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Enhancing Sustainable Thermal Comfort of Tropical Urban Buildings with Indoor Plants

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Abstract: Rapid urbanization exacerbates the urban heat island effect, raising local temperatures and endangering residents' health and well-being. The decreasing green spaces resulting from urbanization necessitate global action focused on reducing heat island intensity and addressing heat stress. Urban green infrastructure (UGI) offers solutions for enhanced comfort and reduced pollution through passive methods. Various large-scale UGI projects have been implemented to regulate temperature and improve air quality in urban areas. More research on smaller green spaces is essential to improve the microclimate in space-constrained urban cities. This experimental study examines the thermal effectiveness of potted plants located on balconies of a mid-rise residential building in Chennai, India. The study aims to enlighten balcony greening's role in reducing heat stress by monitoring temperature and humidity indoors and outdoors, with and without potted plants at similar solar radiation. Potted plants significantly lowered indoor air and surface temperatures by about 3 °C. Thus, balconies offer untapped potential for green interventions that are often unnoticed in tropical climates like India. The challenges in the installation and maintenance of UGI hinder the widespread adoption of UGI even though UGI positively influences residential well-being. The significant findings benefit urban planners and architects, enlightening strategies to enhance urban thermal comfort and mitigate heat stress through small-scale and cost-effective green interventions. This research contributes to sustainable urban development in tropical climates, aligning with several UN Sustainable Development Goals (SDGs), including SDGs 3, 7, 11, 13, and 15.

Keywords: sustainable development; urban greeneries; green buildings; potted plants; urbanization; microclimate; urban heat island; thermal comfort; tropical region; climate change

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1. Introduction

Expeditious urbanization in recent decades has brought many detrimental effects on the environment. The urban heat island (UHI) effect is the most conspicuous due to soaring temperatures in urban areas. Compromising the green spaces for concrete construction jeopardized the health of the people in urban regions. Mitigating the impact of UHI and heat stress has become the primary concern for researchers globally. Urban green infrastructures (UGIs) have proven to be a promising passive heat mitigation technique for several problems, including urban heat stress. UGI has multiple benefits, such as the reduction of air pollution and noise pollution, the mitigation of UHI impacts, improved thermal comfort, aesthetics, and energy savings [1]. Green infrastructures offer ecological, economic, social, and cultural value for sustainable urban development and help mitigate UHI in cities [2].

UGI has been classified into multiple categories as trees, green walls, green roofs, grasses and shrubs, waterbodies, etc. Many researchers have quantified the performance of the UGI against various climatic backgrounds. The decrease in air temperature observed around the park during the 2016–2017 summer compared to 2007–2008 suggested a positive impact of the park's vegetation on local climate conditions, and this highlighted the importance of green infrastructure in moderating UHI effects [3]. In tropical locations, trees have been proven to reduce air temperature ranging from 0.7 °C to 9.2 °C, standard effective temperature (SET) from 4.4 °C to 9 °C, mean radiant temperature (MRT) from 2.2 °C to 4.6 °C, and physiological equivalent temperature from 2.6 °C to 0.5 °C. Vertical greening systems (VGSs) have shown a reduction of indoor air temperature (IAT) from 0.2 °C to 11.9 °C, indoor surface temperature (IST) of 0.67 °C to 4 °C, outdoor air temperature (OAT) of 0.9 °C to 5.7 °C, and outdoor surface temperature (OST) of 2.4 °C to 11 °C. Green roofs showed a reduction of MRT by 10 °C, IAT by 1.73 °C, OAT by 10 °C to 15 °C, OST by 4 °C to 30 °C, and IST by 7.86 °C [4]. Grasses and shrubs had a negligible effect when used alone compared to green roofs/walls.

Despite the multiple benefits of UGI, incorporating greeneries in design has significant challenges, like installation, maintenance, cost and space constraints, orientation, and plant selection for varying seasons. A questionnaire survey on people's satisfaction regarding residential green views between detached houses and apartment dwellers indicated that apartment dwellers suffer from minimal green spaces on their premises [5]. The benefits of green wall and roof applications are widely recognized by users [6]. Residents had a positive perception of the benefits rendered by the greening systems and strongly supported promoting UGI-related policies. Despite space constraints, greeneries even on a microscale can be effective in cooling the surrounding areas [7]. Increasing the green cover using green façade even to a minimum of 10% has significantly contributed to mitigating pedestrian-level heat stress [8]. Even small-scale residential green elements have shown a positive influence on the well-being of urban residents [9]. Indeed, studies on residential greeneries, including gardens, parks, and other green spaces within residential areas, are conducted extensively across various countries. These studies have investigated greenery in relation to multiple aspects of urban living and human well-being.

The simulated residential block in Stuttgart showed that while façade greening with living walls had only a modest impact on air temperature (a decrease of -0.57 K), it significantly reduced the MRT by up to 3.04 K and the interior air temperature by up to 3.8 K [10]. These reductions are particularly significant for improving thermal comfort in urban spaces and integrating green infrastructure strategies, like living walls, into urban planning and design to promote sustainable and resilient cities.

Role of Vegetation in Residential Spaces

Most of the preceding studies have analyzed the impact or thermal performance of UGI in parks, botanical gardens, forests, streets, and neighborhoods at the urban scale level and green walls, green roofs, and trees at the building scale level, even though microscale interventions have proven to be more beneficial at the local residential scale [11]. High-rise development and urban densification cause a scarcity of land for implementing large-scale UGI. Hence, it is important to consider applying green infrastructure in small spaces like balconies and transition spaces [12]. The role of balconies, small terraces, and other small pockets of space at the residential building level has not been explored much in the literature. Very few studies have considered green balconies [13]. The most widely distributed spaces for greeneries close to urban dwellers are balconies and terraces. Scenes with a vegetation green index between 60% and 80% and a three-layer vegetation structure were most suitable for a human brain response that enhances positive human reactions to green spaces [14].

The sub-tropical climate of Taiwan demonstrated that implementing a greening curtain system on balconies can effectively improve air quality, reduce PM2.5 exposure, and mitigate associated health risks [15]. A study in condominiums compared temperatures with and without green curtains over 48 days in Japan, and green curtains enhanced thermal comfort and reduced energy as green infrastructure [16]. Homes with curtains had a balcony temperature 0.6 °C lower during air-conditioning and used 40% less energy by showing substantial savings and improved comfort. This suggests that green curtains contribute to cooling built spaces by reducing heat transfer into indoor spaces. Balconies in apartments and high-rise buildings provide opportunities for multiple green applications, such as VGS (direct, indirect, and living façade), potted plants, and even trees in some cases based on the size of the balcony. However, most of the studies on balconies, like green walls and trees, stated the requirements of high installation and maintenance costs [17,18].

Moreover, while implementing greeneries on balconies, it is important to make sure that the system is easier to maintain and less costly. A correlation observed between socioeconomic status and urban green space distribution highlights disparities in greening provisions, particularly for disadvantaged populations residing in dense residential areas, and they are not only applicable to the specific study region but also hold significance for developing countries in the Global South facing similar challenges [19]. Developing countries like India have minimal studies regarding the thermal benefits of urban greening [20]. Asian tropical countries are anticipated to face urban expansion of 1.1% every year [21]. Summer heat waves caused 2330 deaths due to urban temperature rise in India in 2015 [22]. Like many Indian cities, Chennai has also faced shrinkage of green cover due to urban densification [23]. Chennai has a per capita green space of 1.03, which falls far behind the World Health Organization's recommended standard of 9 m^2 per capita [24]. The urban population of Chennai surged from 2.64 million to 4.68 million between 1971 and 2011 as per the 2011 Census of India, and it is expected to reach 14 million by 2030 [25].

Several studies analyzing greeneries' influence in the same space on various days have been carried out. A high-rise residential balcony in Penang was assessed before and after installing the VGS [26]. Another study in Canberra assessed VGS's influences in a university building corridor pre- and post-VGS installation [27]. Urban green spaces provide natural shade, reducing direct sunlight exposure and heat absorption through building surfaces, which lowers indoor temperatures and reduces the need for air-conditioning [28,29]. Dense vegetation on balconies absorbs noise pollution by enhancing the living environment's tranquility [30]. Plants can lower the surface temperature of balconies and adjacent walls, decreasing heat transfer into the building [31,32]. Plants release moisture through transpiration and cool the surrounding air through evaporative processes, which are particularly effective in dry, tropical climates [33,34]. Plants help maintain comfortable humidity levels, which are particularly beneficial during dry seasons [35]. By cooling balconies and nearby areas, potted plants contribute to mitigating the UHI effect, which is particularly beneficial in densely built urban areas [36,37]. The residential plants filter pollutants and increase oxygen levels, enhancing indoor air quality and promoting better health and comfort [38,39]. Indoor air phytoremediation using potted plants and green walls improved indoor air quality by controlling temperature, lowering noise, and easing social stress through the removal of pollutants [40]. The potted plants improved ventilation and reduced tobacco smoke pollutants by significantly reducing CO_2, formaldehyde, volatiles, and particulate matter [41]. It highlighted the role of plant leaf area and airflow management in enhancing pollutant removal efficiency.

Greenery enhances balcony aesthetics and contributes to psychological well-being by reducing stress among residents [42]. Potted plants support local biodiversity, providing habitats for insects and birds, while also contributing to ecosystem services, such as carbon sequestration and water regulation [43,44]. Residential greenery improves urban ecosystems [45,46]. Integrating potted plants on balconies not only enhances thermal comfort but also promotes environmental sustainability and improves the overall quality of urban living spaces [47,48]. Researchers showed that indoor plants improved perceived environmental quality in educational settings, but the short-term cognitive and health benefits of indoor plants may be limited and warrant further research [49,50].

The main reason for temperature increases in urban areas is due to shrinkage of green and blue covers, a rise in impervious surfaces, construction materials, canyon geometry, and the sky view factor. It is also suggested that an increase in green cover would help mitigate UHI effects [51]. Urban hotspots are observed in the fast-growing southeastern and western parts of Chennai city using satellite data from 2008 to 2018, which revealed a rising land surface temperature (LST) in Chennai's urban areas, linked inversely to land use and land cover [52]. The model utilized satellite data to highlight UHI hotspots that could enhance the city's prediction of LST and aid in urban planning efforts. A significant correlation between temperature patterns and vegetation was observed throughout the city [53]. An analysis of green cover and LST showed that a green cover reduction of 13.33% increased the LST up to 6.53 °C in Chennai. Areas with more green cover exhibited poor UHI [54]. A simulation study in the warm humid tropical climate of Chennai with greening systems reduced cooling demand by 10.5% for green roofs and 13% for green walls. Greening systems have been proven to improve buildings' energy performance and air quality in Chennai [55].

Urban green spaces mitigate heat islands and enhance air quality. A survey of 578 respondents in Tamil Nadu, India regarding their preferences for residential greenery revealed that approximately 90% expressed a desire for gardens, with balconies being the most accessible space in urban Chennai [56]. Potted plants and climbers emerged as the preferred choices due to their lower installation and maintenance costs. Furthermore, preferences were influenced by house type, ownership, and location, offering valuable insights for designers and architects in planning residential greenery. Indoor greening of small-scale greenery emphasized the stress-reducing effectiveness by endorsing its potential for urban stress relief and advocating for improved research standards [57]. The thermal performance of greenery on balconies in tropical climates is an under-researched area, despite the potential for significant impact on building energy efficiency and occupant comfort [58].

Most urban greening studies focus on large-scale greeneries through experimental methods and simulations using satellite data. Indoor and balcony greeneries, however, have not been extensively investigated in the literature due to the inability to observe these spaces through satellite imagery. This limitation in data collection methods has resulted in a gap in research regarding small-scale urban greenery interventions. Multiple factors are involved in the practical determination of thermal comfort effects in built environments, making such studies more complex and challenging. This multifaceted nature of thermal comfort in urban settings necessitates a more nuanced approach to research, particularly when examining smaller-scale greenery interventions like those found in indoor spaces and on balconies. Further research is required to study the enhancement of the thermal comfort of residential buildings with small green spaces like potted plants and indoor plants. This knowledge gap is particularly notable given the prevalence of balconies in urban residential architecture and their role as intermediary spaces between indoor and outdoor environments.

This experimental study's focus on potted plants is significant, as it represents a practical and widely adoptable approach to balcony greening. Potted plants offer flexibility in terms of species selection, staggered arrangement, and maintenance, making them suitable for a variety of balcony configurations and resident preferences. By conducting field experimentation in Chennai, the research aims to provide empirical data on the thermal effects of balcony greenery in a specific tropical urban context. The emphasis on IAT as a primary metric is crucial, as it directly relates to occupants' thermal comfort and potential energy savings for cooling. This approach allows for a quantitative assessment of how balcony plants influence the thermal environment of adjacent interior spaces. The study's findings could have significant implications for sustainable building design and urban greening strategies in tropical cities, potentially informing building codes, energy efficiency standards, and architectural practices. Moreover, it may contribute to a broader understanding of passive cooling techniques in the context of climate change and increasing urbanization in tropical regions. The major findings of this current research could aid urban planners and architects in comprehending the role of even small green spaces in mitigating heat stress for urban dwellers.

The Sustainable Development Goals (SDGs) closely associated with this present research work "https://sdgs.un.org/goals (accessed on 30 April 2024)" are as follows.

- SDG 3: Good Health and Well-being—By addressing UHI effects and reducing heat stress, the research aims to improve residents' health and well-being.
- SDG 7: Affordable and Clean Energy—UGI can contribute to cooling energy savings due to reduced IAT.
- SDG 11: Sustainable Cities and Communities—The study focuses on mitigating heat stress in urban areas through green interventions, aligning to create sustainable cities and communities if similar measures are adopted on a larger scale.
- SDG 13: Climate Action—By investigating the thermal effectiveness of potted plants in reducing heat stress, the research contributes to climate action efforts by promoting strategies to combat rising temperatures in urban environments.
- SDG 15: Life on Land—The use of greenery, particularly potted plants, contributes to enhancing green spaces within urban residential environments, supporting terrestrial ecosystems and biodiversity.

The reported research on enhancing thermal comfort using potted plants in residential buildings is summarized in the following six comprehensive sections:

- Section 1 introduces residential greenery, particularly potted plants in multi-story buildings in tropical regions with recent and relevant literature. It further discusses the identification of research gaps, the need for the present study, its major contributions to the microclimate, and the overview of the sections of the reported present work.
- Section 2 details the materials and methods employed in the study to estimate the thermal comfort effect of potted plants on the balcony of a mid-rise residential building. The measurement of solar radiation, the relative humidity of the air, and surface and air temperatures with uncertainty analysis is discussed.
- Section 3 presents the experimental results regarding solar radiation, ambient conditions, and surface and air temperatures with and without plants.
- Section 4 discusses the major findings, implications, and future perspectives of the present experimental study.
- Section 5 concludes with the significant findings of the present experimental study and outlines further research directions regarding residential greenery using potted plants.

