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Chasing cool: Unveiling the influence of green-blue features on outdoor thermal environment in Roorkee (India)

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ABSTRACT

Urban environments in humid subtropical climates, like Roorkee, India, often experience high summer temperatures and uncomfortable outdoor thermal conditions. However, the impact of green-blue landscape configurations on cooling intensity (ΔT_a) and outdoor thermal comfort (OTC) is insufficiently understood. This study, conducted in Roorkee during summer 2022, assessed the effect of green-blue landscape configurations on OTC using Physiological Equivalent Temperature (PET) and mean radiant temperature (T_{mrt}). PET values ranged from slight to extreme heat stress, with statistically significant differences in cooling intensity across varied landscape configurations. Tree shaded canal front locations registered lower T_a (1.6 °C) and T_{mrt} (9.3 °C). Similarly, shaded canal front locations registered 4.7 °C lower PET than sun-exposed locations

Different tree species showed significant variation in ΔT_a, with the highest cooling effect (maximum average ΔT_a of 3 °C) occurring during the morning hours. Notably *Morus alba* and *Mangifera indica* yielded the highest cooling effect, outperforming artificial and mixed shade. *Eucalyptus alba*, on the other hand, registered adverse comfort conditions. Denser tree canopies and attributes - canopy diameter, leaf area index, and height were strongly correlated to improved cooling performance.

Additionally, increasing pervious surfaces and tree cover within 100 m of intervention areas enhanced cooling, with significant effects noted within a 25–50 m radius. This study highlights the role of green-blue infrastructure, particularly the combination of low sky-view factor (SVF), dense canopy trees, and proximity to water, in reducing heat stress. These findings offer crucial insights for climate-responsive open space design, particularly in Indian cities facing rampant urbanization and global warming.

1. Introduction

The last few decades have witnessed escalating heat stress in cities. With global climate change, making cities climate-proof is becoming increasingly critical [1]. Designing ‘climate responsive’ outdoor spaces is imperative for climate proofing cities. Outdoor spaces are crucial containers of life as they host a variety of outdoor activities, facilitate pedestrian movements and contribute to livability of urban areas. Consequently, designing thermally comfortable and attractive outdoor spaces is an emerging area of research enquiry and aligns significantly with several sustainable development goals (e.g., Goal 11 - Sustainable Cities and Communities and Goal 13 - Climate Action). A comprehensive understanding of the outdoor microclimate is crucial for facilitating climate sensitive city planning, designing climate responsive outdoor spaces and developing heat mitigation and adaptation strategies. Furthermore, in order to design ‘climate responsive outdoor spaces’, it is vital for designers to understand how microclimate is influenced by various landscape elements. It is also imperative to appreciate that microclimates are characterized by strong variability [2,3]. Each space outdoors is unique in terms of the prevalent micrometeorological conditions. Information pertaining to micrometeorological measurements and observations is therefore essential to guide the ‘evidence based’ climate responsive design process [4]. Paradoxically, detailed spatial and temporal climate data from diverse urban environments is often lacking in the urban planning process and practice (e.g. [5–7]). Such data are crucial for developing solutions to create thermally amicable environments.

Application of Nature-based Solutions (NbS) and green and blue infrastructure is an emerging strategic approach that leverages the

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List of symbols

Symbol	Description (Unit)
SVF	Sky view factor (%)
T_{mrt}	Mean radiant temperature (°C)
T_g	Globe temperature (°C)
T_a	Air Temperature (°C)
PET	Physiological Equivalent Temperature (°C)
RH	Relative humidity (%)
v	Wind speed (ms^{-1})

intrinsic potential of urban green and blue for creating favorable human thermal environments. NbS have been defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"[8].Urban blue and green infrastructure comprising of water and vegetation can play a significant part in improving the outdoor thermal environment [9].

The effect of green features on micrometeorological conditions and thermal exposure in cities has been investigated much in bioclimatic and outdoor thermal comfort (OTC) studies. Numerous research studies have demonstrated the effectiveness of vegetation in creating conducive outdoor thermal environments through the provision of shade, evapotranspiration, and a reduction in air and surface temperatures [10–13]. Studies have investigated how different tree types impact radiation fluxes in the environment due to their variable sizes and canopy characteristics [14–17]. Studies have underscored the relevance of planting arrangement and tree species in optimizing outdoor thermal comfort [18,19]. However, the cooling potential of green features varies in accordance with prevailing weather conditions, tree type, density and size of crown, hour of the day, and the overall area of the green space [20–22]. Additionally, the cooling potential of green is also dependent on its typology. For example, green roofs with a low coverage ratio offer limited thermal benefits at the pedestrian scale [23,24]. Similarly, non-irrigated lawn surfaces report lower cooling effect [25,26].

Blue spaces on the other hand ameliorate the thermal environment through evaporation, large heat capacity [27] and radiation characteristics [28]. Blue spaces can affect the local climate and form cooling benefits. The range of benefits around diverse water bodies however varies [29,30]. For example, Yang et al. [31] established that lower the proportion of water bodies, higher the average land surface temperature. Cai et al. [32] found that the cooling effect of the water body extended up to 1 km, while Moyer et al. [33]. established that a 1000 m increase in distance to the river corresponded to a temperature reduction of 0.3 °C. The ability of a water body to mitigate heat is primarily influenced by factors such as distance to the water body or downtown, size, depth, surrounding land use, and period of the day (e.g. [34–36]), and its type (static or dynamic) [37].While the primary cooling mechanism in static water bodies is evaporation, flow variables and meteorological conditions are significant for the dynamic ones [37]. Sun et al. [38] examined the relationship between varied metrics (vegetation coverage, water coverage, leaf area and patch shape index) and land surface temperature. This study established that increasing the vegetation up to 28% can alleviate the thermal environment in residential areas. Similarly, Du et al. [39] showed that water cooling intensity and distance are negatively correlated to the geometry of the water body and the proportion of impervious surfaces but positively correlated to the proportion of vegetation around [38]. However, the interaction between green and blue features for urban heat stress mitigation interestingly is largely unexplored [29]. The configuration characteristics of urban green – blue spaces with high cooling efficiency is also less understood. Urban parks can decrease temperature by 0.94 K on average [40] while blue spaces by 2.5 K on average relative to their context [41]. The benefit of green/blue features on urban thermal environment varies significantly based on the location, climate type, spatial structure of the city, size of the green/blue space and the surrounding landscape [42,43]. For example, the cooling effect of green/blue space is dominated by the vegetative fraction within 30 m along the riverside [44]. Shi et al. [45] established that waterfront forests and impervious surfaces experience lower air temperature than the non-waterfront spaces. Interestingly, the water front lawn was 0.8 – 2.1 °C hotter than the non-water front counterpart. However, the conditional cooling capacity of the green or blue space is largely unknown [46]. Xu et al. [47] showed that greatest improvement in thermal comfort was observed 10 – 20 m from the water's edge. The study suggested that significant improvement in thermal comfort could be attained through appropriate landscaping in the littoral zone [38]. While many studies have examined the influence of water bodies in mitigating urban heat islands, theoretical and applied studies on urban water bodies from the point of view of human comfort are scarce [47].

Although the evidence of heat mitigation through blue and green spaces exists in literature, studies investigating the synergistic effect of green and blue are limited [45,46],. Mostly research on urban cooling is limited to green alone. Studies investigating blue spaces have examined the effect of large water bodies (e.g. rivers, lakes, canals) on the urban thermal environment. The impact of blue green features at a micro scale has received less research attention [48]. Further, few studies have examined the role of vegetation and associated morphological characteristics impacting the thermal environment in diverse open space typologies especially along waterfronts as well [49].

Previous research has mostly used three types of data to examine how green/blue spaces affect the urban thermal environment: field measurements using fixed sensors, satellite views, and mobile measurements. While using satellite data allows for studying multiple green/blue spaces over a large spatial extent, lack of humidity data makes it difficult to evaluate the impact of green/blue on the thermal environment comprehensively. Additionally, remote sensing-based methods lack in temporal resolution as well. Consequently, studies addressing the effectiveness of the green/blue features in terms of thermal comfort at the pedestrian scale are limited. Field measurements on the other hand can establish the effect of green/blue spaces at the pedestrian level, thereby linking the local landscape with the prevalent micrometeorological conditions. For example, Wang et al. [50]. established that small urban green infrastructure (UGI) such as a single tree or urban lawns significantly affect the micro-meteorological conditions and thermal comfort outdoors, thus necessitating research at the micro-scale. Potchter et al. [51] established through field observations a reduction of nearly 1 °C near a small pond during midday hours in Israel. Few studies have explored the influence of blue–green features on ameliorating adverse micro-meteorological conditions in public spaces [52]. Examining the impact of blue–green features at the micro-level can provide evidence for estimating the human thermal benefits of blue-green infrastructure application in urban environments [48] and promoting outdoor thermal comfort [44].

