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The impact of local microclimates and Urban Greening Factor on schools' thermal conditions during summer: A study in Coventry, UK

Yasaman Namazi [a,*], Susanne Charlesworth [a], Azadeh Montazami [a], Mohammad Taleghani [b]

[a] Centre for Agroecology, Water and Resilience, Coventry University, Coventry, UK
[b] School of Architecture, Leeds Beckett University, Leeds, UK

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ABSTRACT

Thermal comfort in schools affects children's wellbeing and educational outcomes. Global warming and frequent heatwaves have worsened the overheating issue in schools, especially in Western European countries, like the UK. While previous studies have mainly focused on residential and commercial buildings, school-related research often emphasised indoor thermal conditions, neglecting the broader influence of microclimates on the overall thermal conditions. Therefore, this research explores the thermal conditions in schools, during the summer of 2023, with a specific focus on the impact of greenery and materials. Urban Greening Factor (UGF) and its relationship with indoor and outdoor air temperatures were explored for the first time.

Field studies were conducted in four primary schools in Coventry, UK, measuring indoor air temperatures and micrometeorological parameters. Tree shade demonstrated a substantial cooling effect, reducing air temperature and mean radiant temperature by up to 6.4 °C and 22.9 °C, respectively. Considerable difference between measured air temperatures in sunlight and official meteorological records highlights the need for microclimatic studies in schools. Thermal imagery identified high surface temperatures on artificial grass (67 °C) and asphalt (55 °C). Urban Greening Factor showed a strong correlation with classroom temperatures but failed to account for spatial greenery distribution and subsequently outdoor thermal conditions. The study concludes that optimising tree shade and replacing dark and artificial materials, are necessary for effective heat mitigation, offering valuable insights for policymakers and urban planners to create thermally comfortable and sustainable school environments.

1. Introduction

Global warming and climate change have brought new challenges for both developed and developing countries [1]. The rise in average global temperatures, attributed to greenhouse gas emissions, intensifies the urban heat island (UHI) effect [2] and heatwaves [3], resulting in a higher mortality rate due to the exposure to extreme heat for urban dwellers [4]. Western European countries, including the UK, are among the most affected countries by rising temperatures as most buildings rely on natural ventilation. A recent study indicates that if global warming progresses from 1.5 °C to 2 °C, cooling degree days in the UK will increase by 30 % [5]. Green infrastructure (GI) plays a crucial role in the cooling of urban areas by providing shade [6,7] and facilitating evapotranspiration [8,9]. The presence of GI elements within urban areas can reduce air and surface temperatures [10–12], and incident solar radiation [6,13]. Consequently, insufficient GI contributes to an increase in temperatures in the urban context, leading to a higher UHI intensity [14,15].

Children are among the most vulnerable groups to this temperature rise as their physiological, metabolic and behavioural traits differ from those of adults [16]. Higher temperatures negatively impact their wellbeing [16,17] and educational performance [18,19]. While thermal comfort standards, such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), focus on adults [20], studies on children reveal that their thermal comfort range is different. For example, a study showed that children's neutral temperature in summer in naturally ventilated schools is 3 °C lower than that of adults [21]. Another study in UK primary school classrooms showed children's higher sensitivity to heat compared to adults, with a comfort temperature 4 °C lower than the PMV model predictions [22]. Moreover, differences in

* Corresponding author.
E-mail addresses: namaziy@uni.coventry.ac.uk (Y. Namazi), apx119@coventry.ac.uk (S. Charlesworth), ab0404@coventry.ac.uk (A. Montazami), m.taleghani@leedsbeckett.ac.uk (M. Taleghani).

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personal and environmental adaptation behaviours exist between children and adults in school environments. For instance, it has been shown that a lower percentage of children choose to wear lighter clothes during warm conditions, and the control of windows 80 % of the time was undertaken by the teacher and not based on children's needs [23].

While previous research on buildings' overheating and cooling demand mainly concentrated on residential and commercial buildings [24,25], the emphasis in school studies is often on building characteristics such as thermal mass [26,27], ventilation [28,29], and night time cooling [30], whereas outdoor and microclimate features also significantly influence overall thermal conditions in schools [31]. Additionally, pupils use outdoor areas for both recreational and educational purposes [32], which they are likely to access on a daily basis, thus regularly coming in contact with the resulting outdoor thermal environment. Despite this, thermal conditions in the schools' outdoor areas remain underexplored. The lack of adequate shade and trees, coupled with the use of low albedo materials, are among the primary contributors to heat stress and thermal discomfort in schools [33–35].

In the UK, for evaluating both the quantity and quality of urban greening on a site, Urban Greening Factor (UGF) calculation is mandated by London Plan Policy G5 for all major developments, including schools. Using UGF, planning authorities and developers can ensure the appropriate green infrastructure is applied to a site to enhance climate resilience (e.g. UHI mitigation, improved biodiversity, and stormwater runoff reduction) [36,37]. However, the effect of UGF on indoor and outdoor air temperatures has not been studied yet. The minimum UGF score of 0.4 is required for developments, while the impact of this UGF score is not clear and has not been explored in previous studies.

Coventry with a population over 345,000, ranks as the eleventh most populous city in the UK. It experienced a substantial population growth rate of 8.9 % from 2011 to 2021, higher than the England average of 6.6 % [38]. Due to this growth, Coventry is experiencing significant urban development, which may cause environmental destruction and the loss of green spaces in and around the city [39]. In Coventry, tree canopy coverage or the proportion of an area covered by tree crowns [40], is as low as approximately 14 % while the English average is 17.5 % [41]. These numbers are lower than most EU countries [42].

Considering the connection between summertime overheating, lack of GI, and the vulnerability of schoolchildren, this research aims to investigate the indoor and outdoor thermal conditions in primary schools in Coventry during summer, with a focus on the impact of greenery, shade and materials. In this study, the potential causes of high temperatures in schools are investigated. This study considers microclimatic features as an important factor affecting overheating in schools. In addition, this is the first time that the impact of UGF on the air temperature in schools is studied.

2. Methodology

An overview of the methodology of this paper is illustrated in Fig. 1. Four primary schools (A, B, C, and D) in Coventry, UK, were selected for field studies. On hot summer days in 2023, field measurements, including classrooms air temperature measurements with dataloggers, micrometeorological measurements with HOBO sensors, and thermal imagery, were conducted in the case studies. The obtained data were then statistically analysed to investigate the summertime indoor temperatures and microclimatic conditions in schools.

2.1. Field study: Coventry, United Kingdom

Coventry (52° 24′ N, 1° 30' W) is situated in the West Midlands region of England, United Kingdom. The city features an oceanic climate with warm summers, categorised as Cfb, according to the Köppen-Geiger climate classification [43]. Over the period from 1991 to 2020, Coventry experienced a climatic range with the warmest average air temperature of 21.97 °C in July and the coldest average temperature of 1.75 °C in February [44].

Four naturally ventilated primary schools, (A, B, C, and D) were selected for this field study, locations of which are shown in Fig. 2.

