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Global investigation of pedestrian-level cooling and energy-saving potentials of green and cool roofs in 43 megacities

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A R T I C L E I N F O

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A B S T R A C T

Green roofs and cool roofs are emerging as two potential solutions to combat the negative impacts of urban warming in the context of climate change. However, the existing body of research has not clearly established the connection between the local built environment and the effectiveness of these solutions. Moreover, a lack of standardized methodologies for integrating micro-scale climatic data has impeded the precision of modeling endeavors. In light of these knowledge gaps, an extensive study was conducted across 43 megacities to evaluate the impact of green and cool roofs on reducing urban temperatures and building energy consumption. A novel integrated approach, combining a micro-level computational fluid dynamics (CFD) model and a building energy simulation method, was used. The results reveal that both cool and green roofs moderately cool pedestrian areas, with green roofs slightly outperforming cool roofs, reducing temperatures by an average of 0.10 °C. Delhi reported the highest cooling effect from green roofs at 0.80 °C, while Beijing recorded the top cooling performance from cool roofs at 0.23 °C. Cool roofs showed significant cooling energy savings, from 5.4 to 63.8 kWh/m^2/year, particularly in sun-drenched cities like Bangalore, Dhaka, and Ahmedabad, albeit their inability to save heating energy in higher latitudes. Conversely, green roofs provided consistent energy savings, typically from 1.1 to 7.3 kWh/m^2/year, with Dhaka exhibiting the highest energy-saving amount. Additionally, the study also identified that urban morphology influences the effectiveness of these strategies. The cooling effect becomes less noticeable with increasing building height, and open layouts are more conducive to roof-level strategies. The findings from this study will help optimize the implementation of these strategies in different climates and built environments, contributing to efforts to mitigate global climate change and enhance urban livability.

1. Introduction

Urbanization has become a worldwide trend, with an expected rise to over two-thirds of the global population living in cities by 2050, as predicted by the United Nations [1]. Urban and industrial development has led to significant environmental and health challenges [2]. Some of these challenges include the urban heat island (UHI) effect [3,4], decreased air and water quality [5], increased energy demands [6,7], declined vegetation production and carbon sequestration [8], and detrimental effects on human health [9]. The rapid urban sprawl has increased the proportion of roof surfaces in cities, which now account for approximately 20 % to 25 % of the total urban surface area [10–12]. Roofs significantly contribute to heat gain and loss, since they are directly exposed to solar radiation [13]. As urbanization progresses and buildings occupy a greater fraction of the urban surface, less land is dedicated to green spaces and mitigation infrastructures. In this context, roofs offer a promising space to implement mitigation solutions. Roof-level strategies for mitigation not only provide a cost-effective approach but also significant energy-saving potential for buildings, making them a valuable means to enhance urban environmental sustainability.

Rooftops present a variety of opportunities to lessen heat absorption and reduce energy use, with green roofs and cool roofs being two widely adopted strategies [7,14,15]. Cool roofs utilize high-albedo reflective

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surfaces to minimize heat absorption, while green roofs use plants to provide insulation and reduce heat levels. Numerous research studies have demonstrated their effectiveness in reducing roof surface temperatures [15], leading to a decrease in sensible heat dispersion into the atmosphere and a reduction in energy use [16]. A recent review paper investigated the typical impact of cool and green roofs on building energy conservation, considering varying designs, materials, and constructions [10]. The literature survey results revealed that the impact varies between 15 % and 35.7 % across different climatic zones, with average reductions in roof surface temperature ranging from 1.4 °C to 4.7 °C [10,16]. For green roof equipped buildings, nearly 2.2 % to 16.7 % less energy is consumed compared to buildings with conventional roofs. Additionally, the use of green roofs can lead to surface temperature reductions of up to 4 °C in winter and 12 °C in summer [10]. However, a greater concern in the urban environment is the temperature at the pedestrian level. For instance, Rosenzweig et al. [17] found that average daily temperature reduction by cool roofs ranged from 0.18 K to 0.36 K in different parts of New York City, with peak air temperature reduction of 0.31 K to 0.62 K at 3 PM, depending on the site characteristics. A global study on the cooling potential of green roofs found that dry climate has the highest median cooling effect, with green roofs reducing temperatures by up to 3 K [18]. Specifically, in New York City, green roofs resulted in a peak air temperature reduction of 0.37 to 0.86 K, with daily average temperatures decreasing by approximately 0.3 to 0.55 K [17]. Research in Taipei, Taiwan, demonstrated that green roofs led to an average ambient air temperature decrease of 0.26 K, with a maximum temperature decrease of approximately 1.6 K [19]. A study conducted in the heatwave scenario of the Greater Beijing Region of China demonstrated that the installation of green roofs led to a maximum reduction of 2.5 K in near-surface air temperature [20].

