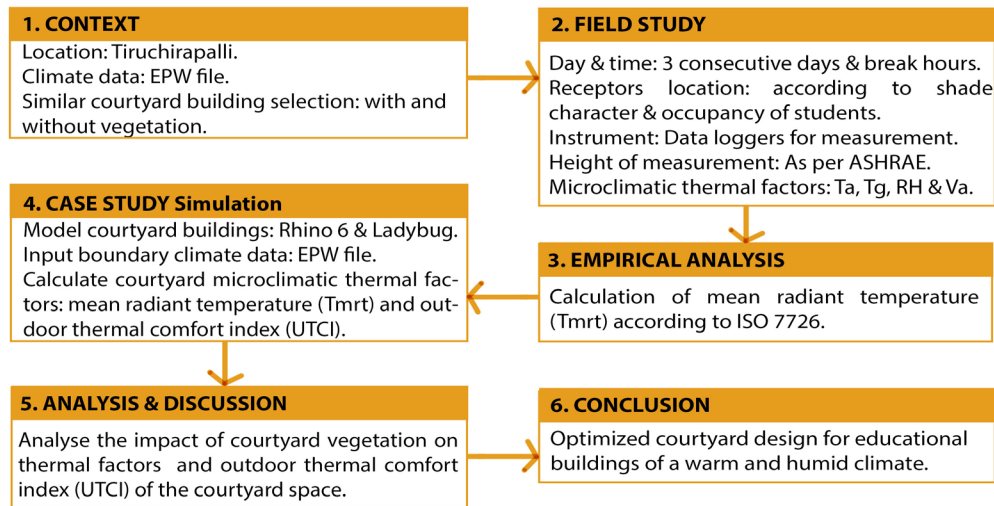


Figure 1. Methodology of the study

2.2 Description of selected case study buildings

Two identical star-shaped educational buildings, each featuring a central circular open-to-sky courtyard, were selected for the study. One courtyard was filled with vegetation, while the other remained without any vegetation (Figure 2). Students actively used both courtyards during break hours for social activities, reading, relaxing, and chatting with friends. Details of both courtyards are provided in Table 1.

2.3 Field study and measurement procedure

To evaluate the influence of vegetation on thermal performance and comfort, a series of measurements were conducted on November 16, 17, and 18, 2022, in the Architecture building's and the Orion building's circular courtyards, in their existing configurations. Five different

receptor points were strategically placed, based on shading patterns and spatial use by students in the courtyard, to measure thermal factors for each point. The selected points were the north, south, east, and west corners and the center point of the courtyards. Each point in the two buildings had a different shade pattern during break hours. The break hours of the college were 10:15 am–10:30 am, 12:15 pm–1:00 pm, 3:15 pm–3:30 pm, and 5:15 pm–5:30 pm. During every break hour, microclimate parameters, including air temperature (t_a), globe temperature (t_g), RH, and air velocity (v_a), were measured at the five receptor points in the courtyards using an Extech heat stress meter, model HT30, with a 40-mm diameter globe, and a Testo anemometer, model Testo 400. The measurements were taken at a height of 1.1 m according to ISO 7726.

Table 1. Details of the selected courtyards

	Architecture building	Orion building
Shape	Circular	Circular
Diameter	23 m	25 m
Floor area	415 m ²	490 m ²
Height	3 floors = $4.5 \times 3 + 1 + 0.75 = 15.25$ m	3 floors = $5 \times 3 + 1 + 0.45 = 16.45$ m
Circumference/Ht	$\frac{(2 \times 3.14 \times 11.5)}{15.25} = 4.7$	$\frac{(2 \times 3.14 \times 12.5)}{16.45} = 4.7$
Wall material	Brick with plaster (230 mm brick with plaster)	Brick with plaster (230 mm brick with plaster)
U value wall	2 W/m ² .K	2 W/m ² .K
Wall color	White	White
Features	No of trees: neem tree = 3, almond tree = 6 Height of trees = 11–13 m Crown width of neem tree = 5–6 m Crown width of almond tree = 3–4 m Tree present on the periphery	No major trees 7 indoor areca palms on verandah Height of areca palm plant = 2 m
Ground cover	Grass and soil	Grass
Albedo	0.25	0.3
Corridor width	2.5 m	2.5 m
Surrounding rooms	Classrooms	Classrooms
Remarks	More tree shade	No tree shade