2.1.1. Selection criteria for outdoor and indoor measurements

The selection of schools and their classrooms for outdoor and indoor measurements was based on several criteria. Different schools were chosen to represent varying distances from the city centre, deprivation levels, and green areas. Email and telephone contacts were made with schools' headteachers to enquire if they would be interested in joining the study, resulting in approximately 13 % of schools willing to participate. Table 1 summarises the socio-environmental characteristics of the surrounding areas of these schools. For example, school B is in an area with the highest heat risk [45], the lowest tree canopy cover [46], the most deprived neighbourhood [47], and the highest population density [48]. It should be noted that the areas closer to Coventry city centre and its northern areas, including Schools A, B, and C, have more challenging

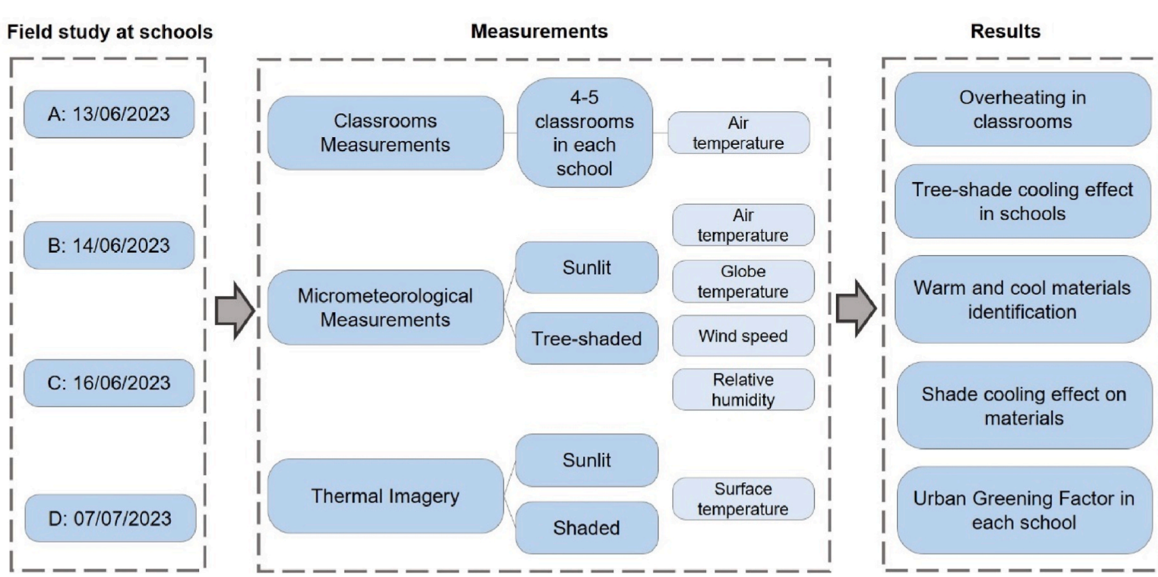


Fig. 1. The overview of methodology.

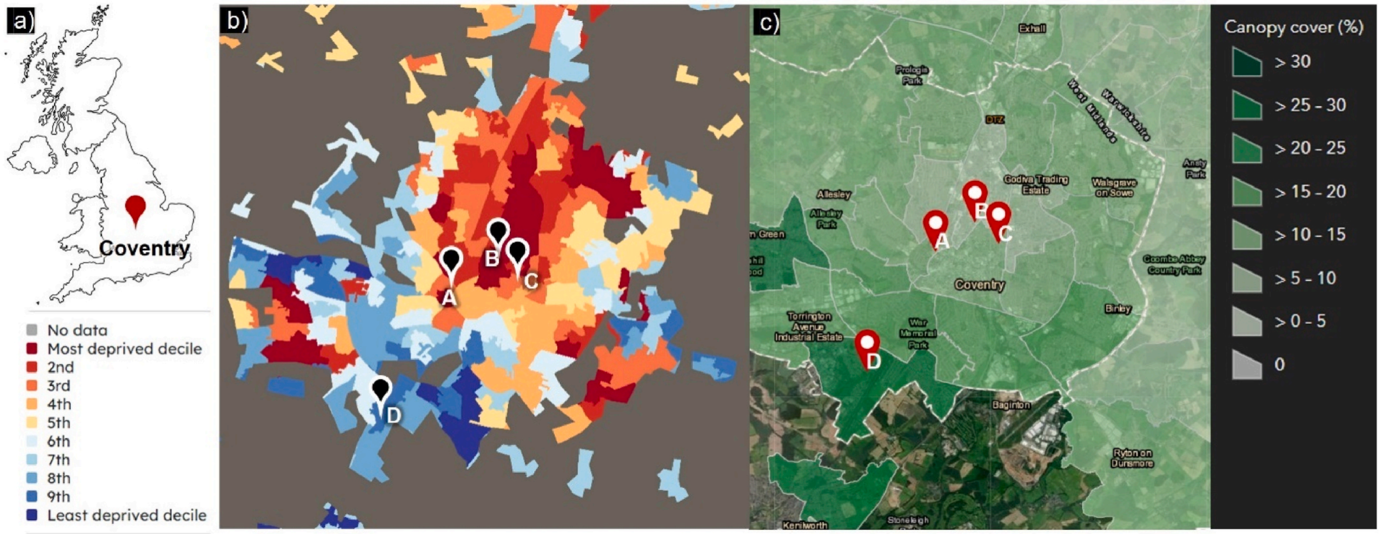


Fig. 2. a) Coventry on the map of United Kingdom, b) locations of studied schools on the map of Index of Multiple Deprivation after [47], and c) locations of studied schools on the map of Coventry tree canopy cover [46]. The deprivation map (middle panel) is an output of Consumer Data Research Centre, an ESRC Data Investment, ES/L011840/1; ES/L011891/1″, Contains OS data © Crown copyright and database right 2022.

Table 1
Socio-environmental characteristics of school surroundings.

School	High Heat Risk Score [45]	Area Average Tree Canopy Cover [46]	Index of Multiple Deprivation in 2019 [47]	Neighbourhood Population Density (Persons km^{-2}) [48]
A	2	15 %	3rd most deprived	3249
B	3	8 %	Most deprived	10,415
C	2	10.2 %	2nd most deprived	9004
D	1	25.8 %	9th most deprived	1431

socio-environmental conditions compared to southern areas of the city (School D).

After selecting schools, a short interview was conducted with each headteacher, where the warmest and coolest classrooms were introduced by them, based on the experience of the occupants. Next, hot and sunny summer days in June and July 2023 were chosen for field measurements. It is noteworthy that 2023 was the planet's warmest year on record [49].