Interestingly, previous studies on OTC have primarily focused on mid latitude temperate cities [53]. Recently, increased research attention is being accorded to cities in hot, humid tropical and sub-tropical climates. Furthermore, in the Indian context, research on urban heat has largely focused on the urban heat island studies [54–58]. It is however crucial to note that creation of a comfortable thermal environment in urban areas has many other dimensions ranging from heat island mitigation to reduced energy consumption for health and well-being of the urban dweller. Studies in the Indian context, however mostly focus on land surface temperature (LST) dynamics and identification of urban hot spots [59–62]. Recent studies have begun investigating urban cooling and the influence of green and blue features on urban thermal environment through remote sensing and GIS [63,64]. Understanding the influence of green and blue features on the thermal environment at a micro-scale has received limited research attention in Indian cities. It is however imperative to note that adoption of a human centered approach for understanding thermal stress at a pedestrian scale is vital [65]. Also, there is a dearth of information on OTC in different outdoor spaces in the Indian context [66]. Further, the limited number of OTC studies conducted in the Indian context are focused exclusively on specific open space typologies (e.g., informal neighborhoods, open air markets, street canyons, religious squares) (e.g. [66–70]. Additionally, majority of the OTC research in India has been conducted in the country's capital cities (e.g. New Delhi, Bhopal, Nagpur, Kolkata) [71], while studies in Class I cities (population between 0.1 and 1 million) such as Roorkee are rare [65].

Fig. 1. Study locations in Roorkee, India (above) and graphical information and photos of the study locations (below).

In light of the above, this study attempts to gain a comprehensive understanding of the microscale variations prevalent in thermal environments and associated thermal comfort in urban open spaces characterized by different green and blue features. This study is limited to prevalent thermal environments outdoors in an Indian city (Roorkee) located in the humid sub – tropical climate. The objectives of this study are: (a) to quantify the thermal environment in different urban open spaces through micrometeorological monitoring; (b) to examine the effect of green /blue features on the thermal environment and comfort conditions; and (c) to showcase the improvement of OTC and cooling intensity based on different green and blue features.

2. Study area, data and methods

2.1. Study area and data

Located in Uttarakhand, Roorkee lies at an average elevation of 268 m, at the foothills of the Himalayas. Situated at a latitude of 29.85 °N and a longitude of 77.88 °E, the city has developed along the Ganga Canal. With an average width of 50 m and a depth of about 9 m, the Ganga Canal flows north-south and bisects the city. Roorkee is an urban agglomeration coming under the category of class UAs/Towns as per census 2011. The current estimated population of the city is 165,000. Roorkee is characterized by a Cwa climate as per the Koppen Geiger classification system [72]. The city experiences an average annual temperature of 23.7 °C with average summer temperatures exceeding 35 °C [73], while the average annual precipitation is 1170 mm. The city is characterized by rich flora which predominantly includes *Mangifera indica, Dalbergia sissoo, Haldina cordifolia, Syzygium cumini, Mallotus philippinensis, Mitragyna parvifolia, Terminalia* spp., *Ficus* spp. *Bauhinia variegata, Bombax cobia, Holoptelea integrities, Siamese Senna, Broussonetia papyrifera, Morus alba, Cassia fistula, and Albizia lebbeck* (Koshal, 2022).

2.2. Methods

2.2.1. Micrometeorological measurements

Since a wide range of micro-scale human bio meteorological conditions exist in a city, different microenvironments were firstly identified (e.g., canal quay, street, building courtyard and urban green space). The 19 study locations (Fig. 1) in the identified sampled micro-environments were thereafter chosen through a reconnaissance survey. We selected these locations due to their diverse micro environments in terms of exposure (shade, semi-shade, exposed to Sun), different types of trees at the locations, and different ground cover. The majority of the measurement locations (13 out of 19 locations) are at a distance <50 m from the Ganga Canal; 2 locations are between 50 m and 100 m; and 4 locations are >350 m (Table 1). Sky View Factor (SVF) was calculated in RayMan software [74] using fisheye photos. Additionally, morphological characteristics of trees (e.g., tree height, canopy diameter, canopy type, leaf area index - LAI) at the study locations were also recorded. LAI was computed from the hemispherical photographs captured during the study as outlined by [75]. The landscape and exposure values of the study locations are presented in Table 1. The relief of the city is flat with the measurement location altitudes in the range from 262 m to 274 m (Table 1).

Measured micrometeorological parameters include air temperature (T_a, °C), relative humidity (RH, %), globe temperature (T_g, °C) and wind speed (v, ms^{-1}). The measurements took place during seven days between 7th and 15th June 2022. The micrometeorological data were recorded at an interval of 5 min between 9:00 h and 18:00 h local time (IST). The measurement days were hot and sunny with low wind speed. The average T_a during the measurement period was between 35.47 °C and 40.26 °C, RH was between 38.36% and 49.53%, and v was between 0.11 and 1.33 m/s (Table A.6 in Supplementary). Kestrel heat stress trackers were employed for the micrometeorological monitoring. The heat stress tracker was mounted on a tripod at a height of 1.2 m as per protocol suggested by [76] and consistency check was performed before the deployment. The heat stress tracker was deployed 15 min prior to the start of the measurement in order to allow the sensors to equilibrate to the atmospheric conditions [36]. The obtained micrometeorological data was used for computing bio meteorological indices, such as mean radiant temperature (T_{mrt}) and Physiological Equivalent Temperature (PET) (see Section 2.2.2).

2.2.2. Estimation of outdoor thermal comfort and cooling intensity

The OTC conditions in Roorkee were estimated through T_{mrt} (°C) and PET (°C) [77].T_{mrt} is computed on the basis of the measured T_g, T_a and v based on Eq. (1) [78]:

$$T_{\mathrm{mrt}} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right) \right]^{1/4} - 273.15 \tag{1}$$

with globe emissivity ε = 0.97 and globe diameter D = 25 mm. PET was computed after obtaining T_{mrt}.

PET was chosen for assessing the OTC conditions because it has been widely evaluated in varying climatic contexts worldwide (e.g., [79–84]) and especially in the humid subtropical climates (e.g., [85–88]). PET furthers comparison by utilizing °C as a measurement unit and is consequently easily understood by urban planners and designers (S and Rajasekar [84]). PET is estimated using RayMan software [74] based on the calculated values of T_{mrt} from Eq. (1), measured *Ta, RH*, and v from Kestrel stations, calculated SVF values for each location, and default

Table 1
Characteristics of the study locations in Roorkee, India.

Location	Measurement day	Micro-environment	Sun exposure	Shade type	Tree type	SVF	Distance to Canal (m)	Altitude (m)	Surface type
P1	7/Jun/22	Canal quay	Mostly exposed	None		0.95	3	262	Paved (red sandstone)
P2	7/Jun/22	Canal park	Semi shade	Tree shade	Ficus religiosa	0.21	6	262	Grass
P3	7/Jun/22	Canal park	Mostly exposed	None		0.85	9	262	Soil (sand)
P4	8/Jun/22	Canal quay	Semi shade	Building and tree shade	Ficus religiosa	0.36	6	269	Paved (red sandstone)
P5	8/Jun/22	Paved area with trees	Mostly shaded	Tree shade	Ficus religiosa, Broussonetia papyrifera	0.02	9	269	Paved (concrete)
P6	8/Jun/22	Green along canal	Mostly shaded	Tree shade	Cassia siamea	0.01	15	270	Soil (barren earth)
P7	9/Jun/22	Canal front	Mostly exposed	None		0.92	4	266	Paved (red sandstone)
P8	9/Jun/22	Canal front	Semi shade	Tree shade	Thepesia populanea	0.61	3	267	Paved (red sandstone)
P9	10/Jun/22	Street intersection without trees	Mostly exposed	None		0.90	42	267	Paved (concrete)
P10	10/Jun/22	Street with trees	Semi shade	Tree shade	Eucalyptus globulus	0.27	34	274	Paved (concrete)
P11	10/Jun/22	Street with trees	Mostly shaded	Tree shade	Morus alba	0.04	44	272	Paved (concrete)
P12	11/Jun/22	Urban square	Mostly exposed	None		0.95	489	269	Paved (asphalt)
P13	11/Jun/22	Street intersection with trees	Semi shade	Tree shade	Eucalyptus globulus, Alstonia scholaris	0.26	32	269	Paved (concrete)
P14	12/Jun/22	Building courtyard	Mostly exposed	None		0.86	376	268	Paved (kota stone)
P15	12/Jun/22	Building courtyard	Semi shade	Building and tree shade	Cassia spp	0.43	365	267	Grass
P16	12/Jun/22	Parking	Mostly shaded	Artificial shade		0.01	421	266	Paved (concrete)
P17	15/Jun/22	Urban green (old cemetary)	Mostly shaded	Tree shade	Mangifera indica	0.02	100	271	Soil (barren earth)
P18	15/Jun/22	Urban green (old cemetary)	Mostly exposed	None		0.81	64	272	Grass
P19	15/Jun/22	Street	Semi shade	Creeper		0.12	31	266	Paved (concrete)

values for personal characteristics (for more information see [74]).