Figure 2. Selected circular courtyard case study buildings in NIT Trichy campus—Architecture building (left) and Orion building (right)

2.4 Case study model simulation

The Ladybug tool in Rhino software was utilized to analyze the selected courtyards' microclimatic conditions and thermal comfort. Measurements for t_a , t_g , RH, and v_a were obtained onsite, and the $\bar{t}_r$ and UTCI for both courtyards were calculated using the Ladybug tool. The existing layout of the courtyards in the case study was replicated in Rhino 6, and all elements of the study area were defined in the model. The simulation was conducted for 1 day during break hours and utilized weather conditions sourced from the EPW file for Tiruchirappalli. The reliability of the Ladybug tool in simulating outdoor thermal conditions has been explored through multiple research papers where different scenarios of thermal comfort were examined using Ladybug UTCI simulations (El-Bahrawy, 2024; Ibrahim et al., 2020).

2.5 Model calibration

Software validation was conducted by taking the measurements of 1 day from the 3 consecutive days on which the field studies were conducted. It was calibrated by comparing the empirically calculated $\bar{t}_r$ values to the software-simulated values and finding the relative root mean square error (RMSE). $\bar{t}_r$ is the average temperature of all surrounding surfaces with which an individual exchanges radiant heat. It is influenced by short and long-wave radiation and plays a significant role in determining outdoor thermal comfort. As per the ISO 7726 standard, $\bar{t}_r$ is calculated using t_a , v_a , and t_g , with a globe diameter (D) of 40 mm and emissivity of 0.95, given in Equation 1:

$$t_r = \left\{ (t_g + 273)^4 + \left[\frac{1.1 \times 10^8 \times v_a^{0.6}}{\epsilon_g \times D^{0.4}} \right] \times (t_g - t_a) \right\}^{\frac{1}{4}} - 273 \quad (1)$$

The utilization of a 40-mm diameter globe thermometer for $\bar{t}_r$ measurements is subject to certain inherent limitations identified in existing literature. Studies (d'Ambrosio Alfano et al., 2021, 2022, Manavvi and Rajasekar, 2020) have highlighted systematic errors associated with pocket-sized globe thermometers such as the Extech heat stress meter, particularly due to trivial shielding by the device's chassis or the operator's hand. Despite the acknowledged limitations, the decision to

employ a 40-mm diameter globe thermometer for $\bar{t}_r$ measurements in our study was influenced by considerations related to response time and practical field deployment. Standard 150-mm diameter globes recommended by ISO 7726 typically require a longer response time of approximately 20–30 minutes to reach thermal equilibrium. Given the dynamic shading characteristics of courtyard environments that change with the sun's path over time, a smaller globe size was deemed necessary for faster response and adaptability to varying shading conditions. This choice facilitated more agile data collection and allowed for timely measurements aligned with the evolving thermal dynamics within educational courtyards. The relative RMSE was calculated as per Equation 2:

$$RMSE = \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{n} \right]^{1/2} \quad (2)$$

where ' P_i ' is the simulated $\bar{t}_r$ value, ' O_i ' is the empirically calculated $\bar{t}_r$, and ' n ' is the number of data points.

3. RESULTS AND DISCUSSION

Based on the field study and software simulations of the two courtyards, the following results and findings were reported. As previously mentioned, the Architecture building's courtyard contains trees, whereas the Orion building's courtyard does not.