2.2. Equipment and measured parameters

Measured parameters included air temperature (T_a), globe temperature (T_g), wind speed (WS), relative humidity (RH), and surface temperature (T_s). Table 2 presents the specifications of the sensors employed during the field study along with their pictures in Fig. 3. The sampling frequency for all sensors was set at 5-min intervals. Additionally, a FLIR T620 thermal camera was utilised to record T_s of various outdoor materials four times during the fieldwork period at each school. Data collection in each school started at 9:00 and finished at 16:30. The selection of this time frame was due to the school's opening hours and the presence of students, ensuring that the thermal conditions monitored reflected the realistic situation to which students were exposed. Outdoor T_a and T_g were measured in both tree-shaded and sunlit locations to investigate the potential cooling effect of trees. Therefore, a tree-planted spot on the south or southwest side of the building was preferred to optimise the proportion of tree shade and sunlight and to minimise the effect of the building's shade on sensors.

Fig. 4 provides the locations of the studied classrooms and the outdoor sensors on the site plan of school on Google Earth images.

3. Results and discussion

3.1. Indoor air temperature

Fig. 5 illustrates the hourly average T_a measured in each classroom (classroom air temperature or T_c) across the four schools. Given the relatively gradual changes in indoor T_a over time, this section focuses on discussing the hourly averages rather than the detailed 5-min records. Upon comparing the four schools, it becomes apparent that School C has the most significant difference between its classrooms, with maximum

Table 2
Specifications of the sensors and dataloggers used in this field study.

SENSOR/INSTRUMENT		MEASURED PARAMETER	RANGE	ACCURACY	QUANTITY
A	HOBO S-TMB + black table tennis ball	T_g	−40 °C–100 °C	< ± 0.2 °C (from 0 °C to 50 °C)	2
B	HOBO S-WSB	WS	0 m/s to 76 m/s	±1.1 m/s or ±4 % of reading	1
C	HOBO UX100-003 + shield	T_a	−20 °C–70 °C	±0.21 °C (from 0 °C to 50 °C)	2
		RH	15 %–95 %	±3.5 % RH (from 25 % to 85 %)	
D	EL-USB-2+	T_a	−35 °C–80 °C	0.45 °C (from 5 °C to 60 °C)	3
E	EL-USB-1	T_a	−35 °C–80 °C	±0.5 °C	1
F	EXTECH RHT10	T_a	−40 °C–70 °C	±1 °C (from −10 °C to 40 °C)	1

Fig. 3. Sensors and dataloggers and the sunlit and shaded measurement locations.

Fig. 4. Locations of outdoor sensors and studied classrooms in each school. Blue and red crosses show, respectively, tree-shaded and sunlit locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and average measured differences of respectively 3.5 °C and 2.6 °C between the warmest and coolest classrooms. One-way ANOVA tests also showed a significant difference between classrooms within each school with $p < 0.05$. Furthermore, School D had the highest/fastest temperature rise from morning to afternoon, potentially due to the lower insulation or thermal capacity of the building exterior surfaces.

All schools, particularly School B, show higher morning T_c compared to the measured outdoor T_a (T_o), possibly because of a lack of night cooling. Notably, despite the potential for night time ventilation to cool down the buildings considerably, it was observed that all openings in each school were closed after approximately 16:30. This could explain why, by mornings, T_c remained high despite cooler outdoor conditions.

According to CIBSE TM52 [50], the comfort temperature (T_{comf}) in non-heating seasons is calculated based on Equation (1):

$$T_{comf} = 0.33T_{rm} + 18.8\ ^{\circ}C \tag{1}$$

where T_{rm} is the exponentially weighted running mean temperature.

Based on this formula, a previous study calculated children's T_{comf} in UK schools as 22.9 °C in the non-heating season [23]. Therefore, thermal discomfort is evident in the studied schools, as T_c is higher than T_{comf} in all studied classrooms between 70 % and 100 % of the time.

In Appendix A, floor plan of each school with highlighted studied classrooms are shown. Following, results of T_c within each school are discussed:

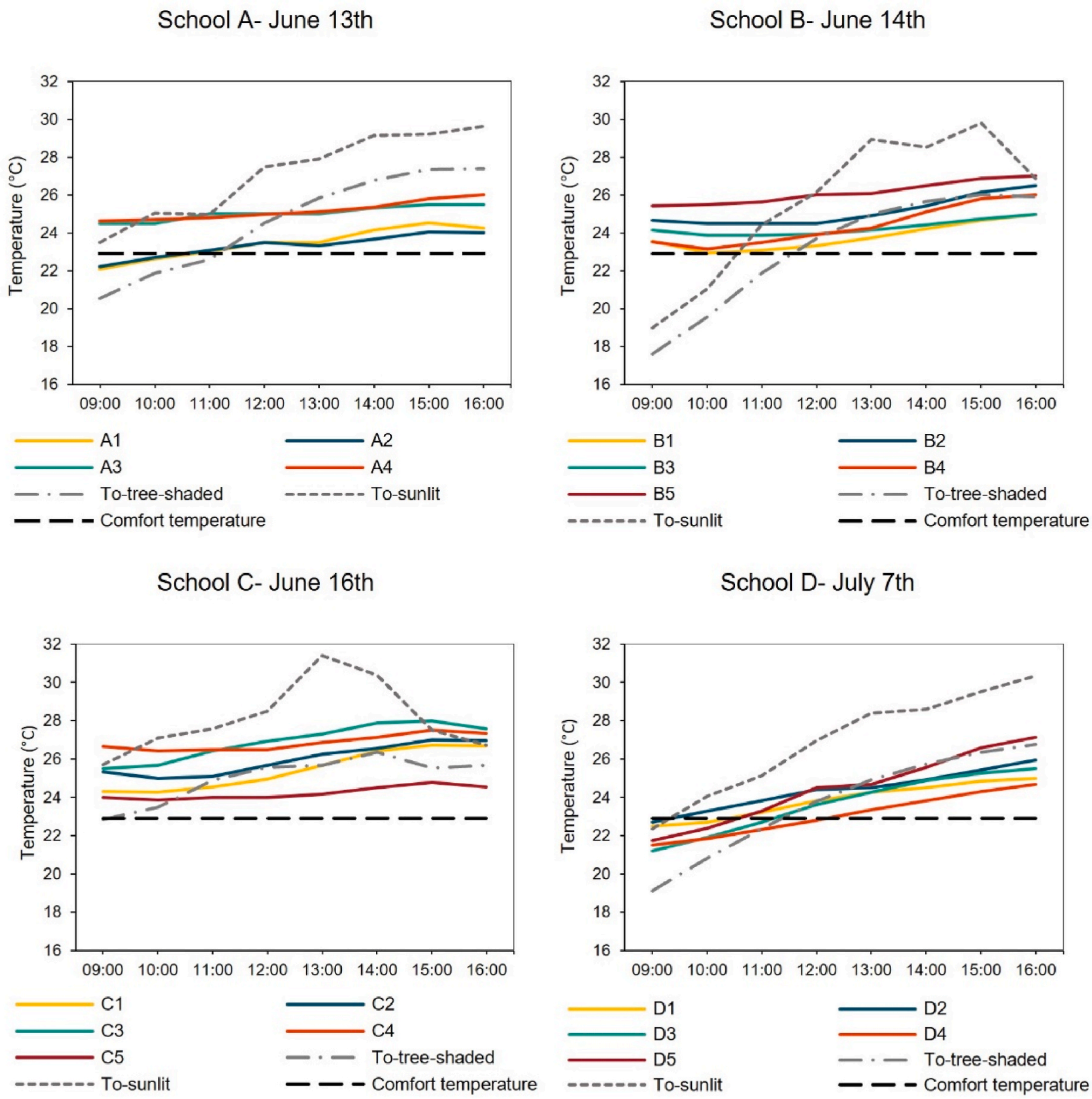


Fig. 5. Measured air temperature in different classrooms (T_c) in each school compared to each other and to outdoor measured temperature (T_o) in tree shade and sunlight and to comfort temperature calculated by Ref. [23]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