2. Materials and Methods

2.1. Study Location

According to the Chennai Metropolitan Development Authority's proposed land use plan, primary residential areas would cover 33.58% of Chennai city and 31.68% of the broader metropolitan area. This allocation highlights residential greenery's potential to mitigate urban heat. Residential zones contribute to the UHI effect via high-albedo surfaces and anthropogenic heat, but they also offer opportunities for distributed green infrastructure. Enhancing residential greenery can mitigate heat stress through evapotranspiration, shading, albedo modification, microclimate regulation, and reduction of anthropogenic heat. The distributed nature of residential areas supports a network of green spaces, creating cooling corridors and promoting urban ecological networks. Implementing residential green space strategies could significantly lower Chennai's urban heat budget, potentially reducing surface temperatures by several degrees Celsius. The selected premises predominantly featured balconies facing north. For this study, a residential building with a similar orientation was chosen. Most of the investigated balconies in the region have faced south, and a few studies have been conducted to study the influence of north-side balconies with plants. The experimental study aims to assess the influence of indoor thermal comfort with and without potted plants. Figure 1 shows the general research methodology adopted in the present experimental study.

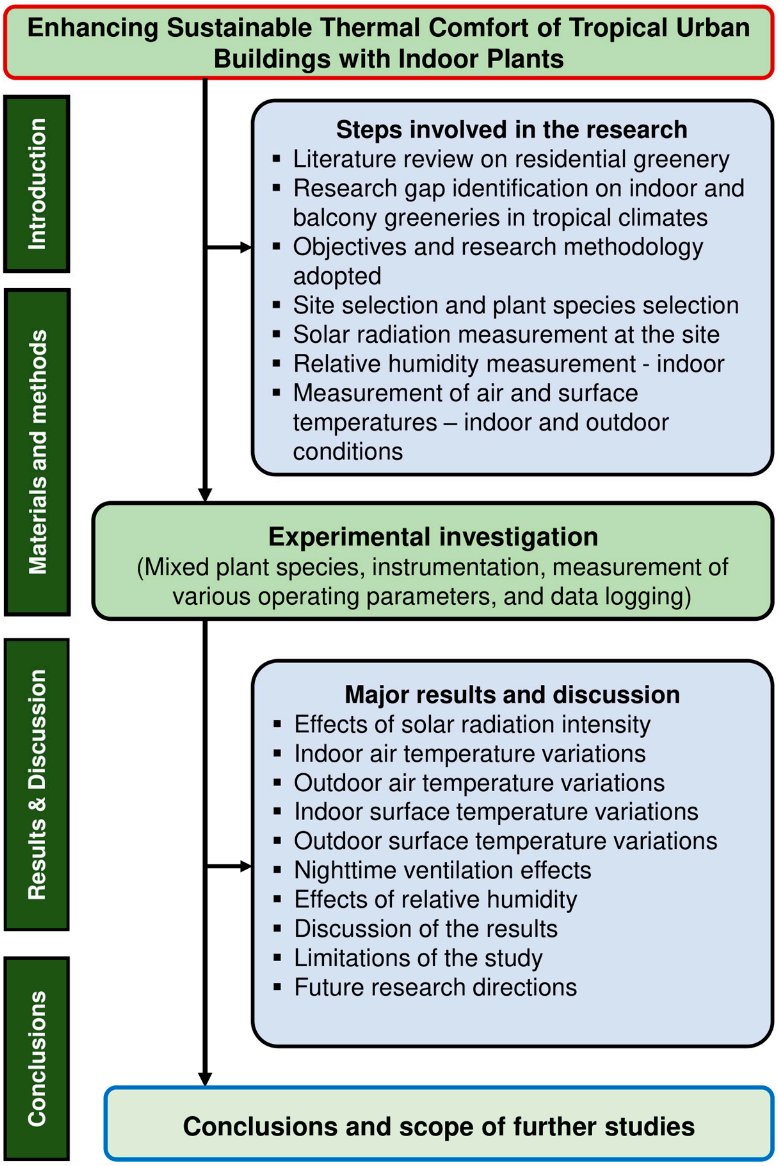


Figure 1. The research methodology adopted in the present study.

The study was carried out in Chennai, Tamil Nadu, located in the southern coastal region of India and experiencing a warm, humid climate (Figure 2). The test site's latitude and longitude are 13°5′ N and 80°11′ E, respectively. It falls under category A of the Köppen climate classification system. The hottest months are from April to June, with a maximum temperature of around 40 °C and a minimum temperature of around 23 °C from November to January. Thus, the site selected has an annual variation of ambient temperatures between 23 °C and 40 °C.

Most dwellers at the study location expressed a preference for mixed plants on their balconies, seeking to attain a variety of benefits [56]. This preference likely stems from the diverse advantages offered by different plant species, such as varied aesthetic appeal, air purification capabilities, and potential for small-scale urban agriculture. Based on these user preferences, the study was designed to incorporate the most-used plant species found in Chennai's residential buildings. This approach ensured that the research findings would be directly applicable and relevant to residents. The selection of plants likely included a mix of ornamental, air-purifying, and potentially edible species, reflecting the multifunctional nature of balcony gardens in urban settings. By aligning the experimental design with local preferences and practices, the study aimed to produce results that could be readily translated into practical recommendations for enhancing thermal comfort in Chennai's residential spaces.

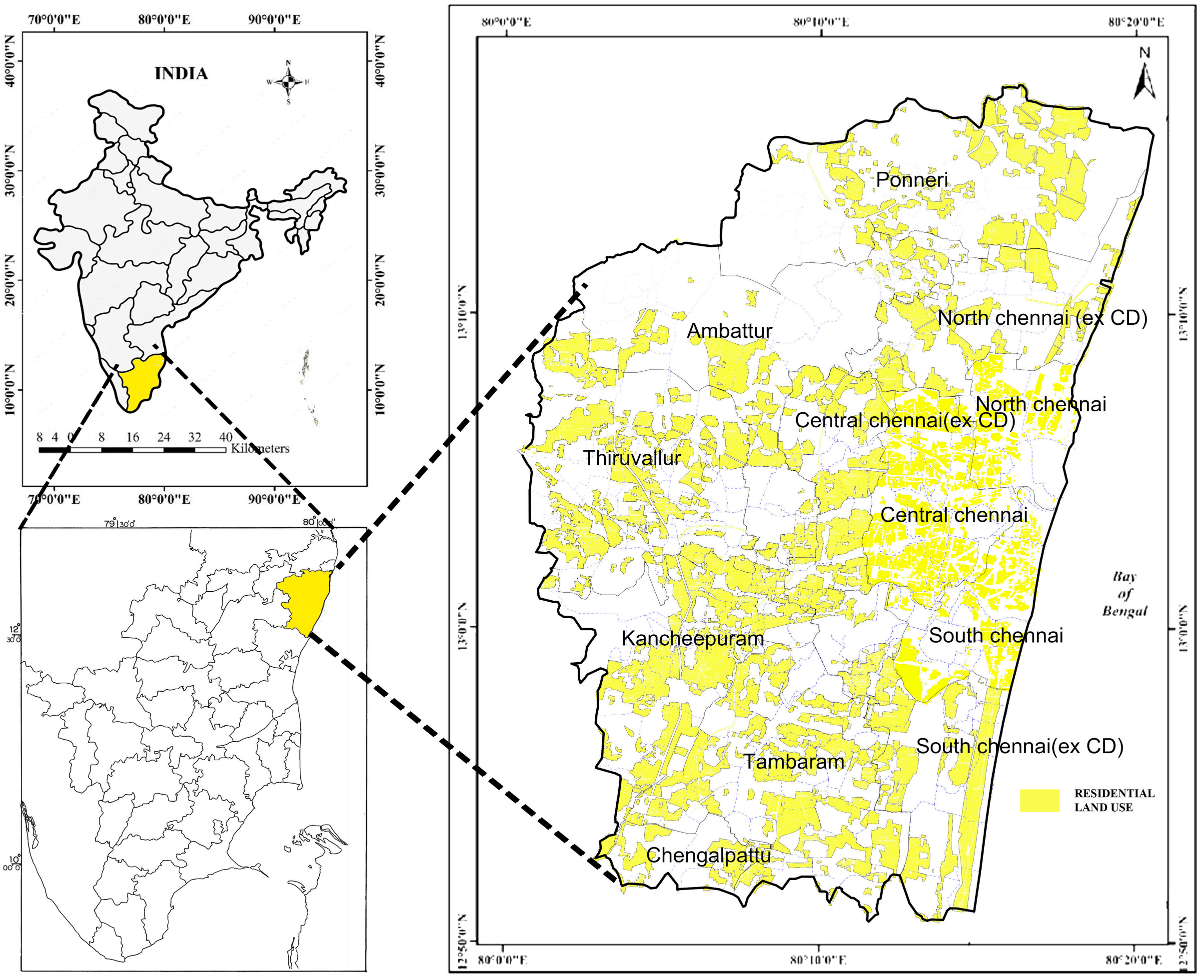


Figure 2. The selected study location of the present study "https://www.cmdachennai.gov.in (accessed on 30 April 2024)". (Residential land use map of Chennai extracted and edited by the authors from a proposed land use map 2026 by the Chennai Metropolitan Development Authority, Tamil Nadu, India).

2.2. Experimental Work

A potted plant in situ experiment was conducted to examine the effects of plants on the balcony and indoors. The study was conducted in a three-story apartment building in Chennai. The selected test site contains a majorly similar building typology. There are two dwellings on each of the first and second floors, and one on the ground floor, for a total of five residential units in the apartment. The structure is surrounded by streets in the north, vacant land in the west, and residential buildings of a similar height in the east and south. For experimental objectives, the second-floor balcony facing the street was chosen to minimize the shading impact from nearby buildings. To evaluate the plants' effectiveness in real time, the experimentation attempted to maintain the typical daily working conditions and environment of the residents as much as possible. The balcony measures 6 m × 1 m × 2.89 m and is in the north, receiving direct sunlight in the morning between 6:00 a.m. to 9:00 a.m. and in the evening from 3:00 p.m. to 6:00 p.m. during summer. In the winter, the balcony remains shaded almost throughout the day with indirect sunlight. An informal living area measuring 4.37 m × 3 m × 2.89 m situated adjacent to the balcony is the chosen indoor measurement space (Figure 3).

Figure 3. (**a**,**b**) Actual views of potted plants on the balcony, (**c**) location of indoor temperature and relative humidity (RH) sensors, (**d**) IST sensor, (**e**) weather station, including pyranometer, hygrometer, anemometer, and temperature sensor, (**f**,**g**) plan and section of the experimented balcony and room with sensors installed, respectively.

2.3. Plant Species

Potted plants of various sizes and plant varieties were placed on the balcony. The plant species chosen were those that required less watering, less maintenance, and less exposure to sunlight (Table 1). Residents at the study site preferred mixed plants on balconies for various benefits. The present experimental study incorporated the most common plant species used in Chennai's residential buildings. The plant species used were *Aglaonema modestum*, *Syngonium angustatum*, *Dracaena trifasciata*, *Monstera delisiosa*, *Philodendron erubescens 'gold'*, *Dracaena fragrans*, *Epipremnum aureum*, and *Tradescantia spathace*.

Table 1. Plant species used.

Species	Common Name	Type	Water	Sunlight	Plant Height (mm)	Foliage Type
Aglaonema modestum	Chinese evergreen	Herb	Every 5 to 10 days	Shade to partial sun	381	Evergreen
Syngonium angustatum	Arrowhead plant	Climber	Every 13 days	Shade to partial sun	1219	Evergreen
Dracaena trifasciata	Snake plant	Succulent herb	Once or twice a month	Partial shade	990	Evergreen
Monstera delisiosa	Swiss-cheese plant	Climber	Every one to two weeks	Partial shade	711	Evergreen
Philodendron erubescens gold	Blushing philodendron	Climber	Once every 7 to 10 days	Partial shade	1524	Evergreen
Dracaena fragrans	Corn palm	Shrub	Every 10–14 days	Partial shade to full sun	483	Evergreen
Tradescantia spathacea	Moses-in-the-cradle	Herb	Every 10 days	Partial shade to full sun	990	Evergreen
Epipremnum aureum	Money plant	Climber	Once a week to 10 days	Shade to partial shade	990	Evergreen

2.4. Measurements

Three stages of thermal measurements were conducted. In the first phase, potted plants were measured on the balcony with natural ventilation during the day, and windows and doors were closed for ventilation during the night by imitating the inhabitants' usage of the space. Measurements using potted plants and permitted ventilation during the day and night were part of the second phase. In the third phase, measurements without plants on the balcony were conducted with phase one's ventilation conditions. The measurements primarily focused on solar radiation, surface temperatures, and indoor and outdoor air temperatures to observe how small plants kept between indoor and outdoor spaces on balconies influence the thermal conditions.

To quantify the influence of plants on the same area with and without plants, and the constraints to acquiring equivalent utilization of spaces between two residential units in real time, the measurements for the three phases were taken on the same balcony on distinct sets of days. Hence, the experimentation was conducted in three phases of 10 days each from 20 April 2024 to 20 May 2024. The second phase was carried out for five days. Temperature measurements were taken in three parts: IAT, IST, and indoor RH in the room next to the balcony; OAT, OST, and outdoor RH on the balcony; and daily weather parameters like solar radiation, wind speed, and exterior air temperature measured on the terrace. The temperature and RH measurements were recorded using an Elitech GSP-6 data logger installed at 1500 mm from the floor. The data logger's accuracy for temperature is ±0.5 °C. The temperature range is from −40 °C to +150 °C. The range and accuracy for RH measurement are 0% to 100 and ±3% RH, respectively. The surface temperatures were recorded using Elitech RC-5+ data loggers with an accuracy of ±0.5 for −20 °C to +150 (Table 2).

The solar radiation, wind speed, and air temperature were recorded using a weather station installed on the roof. Ten-minute intervals were used to record the temperature and humidity values. To ensure the accuracy of the plants' performance, the mechanical ventilation systems in the room were turned off during the measurement period. The wind speed range recorded by the anemometer during the test days ranged between 2 and 4 m/s. The average wind speed across all test days fell within the range of 2.4 to 2.6 m/s. Therefore, convective heat transfer due to wind speed on the outer walls appears consistent, and the wind convective heat transfer characteristics are considered negligible throughout the test days. Radiative heat transfer is also minimal at the selected operating temperature conditions, and thus convective and radiative heat losses are not considered in this research.