3.1 Variations in thermal factors

3.1.1 Air and globe temperature variations

Figure 3 illustrates the average t_a and t_g measurements recorded at five receptor points located 1.1 m above the courtyard ground. The average t_a difference between the two courtyards was found to be approximately 1–2°C during the morning and noon hours, with the courtyard containing trees having the lowest temperature. The northern side of the courtyard, which receives most of the direct sunlight, exhibited a higher t_a during the morning and noon periods. However, when shaded by trees, the t_a on this side of the courtyard decreased by 2–3°C. By 3 pm,

the t_a difference between the two courtyards had decreased to around 0.5–1.5°C. Additionally, the shade provided by trees in the Architecture building's courtyard led to a significant reduction in t_g compared with the t_a difference between the two courtyards. Regarding t_g , the maximum average t_g difference between the two courtyards was about 4–6°C during the morning and noon hours. The north side of the Architecture building's courtyard had the highest difference during morning and at noon, which was about 6–8°C less than that in the Orion Building. After 3 pm, the t_g difference was around 1.5–3°C.

Both t_a and t_g were higher in non-shaded regions and reduced in the tree-shaded regions, which was clearly exhibited in the north side of both courtyards during the morning and noon hours. The north side of the Architecture building receives tree shade in the morning and noon hours compared with the Orion building, which is not shaded. Therefore, the Architecture building reported lower t_a and t_g than the Orion building, particularly in the morning and noon times. Compared with changes observed in t_a , the fluctuations in t_g were more pronounced.

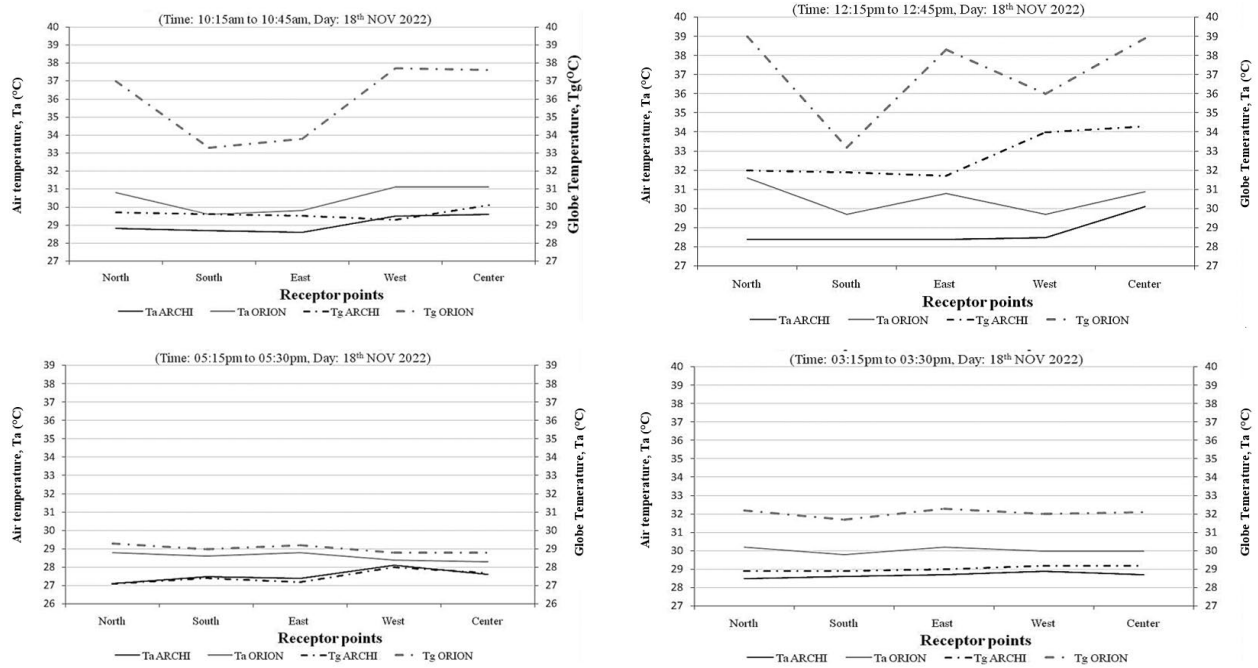


Figure 3. Air and globe temperature variations between courtyards

3.1.2 RH analysis

The presence of trees resulted in higher humidity in the Architecture building's courtyard than in the Orion building's courtyard. Overall, the maximum RH difference between the two courtyards was about 5–10%. The north side of the Architecture building's courtyard had 10–15% less RH than the Orion building's during morning and noon times. After 3 pm, the humidity difference was about 3–9%. Variations in t_a and RH and their differences are plotted in Figure 4. RH was found to increase as t_a decreased and vice versa.