The cooling intensity (ΔT) was calculated using Eq. (2) as follows:

$$\Delta T = T_{ref} - T_x \quad (2)$$

where T_{ref} is the reference (sun-exposed) location during the measurement day and T_x represents other (mostly shaded) locations during the same measurement day. The obtained value indicates the cooling intensity of diverse urban microenvironments compared to sun-exposed locations in the city, expressed in °C. The cooling intensity was calculated for T_a (ΔT_a), T_{mrt} (ΔT_{mrt}) and PET (ΔPET).

2.2.3. Impact of land cover on cooling intensity

The impact of land cover fractions on the cooling intensity was assessed using the MetObs-toolkit [89]. The toolkit is a Python package that offers tools for analyzing the data, e.g. linkage with popular land-use datasets (e.g. [90,91]). The tool enables the investigation of the microclimate effects of impervious (built-up), pervious (including trees) and water fractions in a user-defined radius around each measurement station. In this study, we have used MetObs to calculate impervious, pervious, tree and water fractions (in %) in eight radii around each measurement location. The land cover fractions are obtained for eight radii of 15 m, 25 m, 50 m, 100 m, 150 m, 250, 350 m and 500 m (Table A2 in Supplementary), which enables the investigation of the micro- and local-scale impacts of urban land cover on the cooling intensity. This approach was previously tested and successfully applied in a study by Top et al. [92] on the impact of land cover fractions on OTC conditions in Ghent, Belgium. Since majority of the measurement locations in our study are within <50 m distance from the Ganga Canal, we have focused our investigation on the impact of land cover fractions on the cooling intensity at a distance <50 m from the Canal.

3. Results

3.1. Micrometeorological conditions (Ta, RH, T_g and v)

The lowest median T_a were registered at locations with tree and/or building shade in proximity to the canal such as locations P6 ($T_a = 35.7$ °C) and P4 ($T_a = 36.7$ °C) (Fig. 2a). On the contrary, the hottest microenvironments were sun-exposed locations further away from the canal, such as locations P9 at street intersections with concrete surface cover ($T_a = 40.3$ °C) and P18 located in an old urban cemetery with short grass cover ($T_a = 40.5$ °C) (Fig. 2a).

Locations in proximity to the canal with an abundance of water such as P1 reported the highest median values of RH (RH= 55%) (Fig. 2b). On the contrary, locations with a high fraction of paved surfaces such as P9 showed the lowest median RH values (RH = 37%) (Fig. 2b).

The highest median T_g values were registered at location P9, which is a sun-exposed street intersection (T_g = 50.8 °C), and at location P12, which is a sun-exposed urban square (T_g = 50.1 °C) (Fig. 2c). Both locations have high SVF values between 0.9 and 0.95 leading to higher T_g values. On the contrary, low SVF (0.01–0.02) and tree shade substantially decrease median T_g to about 37 °C at locations such as P5 and P6 (Fig. 2c).

Wind speed (v) was low during the measurement period as indicated in Fig. 2d. The highest median v of about 1.2 m s^{-1} were registered at locations P2 and P3, while the lowest wind speeds (v) were registered at locations P4, P6 and P19 (Fig. 2d).

3.2. T_a dynamics and cooling intensities

3.2.1. T_a dynamics

Hourly T_a dynamics were assessed between 19 diverse locations in Roorkee, India, during June 2022. Cooling intensities, i.e., T_a differences between shaded locations and a sun-exposed reference location on the same measurement day, were also assessed on an hourly level. The measurement days were very hot with T_a values ranging from about

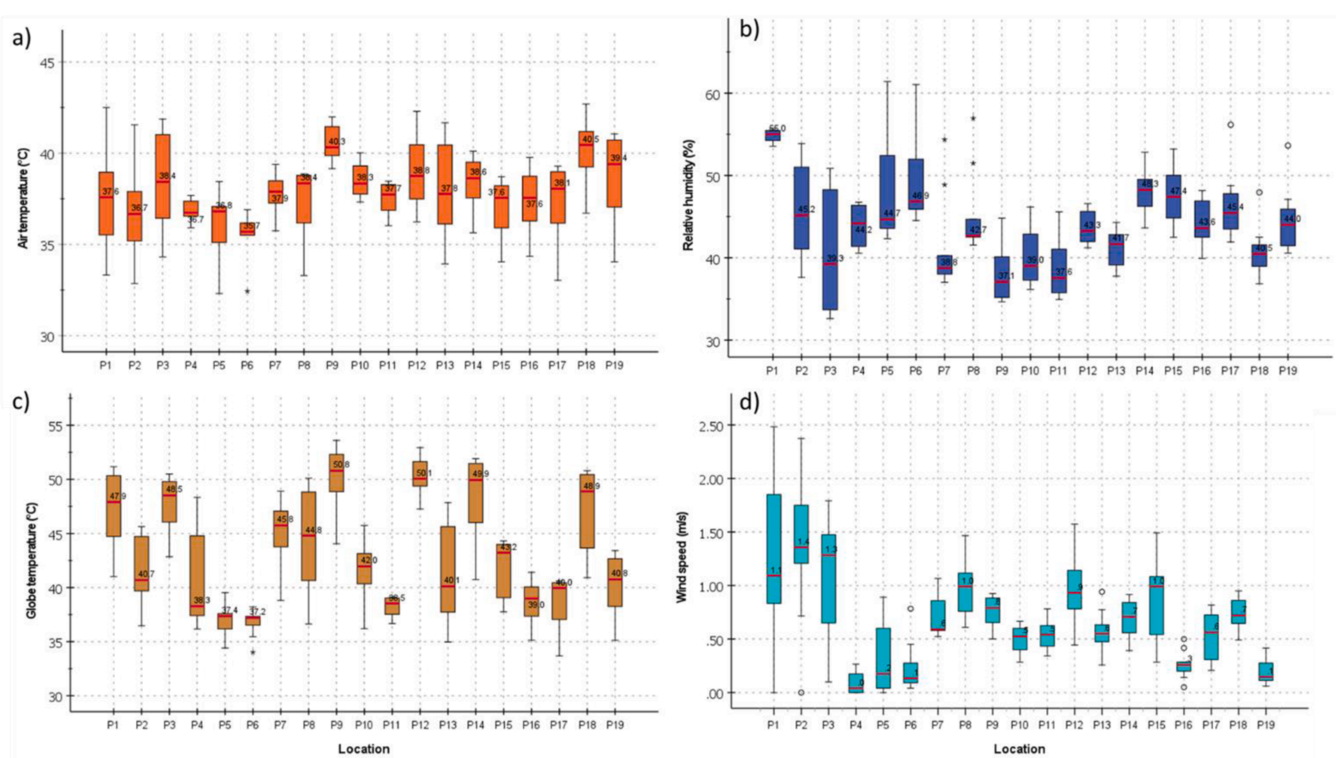


Fig. 2. Micrometeorological conditions at studied locations in Roorkee, India: a) Air temperature; b) Relative Humidity; c) Globe temperature; and d) Wind speed.

32–38 °C in the morning (9h) to about 36–43 °C during midday (14–16 h) and 35–41 °C in the evening (18h), depending on the measurement location and day (Figure A.1 in Supplementary). During morning, the hottest area of the city was sun-exposed street intersection (P9), while the coolest (P5) was under tree shade (*Ficus religiosa* and *Broussonetia papyrifera*) near the Ganga Canal. The hottest location during midday hours was sun-exposed paved area near the canal (P1), while tree shade (*Cassia siamea*; P6 location) near Canal provided the coolest environment. In the evening, the hottest location was the street intersection with a semi shade of trees (P13), while P6 continued to be the coolest. These findings underscore the role of tree shade near water bodies in mitigating heat in urban environments. Further, tree shade is an effective measure for ameliorating adverse micro meteorological conditions consistently through the day. Conversely, sun-exposed and paved areas report adverse comfort conditions, particularly during peak hours highlighting the role of solar exposure and surface characteristics in heat retention.