Table 2. Data loggers used for field monitoring and measurements.

Measurement	Instrument	Manufacturer and Model	Range and Accuracy
IAT OAT	Temperature sensors	Elitech GSP-6, Elitech Technology, Inc., San Jose, CA, USA	Range: −40 °C~+150 °C Accuracy: ±0.5 °C
Indoor RH Outdoor RH	Humidity sensors	Elitech GSP-6, Elitech Technology, Inc., San Jose, CA, USA	Range: 0–100% Accuracy: ±3%
IST OST	Temperature sensors	Elitech RC-5+, Elitech Technology, Inc., San Jose, CA, USA	Range: −30 °C~+150 °C Accuracy: ±0.5 °C
Solar radiation	Pyranometer	AT Delta-T SPN1, Delta-T Services Ltd., Maldon, UK	0–2000 W/m^2, ±10 W/m^2
Wind speed	Anemometer	AT Delta-T RS485, Delta-T Services Ltd., Maldon, UK	0–40 m/s, ±0.5 m/s

3. Results

3.1. Solar Radiation

Given that the data collection for the balcony with and without green occurred on separate measurement days, the days with a similar climatic tendency in the two sets of days—one with and one without a plant—must be identified. It is important to understand various processes through which plants reduce the surrounding temperatures. The primary processes supporting the thermal performance of plants as reported in the literature are shading, evapotranspiration, and the insulating effects of plants. The most significant climatic component for evapotranspiration and the shading impact of the VGS has been determined to be solar radiation [59]. In a humid, tropical climate where solar radiation levels exceeded 300 W/m^2, the thermal effect of the VGS was observed to be more prominent [60]. Hence, we compared the two sets of days with 10 days each, leading to 100 combinations, out of which the three sets with and without plants with similar solar radiation trends and the least percentage of deviation were identified, as shown in Figure 4.

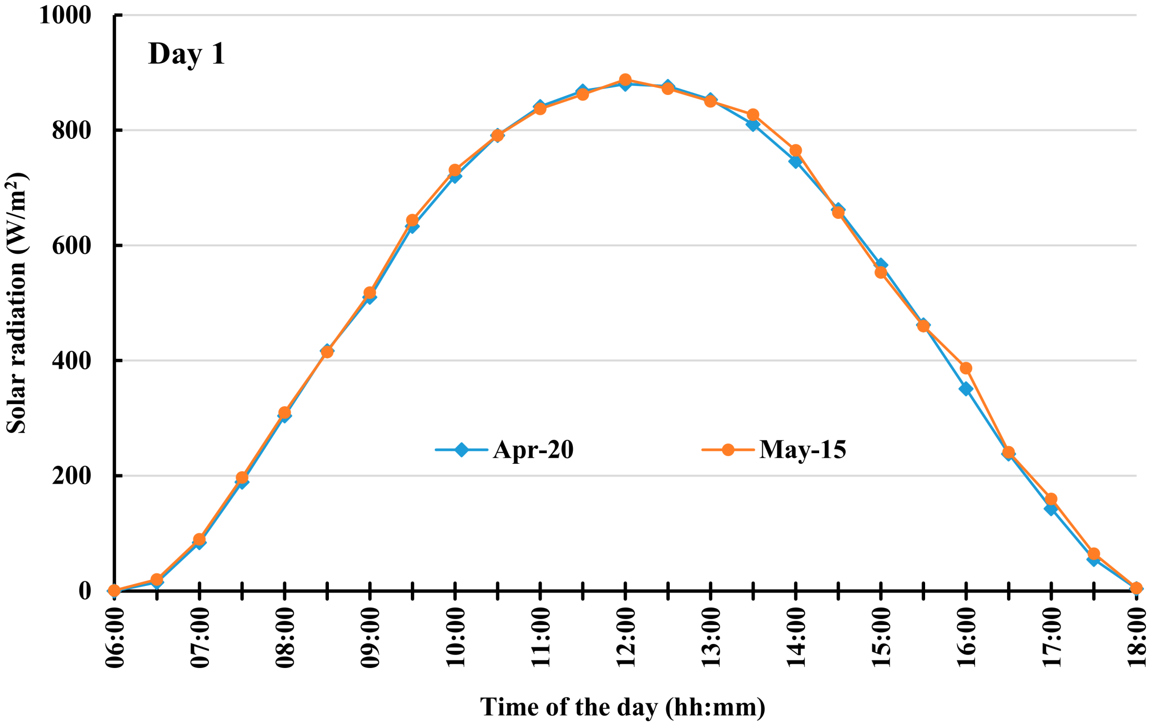


Figure 4. *Cont.*

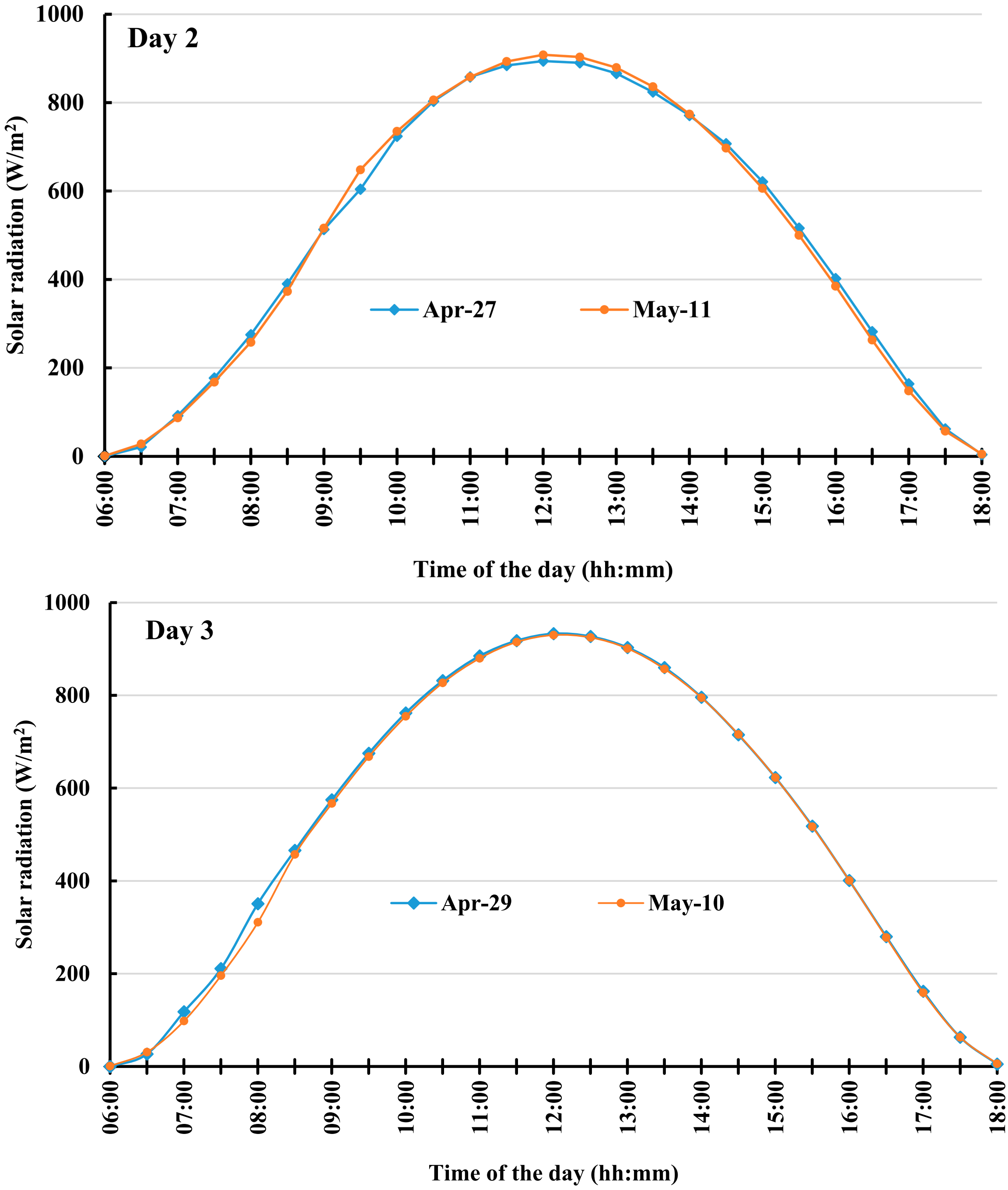


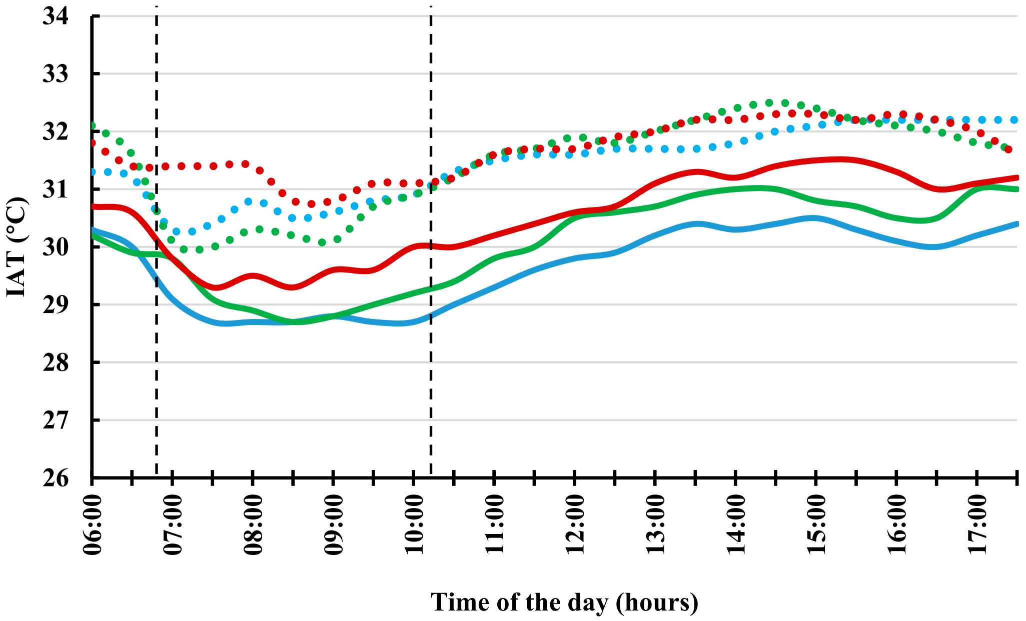
Figure 4. Identified similar solar radiation trends with and without plants.

These three combinations were named day 1, day 2, and day 3 for further analysis. IAT, OAT, IST, and OST are the factors taken into consideration in this study. Solar radiation significantly affects surface and air temperatures at the site. For consistency in the analysis, comparable solar radiation data were used throughout the study. Thus, the present study is mainly focused on similar radiation conditions. Indoor solar radiation effects are minimal and almost similar over the selected short test periods. Furthermore, the amount of solar radiation received inside of the balcony is mainly subjected to seasonal variation of the sun for every 3–5 days. Thus, the present investigation considered similar solar radiation days for the data analysis and the measurement of indoor solar radiation inside of the balcony, and its effects will be investigated in further studies.

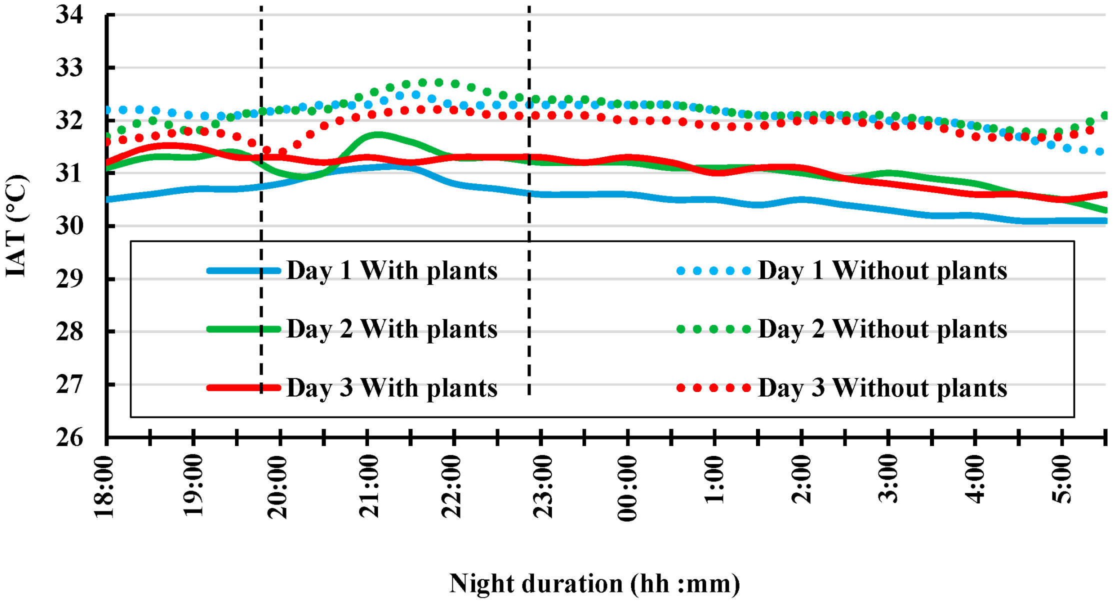
3.2. Indoor Air Temperature Fluctuations

3.2.1. Daytime

Figure 5 shows the daytime IAT recorded with and without plants for all three days. The hourly daytime IAT trends indicate that temperatures fluctuate throughout the day, with a general decrease during the earlier hours of the day and an increase around the latter part of the day. This pattern is visible both with and without plants, though the amplitude of the temperature is generally less significant on days with plants. Over the three days, daytime IAT is consistently lower with plants (Figure 5a).