3.1.3 v_a variations

v_a within a courtyard is influenced by nearby buildings and can be relatively low. Figure 5 illustrates the average v_a inside the courtyards, which remained constant throughout the day for both courtyards. The wind speed and its impact were comparable, with an average wind speed of 0.6 m/s in both courtyards. However, the highest v_a was in the south side in the Orion building, whereas it was in the west in the Architecture building. This difference could be attributed to the semi-open entrance lobby and smaller courtyard situated west of the Architecture building, as well as the semi-open space located south of the Orion building.

3.1.4 t_r variations

t_r was empirically calculated and determined through simulation using the Ladybug tool of Rhino Grasshopper. For the research study, the RMSE value was found to be 3.4°C, confirming the simulation results' reliability (Ouyang et al., 2022). Similar to t_g , there was a significant reduction in t_r due to the shade of trees in the Architecture building's courtyard, which was more evident during the morning and noon hours. Figure 6 displays the t_r empirical results against the t_r simulated results for the two different scenarios. In the morning hours, from 10:15 to 10:45 am, t_r of the Architecture building's courtyard ranged from 31.3 to 46.4°C, whereas that of the Orion building ranged from 31.3 to 50.2°C. For the Architecture building courtyard, 13% of the area to the NW side had a higher t_r , whereas for the Orion building, it increased up to 31% of the courtyard area. t_r decreased by 4–12°C in the Architecture building's courtyard during the morning hours, and at noon, it ranged from 33.4 to 49.9°C, whereas that in the Orion building ranged from 33.4 to 54.1°C. For the Architecture building's courtyard, 19% of the area to the north had a higher t_r , whereas for the Orion building, it increased up to 58% of the courtyard area. This indicated a decrease in t_r of up to 5–21°C in the Architecture building's courtyard.

After 3 pm, both courtyards were fully shaded by geometry and had almost similar $\bar{t}_r$, ranging from 33.6 to 44.2°C. In the Architecture building's courtyard, a small portion on the NE side, about 2% of the courtyard, had a higher $\bar{t}_r$, whereas, for the Orion building, it increased up to 9% of the courtyard area. The presence of trees and their shade could decrease $\bar{t}_r$ on average by 5–7°C in the Architecture building's courtyard. After 5 pm, both courtyards had the same $\bar{t}_r$, ranging from 30.6 to 31.7°C.

3.1.5 UTCI analysis

The impact of $\bar{t}_r$ on UTCI was significant. Figures 7-10 illustrate the UTCI results for the two different scenarios, showing similar trends between $\bar{t}_r$ and UTCI results. In the evening and after 5 pm, the UTCI was similar for both courtyards, and less area of the courtyard was under strong heat stress. In the morning and at noon, the presence of trees in the Architecture building's courtyard resulted in a significant reduction of approximately 50–70% in the area that experienced strong heat stress. In the morning hours, the UTCI of the Architecture building's courtyard ranged from 30.6 to 34.4°C, whereas, that of the Orion building

ranged from 30.6 to 35.4°C. For the Architecture building's courtyard, 13% of the area to the NW side had strong heat stress, whereas for the Orion building, it increased up to 31% of the courtyard area. The remaining areas of both courtyards were under moderate heat stress. At noon, the UTCI of the Architecture building's courtyard ranged from 32.4 to 36.5°C, whereas that of the Orion building ranged from 32.4 to 37.5°C. For the Architecture building's courtyard, 19% of the area to the north experienced strong heat stress, whereas for the Orion building, it increased up to 58% of the courtyard area. The remaining areas of both courtyards were under moderate heat stress. During the evening break, after 3 pm, both courtyards were fully shaded by geometry, and the UTCI of both courtyards ranged from 32.4 to 35.9°C. For the Architecture building's courtyard, a small portion on the NE side, about 2% of the courtyard, experienced strong heat stress, whereas for the Orion building, it increased up to 9% of the courtyard area. Larger areas of both courtyards were under moderate heat stress. After 5 pm, the UTCI of both courtyards ranged from 31.7 to 32°C, and the entire area of both courtyards was under moderate heat stress.