Previous research have also suggested a significant correlation between the cooling and energy saving performance of green and cool roofs and the structure of urban areas [21]. The idealized bi-dimensional experiments carried out by Zonato et al. [22] revealed that during summer months, there is a linear relationship between the cooling effect of roof materials on air temperature and the building coverage ratio. Additionally, they found that this cooling effect was more pronounced for shorter buildings, demonstrating a nonlinear reduction in impact as building height increased. However, the influence of urban morphology on the mitigation effect of roofs can be affected by the geographic settings and local climate. For example, research conducted in Chicago revealed that the use of cool roofs and green roofs can reduce cooling energy consumption by 16.6 % and 14.0 % respectively [23]. Another study conducted in Europe found that the energy required for space cooling varied between 1 % to 11 % in Tenerife, 0 % to 11 % in Sevilla, and 2 % to 8 % in Rome [24]. In Hong Kong, it was found that the potential decrease in ambient temperature at street level, brought about by roof-level strategies in areas with high-rise, high-density buildings, was virtually negligible [25]. Existing studies have discussed the impact of urban morphology on the cooling and energy-saving performance of roof-level strategies, but there is limited understanding of the specific relationships and factors involved. Additionally, there is a lack of efficient methods for quantifying these effects at a city-scale. A recent study published in *Nature Cities* addressed this gap by simulating over three thousand buildings in the Al Masiaf precinct of Riyadh using the CityBES simulation platform [26]. However, applying such detailed methods to even larger scales, such as the global level, becomes challenging. Therefore, delving deeper into the connection between built environments and the global potential of cool and green roofs to alleviate heat is essential. This exploration should emphasize devising methods that are both highly efficient and precise.

Meteorological conditions have a substantial impact on the energy usage of HVAC (Heating, Ventilation, and Air Conditioning) systems [27]. As per various studies, a decrease of 1 °C in outdoor air temperature could result in a 5 % reduction in energy consumption within buildings [28,29]. It is thus crucial to accurately model the dynamic interplay between buildings and their surrounding environment to enhance energy efficiency and reduce energy consumption. However, current weather inputs used in building energy simulations have certain shortcomings. Typical Meteorological Year (TMY) weather files, which are widely used to represent historical and current weather conditions in building energy simulation tools [30], are derived from long-term historical data gathered from a single weather station. The utilization of TMY fails to capture the weather conditions of other locations and may not adequately represent the urban effects on temperature [31]. Hence, there is a growing need for more precise techniques that account for the meteorological feedback on building energy consumption.

Consequently, in view of the existing research gaps, this study aims to develop new techniques to enhance the accuracy of modeling building energy use. To address the primary limitation in the model domain scale, local climate zone (LCZ) scheme was introduced as a climate-based classification scheme for urban temperature studies [32]. The LCZ is an urban form and land cover/land use classification system based on their spatiotemporal climatic characteristics [33]. Utilizing LCZ allows the scale of simulation to be enhanced from micro-level to city-level. Additionally, the study introduces a novel approach that couples the micro-climatic model with the building energy simulation to correct inaccuracies in weather data. By replacing the TMY weather information with localized climatic data, the model accuracy can be greatly enhanced. The study provides a global overview of the effectiveness of common roof-level strategies in cooling and energy saving across a variety of climates and built environments. The findings offer potential solutions to global climate change and can contribute to enhancing urban livability.

2. Material and methods

2.1. Study area

To explore the impact of cool and green roofs on the urban thermal environment and energy conservation of buildings, this study conducted a global assessment of all megacities, defined as cities with populations exceeding 10 million. In 2018, there are 33 megacities in total, and it is anticipated that an additional 10 cities will achieve megacity status between 2018 and 2030 [1]. The simulations in this study were conducted among 43 megacities. Fig. 1 shows the locations of these megacities with their projected populations by the year 2030.

As shown in Fig. 1, most of the megacities are located in Asia. China alone has eight megacities, while India also has seven megacities. The study is expected to yield important insights into the efficacy of cool and green roofs in reducing heat and promoting energy savings in various urban contexts worldwide. By encompassing a diverse range of megacities, the research findings can have a far-reaching impact on urban policies, planning strategies, and investments, within and beyond the megacities.

2.2. Data collection

The study utilized a global database of LCZ with 100 m-resolution developed by Demuzere et al. [34] to characterize the urban environment. Hourly weather data for each of the 43 megacities was obtained from TMY datasets, which provide a one-year profile of solar radiation and meteorological conditions derived from at least ten years of historical observations [35]. The TMY data used in the analysis spanned the period from 2007 to 2021, ensuring the representation of current climatic conditions in these urban centers [36]. For most cities, TMY files were downloaded from the EnergyPlus weather website. For cities where TMY files were unavailable from the EnergyPlus weather website, this information was derived from hourly weather data through 2023 in the ISD (US NOAA's Integrated Surface Database) using the TMY/ISO 15927–4:2005 methodologies. More details about the data collection and processing can be found at https://climate.onebuilding.org/.

Population (unit: k persons):

City	Population	City	Population	City	Population	City	Population
East Asia and Pacific:		Nanjing	11011	Sao Paulo	23824	Karachi	20432
Tokyo	36574	Chengdu	10728	New York	19958	Kolkata	17584
Shanghai	32869	Seoul	10163	Buenos Aires	16438	Lahore	16883
Beijing	24282	**Europe and Central Asia, Middle East and North Africa:**		Rio de Janeiro	14408	Bangalore	16227
Chongqing	19649			Los Angeles	13209	Chennai	13814
Osaka	18658	Istanbul	17124	Bogota	12343	Hyderabad	12714
Manila	16841	Moscow	12796	Lima	12266	Ahmadabad	10148
Guangzhou	16024	Paris	11710	**South Asia:**		**Sub-Saharan Africa:**	
Tianjin	15745	Tehran	10240	Delhi	38939	Kinshasa	21914
Shenzhen	14537	London	10228	Dhaka	28076	Lagos	20600
Jakarta	12687	**North America:**		Cairo	25517	Luanda	12129
Bangkok	12101	Mexico City	24111	Mumbai	24572	Dar es Salaam	10789
Ho Chi Minh City	11054						

Fig. 1. Study area overview – locations and projected populations of 43 megacities by 2030.