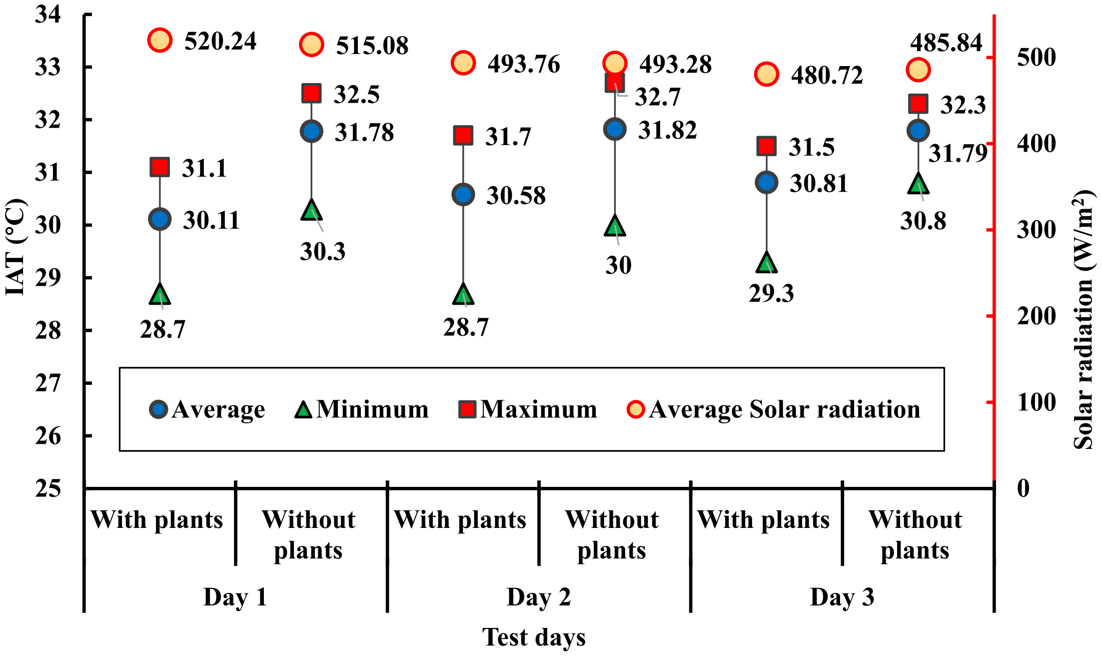


(**a**) Daytime IAT variation.



(**b**) Nighttime IAT variation.

Figure 5. *Cont.*



(**c**) Diurnal maximum, minimum, and averages with and without plants.

Figure 5. Temperature observations of IAT with and without plants on balcony.

The daytime IAT differences range from a low of 0.3 °C to a high of 2.3 °C, suggesting a variable impact of plants on temperature throughout the day. Across all three days, the daytime IAT difference in the early hours (6:00 a.m. to 10:00 a.m.) tends to be more significant up to 2.3 °C than during the middle of the day (11:00 a.m. to 3:00 p.m.). In the afternoon, the effectiveness of plants in reducing temperatures seems to diminish. Evening time on all three days shows a minimal difference, reaching as low as 0.4 °C, indicating a negligible cooling effect from the plants currently.

3.2.2. Nighttime

Throughout all three days, the nighttime IATs with plants are consistently lower than without plants during early night to early morning hours. This consistent pattern suggests that plants might be contributing to cooler temperatures, potentially through processes like releasing moisture into the air (transpiration), as shading is not possible during these hours. The hourly nighttime IAT trends indicate that temperatures fluctuate throughout the night, with a general increase between 8:00 p.m. and 11:00 p.m. during the night and a very gradual decrease early in the morning around 4:00 a.m. (Figure 5b). The maximum difference in nighttime IAT occurs between 12:30 a.m. and 5:00 a.m., with temperature differences ranging from 1.3 °C to 1.8 °C across three days, showing that the cooling effect of plants was strongest in the late night to early morning hours. The minimum temperature differences were more varied in timing across the nights but consistently lower in the early night period between 6:30 p.m. and 9:00 p.m. in a range of 0.1 °C to 0.5 °C.

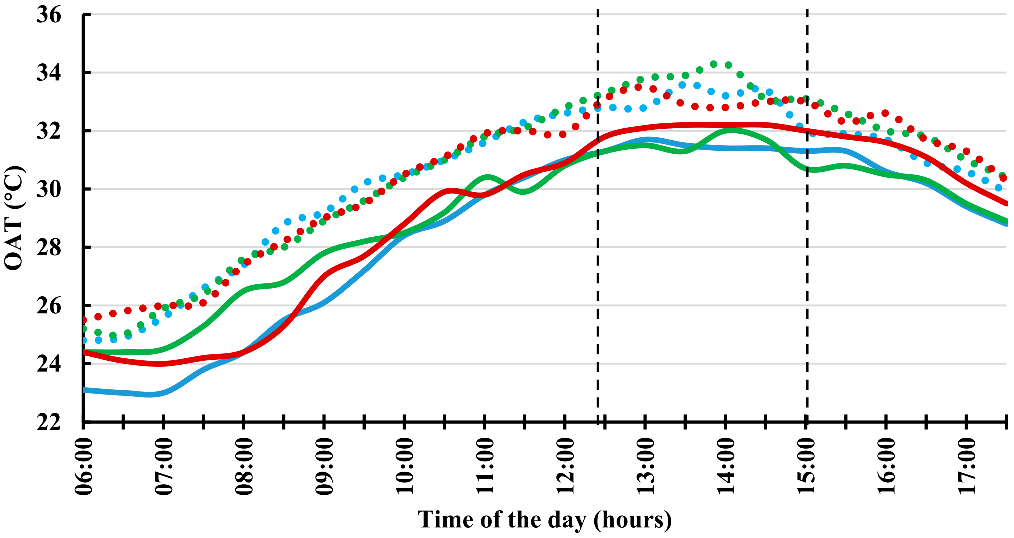
3.2.3. Diurnal Variation

The presence of plants generally sees lower temperatures, which is particularly evident in the minimums and maximums. This effect is more significant on days with higher solar radiation (Figure 5c). However, the presence of plants saw a higher diurnal temperature variation compared to the absence of plants. The diurnal variation with plants ranged from 2.2 °C to 3.0 °C, whereas without plants it was between 1.5 °C and 2.7 °C. The diurnal variation between with plants and without plants is greater at minimum temperatures than at maximum temperatures. Thus, the presence of plants helped to maintain the minimum temperature both at temperature peaks and at lows, reducing the cooling demands both day and night.

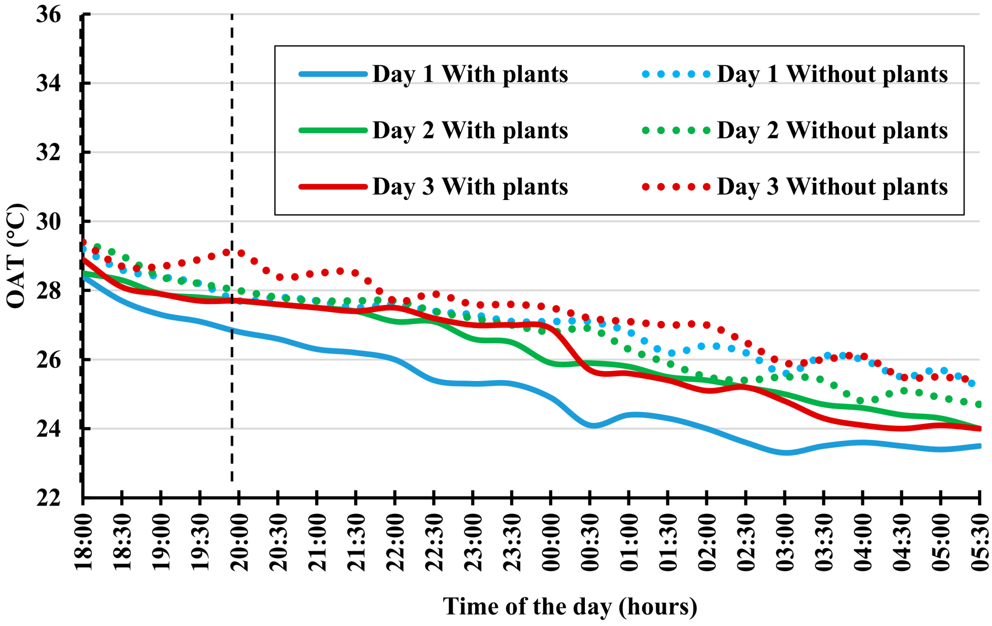
3.3. Outdoor Air Temperature Fluctuations

3.3.1. Daytime

Daytime OAT recorded with and without plants for all three days is shown in Figure 6. Daytime OAT across each day starts with a lower temperature and then gradually rises and reaches its peak during the midday between 12:30 p.m. and 3:00 p.m. and decreases gradually towards the evening. The pattern is similar in both sets with and without plants, but days with plants consistently maintained lower temperatures compared to days without plants (Figure 6a). The average daytime OAT differences range from 0.1 °C to a maximum of 3.3 °C, suggesting a variable impact of plants on temperature throughout the day. The daytime OAT gradually rises and tends to be more significant, around up to 3.3 °C, between 7:30 a.m. and 9:30 a.m. After peaking, the difference slightly decreases throughout the afternoon until late evening. Day two also follows a similar pattern, with a slight shift in the peak time, reaching around 1:00 p.m.

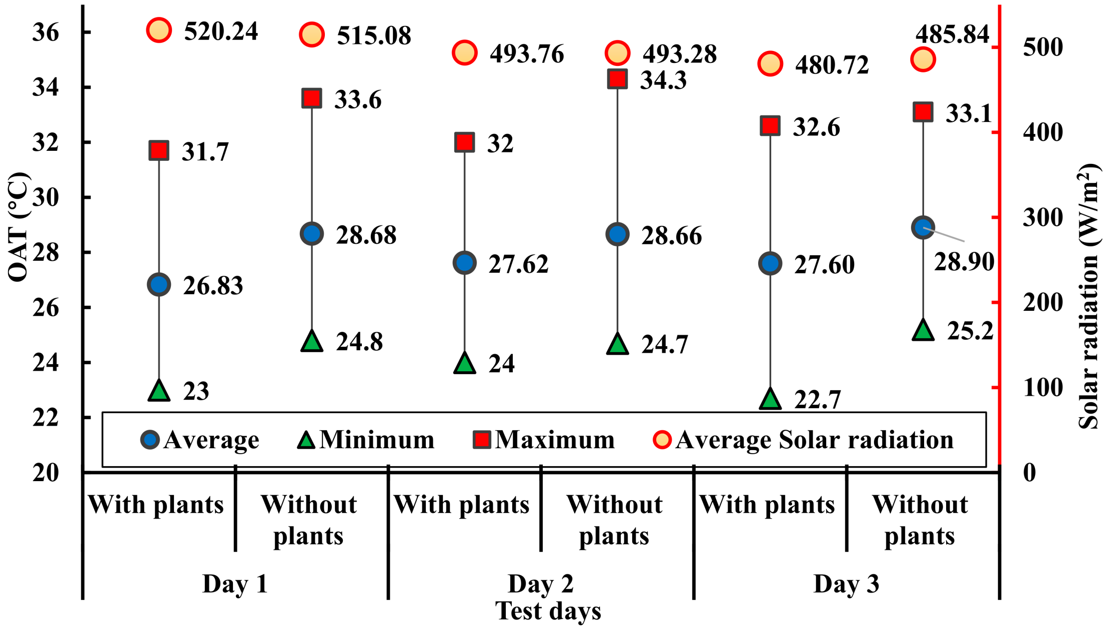


(**a**) Daytime OAT variation.



(**b**) Nighttime OAT variation.

Figure 6. *Cont.*



(**c**) Diurnal maximum, minimum, and averages with and without plants.

Figure 6. Temperature observations of OAT with and without plants on the balcony.

3.3.2. Nighttime

For all three days, nighttime OAT temperatures with plants consistently start with higher temperatures during the late evening at 6:00 p.m. and decrease gradually without much fluctuation until early morning at 6:00 a.m. The temperature trend on days with plants is persistently lower than on days without plants. This pattern suggests the cooling potential of plants even at night without solar radiation and shading effect (Figure 6b). Across all three days, the temperature differences generally increase as the night progresses, peaking around midnight to early morning hours before beginning to decline as dawn approaches. The maximum difference in the nighttime OAT of up to 3 °C occurs between 12:30 a.m. and 2:30 a.m., showing the strongest cooling effect of plants. The minimum temperature differences were more varied in timing across the nights but consistently lower in the early night period between 6:30 p.m. and 10:00 p.m. in a range of 0.1 °C to 0.9 °C.

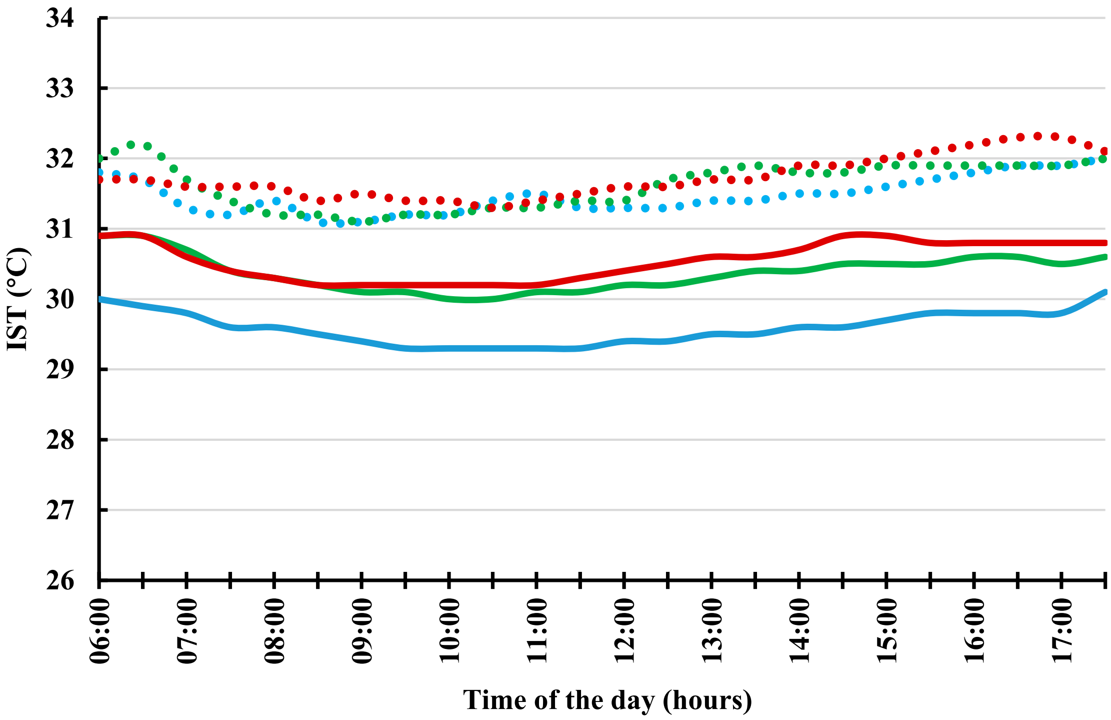
3.3.3. Diurnal Variation

Compared to the IAT diurnal variation, the temperature range of OAT is slightly smaller with plants than without on day 1, suggesting a moderating effect on temperature extremes. However, on day 2, the range is significant and up to 1.6 °C, indicating more significant temperature fluctuations without the moderating influence of vegetation (Figure 6c).