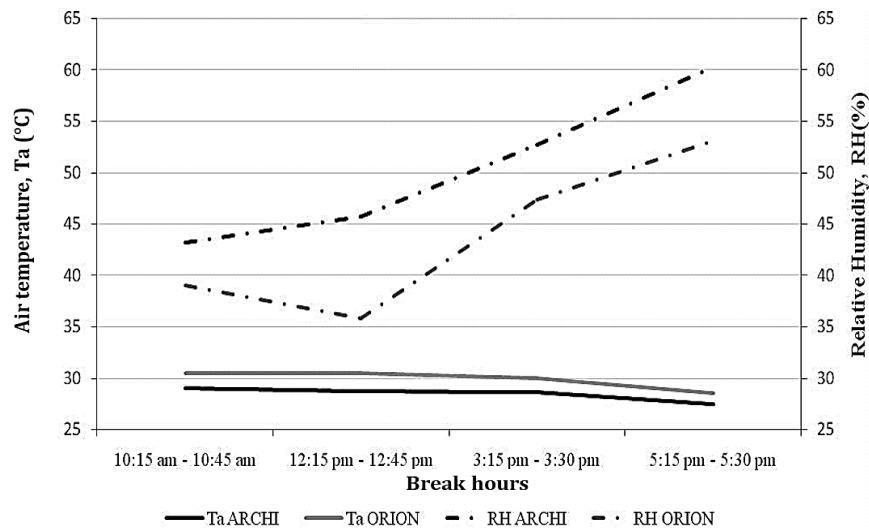


Figure 4. Average air temperature and relative humidity variations between courtyards