3.2.2. *Cooling intensities*

Average hourly cooling intensities (ΔT_a) of shaded locations compared to the sun-exposed reference location are presented in Table 2. Two periods with different cooling intensities are observed: 1) morning and midday period (9–15 h) with higher cooling intensities; and 2) afternoon/early evening period (16–18 h) with lower cooling intensity and occasional heating effect (i.e., reference locations having lower T_a). Cooling intensity generally declines after 15:00 and into the evening, with certain semi-shaded locations exhibiting higher air temperatures (T_a) compared to the reference location.

Study results indicate that different trees provide different daytime (9–18 h) cooling intensities across varying micro- environments in the city (Table 2). Average daytime ΔT_a ranged from 0.4 °C below *Thepesia populanea* (P8) to 3 °C below *Morus alba* (P11). The mixed shade (tree + building at P15) provided an average daytime ΔT of 1.2 °C. Artificial shade (3–5 mm thickness) at P16 was able to provide an average ΔT_a of 0.8 °C. At the hourly scale, the maximum ΔT_a of 5.5 °C was registered under tree shade (*Ficus religiosa and Broussonetia papyrifera*) at location P5, followed by a cooling intensity of 5.2 °C at location P6 (*Cassia siamea*) near the Ganga Canal. These findings suggest that varied tree species exhibit varying cooling intensities based on the micro – environment, grouping characteristics and morphological attributes. Mixed shading from trees and buildings, on the other hand exhibits moderate cooling, while artificial shade structures (3 - 5 mm) offer minimal temperature reduction compared to vegetation.

3.3. *Estimated biometeorological conditions and heat stress occurrence*

Locations in proximity to the Canal and under the shade of *Cassia siamea* with natural soil underneath (P6) reported the lowest median PET values (37.1 °C) as compared to sun-exposed locations characterized by concrete surface (P9) which reported the highest median PET value of 47.1 °C (Figure A.7 in Supplementary). Similarly, locations P9 (street intersection) and P12 (urban square) characterized by high SVF (0.9 - 0.95) and impervious surfaces reported the highest median T_{mrt} values of around 52 °C. On the contrary, locations P5 and P6 located under the dense canopies of *Ficus religiosa, Broussonetia papyrifera* and *Cassia siamea*, respectively, with low SVF (0.01 - 0.02) had the lowest median T_{mrt} of about 37 °C (Figure A.7 in Supplementary).

In terms of thermal perception and grades of physiological stress, PET values ranged from slight to extreme heat stress depending on the study locations and measurement day (Table 3). None of the studied sites corresponded to the "no thermal stress" category during the measurement period. Measurement sites characterized by high SVF, no shade and impervious surfaces (e.g., P9 and P12) corresponded to extreme heat stress (>42 °C PET), while locations with mixed shade (P15) and artificial shade (P16) were able to mitigate the heat and corresponded to strong heat stress (38–42 °C PET). The most successful in mitigating the heat were the locations with dense tree canopies and low SVF (e.g., P6 under *Cassia siamea* tree and P5 under *Ficus religiosa* and *Broussonetia papyrifera*) characterized by moderate heat stress (34–38 °C PET) (Table 3).

The OTC results show that shading is effective in mitigating heat stress, but there are hourly differences in the heat stress mitigation intensity depending on the type of shade (tree, mixed, artificial) (Table 4). Average difference in PET between shaded and sun-exposed location (ΔPET) ranged from 0.7 °C below *Thepesia populanea* (P8) to 8.1 °C below *Morus alba* (P11), indicating that some trees were able to mitigate the heat stress more substantially compared to others. *Mangifera indica* (P17) was also a very effective tree for heat stress mitigation with ΔPET of 6.4 °C. The artificial shade (3–5 mm thickness galvalume sheet) (P16) was able to provide an average ΔPET of 5.6 °C, while mixed shade (partially defoliated tree in building courtyard at P15) had ΔPET of 4.3 °C. In terms of hourly reduction, the maximum hourly ΔPET of about 10 °C was registered under *Ficus religiosa* and *Broussonetia papyrifera, Morus alba,* and *Cassia siamea* trees located near the Canal. As was previously shown for *ΔT*, the PET is also more effectively lowered in the morning and midday hours compared to the early evening when a few locations with semi shade conditions even showed higher PET compared to the reference location.

3.4. *Factors impacting thermal and biometeorological conditions (Ta, t_{mrt} and PET)*

3.4.1. *Influence of micro-environment*

Fig. 3 presents the variation in the cooling pertaining to the three thermal comfort metrics (T_a, PET and T_{mrt}) across the day. Varied urban microenvironments (e.g. canal front; street; building courtyard; urban green space and canal park) exhibited statistically significant variation ($p < 0.05$) in cooling across the day (refer to Table A.3 in Supplementary

Table 2
Cooling intensities (ΔT_a), i.e., hourly *Ta* differences between shaded and sun-exposed locations in Roorkee, India, during the period 7–15 June 2022.

Time/Locations	P3 P1	P3 P2	P4 P5	P4 P6	P7 P8	P9 P10	P9 P11	P12 P13	P14 P15	P14 P16	P18 P17	P18 19
9:00	1.2	1.5	5.5	5.2	1.0	3.5	3.6	2.3	1.6	1.3	3.7	2.9
10:00	1.3	1.4	5.0	4.9	2.0	1.8	3.1	1.4	1.7	1.0	3.6	2.5
11:00	1.0	1.3	2.6	1.8	1.6	2.3	3.2	1.4	1.6	1.3	3.3	2.5
12:00	1.2	1.6	0.4	0.1	0.7	2.0	2.6	1.5	0.7	0.4	3.0	1.5
13:00	0.9	1.8	-0.9	-0.8	-0.2	2.9	3.6	1.0	0.9	0.2	3.1	1.9
14:00	1.5	3.1	-0.2	0.9	0.6	2.0	3.6	0.8	1.4	0.0	3.7	2.2
15:00	-0.3	2.0	-0.4	1.2	0.0	-0.2	3.0	0.5	1.4	0.3	1.4	-0.3
16:00	-0.9	0.1	-0.8	0.4	-0.1	1.8	2.9	0.6	1.2	0.8	0.7	-1.4
17:00	0.1	0.9	-2.5	0.3	-0.5	2.1	2.5	0.0	1.1	1.3	0.2	-2.3
18:00	0.5	0.1	-2.5	0.3	-0.7	1.8	1.9	-2.1	0.4	1.2		
Shade provider		*Ficus religiosa*	*Ficus religiosa, Broussonetia papyrifera*	*Cassia siamea*	*Thepesia populanea*	*Eucalyptus globulus*	*Morus alba*	*Eucalyptus globulus, Alstonia scholaris*	Building and *Cassia spp*	Artificial shade	*Mangifera indica*	Creeper
Average Cooling Intensity	0.6	1.4	0.6	1.4	0.4	2.0	3.0	0.7	1.2	0.8	2.5	1.1
Maximum Cooling Intensity	1.5	3.1	5.5	5.2	2.0	3.5	3.6	2.3	1.7	1.3	3.7	2.9

Table 3
Hourly PET values and corresponding thermal perception and physiological stress categories for measurement sites in Roorkee, India, during the measurement days in June 2022.

Time	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19
09:00:00	36.7	34.4	39.4	42.9	33.4	34.1	39.6	35.3	43.3	35.9	35.1	42.8	35.0	41.8	36.3	35.2	33.8	41.6	35.2
10:00:00	39.5	36.3	41.3	45.1	34.7	35.1	41.7	36.1	46.1	41.2	36.9	44.1	36.4	43.9	39.9	36.4	36.1	45.1	37.4
11:00:00	42.2	38.1	43.2	43.2	36.2	37.1	43.4	38.8	47.1	40.6	37.9	45.0	37.5	45.2	40.9	37.5	38.1	47.0	39.1
12:00:00	43.4	38.6	44.5	38.9	37.7	38.2	44.5	42.5	47.5	40.1	38.7	46.0	38.0	46.1	41.7	38.8	39.5	47.4	40.2
13:00:00	45.3	41.7	45.7	37.7	37.9	37.8	44.9	45.7	49.6	41.5	39.4	47.1	39.9	46.8	41.8	40.0	40.7	47.7	41.0
14:00:00	46.4	41.9	46.7	37.8	37.9	37.2	44.4	45.9	49.6	44.0	39.6	48.3	44.0	47.2	41.8	41.1	40.8	47.9	42.1
15:00:00	47.4	43.0	46.6	37.5	37.7	36.6	43.3	45.4	48.8	46.2	39.5	48.3	45.9	46.8	40.4	41.3	41.0	43.3	42.6
16:00:00	45.9	43.4	46.2	37.1	38.2	37.1	41.6	43.0	46.4	42.2	39.2	47.4	44.7	43.2	39.4	39.5	40.5	41.4	42.9
17:00:00	41.6	39.9	41.9	36.4	39.3	36.6	39.1	41.1	43.1	39.7	38.0	44.0	42.5	40.5	38.2	38.1			
18:00:00	39.1	39.3	39.5	35.5	38.7	36.2	38.9	40.4	40.9	38.6	37.1	41.2	39.9	39.2	37.3	37.1			

	PET	Thermal perception	Grade of physiological stress
	30-34	Slightly Warm	Slight heat stress
	34-38	Warm	Moderate heat stress
	38-42	Hot	Strong heat stress
	>42	Very hot	Extreme heat stress

Table 4
The hourly PET differences (ΔPET) between shaded and sun-exposed locations in Roorkee, India, during the period 7–15 June 2022.