School A: A1 and A2 maintained a lower temperature consistently, compared to A3 and A4. This difference is likely due to the elevation, as A1 and A2 both are situated on the ground floor where temperatures typically remain cooler, while A3 and A4 are located on the first floor, where warmer conditions often dominate. The average T_c difference between the coolest classroom (A2) and the hottest classroom (A4) is 1.6 °C and a maximum difference of 2.7 °C is observed in early morning hours.

School B: B5 consistently maintained the highest T_c throughout the day, likely due to its large southwest-facing openings. Another hot classroom is B2, similarly, facing southwest. On the other hand, B1, the coolest classroom, mainly faces northwest. However, the lower T_c in B1 may be attributed not only to its orientation but also to its irregular usage, which results in lower anthropogenic heat generation. B3 and B4, other cooler classrooms, both face northeast. The average T_c difference between B1 and B5 is 2.3 °C with a maximum difference of 2.9 °C at 11:15.

School C: The coolest classroom, C5, faces east, while the warmest classroom, C3, faces west. The average and maximum T_c differences between C5 and C3 were 2.6 °C and 3.5 °C, respectively. Another warm classroom, C4, lacks ventilation and direct outdoor access. It is noteworthy that this classroom also recorded the highest morning T_c, likely due to the absence of night time cooling through ventilation and radiation, as it has no direct connection to the outdoors except through its high roof.

School D: D5, from noon onward, consistently had the highest T_c, potentially due to its west-facing orientation. D2, with an east-facing orientation recorded the highest T_c until noon. D4 is the coolest classroom among them, with an average hourly T_c of 2.5 °C lower than D5, by the end of the recording period at around 16:00.

Interestingly, D4 and D3, located next to each other and faced towards south, did not have the same thermal conditions. D3 had a maximum 1.5 °C higher T_c compared to D4. The reason can be that D4 has a larger opening (a door) leading to outdoors, while D3 lacks such direct opening towards the outdoors, although it has access to the courtyard. The difference of the amount of potential ventilation that a classroom could get from the courtyard compared to the main outdoor area may be account for this incident.

3.2. Outdoor thermal conditions

3.2.1. Air temperature

Fig. 6a shows T_o in both tree-shaded and sunlit locations every 5 min for the four schools. A significant difference in T_o between sunlit and shaded areas is evident, highlighting the substantial cooling effect of trees on air temperature in this climatic condition. The average and maximum T_o differences between sunlit and shaded locations were 2.5 °C and 4.4 °C in School A, 2.5 °C and 5.3 °C in School B, 3.3 °C and 6.4 °C in School C, and 3.2 °C and 4.4 °C in School D, respectively. These temperature differences could be due to both shade and the evapotranspiration effects of trees.

Sunlit T_o graphs (red lines) show more fluctuations compared to the tree-shaded areas (blue lines). As the sensors were located around trees, it can be inferred that the surrounding trees influenced sunlit T_o, for example with dappled sunlight from tree canopies, and led to these fluctuations.

Maximum T_o in all four schools exceeded 30 °C in sunlight while the maximum air temperature reported by the Met Office (air temperature at weather station or T_w) during the study days were between 25.0 °C

Fig. 6. Outdoor thermal data: a) measured air temperature in outdoor (T_o, in tree-shaded and sunlit locations) and air temperature from Met Office report (T_w), b) calculated MRT (in tree-shaded and sunlit locations) and solar radiation at Ryton weather station.

and 27.2 °C, more closely similar to the shaded T_o in the schools. This indicates the impact of microclimatic features, such as tree shade, on outdoor air temperatures, which causes schools having higher heat risk in the locations with no trees. Moreover, different inclinations in T_o graphs compared to T_W also demonstrate the microclimatic variations between these schools and proves the need for outdoor investigations when speaking about overheating in schools, which is underexplored in the previous studies.

3.2.2. Mean radiant temperature and solar radiation

This study employed measured globe temperatures (T_g) in sunlight and in tree shade to calculate Mean Radiant Temperature (MRT) using Equation (2):

$$\mathrm{MRT} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 \times WS^{0.6}}{\varepsilon \times D^{0.4}} \left(T_g - T_a\right) \right]^{0.25} - 273.15 \quad (2)$$

where:

T_g = globe temperature (°C)
WS = wind speed (m/s)
T_a = air temperature (°C)
D = globe diameter (m)
ε = globe emissivity

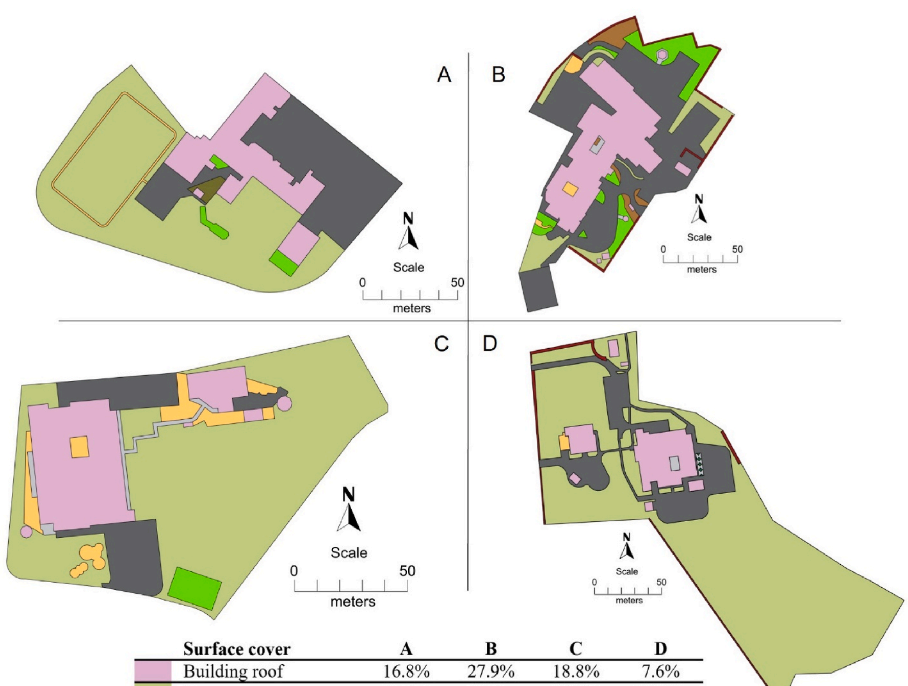
Solar radiation data was retrieved from the weather station situated at Ryton Organic Gardens, Wolston, Coventry, located 9.7 km to the southeast of the city centre. This weather station is equipped with a HOBO U30 where solar radiation is measured at 5-min intervals, which is aligned with the measurements of this study. Fig. 6b shows that the solar radiation levels on different days show minimal variation. The few fluctuations observed across three out of four study days can be attributed to semi-cloudy weather conditions during certain periods in the afternoon. In contrast, MRT graphs indicate numerous fluctuations in both shade and sunlit measurements, as observed in sunlit T_o in section 3.2.1. This could be due to the effect of porous shade of trees on the black globes.