2.3. Design of scenarios

The study evaluated three roof design scenarios: a baseline case with a roof albedo of 0.2, and two optimized scenarios where all buildings were assumed to have either cool or green roofs. Supplementary Note 1 provides more additional details on the various roof system parameters and designs employed in this research. In the scenario design, the LCZ concept has been incorporated. LCZs are defined as areas with consistent surface cover, structures, materials, and human activities [32]. LCZs have been widely utilized in urban heat-related studies [34,37,38]. Urban LCZs were designed according to the LCZ definitions proposed by Stewart and Oke [32]. More detailed information about the properties of employed urban LCZs can be found in Supplementary Note 2.

2.4. Modeling approach

An integrated modeling approach was developed to assess the cooling effects of cool and green roofs at the pedestrian level and their impact on reducing building energy. This approach combined a Computational Fluid Dynamics (CFD) model at micro-scale – ENVI-met (version 5.1.1), with EnergyPlus (version 9.6), a tool used for simulating building energy. By incorporating ambient micro-scale climatic conditions, this integrated approach enhances the accuracy of the modeling. The cooling potentials of green and cool roofs among 43 megacities were firstly modeled using ENVI-met. The ENVI-met model consists of three parts: a one-dimensional boundary sub-model which calculates the inflow profiles and top boundary, a three-dimensional atmospheric sub-model which is the main model, and a 3D/1D soil sub-model [39,40]. ENVI-met applies Reynolds-Averaged Navier-Stokes (RANS) equations to address air movement and thermal dynamics in city settings [41,42]. It employs the Yamada and Mellor E-ε model for turbulence [43]. This model's capability to model interactions between surfaces, vegetation, and the atmosphere in intricate urban layouts has led to its widespread use in urban atmospheric simulations. The model inputs require the climatic conditions and details of the built environments. The boundary conditions for the ENVI-met model were sourced from the EnergyPlus Weather (EPW) files for all the cities under study. The partial validation of the ENVI-met model in simulating meteorological parameters can be found in Supplementary Note 3.

The built environment, comprising buildings, vegetation, and surfaces within the modeled domain, was designed in accordance with the specifications of the LCZ system. The details of the simulation can be found in Table 1. Upon conducting LCZ-based simulations for every city, the overall cooling potential was calculated by multiplying the cooling

Table 1
The ENVI-met simulation details.

Domain size and grid resolution	
Size of computational domain (dx, dy, dz)	500 m × 500 m × 500 m
Grid resolution (dx, dy, dz)	5 m × 5 m × 5 m
Initial meteorological conditions	
Air temperature (°C)	As specified in TMY of each city
Relative humidity (%)	
Wind speed (m/s)	
Wind direction (°)	
Roughness length at the site (m)	0.1

capacities of each LCZ by their respective coverage percentages, as indicated in the global LCZ map [34]. This allowed for an estimation of the city-wide cooling potentials that benefiting from implementing cool roofs or green roofs.

The EnergyPlus tool [44] was utilized to evaluate the potential energy savings achieved with the use of green and cool roofs. This software enables users to model buildings with integrated mechanical and electrical systems, thermal controls, and run simulations based on detailed building specifications [45]. Major meteorological outputs from the ENVI-met (i.e., micro-scale CFD model), such as hourly air temperature and relative humidity, were integrated into EnergyPlus. This integration fine-tuned the Typical Meteorological Year (TMY) data by incorporating micro-scale parameters, yielding more precise estimates of building energy use compared to conventional methods that rely on regional EPW files. For the categories of building energy end-users, it should be noted that in addition to HVAC energy consumption, major end-use categories include interior lighting, receptacle equipment, and miscellaneous uses [46,47]. In this study, a typical design of 20 W/m^2 per zone floor area was adopted for interior lighting, while a design of 30 W/m^2 per zone floor area was used for equipment. Since the energy use of other categories, except for HVAC, will not be affected by microclimate variations after implementing roof-level strategies, only HVAC energy reductions were compared under different scenarios in this study.

By comparing the simulation results of cool roof and green roof scenarios against baseline scenarios, we can assess the effectiveness of these roofs in cooling pedestrian environments and lowering building energy consumption across various ambient conditions. Through validation, the novel approach outperformed the conventional approach in predicting both the annual and daily patterns of building energy consumptions. A detailed validation process and its results are available in Supplementary Note 4.

3. Results

3.1. Cooling and energy-saving performance among 43 megacities

The LCZ-based simulation was run for each urban layout. A total of ten urban layouts were designed in accordance with the geometric and surface cover properties of ten urban LCZs. These designs were created using the standard LCZ scheme proposed by Stewart and Oke in 2012 [32]. Fig. 2 displays the modeling construction of each urban layout.

By evaluating and comparing the cooling and energy-saving performance by cool roofs and green roofs in 43 megacities, it is possible to identify the patterns, trends, and best practices that contribute to significant cooling and energy-saving outcomes. Fig. 3 presents the comparison results, according to the locations of megacities in major world regions. Supplementary Note 5 provides the full list of the model outputs among all 43 megacities.