Time/Locations	P3-P1	P3-P2	P4-P5	P4-P6	P7-P8	P9-P10	P9-P11	P12-P13	P14-P15	P14-P16	P18-P17	P18-P19
9:00	2.7	5.0	9.5	8.9	4.3	7.3	8.2	7.8	5.5	6.6	7.8	6.4
10:00	1.9	5.0	10.4	10.0	5.6	5.0	9.3	7.7	4.0	7.5	9.0	7.7
11:00	1.0	5.2	7.0	6.1	4.6	6.5	9.2	7.5	4.3	7.7	8.9	7.9
12:00	1.1	5.9	1.2	0.7	2.1	7.4	8.9	8.0	4.4	7.4	7.9	7.2
13:00	0.5	4.0	0.2	0.0	-0.8	8.2	10.3	7.2	5.0	6.9	7.0	6.7
14:00	0.3	4.9	0.1	0.6	-1.5	5.6	10.1	4.3	5.4	6.1	7.1	5.8
15:00	-0.8	3.6	0.2	0.9	-2.1	2.6	9.2	2.4	6.5	5.6	2.3	0.6
16:00	0.2	2.8	-1.1	0.0	-1.4	4.2	7.2	2.7	3.7	3.6	0.9	-1.5
17:00	0.3	2.0	-2.9	0.3	-2.0	3.4	5.1	1.5	2.3	2.4		
18:00	0.4	0.2	-3.2	0.7	-1.6	2.4	3.9	1.3	1.9	2.1		
Shade provider		*Ficus religiosa*	*Ficus religiosa, Broussonetia papyrifera*	*Cassia siamea*	*Thepesia populanea*	*Eucalyptus globulus*	*Morus alba*	*Eucalyptus globulus, Alstonia scholaris*	Building and *Cassia spp*	Artificial shade	*Mangifera indica*	Creeper
Average Cooling Intensity	0.8	3.8	2.0	2.6	0.7	5.3	8.1	5.0	4.3	5.6	6.4	5.1
Maximum Cooling Intensity	2.7	5.9	10.4	10.0	5.6	8.2	10.3	8.0	6.5	7.7	9.0	7.9

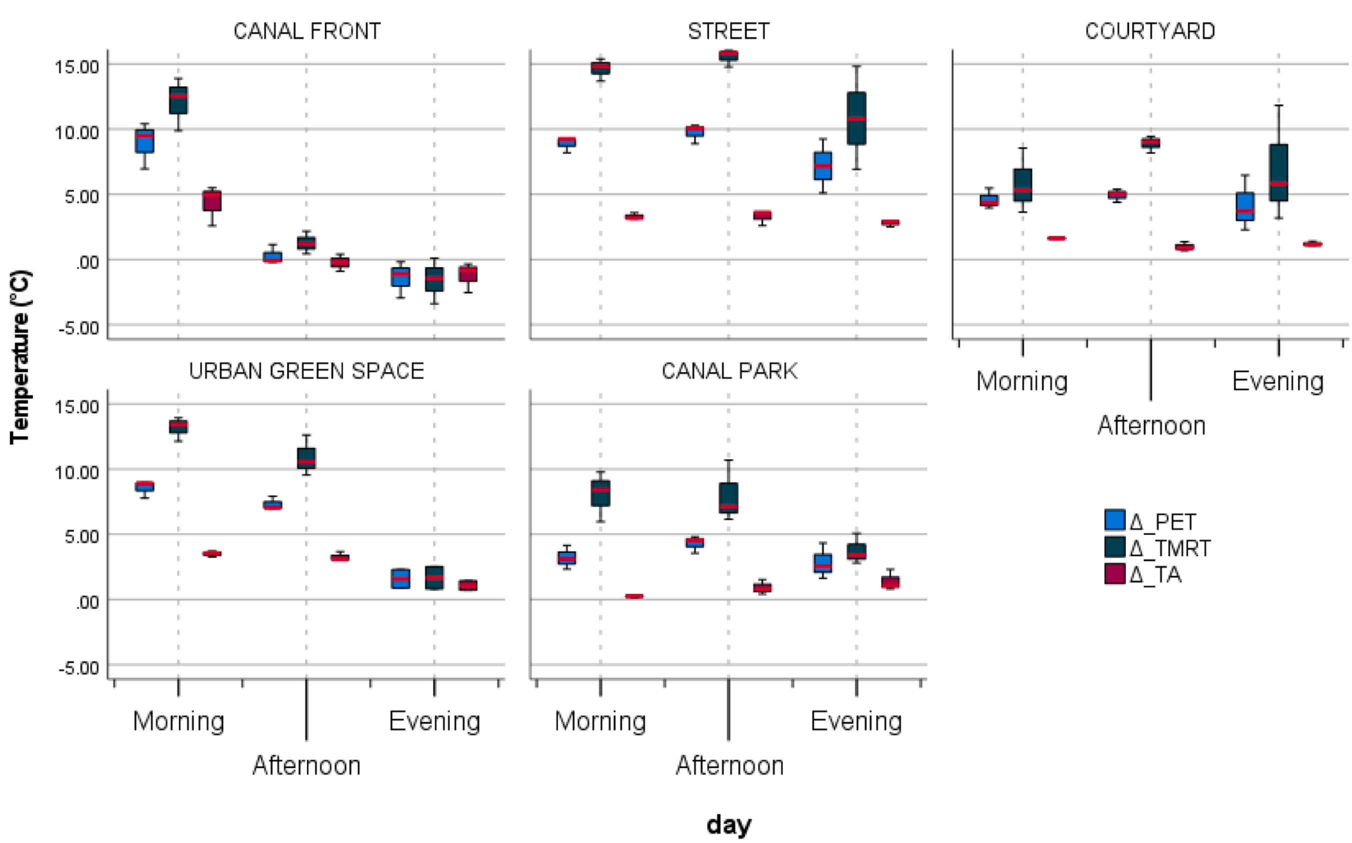
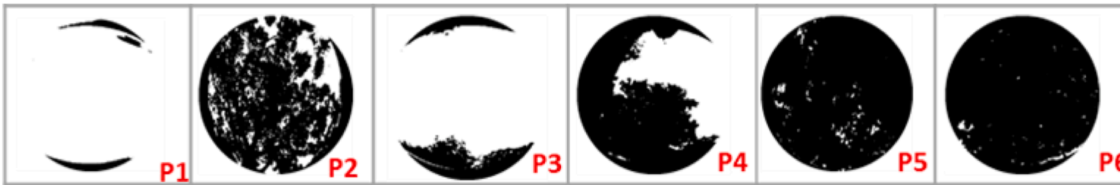
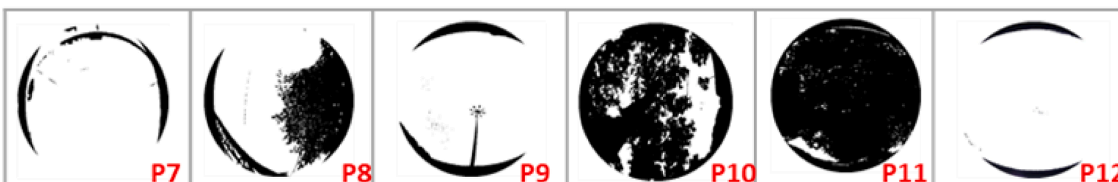


Fig. 3. Variation in the cooling pertaining to the three thermal comfort metrics (T_a, PET and T_{mrt}) in different microenvironments of Roorkee, India.