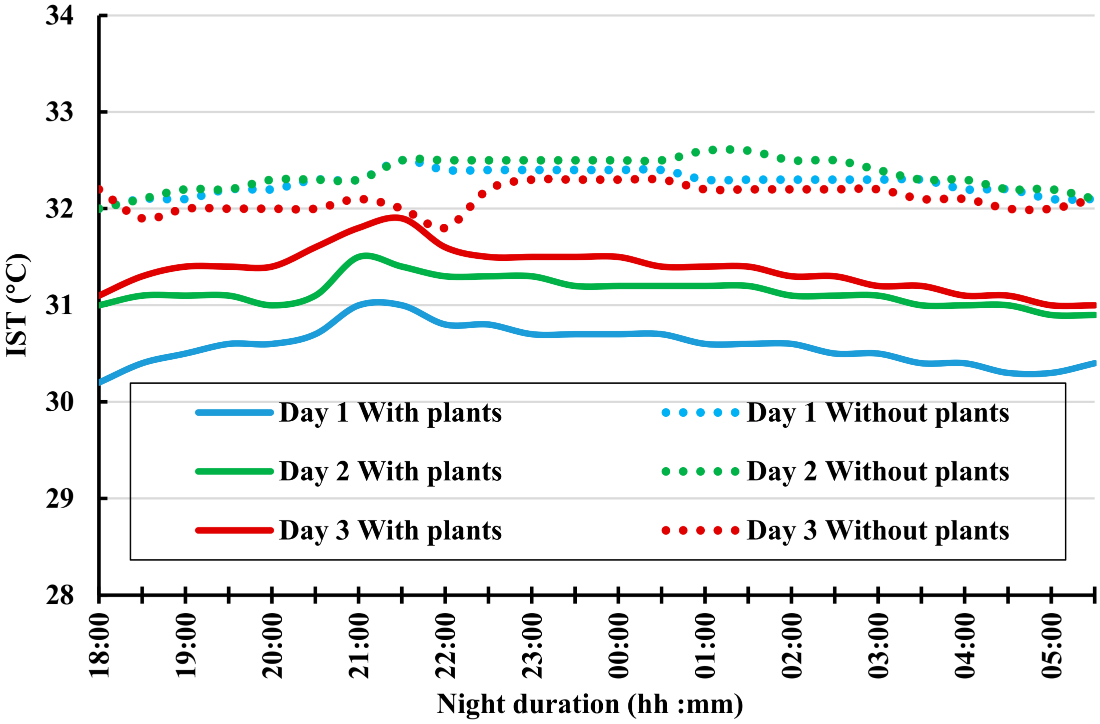
3.4. Indoor Surface Temperature Fluctuations

3.4.1. Daytime

Figure 7 shows the daytime IST recorded with and without plants for all three days. Compared to the air temperature, hourly daytime IST trends indicate less temperature fluctuation throughout the day, with no peak increase or decrease. The pattern is similar both with and without plants, though the degree of the temperature variation is typically less on days with plants. Over the three days, daytime IST is consistently lower with plants (Figure 7a). The average daytime IST differences range from a low of 0.8 °C to a high of 2.2 °C, suggesting a variable impact of plants on temperature throughout the day. The daytime IST difference gradually rises in the early hours from 6:00 a.m. and tends to be more significant, up to 2.3 °C, around 10:30 a.m. After peaking in the late morning, the difference slightly varies throughout the afternoon, without many drops or peaks until late evening.

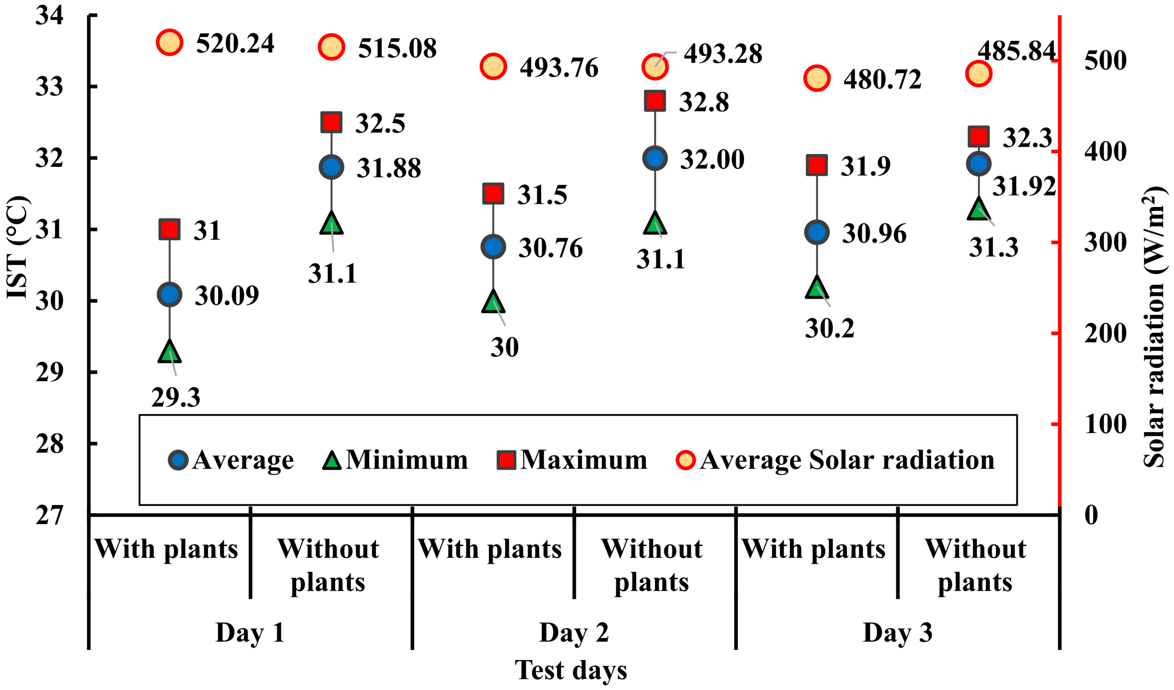


(**a**) Daytime IST variation.



(**b**) Nighttime IST variation.

Figure 7. *Cont.*



(**c**) Diurnal maximum, minimum, and averages with and without plants.

Figure 7. Temperature observations of IST with and without plants on the balcony.

3.4.2. Nighttime

Throughout all three days, nighttime IST temperatures with plants are consistently lower than without plants during these night to early morning hours. This consistent pattern suggests that plants might be contributing to cooler temperatures, potentially through processes like releasing moisture into the air (transpiration). The hourly nighttime IST trends indicate that temperature fluctuation remains stable throughout the night, with a general increase between 8:00 p.m. and 11:00 p.m. during the night (Figure 7b). Temperature differences are more stable during the early evening hours across all days, hovering around 1.6 °C to 1.8 °C between 6:30 p.m. and 8:00 p.m. The period from 9:00 p.m. to midnight shows a gradual decrease in temperature differences with the most significant drop, reaching the lowest point of 0.1 °C at 9:30 p.m., indicating minimal temperature moderation by plants during this time. After midnight, the temperature differences tend to stabilize or slightly increase again. The maximum difference in nighttime IST usually occurs between 12:30 a.m. and 5:00 a.m. with temperature differences ranging from 1.5 °C to 1.9 °C across three days, showing that the cooling effect of plants was strongest during late night to early morning hours. The minimum temperature differences were consistently lower in the early night period between 8:30 p.m. and 10:30 p.m. in a range of 0.1 °C to 1.3 °C.

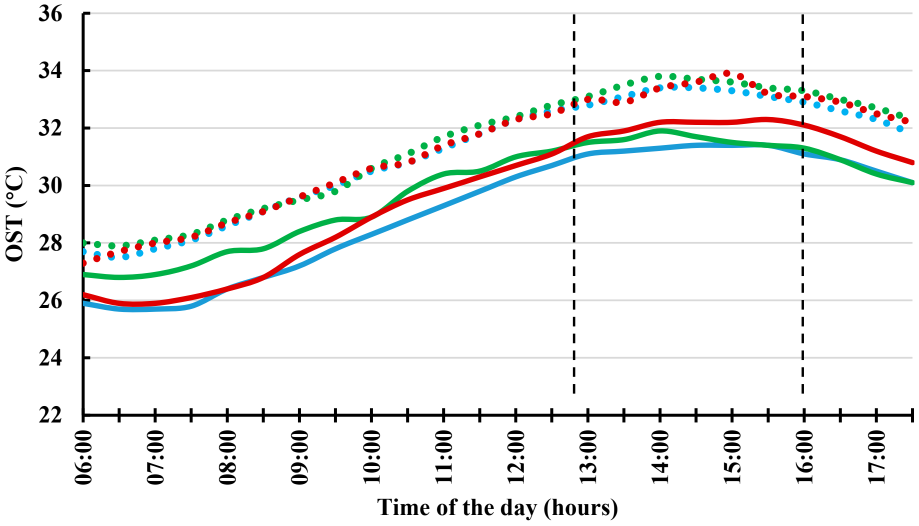
3.4.3. Diurnal Variation

Lower average temperatures are observed with plants compared to without plants across all three days, indicating a cooling effect because of the presence of vegetation. The temperature differences with and without plants range approximately from 0.96 °C to 1.79 °C. However, in areas with plants, the diurnal variations are generally higher compared to areas without plants. This is like the observed diurnal variation of daytime IST. The diurnal variation with plants ranges from 1.7 °C to 1.9 °C, whereas without plants it is between 1.0 °C and 1.7 °C (Figure 7c).

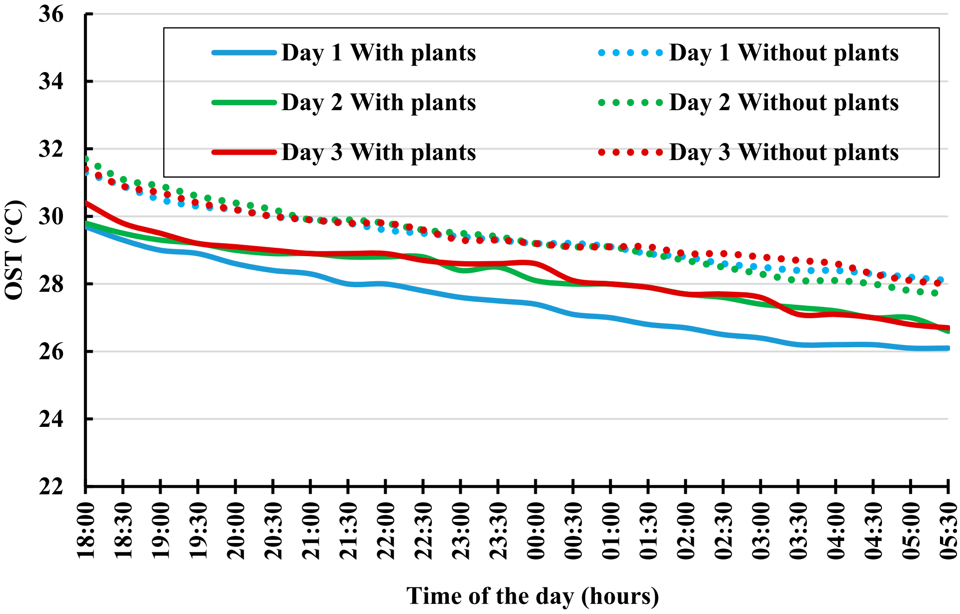
3.5. Outside Surface Temperature Fluctuations

3.5.1. Daytime

The daytime OST recorded with and without plants for all three days is shown in Figure 8. Across all three days, like daytime OAT, for daytime OST, temperatures tend to rise gradually from morning to afternoon, peaking around midday or early afternoon between 12:00 p.m. and 4:00 p.m. and then gradually declining towards the evening hours. This is a typical daily temperature pattern both with and without plants (Figure 8a). Comparing daytime OST with and without plants, there seems to be a consistent pattern of slightly lower temperatures with plants throughout the day. In terms of average OST differences, the daytime OST range reaches as low as 0.9 °C and as high as 2.4 °C. Like daytime OAT, daytime OST gradually rises in the early hours from 6:00 a.m. and tends to be more significant up to 2.3 °C around 9:30 a.m. After peaking in the morning, the difference gradually decreases with drops or peaks until late evening. As observed in daytime OAT, daytime OST also exhibits a slight shift in the temperature change trend on day 2, which might have happened due to external influences on the environment.

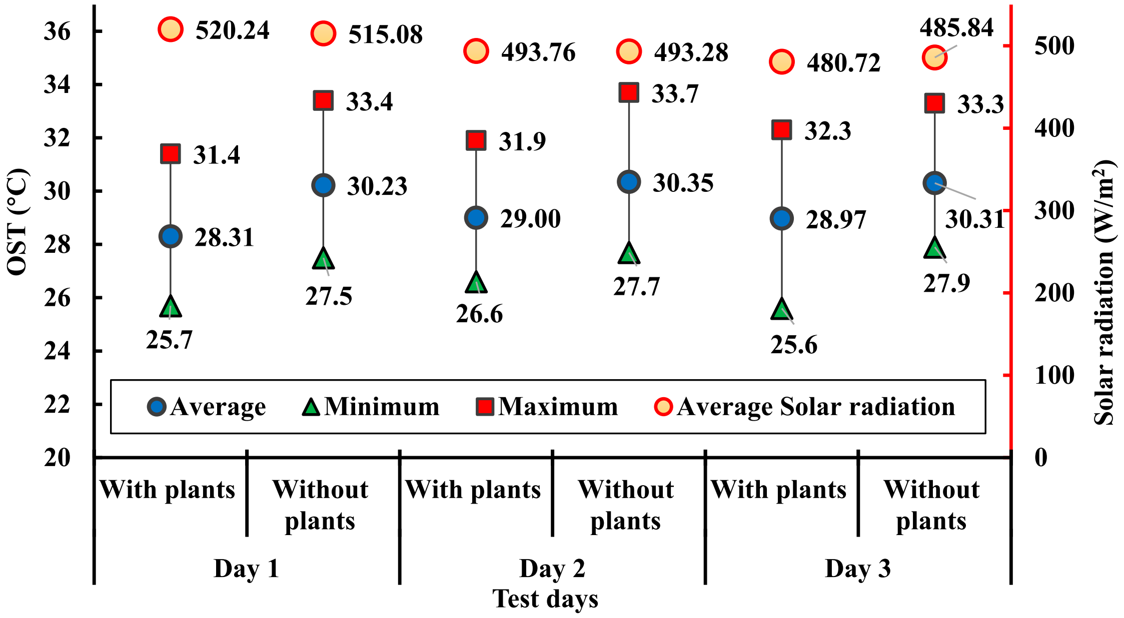


(**a**) Daytime OST variation.