A substantial difference between MRT in tree-shade and in sunlight is observed in each school. The average and maximum MRT differences between tree shade and sunlight were 9.1 °C and 17.8 °C in School A, 7.9 °C and 17.4 °C in School B, 5.1 °C and 12.9 °C in School C, and 10.9 °C and 22.9 °C in School D, respectively. On average, mean radiant temperatures in sunlit areas were 8.3 °C higher than shaded spots. Considering that MRT is a key factor influencing outdoor thermal comfort, it becomes evident that these case studies present a significant difference in thermal comfort between outdoor locations shaded by trees and those exposed to sunlight.

3.2.3. Thermal imagery and surface temperature

A total of 150 Infrared Radiation (IR) images were taken for this part of the study. These images were analysed using FLIR Thermal Studio software, where a linear measurement tool is used along the materials to measure an average T_s on each material. Fig. 7 illustrates the spatial coverage of materials used in the outdoor surfaces of each school.

T_s extracted from IR images were then categorised by schools, time intervals, materials, and the location (sunlit or shaded by either trees or other obstacles), presented in Fig. 8. During the fieldwork, certain outdoor areas in each school were not readily accessible due to ongoing children's outdoor activities, leading to limitations in data collection. Consequently, not all listed materials could be surveyed at all times. Artificial grass, asphalt and rubber pavement had considerably higher surface temperatures, especially after 11:00. The highest measured sunlit T_s of these materials were 69.9 °C, 67.5 °C, and 55.2 °C, respectively, while their T_s in shaded locations were lower than 40 °C. The surface temperatures of green grass never exceeded 35 °C in sunlit and 28 °C in shaded locations. Dry grass experienced a higher T_s at a



Surface cover	A	B	C	D
Building roof	16.8%	27.9%	18.8%	7.6%
Grass	54.5%	8.9%	60.3%	75.1%
Soil	<1%	3.2%	<1%	<1%
Asphalt	25%	46.8%	11.7%	14.3%
Artificial grass	1.6%	9%	2%	0
Concrete	<1%	<1%	2%	<1%
Rubber pavement	1.4%	1.2%	5.3%	<1%
Gravel	<1%	<1%	<1%	0

Fig. 7. Site plan of each school showing the coverage of widely used materials.

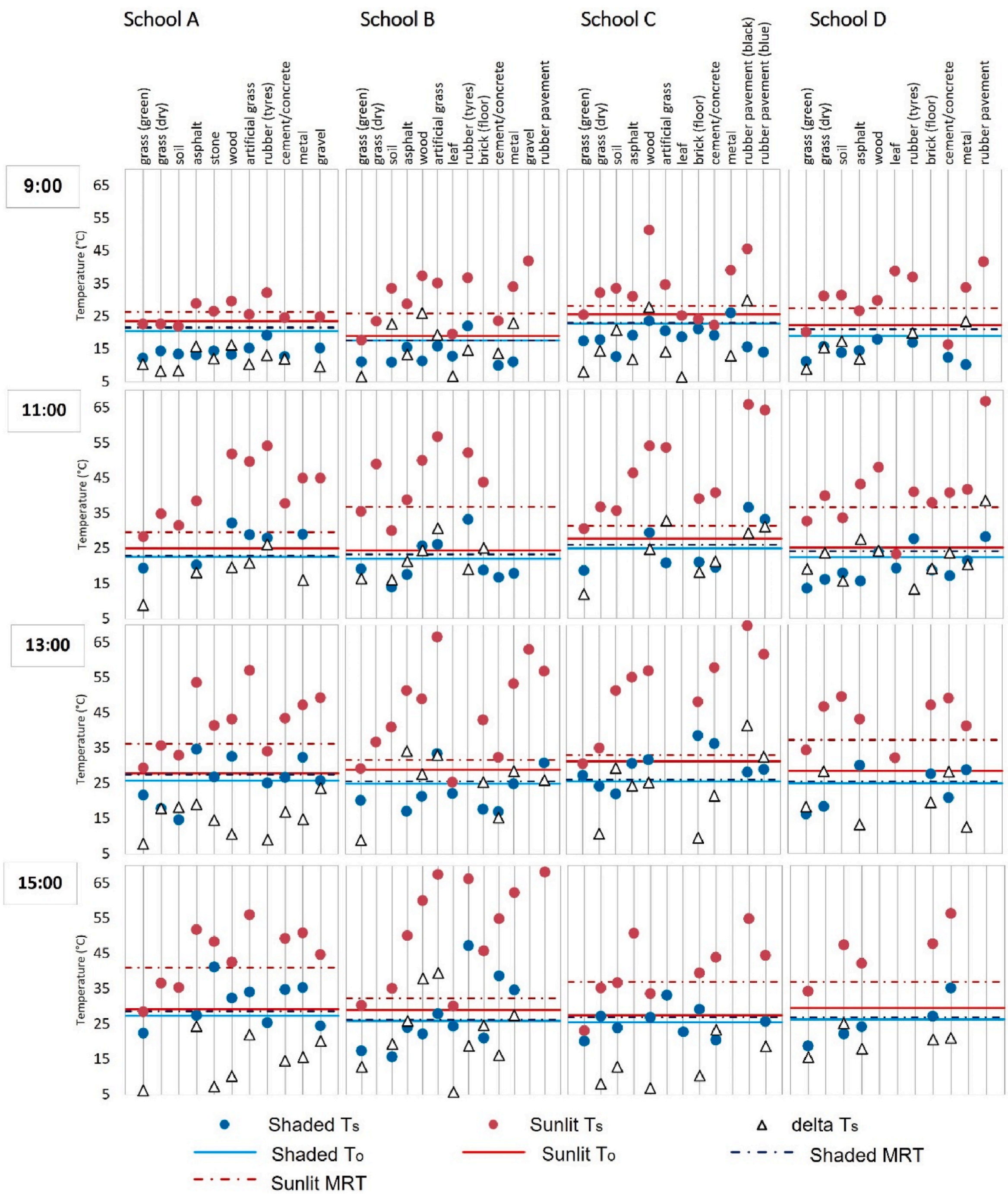


Fig. 8. Surface temperatures of different materials in outdoor areas from IR images using FLIR Thermal Studio.

maximum of 48.9 °C in sunlight. It should be noted that School D is located in the least socio-environmental challenging location based on Table 1 and has the highest amount of natural grass (75.1 %), and no artificial grass. School B on the other hand, located in the most challenging socio-environmental area compared to the other schools, has the most asphalt (46.8 %) and the least natural grass (8.9 %).