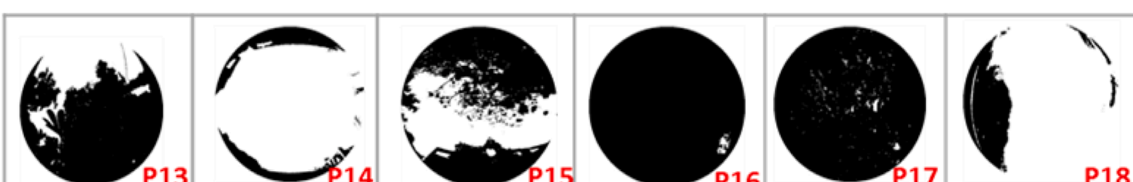
material). For example, canal front and street environments show the highest reduction in PET (μ ΔPET = 8.96 °C and 8.90 °C, respectively) and T_{mrt} (μ ΔTmrt =12.10 °C and 14.64 °C, respectively) in the morning. Higher improvement in the comfort conditions was noted in the Street (μ ΔPET = 9.75 °C); followed by tree grove (μ ΔPET = 7.33 °C) and Canal Park (μ ΔPET = 4.3 °C) during the afternoon hours. It is interesting to note that across the diverse micro environments, PET (σ= 3.26) and T_{mrt} (σ= 4.91) showed larger variations as compared to T_a (σ = 1.51). This



SVF	0.95	0.21	0.845	0.357	0.022	0.01
μ PET (°C)	43.11	39.69	43.91	39.40	37.20	36.69
μ Tmrt (°C)	49.31	42.76	49.65	40.48	37.05	36.83
μ Ta (°C)	37.55	36.72	38.21	36.98	36.25	35.47



SVF	0.92	0.61	0.90	0.27	0.04	0.95
μ PET (°C)	42.47	41.51	46.71	41.44	38.25	45.85
μ Tmrt (°C)	46.36	45.41	51.57	42.87	38.06	51.98
μ Ta (°C)	37.60	37.06	40.26	38.57	37.33	39.04



SVF	0.26	0.86	0.43	0.01	0.02	0.81
μ PET (°C)	40.37	44.56	40.03	38.63	38.82	45.10
μ Tmrt (°C)	41.63	49.70	42.52	38.77	38.85	48.19
μ Ta (°C)	38.02	38.24	36.97	37.51	37.36	40.14

Fig. 4. SVF photos and values as well as T_a, T_{mrt} and PET values for the study locations in Roorkee, India.

can be attributed to varied green and blue features and exposure characteristics prevalent in these urban environments. Further our findings indicate that urban green comprising of tree grove consistently demonstrates a favorable reduction in thermal discomfort in the morning and afternoon (σ= 0.67 and 0.51, respectively), indicating the effectiveness of vegetation in mitigating heat.

3.4.2. Influence of solar exposure, shade and SVF

Statistically significant differences are noted between the sampled locations based on solar exposure and shade. Tukey's post hoc test presented in Table A.4 (Supplementary) reveals that T_{mrt} and *PET* were significantly lower in shaded areas as compared to the sun-exposed areas. T_a was significantly lower in tree shade when compared to sun-exposed locations.

SVF differs from 0.01 to 0.95 among the study locations (Table 1 and Fig. 4) and is strongly correlated with T_{mrt} (R^2 = 0.92) and PET (R^2 = 0.83) as shown in Fig. 5. On the contrary, T_a is weakly correlated to SVF (R^2 = 0.31). The results suggest that 0.1 increase in SVF value corresponds to an increase of about 0.2 °C in T_a, 0.7 °C in *PET* and 1.3 °C in T_{mrt} (Fig. 5).

3.4.3. Effect of tree characteristics (canopy type, tree height, LAI)

The correlation between the morphological characteristics of trees and the thermal environment is presented in Table 5. Tree height was negatively and significantly correlated to T_{mrt} and PET, while there was no significant correlation with T_a. Canopy diameter and LAI were negatively and significantly correlated with all three indicators of thermal environment, i.e., T_a, PET and T_{mrt}. The results indicate that trees with larger canopy diameter and higher LAI are more effective in improving OTC conditions during summer daytime. Conversely, trees with a small canopy (2.9 m) e.g. *Eucalyptus alba* reported adverse thermal comfort metrics (T_a = 38.57 °C, T_{mrt} = 42.87 °C, PET = 41.44 °C). Furthermore, greater variability (σ = 2.48 °C) in T_{mrt} was noted under varied tree species and can be attributed to differences in canopy structure, foliage density and the microenvironments.

Fig. 6 further illustrates that open canopy trees reported the most adverse thermal environment and OTC conditions, while intermediate and dense canopies reported lower values of T_a, T_{mrt} and *PET*. Interestingly, the comfort conditions prevalent under all the three canopy types correspond to strong heat stress as per the Lin scale [93]. When compared to open canopy trees, the dense canopy trees were the most effective in lowering T_{mrt} by 3.5 °C, while the intermediate canopy trees were the most effective in lowering PET by 2.2 °C and T_a by 1.8 °C. These differences are statistically significant and are partially based on the

Table 5
Correlation between morphological characteristics of trees and T_a, T_{mrt} and PET in Roorkee, India.

Morphological characteristics		T_a	T_{mrt}	PET
Tree height	Correlation Coefficient	−0.041	−0.281**	−0.148**
	Sig. (2-tailed)	0.304	0	0
Start of canopy	Correlation Coefficient	.242**	.154**	.237**
	Sig. (2-tailed)	0	0	0
Canopy diameter	Correlation Coefficient	−0.107**	−0.436**	−0.287**
	Sig. (2-tailed)	0.007	0	0
LAI	Correlation Coefficient	−0.125**	−0.397**	−0.330**
	Sig. (2-tailed)	0.002	0	0

** . Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

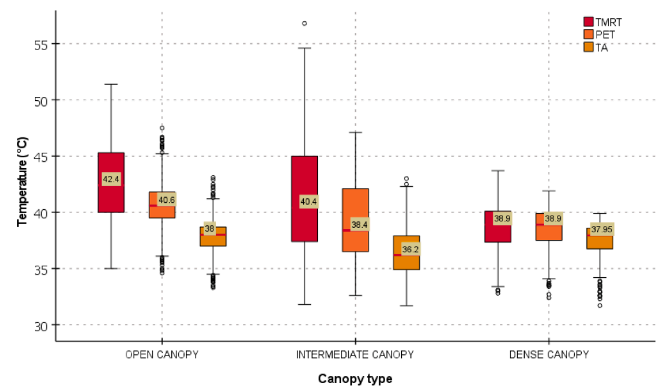


Fig. 6. Impact of tree canopy types on median values of: a) T_a, b) T_{mrt}, and c) *PET* in Roorkee, India.

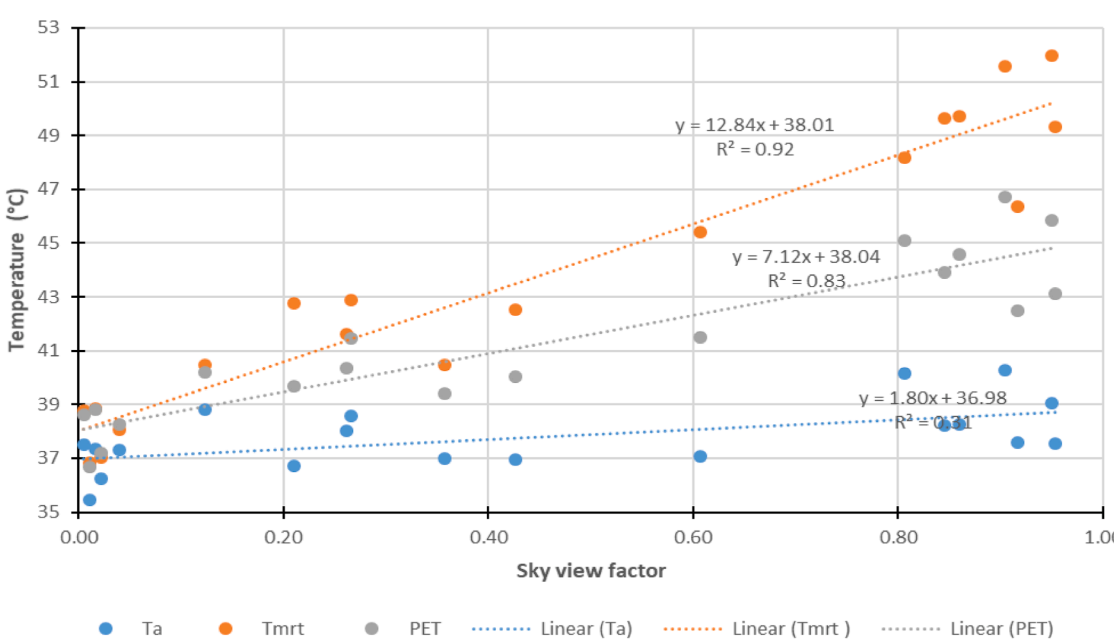


Fig. 5. The correlation between SVF and T_a; T_{mrt}; and PET in Roorkee, India.

canopy characteristics already shown in Table 5.