(**b**) Nighttime OST variation.

Figure 8. *Cont.*



(**c**) Diurnal maximum, minimum, and averages with and without plants.

Figure 8. Temperature observations of OST with and without plants on balcony.

3.5.2. Nighttime

As before, there is a clear distinction between temperatures with and without plants. The temperatures are consistently lower when plants are present. The hourly nighttime OST trends start with a maximum temperature at 6:00 p.m. and gradually decrease until early in the morning, with a minimum temperature around 5:00 a.m. (Figure 8b). The maximum difference in nighttime OST usually occurs between 12:30 a.m. and 5:00 a.m., with temperature differences ranging from 1.0 °C to 2.2 °C, showing that the cooling effect of plants was strongest during late night to early morning hours, except for day 2. As mentioned, because of the shift in the day 2 temperature trend, the maximum temperature on day 2 occurred in the late evening between 6:00 p.m. and 9:00 p.m.

3.5.3. Diurnal Variation

The diurnal variations are generally higher without vegetation compared to areas with plants. The diurnal variation with plants ranges from 5.3 °C to 6.4 °C, whereas without plants it is between 5.9 °C and 6.6 °C (Figure 8c). Plants contribute to moderating temperature variations and enhancing overall thermal comfort in the environment.

3.6. Nighttime Ventilation

As discussed in the methodology section, phase 1 without night ventilation and phase 2 with night ventilation were compared against each other to see the increased exposure to ventilation in the same room. On phase 2, the doors of the balcony and windows were kept open during both day and night hours. Based on solar radiation, a similar day with ventilation was compared against day 3 of days without night ventilation. The temperature observations are presented in Figure 9.

Major differences were observed in nighttime IAT and nighttime IST when ventilation was introduced at night. The daytime temperature trend and outdoor nighttime temperature trend followed similar observations as discussed before, as it was exposed to the same conditions as before. But, during the nighttime when the ventilation was introduced, the temperature indoors dropped further, enhancing the cooling interior. The maximum difference in nighttime IAT occurs around 5:00 a.m., with temperature differences of 1.3 °C without ventilation, whereas it reaches a maximum of up to 3.2 °C around the same time when ventilation is provided. Similarly, the maximum difference in nighttime IST occurs around 5:00 a.m., with temperature differences of 1.1 °C without ventilation, whereas it reached a maximum of up to 2 °C around the same time with ventilation.

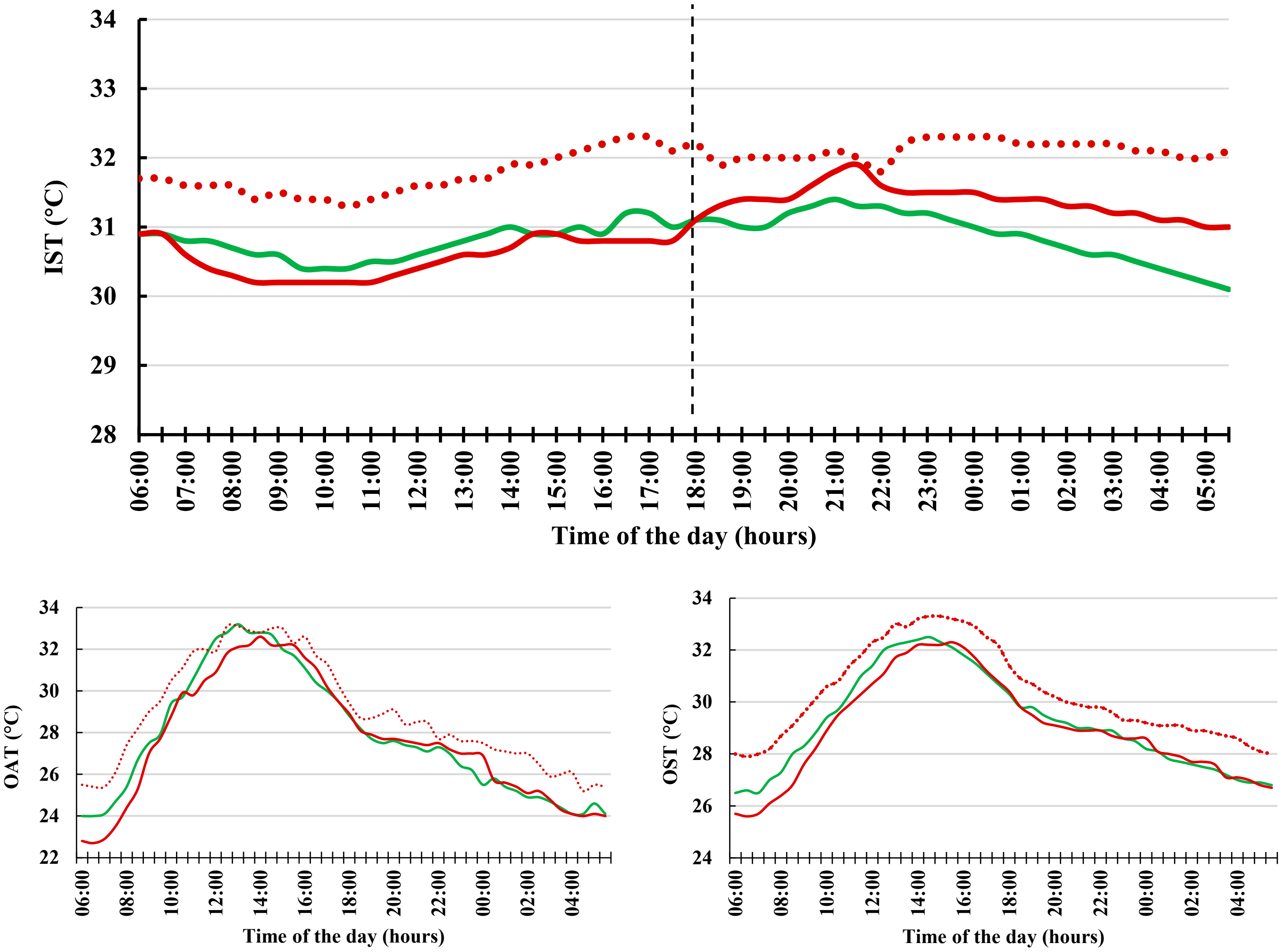


Figure 9. Temperature observations of IAT, IST, OAT, and OST with and without plants and with and without added nighttime ventilation indoors.

3.7. Relative Humidity

Both the indoor and outdoor RH remained low without plants. The RH in both conditions (with and without plants) generally shows a diurnal pattern, decreasing during midday until evening from 10:00 a.m. to 4:00 p.m. and increasing during the evening and night from 4:00 p.m. to morning, 6:00 a.m. The RH reaches its peak in the early morning around 6:00 a.m. at up to 91.7% (with plants) and 88.7% (without plants) outdoors and up to 73.2% (with plants) and 70.2% (without plants) indoors. It drops significantly around 12:00 noon to 4:00 p.m., with 47.6% (with plants) and 43.3% (without plants) outdoors and 50.4% (with plants) and 46.5% (without plants) indoors. The indoor diurnal variation of RH was smaller when compared to the outdoor diurnal variation. Across the three days, there are minor fluctuations between consecutive days. The "with plants" environments generally have a higher average RH (Figure 10). The maximum RH difference reached up to 12% outdoors and 10% indoors with plants.

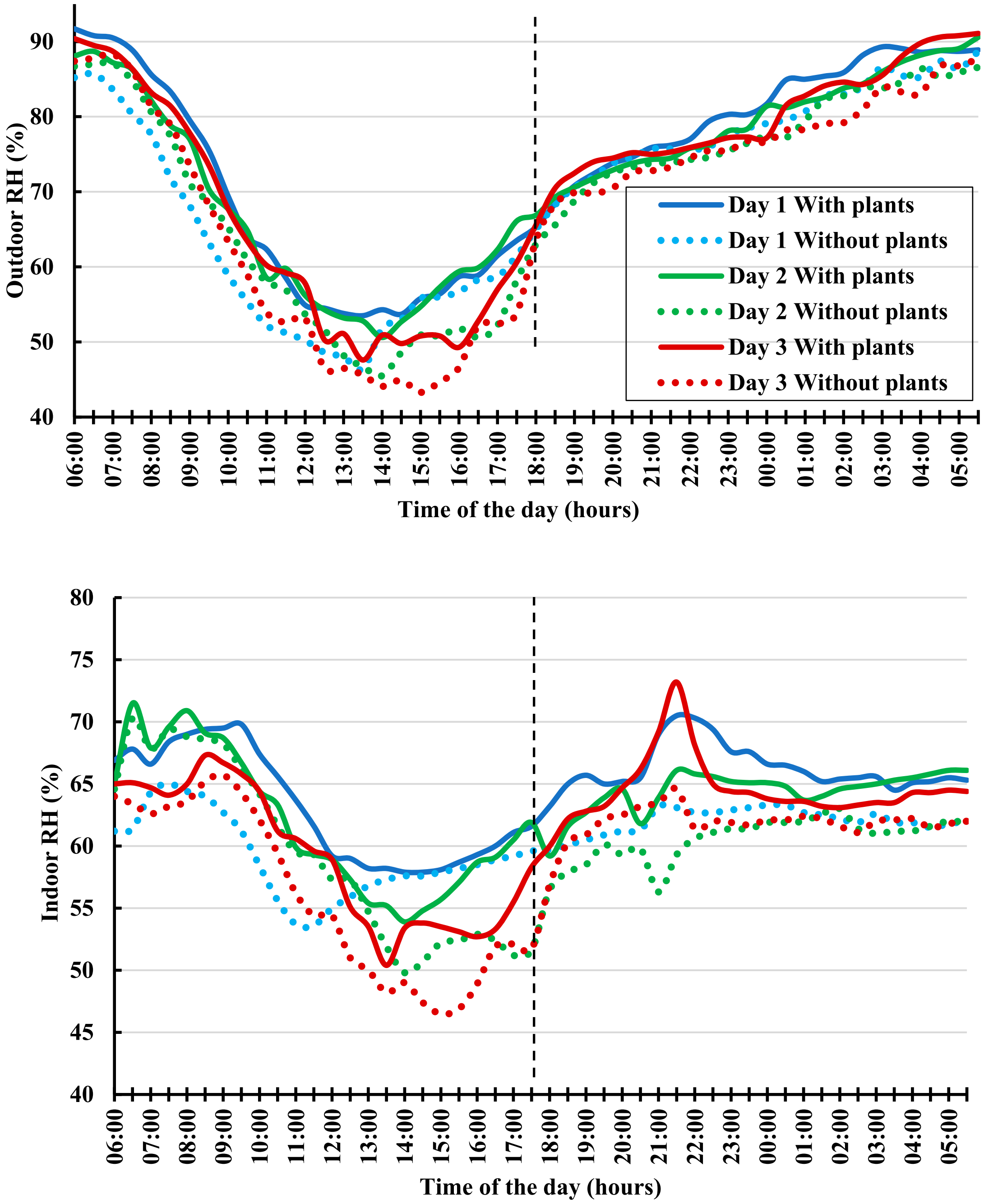


Figure 10. RH observations indoors and outdoors with and without plants.

4. Discussion

The overall comparison of IAT, OAT, IST, and OST under similar solar radiation conditions is shown in Figure 11. It is observed that the IAT with plants is always less than that without plants. Smaller green spaces are also beneficial for temperature regulation of built spaces. Most research that has already been conducted focuses on improving the thermal comfort of building interiors by applying trees, green roofs, and vertical greenery systems to building envelopes. However, the literature shows the potential of the most popular potted plant system, which is utilized in many houses. In particular, low-rise and detached residential buildings lack adequate room for implementing plants. In these situations, vegetated balconies serve as a useful and affordable substitute for more complex systems, while also playing a significant role in bringing people closer to nature [61]. Recent studies have highlighted the interest of residents in incorporating greeneries on balconies. Many residents incorporated potted plants on their balconies, contributing to a greater sense of privacy and separation from neighbors, and its shade from the surrounding greenery was also appreciated for its cooling effect during hot summer days, offering relief from the heat [62]. Therefore, this study evaluates the employment of potted plants to create greenery on balconies to lower inside and balcony temperatures.

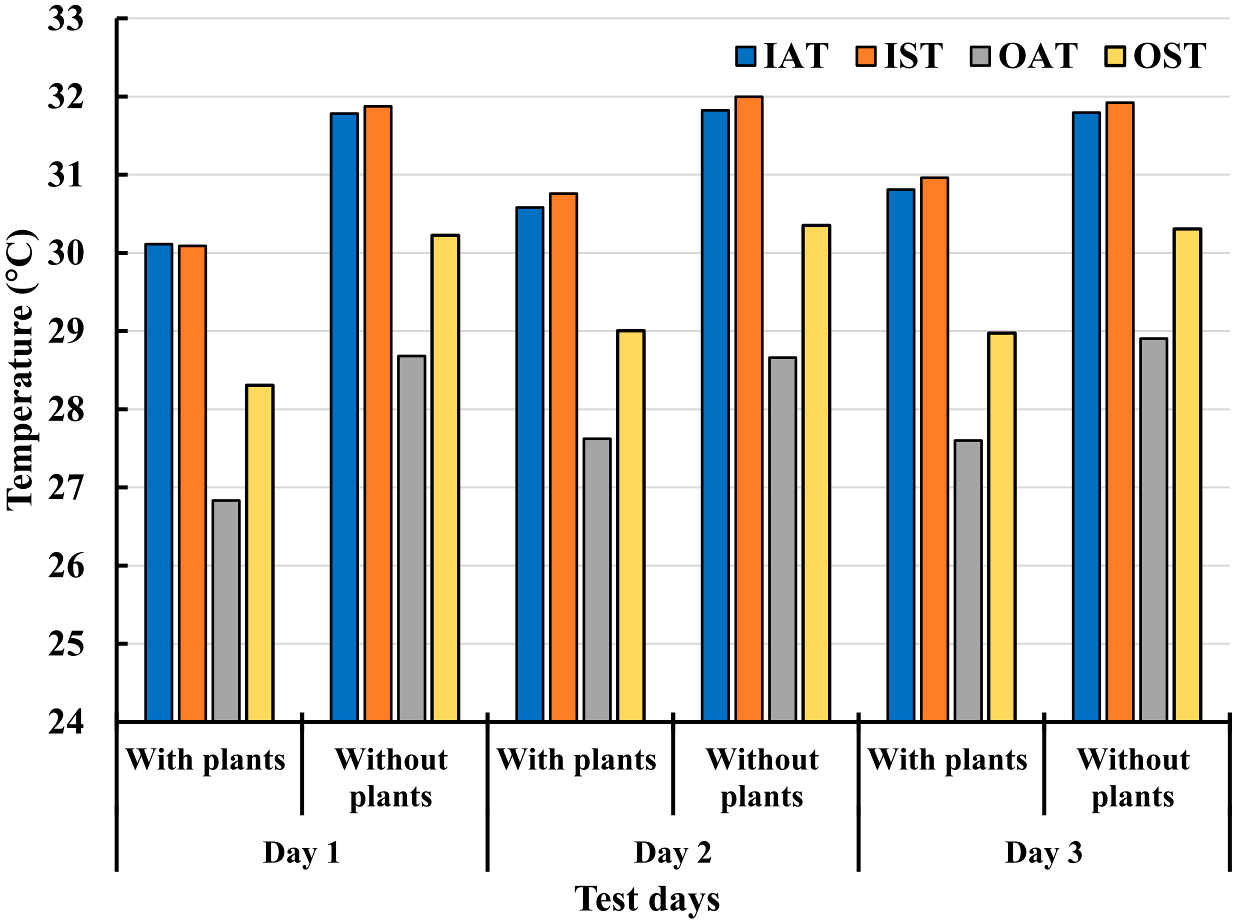


Figure 11. Comparison of IAT, IST, OAT, and OST with and without plants.