In terms of pedestrian-level cooling effects, green roofs demonstrate superior performance compared to cool roofs (see Fig. 3(a and b)). The highest reduction in pedestrian-level temperature by cool roofs was observed in Beijing at 0.23 °C, followed by a cooling effect of 0.11 °C in Guangzhou. However, in all other studied cities, the temperature reduction values at the pedestrian level by cool roofs were lower than 0.1 °C. Green roofs can provide a cooling effect of up to 0.80 °C at the city scale. Delhi showed the highest temperature reduction value, followed closely by Kolkata. Most studied cities worldwide showed significant cooling performance by green roofs, with 37 out of 43 cities experiencing pedestrian-level temperature reductions higher than 0.1 °C. In region E – Sub-Saharan Africa, the average cooling effects by green roofs were the highest at 0.56 °C, followed by regions D (South Asia) and A (East Asia and Pacific) at higher than 0.48 °C.

In terms of building energy-saving effects, cool roofs significantly contribute to energy savings in buildings, particularly during warm seasons, with savings estimated between 5.4 to 63.8 kWh/m^2/year (Fig. 3(c)). Notably, Bangalore demonstrates the highest energy-saving efficiency, with an average of 63.8 kWh/m^2/year, followed by Dhaka with a mean value of 48.9 kWh/m^2/year. Especially, in regions D and E, the average energy-saving amounts were both higher than 28 kWh/m^2/year, while in regions C (North America), the average value was also relatively significant at 26.9 kWh/m^2/year. In contrast, green roofs yield energy savings ranging from 1.1 to 7.3 kWh/m^2/year. Dhaka stands out with the highest energy-saving average for green roofs at kWh/m^2/year, as indicated in Fig. 3(d). Other cities like Moscow, Ahmedabad, Seoul, and Manila also demonstrate considerable energy savings, averaging over 5 kWh/m^2/year. However, the difference between regions is not as pronounced as with cool roofs, with average values ranging from 3.3 to 4.3 kWh/m^2/year.

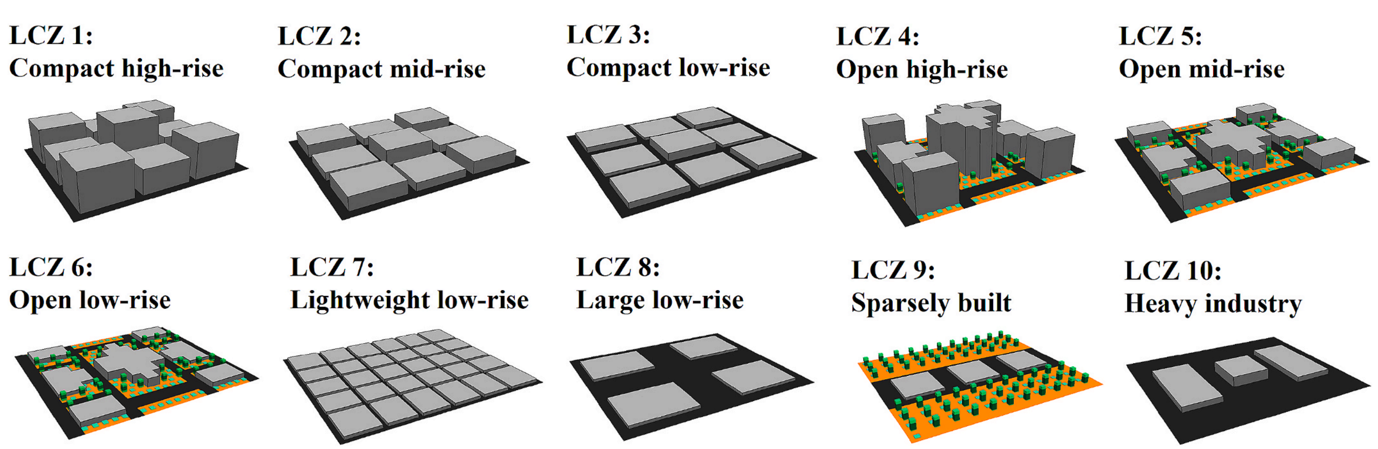


Fig. 2. Model construction in 10 urban layouts according to the concept of LCZ.