3.4.4. Influence of land cover fraction, their synergistic effect, and the distance to the Ganga Canal on cooling intensity

Influence of land cover fractions on the cooling intensity was assessed for eight different radii (from 15 m to 500 m) around 13 measurement positions which are located < 50 m away from the Ganga Canal. Pervious and tree cover fractions (in radii up to 100 m) showed a strong correlation with the cooling potential (Table A.5 in Supplementary and Fig. 7) indicating that increasing pervious and tree cover will lead to a higher cooling potential. The highest R^2 values between pervious fraction and cooling potential are obtained for 50 m radii, while the highest R^2 values between tree fraction and cooling potential are observed at 25 m (for T_a) and 50 m (for T_{mrt} and PET) (Fig. 7; Supplementary table A.5). Impervious and water fractions showed none to weak relationship with the cooling potential (Supplementary Table A.5). Our findings demonstrate the effectiveness of increasing pervious surfaces (like soil, grass) and tree cover for significantly enhancing the cooling effects in urban areas, especially in the radius of 100 m around the intervention area. This is not the case for radius > 100 m (Supplementary Table A.5).

The synergistic effect of trees along the Ganga Canal front led to further improvement in the thermal environment as presented in Fig. 8. For example, locations in proximity of the canal (< 50 m) and under tree shade reported the lowest median PET value of 38.6 °C, while sun-exposed locations in proximity to the canal reported 4.7 °C higher median PET. Similarly, T_a was lower by 1.6 °C and T_{mrt} by 9.3 °C in the tree-shaded Canal front locations compared to the sun-exposed Canal front locations (Fig. 8). In general, as the distance to the Canal increased, the thermal environment got hotter for both sun-exposed and shaded locations.

4. Discussion

This study investigated the cooling intensity and OTC conditions across urban microenvironments influenced by different green-blue features in Roorkee, India. The special focus was on the impact of different types of shade (tree, building, mixed), tree characteristics and water proximity on the mitigation of heat stress and improvement of outdoor thermal environment.

By measuring the micrometeorological conditions in Roorkee, we found that there were crucial differences in the measured parameters based on the micro-environments studied, green blue features and solar exposure. Micrometeorological measurements of T_a showed that the lowest values were registered in shaded locations close to the canal, thus indicating the importance of synergetic effect of tree canopies and water proximity on air temperature decrease. On the contrary, locations that were sun-exposed and further away from the canal showed higher T_a values. The surface cover did not substantially impact the obtained T_a values, with similar values registered above concrete and grass (SVF = 0.8 – 0.9).The highest average daytime (9–18 h) cooling intensity of 3 °C was provided by *Morus alba*, while the maximum hourly cooling intensity was registered in the morning when tree shade under *Ficus religiosa* and *Broussonetia papyrifera* (P5) was able to mitigate the heat by up to 5.5 °C when compared to sun-exposed locations. Our results are in agreement with a study conducted in New Delhi in summer [94]. This study reported that among the tree species studied, *Morus alba* reported 2.6 °C lower temperature under its canopy. However, as the day progressed, the heat mitigation potential of trees decreased and even higher T_a (up to 2 °C) were registered under certain trees when compared to sun-exposed location. This could be a possible consequence of varying shading and sun-exposure conditions between these locations or the heat trapping beneath the tree canopy. "Heat trapping" effect by dense tree canopy was suggested by [95] for Melbourne where a slightly warmer T_a after midnight was noticed in a shallow E-W urban canyon with dense tree canopy. Our results showed that the problem associated with heat trapping by trees was already evident during early evening hours in Roorkee. The relative nocturnal warming can be arguably desirable during cold winter nights [96], but it is definitely not desirable during the hot summer evenings and nights in cities with humid subtropical climate, such as Roorkee, as it enhances heat stress and thermal discomfort of citizens. Interestingly our study brought forth that the combination of layering of shrub and tree can lead to significant improvement when compared to individual tree and shrub in the thermal environment. Further studies are however required to develop a comprehensive understanding of varied combination (e.g., tree; shrub; groundcover) that can help urban planners and landscape architects to maximize cooling benefits in diverse urban environments.

In terms of human biometeorology, the hourly PET values were up to about 10 °C lower under the shade of *Ficus religiosa, Broussonetia papyrifera, Morus alba* and *Cassia siamea trees* (P5, P6, and P11) when compared to the sun-exposed locations. Furthermore, *Morus alba* (P11) with its dense canopy was even able to lower the mean daytime PET by 8.1 °C when compared to sun-exposed location during the 9–18 h of a hot summer day in Roorkee, making it the most efficient tree for heat stress mitigation during the daytime. The artificial shade (P16) and mixed shade (P15) were less efficient in decreasing the heat stress in Roorkee compared to some of the trees (see Table 4) with a decrease of 5.6 °C and 4.3 °C in average daytime PET when compared to sun-exposed locations. Ali and Patnaik [75] showed that high percentage canopy cover (70%) reduced PET by 2.6 °C in urban parks in the tropical climate city of Bhopal, India. This study mentioned that the dense canopy tree species that were encountered during the survey were *Ficus religiosa, Ficus benghalensis, Artocarpus heterophyllus, etc.,* and this study can also add *Morus alba* as an efficient tree for heat stress mitigation during summer days. Accordingly, trees with dense canopies were able

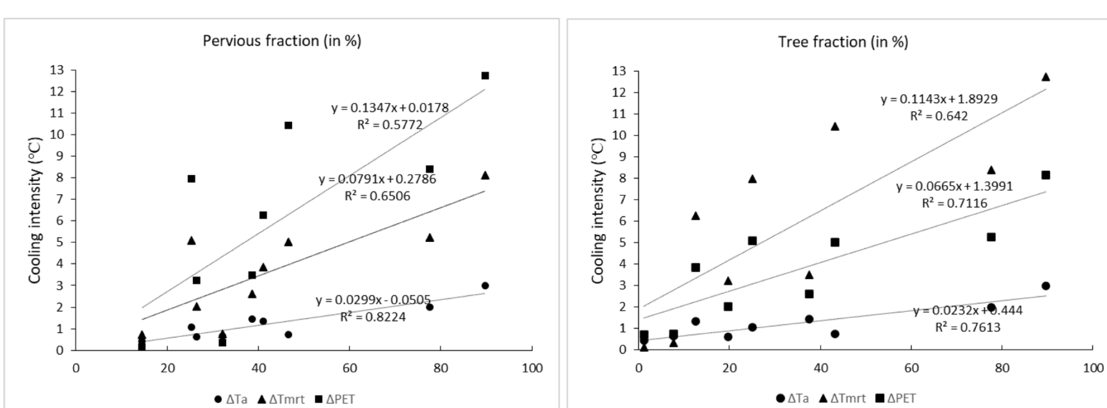


Fig. 7. The impact of pervious and tree cover fractions (in 50 m radius around measurement locations) on cooling intensity in Roorkee, India.

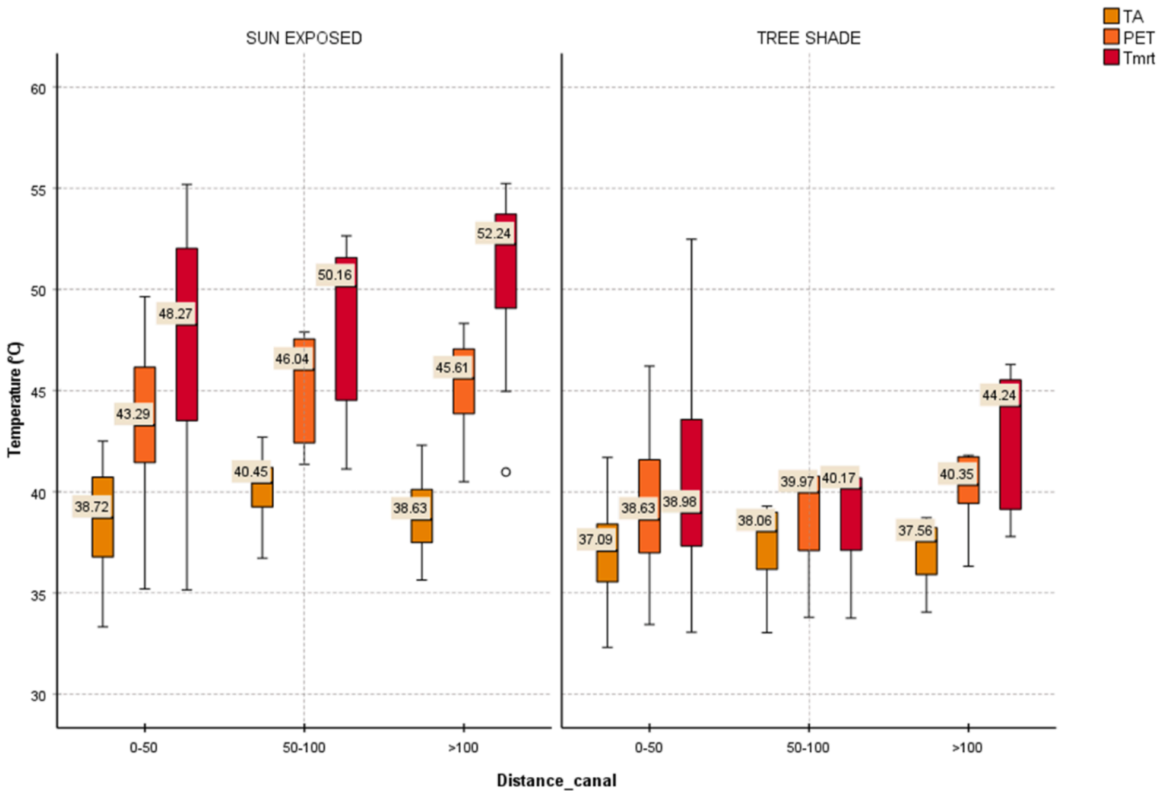


Fig. 8. The synergistic impact of solar exposure, trees and distance to the Ganga Canal at: a) T_a; b) T_{mrt}; and c) PET in Roorkee, India.