Greening the balcony using potted plants of various species has shown proven results. However, the installation of potted plants on the north orientation is ineffective as per the literature [63]. Despite being positioned facing north, potted plants have demonstrated a noticeable reduction in IAT of up to 2.3 °C, IST of up to 2.2 °C, OAT of up to 3.3 °C, and OST of up to 2.4 °C. Thus, similar installations facing other orientations with higher solar radiation levels might create an even greater reduction. Compared to the day, the nighttime reduction was slightly lower, but there was still an apparent reduction of IAT up to 1.8 °C, IST up to 1.9 °C, OAT up to 3.0 °C, and OST up to 2.2 °C. This suggested that the lowering happens during the day because of evapotranspiration, shading, and insulation effects working together. On the other hand, the shading effect is gone at night, which shows a very slight negative influence, indicating that cooling happens more because of other mechanisms of heat reduction by plants. Similar results were observed in the northern orientation and tropical climate. Daytime IST reduction of 1.5 °C in the north orientation and very negligible nighttime reduction were observed in Singapore using green façade systems. IAT reduction of 0.6 °C during the day and 0.25 °C during the night was observed. Another study in Sri Lanka has shown an IAT reduction of 1.86 °C in the north using a green façade at the city scale level [64]. A Chennai study from April to June 2023 examined urban heat challenges by comparing temperature dynamics on a building's terrace, finding a significant reduction in internal room temperatures (4 to 11 °C) in areas with rooftop gardens compared to fully exposed roof configurations [65].

The time of the peaked difference in temperature varied due to many external parameters but mostly occurred around 6:00 a.m. to 10:00 a.m. for daytime IAT, between 12:30 a.m. and 5:00 a.m. for nighttime IAT, between 7:30 a.m. and 9:30 a.m. for daytime OAT, between 12:30 a.m. and 2:30 a.m. for nighttime OAT, around 10:30 a.m. for daytime IST, between 12:30 a.m. and 5:00 a.m. for nighttime IST, around 9:30 a.m. for daytime OST, and between 12:30 a.m. and 5:00 a.m. for nighttime OST. The nighttime peak reduction mostly occurs from midnight to early morning, and daytime peak reduction mostly occurs in the late morning to noon hours.

In the literature, other envelope-level greening systems have caused nighttime temperature increases because of the insulation effect that prevents heat loss during the night. This insulation impedes the rapid nighttime cooling that typically occurs through radiative heat loss to the sky [66]. The surface temperatures are influenced by impervious ground cover and vegetation, suggesting tailored mitigation strategies, such as increasing vegetation for evaporative cooling, implementing shading in modern and industrial areas, and vertical greening [67]. Integrating green spaces and smart city technologies enhances environmental sustainability with green spaces [68]. The present study has shown temperature reduction even during the nighttime. This might be because of the percentage of coverage of building envelopes when compared to the other greening systems. While green walls/roofs covered the envelopes without any gaps, potted plants offered free movement for radiative heat loss at night from building envelopes. Thus, designers can strategically use potted plants or create intentional gaps in coverage to promote effective radiative cooling while still benefiting from the cooling effects of greenery. This also showed that potted plants do not provide much cooling from insulation in this area. Therefore, the evapotranspiration mechanism of the plants followed by shading throughout the day must have played a major role in the temperature drop.

Moreover, the introduction of ventilation during nighttime caused a further reduction of 1.9 °C on nighttime IAT and 0.9 °C on IST, indicating the enhanced benefit of potted plants with the ventilation. The ventilation effects increased the convective heat transfer between the room and the balcony. Integrating UGI into urban planning could benefit the attainment of SDGs [69]. Mahyuddin et al. [70] investigated the influence of five potted indoor plants on the physical environment of office buildings in hot and humid climates in Malaysia. They examined the effects on indoor air quality, air temperature, humidity, and volatile organic compounds, highlighting those potted plants that enhanced indoor conditions through air purification and temperature regulation. Furthermore, the benefits of UGI could be materialized with widespread support, adoption, and implementation of UGI in urban environments.

From the diurnal variation analysis, it is observed that the presence of plants on the balcony reduces the temperature even at night and has caused a high temperature to drop in the interior spaces when compared to the vegetation-less scenario. As seen in most of the literature, the RH remained high with plants when compared to without-plant conditions. Thus, urban greeneries can serve better to increase the RH values in dry climatic zones towards enhanced thermal comfort sustainably. Though this study offered insight into the cooling potential of residential buildings utilizing potted plants on balconies, the present study was carried out in only one orientation that receives minimum solar radiation. The limitations of the present study and scope for further research are discussed here.

4.1. Limitations of the Present Study

This study examines potted plants' cooling efficacy in homes but acknowledges limitations. Focusing on one orientation limits generalizability. Staged experiments due to space constraints hinder real-time assessment, possibly introducing variables. The brief duration overlooks long-term effects and mechanisms. The following constraints highlight the necessity of continued research on potted plants' broader impact on residential cooling.

- The study's focus on only one orientation that receives minimum solar radiation limits the generalizability of the findings to other orientations and solar exposure levels.
- The necessity to conduct the study in stages at the same site due to space limitations hampers real-time assessment and may introduce confounding variables, affecting the accuracy of the results.
- The short duration of the study restricts the understanding of the long-term effects of potted plants on residential cooling, potentially overlooking seasonal variations and sustained benefits.
- A thorough examination of the inherent mechanisms governing the thermal performance of potted plants is vital to exploring practical applications in combating UHI effects.
- The probable errors that need to be accounted for during the estimation of thermal comfort of residential buildings and urban heat studies are the seasonal variation of the solar radiation intensity in south–north orientation, the angle of radiation incidence, various measurement errors of ambient temperature, the surface temperature, shading, the RH, the evapotranspiration rate of plants, plants species selection, plants' arrangement, wind speed and direction, the people occupancy rate, and local climatic factors. Estimation of such errors is essential to accurately quantify the thermal comfort in residential buildings.

4.2. Future Scope

This study explores how potted plants can cool residential spaces, highlighting their effectiveness in reducing heat. A more comprehensive understanding and future research will be carried out regarding various factors, such as different orientations, seasons, and dwelling units. Extending the analysis duration and investigating essential mechanisms like transpiration rates and evaporative cooling are also vital. Through these efforts, we aim to refine the understanding and contribute to the development of sustainable cooling solutions for residential environments.

- The northern facing of residential buildings involves the least influence on thermal comfort and minimal studies were conducted as per the literature. Thus, the present study focused on the potted plants in such an orientation to provide significant research insights. Conducting experiments with potted plants in different orientations and seasons can provide a more comprehensive understanding of their cooling potential across diverse environmental conditions.
- Future research could focus on comparing the cooling effects of potted plants in two comparable dwelling units under similar usage and environmental circumstances, allowing for a more robust assessment of their efficacy related to thermal comfort parameters.
- Extending the study's duration to a longer period could allow for studying the sustained impact of potted plants on residential cooling to validate the findings over an extended timeframe.
- This present study focused on short-term tests, and the variations in solar radiation outdoors were found to be minimal, while the solar radiation indoors was not accounted for. Future research will be considered to investigate long-term effects of seasonal variations in interior spaces (balcony solar radiation) with more extensive measurements of indoor solar radiation on balconies.
- Further studies should be conducted to explore the mechanisms governing the thermal performance of potted plants, exploring factors like transpiration rates, evaporative cooling, arrangement/layout of plants, orientation of the plants, and plant species variations, to enhance their effectiveness and applicability.
- The test site was selected primarily due to the recent exponential growth in population and corresponding expansion of built-up areas, aiming to assess the thermal comfort improvement in residential premises using potted plants on balconies. However, further studies with potted plants, including other geographical locations within the

city (multiple locations in the city) and various building typologies, could yield more robust findings regarding the mitigation of the UHI phenomenon.

5. Conclusions

This research demonstrated the cooling potential of a linear balcony space in a highly urbanized city. Onsite experimentation was carried out in a real-time condition in residential units without mechanical ventilation. The study explored the least expensive potted plants with the most easily maintainable and shade-tolerant plant species considering the difficulty of maintenance and care of plants by residential users. The main findings are as follows.

- Application of potted plants even in small spaces like balconies has shown a significant reduction in IAT of up to 2.3 °C, IST of up to 2.2 °C, OAT of up to 3.3 °C, and OST of up to 2.4 °C during the day.
- An apparent reduction of IAT up to 1.8 °C, IST up to 1.9 °C, OAT up to 3.0 °C, and OST up to 2.2 °C was observed during nighttime without ventilation.
- Potted plants significantly influence the IAT in morning hours compared to during evening hours.
- Adding ventilation at night resulted in a further drop of 1.9 °C in IAT and 0.9 °C in IST, demonstrating the combined effect of both ventilation and potted plants.
- Potted plants are one of the effective alternatives in spaces where the nighttime temperature increases due to the insulation effect of envelopes.
- Potted plants have shown more reduction during the day than at nighttime. Also, the reduced indoor temperatures were more significant on days with higher solar radiation.

Therefore, the steady and passive cooling effects of potted plants can be used in urban planning to lessen heat stress in residential units with limited spaces for greenery. A detailed study of specific mechanisms of evapotranspiration is needed to balance the IAT and RH for human comfort. It can also help to offset the UHI effects if used in greater numbers. This study also highlighted the thermal performance of potted plants in tropical climates towards sustainable thermal comfort.

Thus, integrating potted plants on balconies in tropical climates can significantly enhance thermal comfort, reduce energy consumption for cooling, and improve the overall livability of residential buildings. The reported results are probably significant to the selected city in a warm and humid climate. However, the study can be extended to the other selective geographical locations because of the simplicity in maintenance, economic viability, and scalability of the balcony greenery. Furthermore, the generalization of the effects of potted plants related to various factors could be studied in the future, including climate classification, types of vegetation, ambient conditions, geographical locations, and climatic factors.

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Nomenclature

IAT	Indoor air temperature
IST	Indoor surface temperature
LST	Land surface temperature

MRT	Mean radiant temperature
OAT	Outdoor air temperature
OST	Outdoor surface temperature
RH	Relative humidity
SDGs	Sustainable Development Goals
UGI	Urban green infrastructure
UHI	Urban heat island
VGS	Vertical greening system