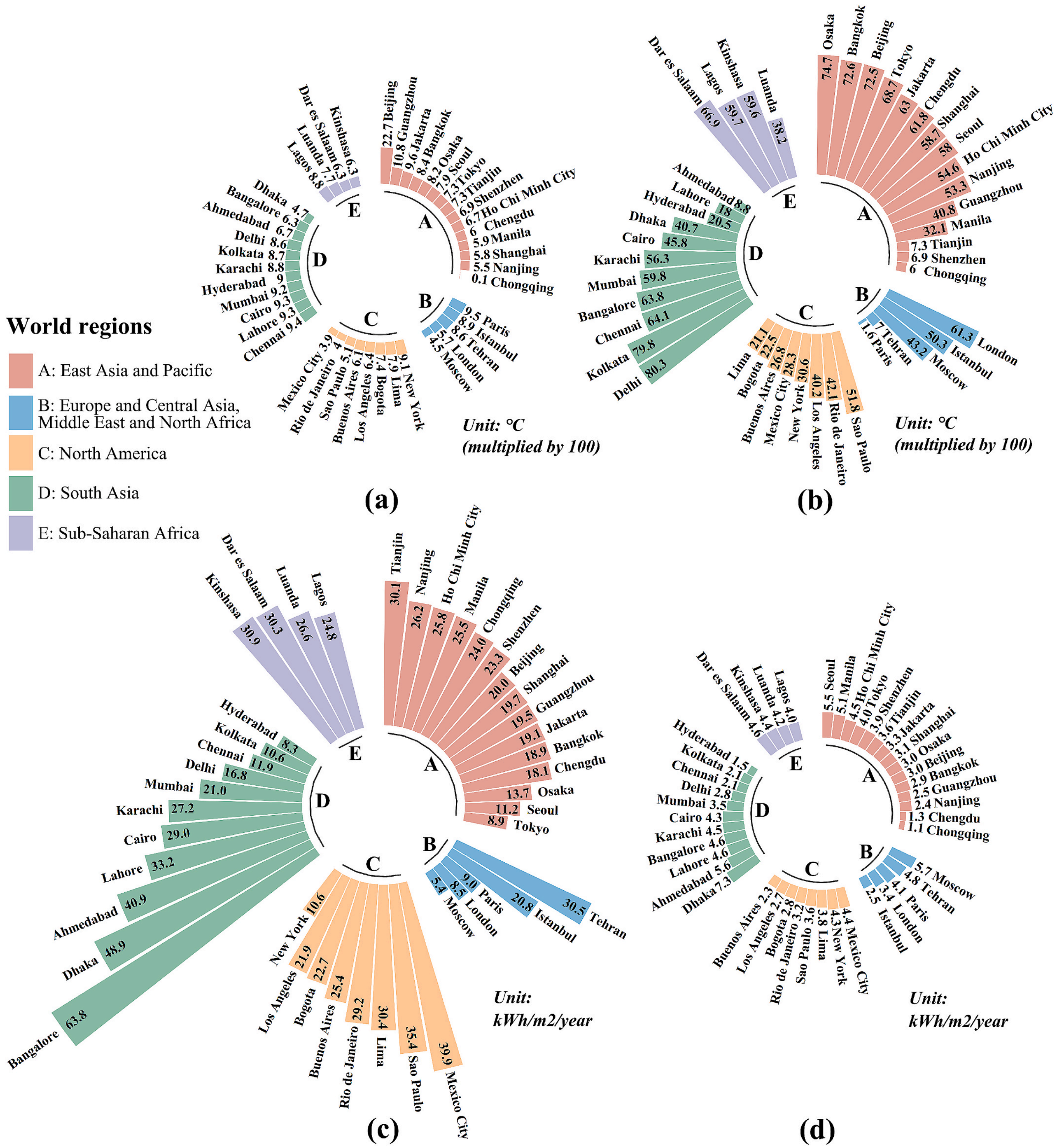
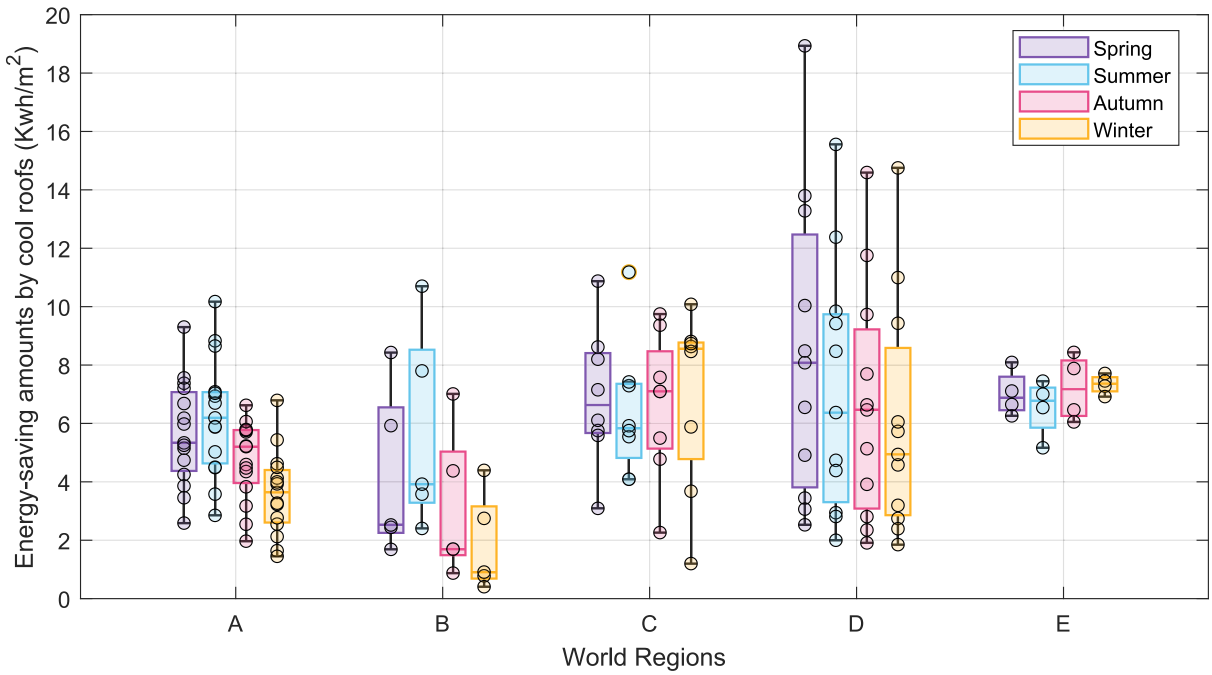