Fig. 9 shows a selection of IR images taken during the monitoring campaign. Fig. 10 indicates that natural green grass had lower average surface temperatures in both shade and sun, resulting in a smaller T_s range, while hot materials (asphalt, artificial grass and rubber pavement) had a wider range of T_s, proving that although they are very hot, they can preserve a low temperature if shaded. Other materials, e.g., concrete, had an intermediate T_s range.

Previous studies have shown that low solar reflectivity (albedo) in materials, such as asphalt, leads to a higher T_s [51]. In addition, the permeability of materials, such as natural grass, assists with evaporative cooling which reduces the T_s [52]. In contrast, lack of evaporative cooling in artificial grass contributes to its excessively high T_s as well as its low thermal conductivity, resulting in the absorption and retention of heat when exposed to sunlight.

3.2.4. *Urban Greening Factor*

UGF is calculated for each school based on the method introduced by Mayor of London [37]. Accordingly, a minimum UGF score of 0.4 is required in each site. Appendix B shows the table detailing the UGF calculation, and Fig. 11 indicates the surface coverage type and UGF for

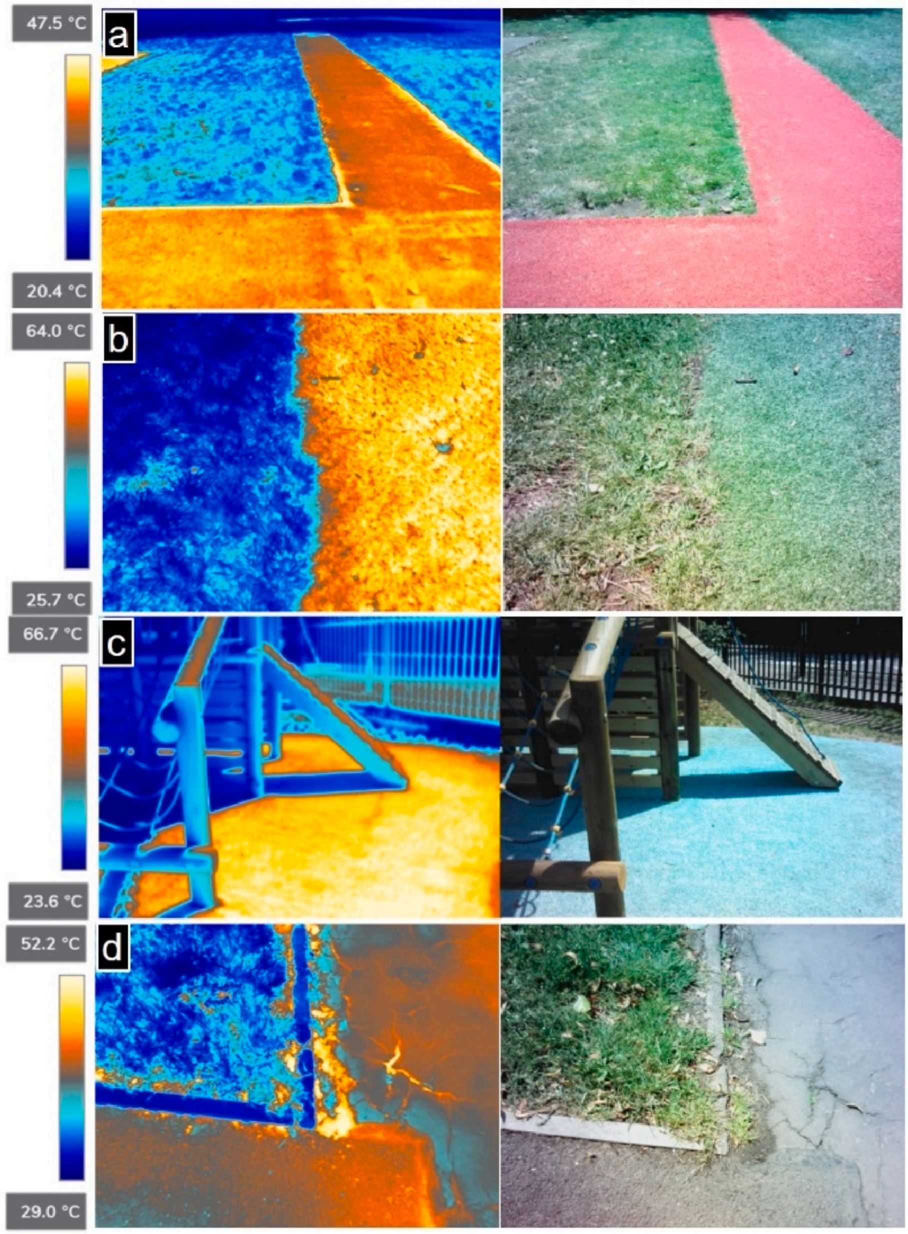


Fig. 9. A selection of IR images coupled with their digital images: a) Natural grass next to rubber pavement in School A, b) Natural grass next to artificial grass in School B, c) Rubber pavement in sunlight and shade in School C, d) Natural grass next to asphalt in School D. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

each school site, showing that school B has the lowest UGF (0.25) and school D has the highest (0.6).

Subsequently, UGF was compared to both outdoor and indoor air temperatures in each school to investigate potential relationships between UGF levels and overheating in schools. Temperature measurements were conducted on various hot sunny summer days, with variations observed between days based on weather station data. For this comparison analysis, the daily average difference between T_o and T_w (as an indicator for outdoor temperature) and the daily average difference between T_c and T_o (as an indicator of indoor temperature) were examined. In Fig. 12, a comparison of UGF with daily and after-12 sunlight and shade temperatures as well as total T_c and the warmest classroom T_c is shown. Based on these scatter plots, UGF appears to significantly influence T_c, with R^2 values ranging between 0.7 and 0.97 (Fig. 12c and d). However, Fig. 12a and b, do not show strong relationships between UGF and T_o. These findings suggest that:

- The current UGF levels in schools may serve as indicators of indoor overheating. Despite this, socio-environmental characteristics shown in Table 1 are aligned with the UGF in schools, suggesting that in challenging areas, additional factors such as average tree canopy cover in the urban area may also contribute to overheating. Therefore, it remains uncertain whether solely increasing UGF in schools in future developments would suffice to mitigate overheating or if broader changes, such as greening the entire urban area, are necessary to combat indoor overheating in schools.
- A minimum UGF score of 0.4 may not adequately mitigate overheating. In School C with UGF score of 0.5, total classrooms average temperature, and the warmest classroom average temperature could exceed those of outdoor shaded areas. One possible explanation is that UGF does not account for how greenery is spatially distributed across the site. Thus, a UGF minimum of 0.4 might be attained on a site where vegetation is primarily concentrated in one corner, rather