References

1. Rajagopal, P.; Shanthi Priya, R.; Senthil, R. A review of recent developments in the impact of environmental measures on urban heat island. *Sustain. Cities Soc.* **2023**, *88*, 104279. [CrossRef]
2. Shao, H.; Kim, G. A Comprehensive Review of Different Types of Green Infrastructure to Mitigate Urban Heat Islands: Progress, Functions, and Benefits. *Land* **2022**, *11*, 1792. [CrossRef]
3. Ruiz, M.A.; Colli, M.F.; Martinez, C.F.; Correa-Cantaloube, E.N. Park cool island and built environment. A ten-year evaluation in Parque Central, Mendoza-Argentina. *Sustain. Cities Soc.* **2022**, *79*, 103681. [CrossRef]
4. Priya, U.K.; Senthil, R. A Review of the Impact of the Green Landscape Interventions on the Urban Microclimate of Tropical Areas. *Build. Environ.* **2021**, *205*, 108190. [CrossRef]
5. Kooshali, A.D.; Parvizi, R.; Azeri, A.R.K.; Hosseini, S.B. A Comparative Study on the Effect of Nature on Satisfaction with Residence at Detached Houses (Single Unit) and Residential Building Complexes (Apartment). *Procedia Soc. Behav. Sci.* **2015**, *201*, 243–254. [CrossRef]
6. Hui, L.C.; Jim, C.; Tian, Y. Public views on green roofs and green walls in two major Asian cities and implications for promotion policy. *Urban For. Urban Green.* **2022**, *70*, 127546. [CrossRef]
7. Honjo, T.; Takakura, T. Simulation of Thermal Effects of Urban Green Areas on their Surrounding Areas. *Energy Build* **1990**, *15*, 443–446. [CrossRef]
8. Zölch, T.; Maderspacher, J.; Wamsler, C.; Pauleit, S. Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban For. Urban Green.* **2016**, *20*, 305–316. [CrossRef]
9. Orban, E.; Sutcliffe, R.; Dragano, N.; Jöckel, K.H.; Moebus, S. Residential Surrounding Greenness, Self-Rated Health and Interrelations with Aspects of Neighborhood Environment and Social Relations. *J. Urban. Health* **2017**, *94*, 158–169. [CrossRef]
10. Alsaad, H.; Hartmann, M.; Hilbel, R.; Voelker, C. The potential of facade greening in mitigating the effects of heatwaves in Central European cities. *Build. Environ.* **2022**, *216*, 109021. [CrossRef]
11. Kumar, P.; Debele, S.E.; Khalili, S.; Halios, C.H.; Sahani, J.; Aghamohammadi, N.; Andrade, M.D.F.; Athanassiadou, M.; Bhui, K.; Calvillo, N. Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. *Innovation* **2024**, *5*, 100588. [CrossRef] [PubMed]
12. Taib, N.; Prihatmanti, R. Optimising balcony for green spaces: Application of edible biofaçade on urban high-rise setting. *Plan. Malays. J.* **2018**, *16*, 92–103. [CrossRef]
13. Raji, B.; Tenpierik, M.J.; Dobbelsteen, A.V.D. The impact of greening systems on building energy performance: A literature review. *Renew. Sustain. Energy Rev.* **2015**, *45*, 610–623. [CrossRef]
14. Zhu, H.; Yang, F.; Bao, Z.; Nan, X. A study on the impact of Visible Green Index and vegetation structures on brain wave change in residential landscape. *Urban For. Urban Green.* **2021**, *64*, 127299. [CrossRef]
15. Chang, Y.H.; Chen, T.H.; Chung, H.Y.; Hsiao, H.Y.; Tseng, P.C.; Wang, Y.C.; Lung, S.C.C.; Su, H.J.; Tsay, Y.S. The health risk reduction of PM2.5 via a green curtain system in Taiwan. *Build. Environ.* **2024**, *255*, 111459. [CrossRef]
16. Abe, H.; Rijal, H.B.; Hiroki, R.; Iijima, K.; Ohta, A. Thermal Mitigation of the Indoor and Outdoor Climate by Green Curtains in Japanese Condominiums. *Climate* **2020**, *8*, 8. [CrossRef]
17. Huang, Z.; Lu, Y.; Wong, N.H.; Poh, C.H. The true cost of "greening" a building: Life cycle cost analysis of vertical greenery systems (VGS) in tropical climate. *J. Clean. Prod.* **2019**, *228*, 437–454. [CrossRef]
18. Radić, M.; Brković Dodig, M.; Auer, T. Green Facades and Living Walls—A Review Establishing the Classification of Construction Types and Mapping the Benefits. *Sustainability* **2019**, *11*, 4579. [CrossRef]
19. Sun, W.; Ren, J.; Zhai, J.; Li, W. 'Just green enough' in urban renewal: A multifunctional and pragmatic approach in realizing multiscale urban green space optimization in built-up residential areas. *Urban For. Urban Green.* **2023**, *82*, 127891. [CrossRef]
20. Bartesaghi, K.C.; Osmond, P.; Peters, A. Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. *Sol. Energy* **2018**, *166*, 486–508. [CrossRef]
21. United Nations, Department of Economic and Social Affairs, Population Division (2014). World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352). Available online: https://population.un.org/ (accessed on 30 April 2024).
22. CNN, Extreme Weather-India Heat Wave Kills 2330 People as Millions Wait for Rain, Retrieved. Available online: https://edition.cnn.com/2015/06/01/asia/india-heat-wave-deaths/ (accessed on 30 April 2024).
23. Imam, A.U.K.; Banerjee, U.K. Urbanisation, and greening of Indian cities: Problems, practices, and policies. *Ambio* **2016**, *45*, 442–457. [CrossRef] [PubMed]
24. Govindarajulu, D. Urban green space planning for climate adaptation in Indian cities. *Urban Clim.* **2014**, *10*, 35–41. [CrossRef]

25. Sánchez, F.G.; Govindarajulu, D. Integrating blue-green infrastructure in urban planning for climate adaptation: Lessons from Chennai and Kochi, India. *Land Use Policy* **2023**, *124*, 106455. [CrossRef]
26. Basher, H.S. Thermal Performance of Edible Vertical Greenery System in High-rise Residential Balcony. *Int. J. Integr. Eng.* **2019**, *11*, 141–153. Available online: https://publisher.uthm.edu.my/ojs/index.php/ijie/article/view/5440 (accessed on 28 July 2024).
27. Ghazalli, A.J.; Brack, C.; Bai, X.; Said, I. Alterations in use of space, air quality, temperature, and humidity by the presence of vertical greenery system in a building corridor. *Urban For. Urban Green.* **2018**, *32*, 177–184. [CrossRef]
28. Lin, H.; Ni, H.; Xiao, Y.; Zhu, X. Couple simulations with CFD and ladybug + honeybee tools for green façade optimizing the thermal comfort in a transitional space in hot-humid climate. *J. Asian Archit. Build. Eng.* **2023**, *22*, 1317–1342. [CrossRef]
29. Freewan, A.A.; Jaradat, N.M.; Amaireh, I.A. Optimizing Shading and Thermal Performances of Vertical Green Wall on Buildings in a Hot Arid Region. *Buildings* **2022**, *12*, 216. [CrossRef]
30. Ogut, O.; Tzortzi, N.J.; Bertolin, C. Vertical Green Structures to Establish Sustainable Built Environment: A Systematic Market Review. *Sustainability* **2022**, *14*, 12349. [CrossRef]
31. Thomas, G.; Thomas, J.; Mathews, G.M.; Alexander, S.P.; Jose, J. Assessment of the potential of green wall on modification of local urban microclimate in humid tropical climate using ENVI-met model. *Ecol. Eng.* **2023**, *187*, 106868. [CrossRef]
32. Gao, Y.; Farrokhirad, E.; Pitts, A. The Impact of Orientation on Living Wall Façade Temperature: Manchester Case Study. *Sustainability* **2023**, *15*, 11109. [CrossRef]
33. Millward, A.A.; Blake, M. When Trees Are Not an Option: Perennial Vines as a Complementary Strategy for Mitigating the Summer Warming of an Urban Microclimate. *Buildings* **2024**, *14*, 416. [CrossRef]
34. Rahman, M.S.; MacPherson, S.; Lefsrud, M. A study on evaporative cooling capacity of a novel green wall to control ventilating air temperature. *J. Build. Eng.* **2023**, *77*, 107466. [CrossRef]
35. Saifi, N.; Belatrache, D.; Dadamoussa, A.; Settou, N. Effects of green roofs and vertical greenery systems on building thermal comfort in dry climates: An experimental study. *J. Build. Pathol. Rehabil.* **2023**, *8*, 35. [CrossRef]
36. Sedláček, J.; Hais, M.; Pouchová, K. Green and blue infrastructure: Means of reducing surface temperatures in the urban environment. *Int. J. Environ. Sustain. Dev.* **2022**, *21*, 388–406. [CrossRef]
37. Kunasingam, P.; Clayden, A.; Cameron, R. How does plant taxonomic choice affect building wall panel cooling? *Build. Environ.* **2024**, *256*, 111493. [CrossRef]
38. Gabriel, E.; Piccilli, D.G.A.; Tassi, R.; Köhler, M.; Krebs, L.F. Improving indoor environmental quality in an affordable house by using a vegetated wall: A case study in subtropical Brazil. *Build. Environ.* **2024**, *250*, 111146. [CrossRef]
39. Li, J.; Zheng, B. Does Vertical Greening Really Play Such a Big Role in an Indoor Thermal Environment? *Forests* **2022**, *13*, 358. [CrossRef]
40. Bandehali, S.; Miri, T.; Onyeaka, H.; Kumar, P. Current state of indoor air phytoremediation using potted plants and green walls. *Atmosphere* **2021**, *12*, 473. [CrossRef]
41. Liu, C.; Zhang, N.; Sun, L.; Gao, W.; Zang, Q.; Wang, X. Potted plants and ventilation effectively remove pollutants from tobacco smoke. *Int. J. Low-Carbon Technol.* **2022**, *17*, 1052–1060. [CrossRef]
42. Abdelrahman, M.; Coates, P.; Poppelreuter, T. Visible outside view as a facilitation tool to evaluate view quality and shading systems through building openings. *J. Build. Eng.* **2023**, *80*, 108049. [CrossRef]
43. Kley, S.; Dovbischuk, T. The equigenic potential of green window views for city dwellers' well-being. *Sustain. Cities Soc.* **2024**, *108*, 105511. [CrossRef]
44. Battisti, L.; Pille, L.; Wachtel, T.; Larcher, F.; Säumel, I. Residential greenery: State of the art and health-related ecosystem services and disservices in the city of Berlin. *Sustainability* **2019**, *11*, 1815. [CrossRef]
45. Schmid, H.-L.; Säumel, I. Outlook and insights: Perception of residential greenery in multistorey housing estates in Berlin, Germany. *Urban For. Urban Green.* **2021**, *63*, 127231. [CrossRef]
46. Li, H.; Zhao, Y.; Sützl, B.; Kubilay, A.; Carmeliet, J. Impact of green walls on ventilation and heat removal from street canyons: Coupling of thermal and aerodynamic resistance. *Build. Environ.* **2022**, *214*, 108945. [CrossRef]
47. Teiri, H.; Hajizadeh, Y.; Azhdarpoor, A. A review of different phytoremediation methods and critical factors for purification of common indoor air pollutants: An approach with sensitive analysis. *Air Qual. Atmos. Health* **2022**, *15*, 373–391. [CrossRef]
48. Kumar, R.; Verma, V.; Thakur, M.; Singh, G.; Bhargava, B. A systematic review on mitigation of common indoor air pollutants using plant-based methods: A phytoremediation approach. *Air Qual. Atmos. Health* **2023**, *16*, 1501–1527. [CrossRef]
49. van den Bogerd, N.; Dijkstra, S.C.; Koole, S.L.; Seidell, J.C.; Maas, J. Greening the room: A quasi-experimental study on the presence of potted plants in study rooms on mood, cognitive performance, and perceived environmental quality among university students. *J. Environ. Psychol.* **2021**, *73*, 101557. [CrossRef]
50. van den Bogerd, N.; Dijkstra, S.C.; Tanja-Dijkstra, K.; de Boer, M.R.; Seidell, J.C.; Koole, S.L.; Maas, J. Greening the classroom: Three field experiments on the effects of indoor nature on students' attention, well-being, and perceived environmental quality. *Build. Environ.* **2020**, *171*, 106675. [CrossRef]
51. Rajan, E.H.S.; Amirtham, L.R. Urban heat island intensity and evaluation of outdoor thermal comfort in Chennai, India. *Environ. Dev. Sustain.* **2021**, *23*, 16304–16324. [CrossRef]
52. Kesavan, R.; Muthian, M.; Sudalaimuthu, K.; Sundarsingh, S.; Krishnan, S. ARIMA modeling for forecasting land surface temperature and determination of urban heat island using remote sensing techniques for Chennai city, India. *Arab. J. Geosci.* **2021**, *14*, 1016. [CrossRef]

53. Jeganathan, A.; Andimuthu, R.; Prasannavenkatesh, R.; Kumar, D.S. Spatial variation of temperature and indicative of the urban heat island in Chennai Metropolitan Area, India. *Theor. Appl. Climatol.* **2016**, *123*, 83–95. [CrossRef]
54. Gloria, S.J.; Gnanasekaran, S.P. Impact of Urban Vegetation Loss on Urban Heat Islands: A Case Study of Chennai Metropolitan Area. *Ind. J. Sci. Technol.* **2024**, *17*, 134–141. [CrossRef]
55. Pragati, S.; Shanthi Priya, R.; Pradeepa, C.; Senthil, R. Simulation of the Energy Performance of a Building with Green Roofs and Green Walls in a Tropical Climate. *Sustainability* **2023**, *15*, 2006. [CrossRef]
56. Priya, U.K.; Senthil, R. Analysis of urban residential greening in tropical climates using quantitative methods. *Environ. Sci. Pollut. Res.* **2024**, *31*, 44096–44119. [CrossRef] [PubMed]
57. Gu, J.; Liu, H.; Lu, H. Can Even a Small Amount of Greenery Be Helpful in Reducing Stress? A Systematic Review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9778. [CrossRef] [PubMed]
58. Ren, J.; Tang, M.; Zheng, X.; Zhang, T.; Xu, Y.; Lin, X. Experimental study on the thermal performance of building external window greenery in a subtropical climate. *Appl. Therm. Eng.* **2024**, *242*, 122291. [CrossRef]
59. Su, M.; Jie, P.; Li, P.; Yang, F.; Huang, Z.; Shi, X. A review on the mechanisms behind the thermal effect of building vertical greenery systems (VGS): Methodology, performance and impact factors. *Energy Build.* **2024**, *303*, 113785. [CrossRef]
60. Jim, C.Y. Thermal performance of climber greenwalls: Effects of solar irradiance and orientation. *Appl. Energy* **2015**, *154*, 631–643. [CrossRef]
61. Al-Kodmany, K. Greenery-Covered Tall Buildings: A Review. *Buildings* **2023**, *13*, 2362. [CrossRef]
62. Smektała, M.; Baborska-Narożny, M. The use of apartment balconies: Context, design, and social norms. *Build. Cities* **2022**, *1*, 3. [CrossRef]
63. Shuhaimi, N.D.A.M.; Zaid, S.M.; Esfandiari, M.; Lou, E.; Mahyuddin, N. The impact of vertical greenery system on building thermal performance in tropical climates. *J. Build. Eng.* **2022**, *45*, 103429. [CrossRef]
64. Susca, T.; Zanghirella, F.; Colasuonno, L.; Del Fatto, V. Effect of green wall installation on urban heat island and building energy use: A climate-informed systematic literature review. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112100. [CrossRef]
65. Visvanathan, G.; Patil, K.; Suryawanshi, Y.; Meshram, V.; Jadhav, S. Mitigating urban heat island and enhancing indoor thermal comfort using terrace garden. *Sci. Rep.* **2024**, *14*, 9697. [CrossRef] [PubMed]
66. Salonen, T.; Hollands, J.; Sesto, E.; Korjenic, A. Thermal Effects of Vertical Greening in Summer: An Investigation on Evapotranspiration and Shading of Façade Greening in Vienna. *Buildings* **2022**, *12*, 1705. [CrossRef]
67. Sützl, B.S.; Strebel, D.A.; Rubin, A.; Wen, J.; Carmeliet, J. Urban morphology clustering analysis to identify heat-prone neighbourhoods in cities. *Sustain. Cities Soc.* **2024**, *107*, 105360. [CrossRef]
68. Hui, C.X.; Dan, G.; Alamri, S.; Toghraie, D. Greening smart cities: An investigation of the integration of urban natural resources and smart city technologies for promoting environmental sustainability. *Sustain. Cities Soc.* **2023**, *99*, 104985. [CrossRef]
69. Herath, P.; Bai, X. Benefits and co-benefits of urban green infrastructure for sustainable cities: Six current and emerging themes. *Sustain. Sci.* **2024**, *19*, 1039–1063. [CrossRef]
70. Mahyuddin, N.; Jamaludin, N.M.; Hussien, A.; Akashah, F.W.; Azmi, N.F.B.; Cotgrave, A.; Riley, M. Assessing the impact of indoor plants towards physical indoor office building environment in hot and humid climates. *J. Design Built Environ.* **2022**, *22*, 34–54.