Fig. 3. Global patterns of cooling and energy-saving performance: (a) cool roof cooling performance; (b) green roof cooling performance; (c) cool roof energy-saving performance; (d) green roof energy-saving performance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

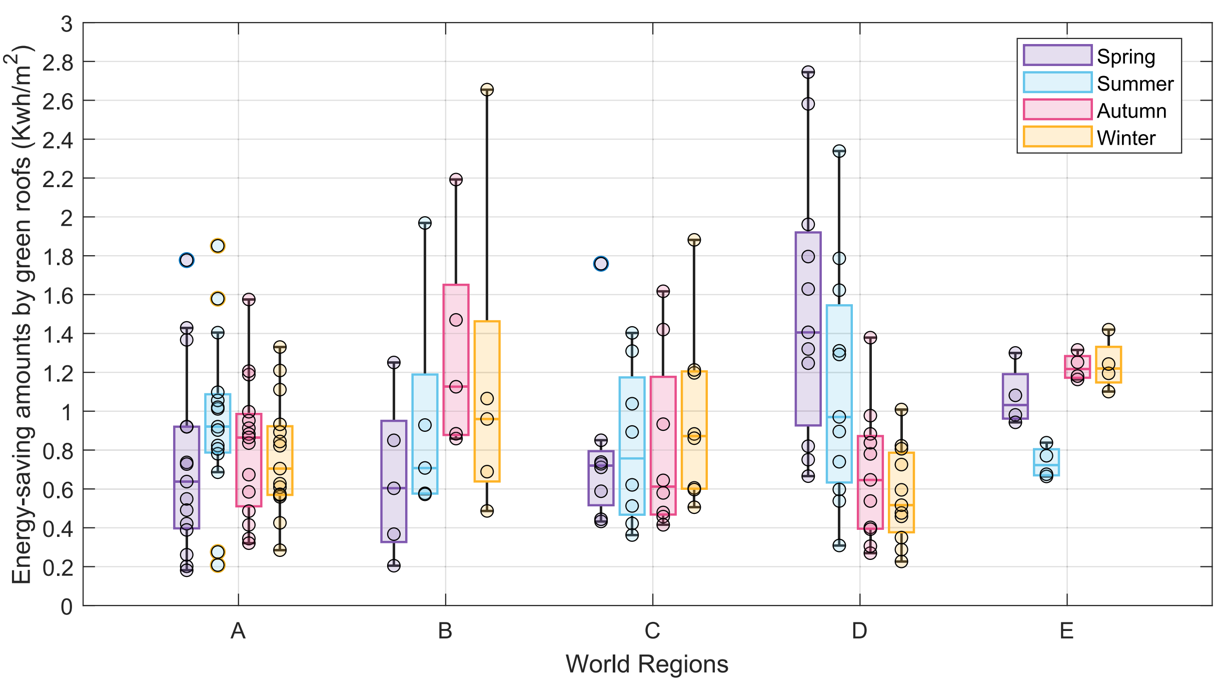
3.2. Seasonal variations of energy-saving effects by cool roofs and green roofs

In this section, the seasonal variations of the energy-saving performance of cool roofs and green roofs and cool roofs are analyzed, as classified by world regions (i.e., A, B, C, D, and E). Fig. 4(a) and (b) illustrate the energy-saving performance patterns of cool roofs and green roofs across the seasons, respectively.

Fig. 4 illustrates that cool roofs and green roofs exhibit different seasonal patterns in building energy reduction. Generally, the energy-saving amounts from cool roofs show a consistent seasonal pattern across various world regions. Significant energy reductions were observed from March to August (spring and summer for the Northern Hemisphere) in regions A-D, and from December to February (summer



(a)



(b)

Fig. 4. Seasonal variations of the energy-saving performance of cool and green roofs: (a) cool roof energy saving effect; (b) green roof energy saving effect. *Note: in the figure, the temperate zones follow the Northern Hemisphere's seasonal divisions: spring begins on 1 March, summer on 1 June, autumn on 1 September, and winter on 1 December.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for the Southern Hemisphere) in region E. Notably, the highest average energy-saving value of 8.46 kWh/m^2 was recorded during the spring in region D (South Asia), followed by the warm seasons in region E (Sub-Saharan Africa). Conversely, the lowest energy-saving amount, averaging 1.85 kWh/m^2, was observed during the winter in region B (Europe and Central Asia, Middle East and North Africa).

In contrast, the seasonal pattern in energy-saving performance by green roofs across different regions is not that consistent. Relatively significant energy-saving effects, with averages higher than 1.2 kWh/m^2, were observed during the warm seasons in regions D and E, as well as during the relatively cold seasons in region B. The results indicate that the energy-saving performance of both cool and green roofs varies with the seasons: cool roofs are more effective at reflecting sunlight and reducing heat absorption during hot seasons, whereas green roofs provide additional insulation, making them effective in preventing heat loss during cold seasons.

3.3. Cooling effects of cool roofs and green roofs at the pedestrian level

In general, green roofs have a greater temperature reduction effect at the pedestrian level compared to cool roofs (see Fig. 5). Cool roofs have a negligible impact on cooling the pedestrian-level ambient environment among the 43 megacities, with an average of 0.02 °C across different urban morphologies. In contrast, green roofs exhibit a cooling effect ranging from 0 to 0.25 °C, with an average of 0.10 °C. However, their performance is heavily influenced by the characteristics of urban morphology.