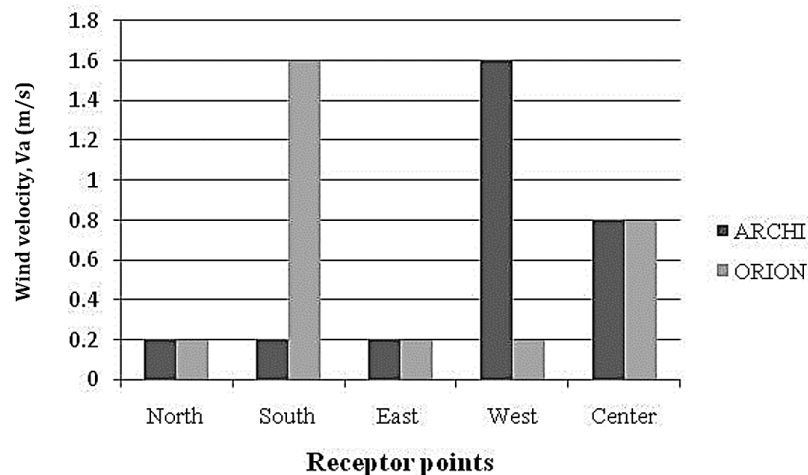


Figure 5. Average air velocity variations between courtyards

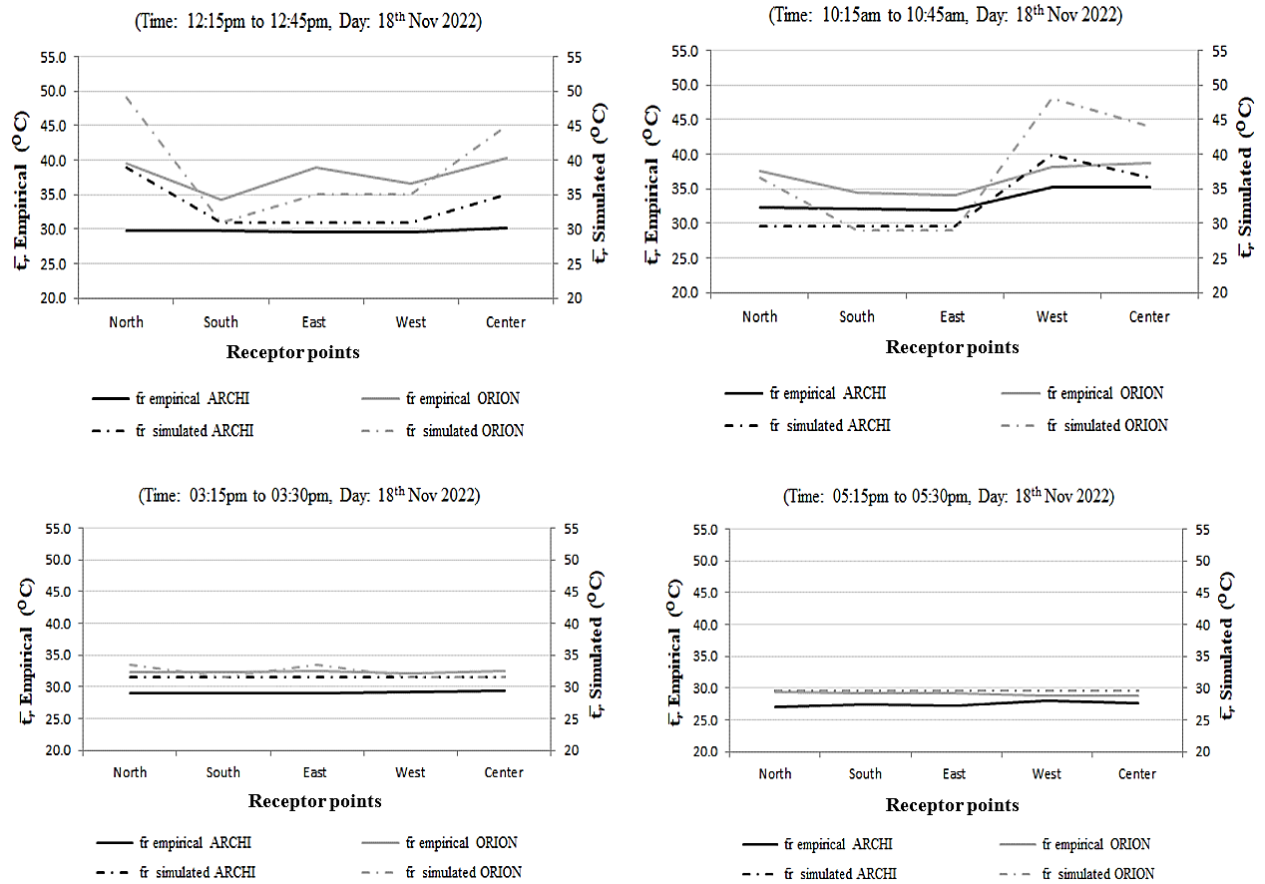


Figure 6. $\bar{t}_r$ empirical and $\bar{t}_r$ simulated variations between courtyards