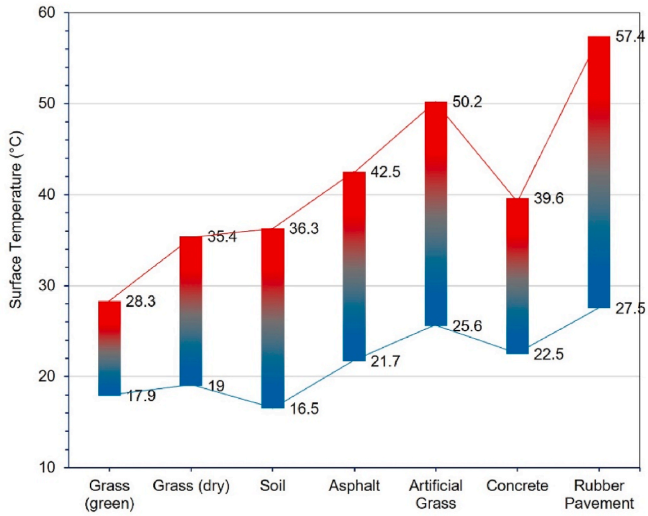


Fig. 10. Range of surface temperatures from average shaded T_s to average sunlit T_s of most commonly used materials in the four schools, obtained from thermal images.

than where it is needed most, resulting in overall high temperatures across the site.

- Outdoor thermal conditions are more complex than indoor conditions and require further investigations. Air temperature near trees, even when measured in both sunlit and shaded areas, may not accurately reflect the overall outdoor air temperature on the school site, thus showing no correlation with UGF. Various factors in the outdoor environment, including sky view factor, tree species, wind, and adjacent buildings and surfaces, influence temperature variations across the entire site. Therefore, comprehensive measurements such as aerial thermal imagery or urban simulations are necessary to explore microclimatic conditions and identify effective heat mitigation strategies.

4. Conclusion

This study investigated the indoor and outdoor (microclimatic) conditions across schools in summer 2023, providing insights into the impact of tree shade, materials and Urban Greening Factor. Field studies were carried out in four primary schools in Coventry, situated in areas with varying socio-environmental challenges related to heat risk, tree canopy cover, index of multiple deprivation, and population density. With the use of various sensors and an IR imagery camera, micrometeorological parameters and indoor air temperatures were measured.

Key findings derived from this study include:

- Western and south-western openings of classrooms were found to be significant factors contributing to the heat in certain classrooms. Other potential contributors were insufficient ventilation, lack of night cooling, thermal capacity of the building materials, and occupancy pattern.
- Tree shade could have a significant cooling effect in this climate, reducing T_a and MRT by a maximum of 6.4 °C and 22.9 °C, respectively. This cooling effect is mainly observed directly in the shade of the tree, as sensors located near trees but in the sunlight still recorded high values of T_a and MRT.
- Measured air temperatures in sunlit areas were considerably higher than the city's official air temperatures measured by the Met Office, emphasising the need for outdoor studies in schools to reveal their overheating, in addition to indoor studies.
- Schools located in more challenging socio-environmental areas had a larger coverage of hot materials, like asphalt and artificial grass, and smaller coverage of natural grass.
- T_s of artificial grass and asphalt exceeded 67 °C and 55 °C, respectively. T_s of natural grass was consistently lower than 35 °C in sunlight and 28 °C in shade. Thermal photography showed that shade could reduce the T_s of those hot materials by up to 39.6 °C for artificial grass and 34.3 °C for asphalt.
- The Urban Greening Factor (UGF), required by the Mayor of London, is explored for the first time. Strong correlation between UGF scores

Fig. 11. Site plan of each school showing surface coverage types based on UGF calculation.