As illustrated in Fig. 5(a), the cooling effectiveness of cool roofs diminishes as building height increases. Notably, the lightweight low-rise layout demonstrates the most effective cooling effect, while the open high-rise layout shows the least cooling effect. However, as Fig. 5(b) indicated, the cooling performance of green roofs does not follow the same pattern with urban morphology as the cool-roof cooling pattern. No clear trend was observed with increasing building height due to the complex mechanisms involved, where building layout and environmental features collectively influence the cooling performance of the green-roof system. The open mid-rise layout exhibits the best cooling performance, followed by the open low-rise layout. Fig. 5(c and d) illustrates the spatial patterns of cooling performance by both cool roofs and green roofs. The significant cooling effect by cool roofs primarily clusters in South Asia (Fig. 5(c)). Most South and East Asian cities, such as Guangzhou, Jakarta, Chennai, Lahore, Mumbai, and Hyderabad, exhibited favourable cooling performance with temperature reductions exceeding 0.10 °C. Relatively high temperature reduction values by cool roofs were also observed in Paris and New York. Green roofs showed a more diverse spatial pattern of significant cooling effects at the pedestrian level (Fig. 5(d)). For instance, in East Asian cities with middle latitudes, such as Osaka and Beijing, substantial cooling effects by green roofs were observed with reductions exceeding 0.70 °C. In high latitude cities like London, a relatively high temperature reduction value of 0.61 °C was observed. In Dar es Salaam located in Africa, a notable reduction of 0.67 °C was identified.

3.4. Building energy-reduction effects of cool roofs and green roofs

Both cool and green roofs offer significant energy-saving benefits for buildings (see Fig. 6). Cool roofs demonstrate notable cooling energy savings, ranging from 1.04 to 10.04 kWh/m^2/year, with an average of 4.66 kWh/m^2/year across diverse urban contexts. In contrast, the range of building cooling energy savings by green roofs falls between 0.23 and 1.82 kWh/m^2/year, with an average of 0.87 kWh/m^2/year. While green roofs may have a lower cooling energy-saving potential compared to cool roofs, they consistently provide effective energy savings, even during colder seasons. Green roofs demonstrate an average heating energy-saving value of 0.02 kWh/m^2/year. However, cool roofs do not contribute to reducing heating energy consumption, and their