to lower the heat stress category from extreme to moderate in Roorkee, leading to better thermal environment compared to locations without the trees and shade. However, it is often not just about trees, but other factors can play a role in heat mitigation. For example, the study by [97] further indicated that the PET reduction potential of trees in Patna (India) depends not only on the canopy size and layout density, but also on wind speed. Furthermore, the physical characteristics of trees such as canopy diameter, LAI and tree height are crucial determinants that influence their capacity to regulate micrometeorological conditions. Our results indicate that trees with larger crown widths are more effective in improving the thermal comfort conditions indicating that crown characteristics are crucial determinants of the urban microclimate [98]. Furthermore, our study showed that incorporating pervious surfaces, not just trees, within 100 m of intervention areas can significantly enhance cooling, with the strongest effects observed at 25–50 m radii. These findings are in agreement with Chen et al. [49] wherein the cooling effect of blue green space was dominated by the vegetative fraction within 30 m along riverside. Pervious and tree cover showed strong correlations with cooling potential, while impervious surfaces and water fractions had minimal impact. These findings highlight the importance of land cover composition in urban heat mitigation strategies.

Previous studies (e.g. [99,100]) have shown that there is a lack of knowledge and a need to transfer urban microclimate data to urban planners and practitioners. With adequate data and knowledge on urban microclimate, urban planners in India can develop targeted climate-proofing strategies and heat mitigation measures and plans in order to mitigate the heat, increase urban livability and contribute to sustainable and healthy cities. This is especially important for fast developing cities in India and other developing countries.

One of the proposed solutions for tackling heat and other environmental problems in cities is the application of NbS and green-blue infrastructure [9,101]. Previous studies mostly focused on urban green and their impact on the microclimate [13,19], while there were a lower number of studies dealing with urban blue (i.e., water) impacts (e.g. [34, 35]). Even lower number of studies investigated the synergistic impact of both urban green and blue on outdoor thermal conditions in cities [45]. Our results established that the synergistic cooling effect of green and blue features was more pronounced in locations close to the canal. These findings are in agreement with Shi et al. [45] where the SCEs of green blue features were obvious in 7–12 m surrounding the waterfront areas. Our study showed that it is important to assess individual as well as synergistic impacts of green-blue features on outdoor heat mitigation, especially if the city has a prominent blue feature, such as river, canal, or lake.

In this way, it is possible to more successfully advocate for the implementation and maintenance of both urban green and blue areas. The ways in which green and blue space infrastructure is applied in future urban growth strategies in countries expected to experience rapid urbanization warrants greater consideration in urban planning in order to mitigate the adverse effects of the UHI and to enhance climate resilience [29]. Our study paid greater consideration to green and blue features and their impacts on microclimate in Roorkee, providing valuable data on heat issues in Roorkee and quantifying the heat mitigation potential of green and blue features that can be used for heat-proofing the city in the coming years.

4.1. Study limitations and research directions

This study focused on specific microenvironments within Roorkee only and therefore may not fully capture the broader urban landscape's variability. Extending the analysis to more diverse urban settings could provide a more comprehensive understanding of urban heat dynamics. Further this study focused on specific microenvironments predominantly located along the Ganga Canal. A limitation of the study is that only 6 measurement locations were at the distance >50 m of the Ganga Canal. In that regard, the majority of our measurement locations (13 out of 19 locations) are at a distance 〈 50 m from the Canal; 2 locations are between 50 m and 100 m; and 4 locations are ⟩ 350 m (Table 1). Thus, in this study, we focused our investigation on the impact of green and blue features on the cooling potential at locations at a distance < 50 m to the Ganga Canal, while the detailed investigation on larger distances was omitted due to limited sample size. Densely built-up areas were also excluded from the investigation. Secondly, this study focused on daytime field studies during summer. Multi-seasonal and diurnal studies are required for a deeper understanding of the impact of green and blue features on thermal comfort outdoors. Real time field studies were utilized and only six tree species were investigated. It is vital to highlight that all the potential confounding variables while quantifying the cooling benefits from green blue features in urban settings especially are difficult to control. Therefore, high-resolution computational models can be utilized to simulate microclimatic conditions under various urban planning scenarios and predict the potential synergistic impact of different green blue features accurately. Additionally, further research should investigate a broader range of tree species and vegetation types, focusing on their specific cooling mechanisms, growth patterns, and maintenance requirements. This will help in selecting the most effective species for urban greening initiatives. Lastly, studies can combine thermal environment studies with socio-economic data to develop an understanding of broader implication of heat stress on public health, social equity and energy consumption. This approach can inform more holistic urban planning and policy-making.

5. Conclusion

Our study on heat occurrence and mitigation in Roorkee revealed significant spatio-temporal variability in micrometeorological conditions across diverse urban microenvironments. The highest temperatures (T_a) were observed in sun-exposed areas distant from the canal, reaching up to 42.7 °C, while shaded locations near the canal exhibited lower temperatures, with median T_a as low as 35.7 °C. Cooling intensities varied across locations and time periods, with shaded areas experiencing significantly lower temperatures compared to sun-exposed reference locations. Trees, buildings, and artificial shade structures contributed to cooling, with *Morus alba* and *Mangifera indica* trees having the most notable cooling effects, even more notable than artificial shade or mixed (building and tree shade). Conversely, *Eucalyptus alba* reported adverse thermal comfort metrics.

Biometeorological conditions, including PET, varied widely across study locations, influenced by factors such as solar exposure, shade, and SVF. PET values ranged from slight to extreme heat stress, with shaded areas exhibiting lower PET values compared to sun-exposed locations. Trees along the canal front contributed to further improvement in the thermal environment, with shaded locations reporting significantly lower PET values compared to sun-exposed areas during the daytime. The reduction in PET by trees varied hourly based on the type of microenvironment and type of tree. *Morus alba* tree was the most efficient tree in lowering PET by 8.1 °C on average during hot summer day, followed by *Mangifera indica* tree. These trees were more efficient in mitigating heat stress when compared to artificial shade and mixed (building and tree) shade in Roorkee.

Statistical analysis revealed the significant influence of solar exposure, shade, and SVF on thermal conditions, with tree characteristics such as canopy type and LAI playing a crucial role. Dense canopy trees were most effective in lowering temperatures, while open canopy trees exhibited adverse thermal environments. Tree species differed substantially in their ΔT values, with peak cooling (maximum average $\Delta T =$ 3 °C) observed during morning hours.

This study highlighted that the low SVF, intermediate or dense canopies of trees (e.g., *Morus alba, Mangifera indica*) and proximity to the water body (< 50 m) is the most effective combination of green and blue feature characteristics for heat mitigation and OTC improvement in Roorkee during hot summer days. This type of (bio)meteorological knowledge is valuable for developing climate-sensitive urban design solutions that are essential for Indian cities in times of global warming and intensive urbanization. Our study further demonstrated that increasing pervious surfaces and tree cover, especially within a radius of 100 m around intervention areas, can significantly enhance cooling effects. The strongest correlations between cooling intensity and land cover fractions were observed at radii of 25 to 50 m, with pervious surfaces and tree cover contributing most to cooling, while impervious surfaces and water fractions showed weak relationships with cooling intensity.

Lastly, our study's findings emphasize the strategic placement of trees and shade structures while accounting for the synergistic effects of shade and water in reducing heat stress and enhancing thermal comfort in urban environments such as Roorkee.

CRediT authorship contribution statement

S. Manavvi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dragan Milosevic:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2024.112238.

Data availability

Data will be made available on request.

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