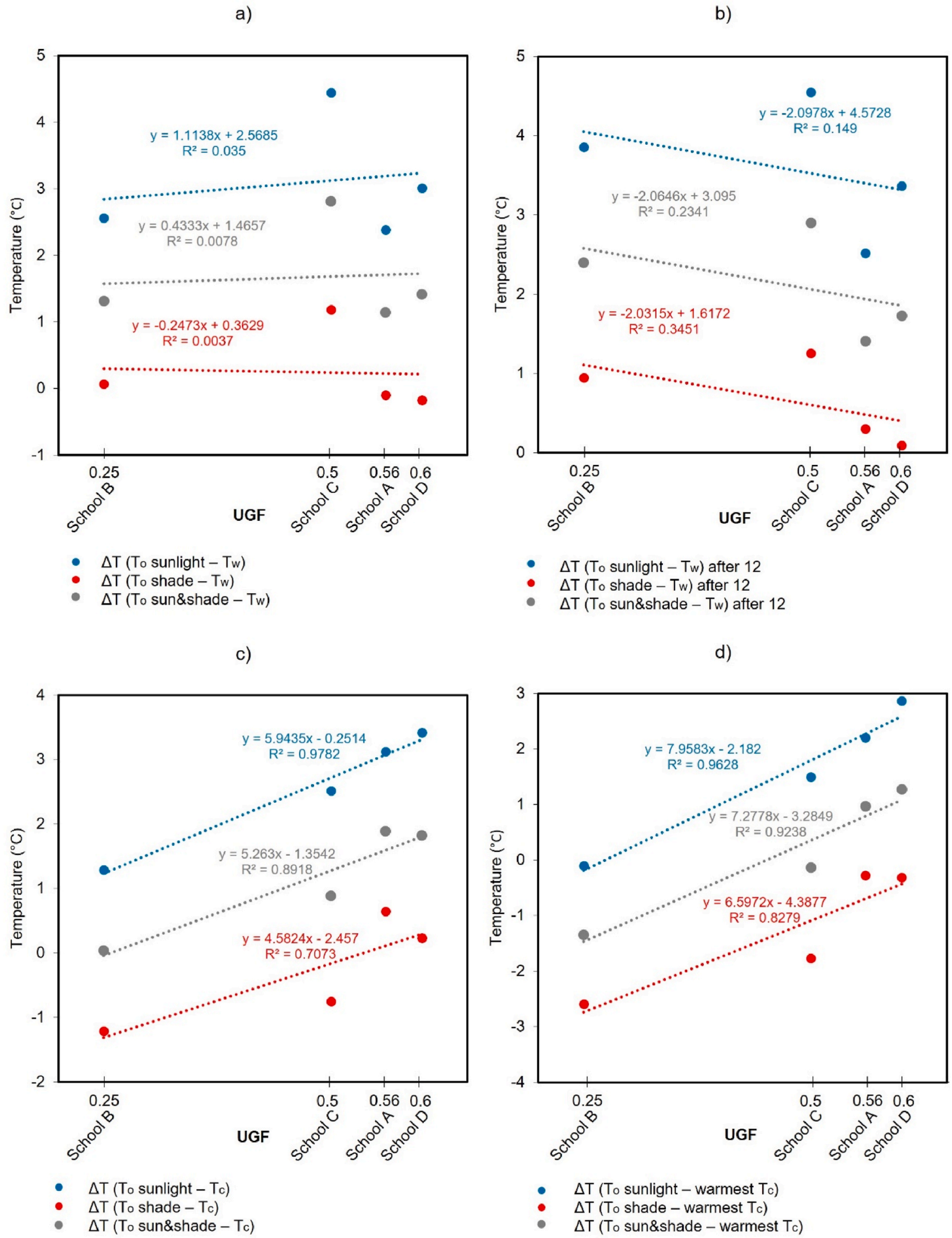


Fig. 12. Comparison of UGF with air temperature differences between a) daily average T_o and T_w, b) daily average T_o and T_w after 12:00, c) daily average T_o and T_c, and d) daily average T_o and warmest T_c.

and average classrooms temperatures in each school is observed. However, UGF does not consider the spatial distribution of greenery on site. Consequently, in the absence of tree shade, outdoor spaces may experience extreme heat. Therefore, the mandated minimum UGF score of 0.4 (which was achieved in three out of four schools of this study) proves inadequate for providing cool outdoor environments in summer.

- Microclimatic variations in schools indicate a need for further comprehensive studies, such as through several outdoor measurement points or microclimatic simulations of different perturbation scenarios to identify suitable strategies to overcome overheating specific to each school and even each playground. Some potential solutions include:

a. Optimising tree shade in school playgrounds to mitigate heat stress caused by solar radiation on sunny summer days.
b. Replacement of artificial materials, such as asphalt, artificial grass and rubber pavement, with natural/permeable materials to maximise evaporative cooling. Materials such as natural grass and grasscrete (concrete pavement combined with grass) are beneficial for both thermal conditions and wastewater management in the English climate with significant precipitation.
c. Where the use of artificial grass, asphalt and rubber pavements is unavoidable, it should be minimised and restricted to shaded spaces only.

The results are limited to the studied dates, schools, and city but can be extended to similar climates. Studying more days, schools and even locations within each school can enhance the comprehensiveness of the results.

By considering these findings and employing proposed measures, urban planners, designers, and policymakers can take substantial steps toward mitigating overheating in schools, creating thermally comfortable educational environments, and ensuring healthier and more sustainable urban environments for future generations.

CRediT authorship contribution statement

Yasaman Namazi: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Susanne Charlesworth:** Writing – review & editing, Supervision, Resources, Conceptualization. **Azadeh Montazami:** Writing – review & editing, Supervision, Resources, Conceptualization. **Mohammad Taleghani:** Writing – review & editing, Supervision, Resources.

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.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A. Floor plans of schools showing different areas including studied classrooms

Fig. A.1. Floor plan of School A. (up: ground floor, down: first floor).

Fig. A.2. Floor plan of School B.

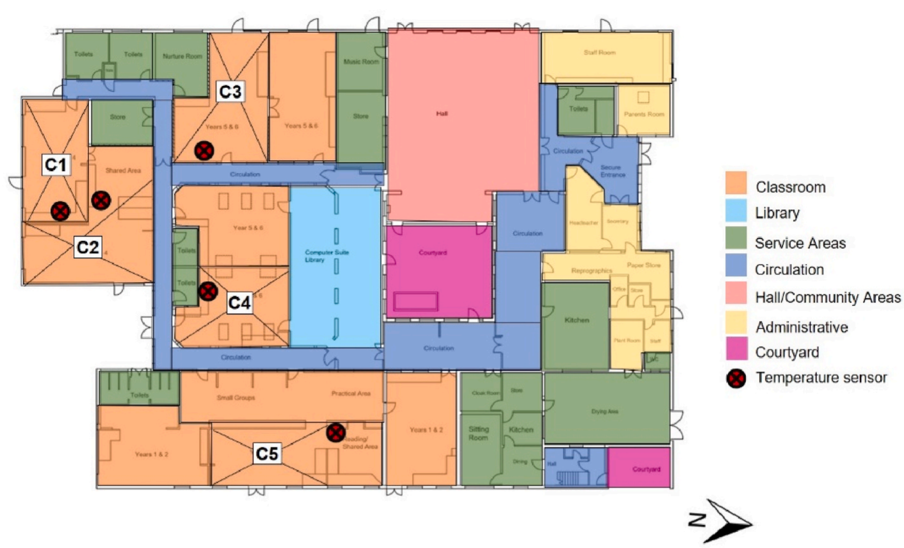

Fig. A.3. Floor plan of School C.

Fig. A.4. Floor plan of School D.

Appendix B. UGF Calculation

Table B.1
Calculation of UGF in each school after [37].

Surface Cover Type	Factor	Area in School A (m^2)	Area in School B (m^2)	Area in School C (m^2)	Area in School D (m^2)
Semi-natural vegetation (e.g. trees, woodland, species-rich grassland) maintained or established on site.	1	0	0	0	0
Wetland or open water (semi-natural; not chlorinated) maintained or established on site.	1	0	0	0	0
Intensive green roof or vegetation over structure. Substrate minimum settled depth of 150 mm.	0.8	0	0	0	0
Standard trees planted in connected tree pits with a minimum soil volume equivalent to at least two thirds of the projected canopy area of the mature tree.	0.8	5945.7	3650.5	18202.6	10851.5
Extensive green roof with substrate of minimum settled depth of 80 mm (or 60 mm beneath vegetation blanket) – meets the requirements of GRO Code 2014.	0.7	0	0	0	0
Flower-rich perennial planting.	0.7	0	0	0	0
Rain gardens and other vegetated sustainable drainage elements.	0.7	0	0	0	0
Hedges (line of mature shrubs one or two shrubs wide).	0.6	0	415.3	97.7	661.2
Standard trees planted in pits with soil volumes less than two thirds of the projected canopy area of the mature tree.	0.6	0	0	0	0
Green wall –modular system or climbers rooted in soil.	0.6	0	0	0	0
Groundcover planting.	0.5	0	123.3	0	15.6
Amenity grassland (species-poor, regularly mown lawn).	0.4	7635.4	1198.1	32353.8	22462.6
Extensive green roof of sedum mat or other lightweight systems that do not meet GRO Code 2014.	0.3	0	0	0	0
Water features (chlorinated) or unplanted detention basins.	0.2	0	0	0	0
Permeable paving.	0.1	113.5	472.8	0	0
Sealed surfaces (e.g. concrete, asphalt, waterproofing, stone).	0	3920.3	8530.7	11434.3	4462.9
Total contribution		7822.1	3757.8	27562.2	18070.8
Total site area (m^2)		14021.5	14795.0	54173.3	29905.3
Urban Greening Factor		**0.56**	**0.25**	**0.5**	**0.6**

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