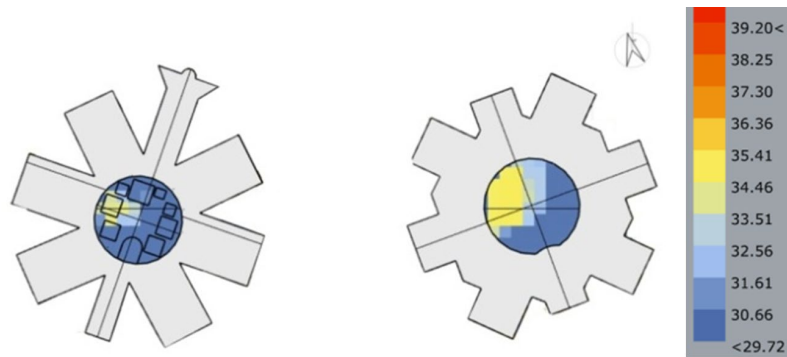


Figure 7. UTCI variation between courtyards during morning break

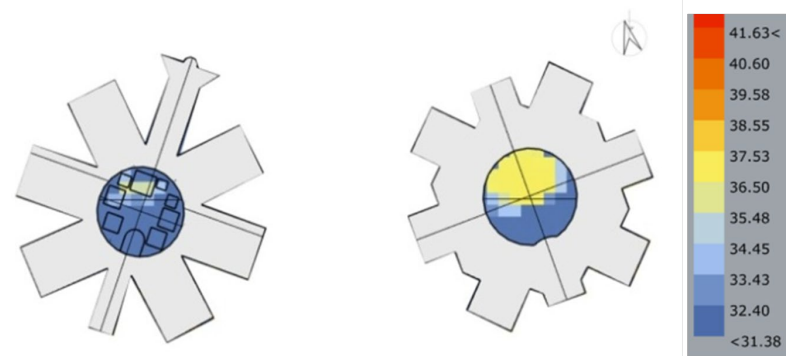


Figure 8. UTCI variation between courtyards during noon break

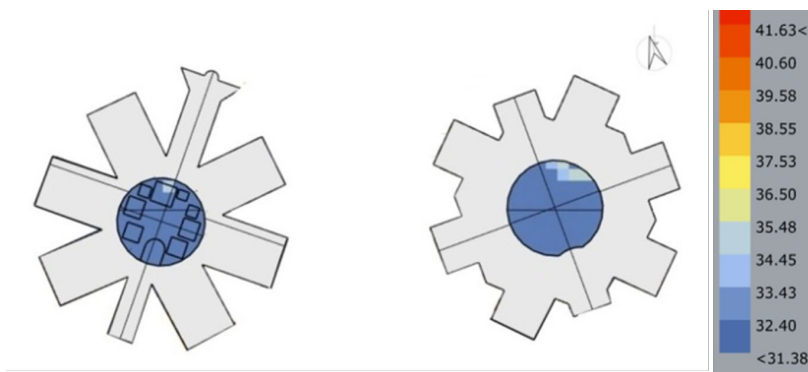


Figure 9. UTCI variation between courtyards during evening break

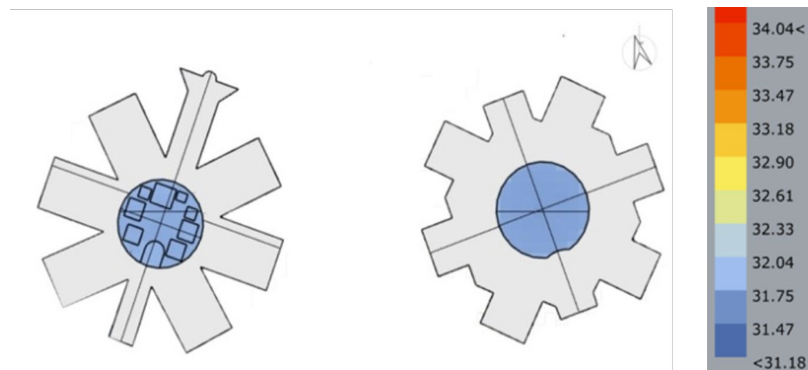


Figure 10. UTCI variation between courtyards after 5 pm

4. CONCLUSION

This research study focused on the impact of courtyard vegetation on outdoor thermal comfort in the Architecture building and Orion building of the NIT Trichy campus. The analysis demonstrated a significant influence of vegetation on the outdoor thermal comfort of courtyards, particularly in the morning and at noon when the geometric shading of the buildings was not fully effective. However, after 3 pm, the two buildings were completely shaded by their geometry, rendering the shade provided by trees ineffective. The presence of trees in the Architecture building resulted in a reduction of 50–70% of the area that experienced strong heat stress during the morning and noon. The percentage of area experiencing strong heat stress in the Architecture building from morning to noon ranged from 13–31%, whereas for the Orion building it ranged from 31 to 58%. The remaining areas were under moderate heat stress for both buildings. Given that Trichy experiences hot days for most of the year with little variation in temperature between summer and winter, sufficient shading provided by trees can improve outdoor thermal comfort in courtyards of educational buildings during the morning and at noontime. This enhancement in comfort allows for increased usage of courtyard space even during the harshest hours of the day. However, other design parameters can also affect the outdoor thermal comfort of courtyard spaces. Future research could investigate these parameters to identify the most effective design strategies for courtyards in educational buildings located in warm and humid climates.

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