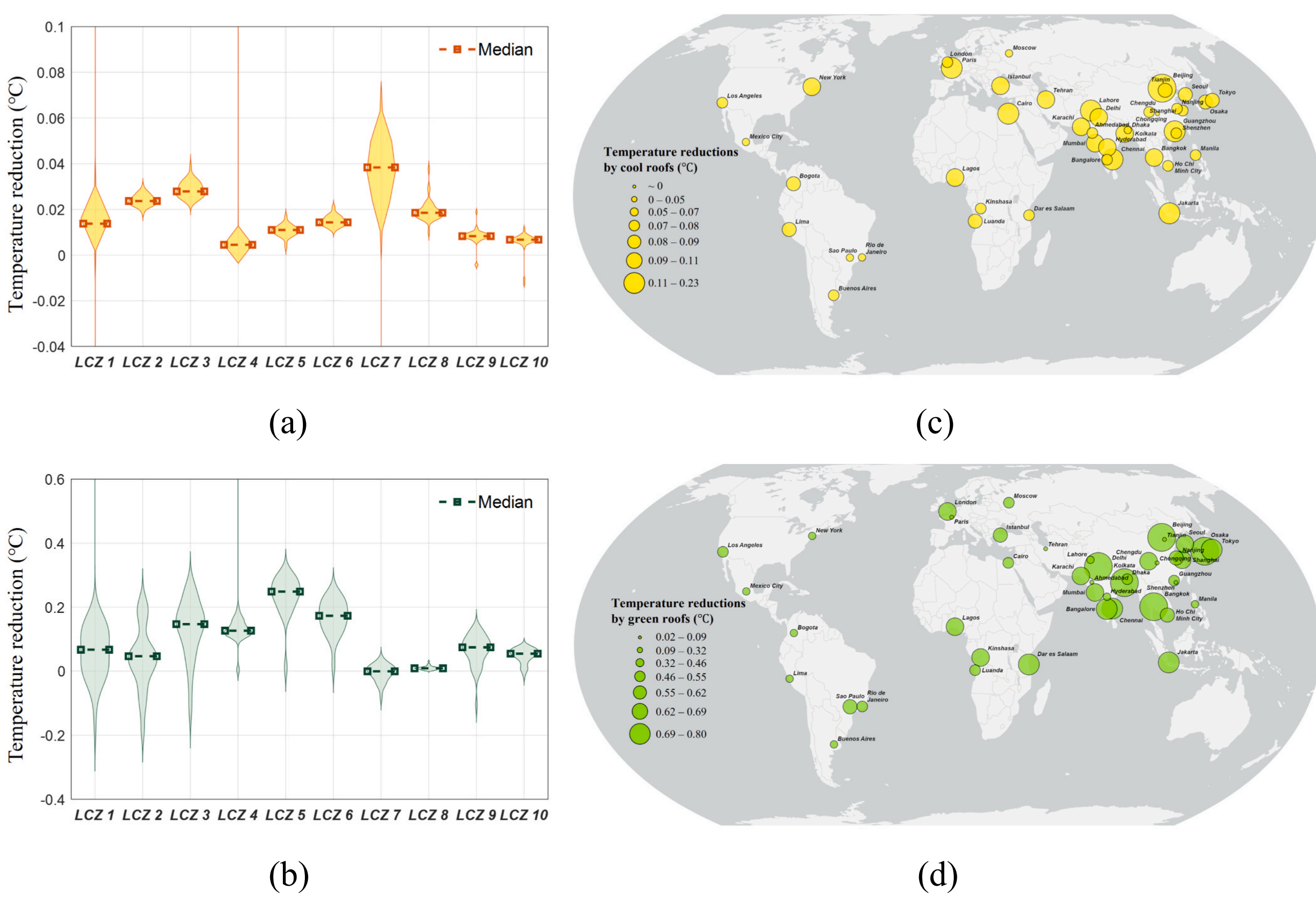


Fig. 5. Pedestrian-level cooling performance by cool and green roofs: (a) cool roof cooling performance in ten urban layouts; (b) green roof cooling performance in ten urban layouts; (c) spatial patterns of cooling performance by cool roofs in 43 megacities; (d) spatial patterns of cooling performance by green roofs in 43 megacities. *Note. In (a) and (b), LCZ 1: compact high-rise layout; LCZ 2: compact mid-rise layout; LCZ 3: compact low-rise layout; LCZ 4: open high-rise layout; LCZ 5: open mid-rise layout; LCZ 6: open low-rise layout; LCZ 7: lightweight low-rise layout; LCZ8: large low-rise layout; LCZ 9: sparely built layout; LCZ 10: heavy industry layout.* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

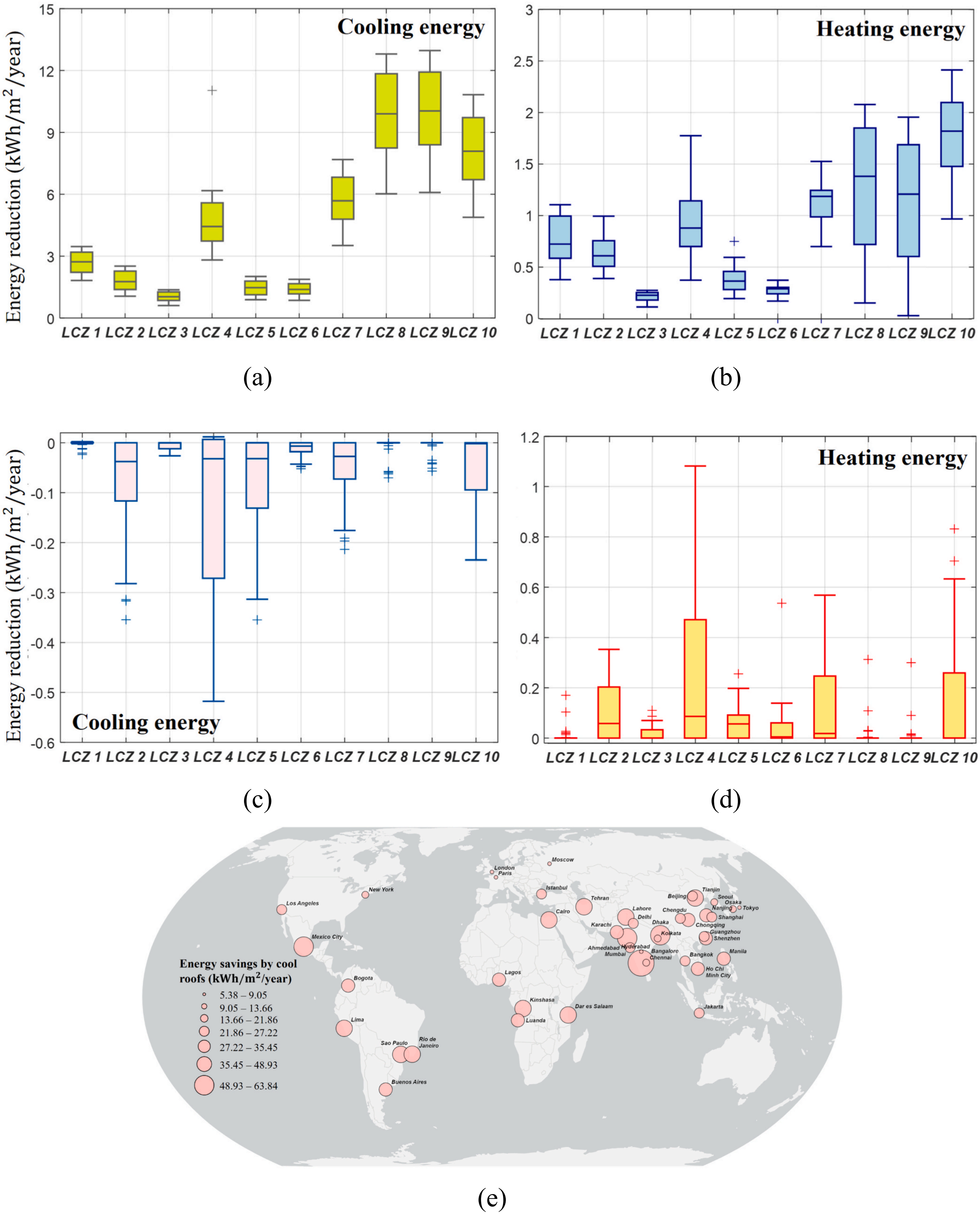
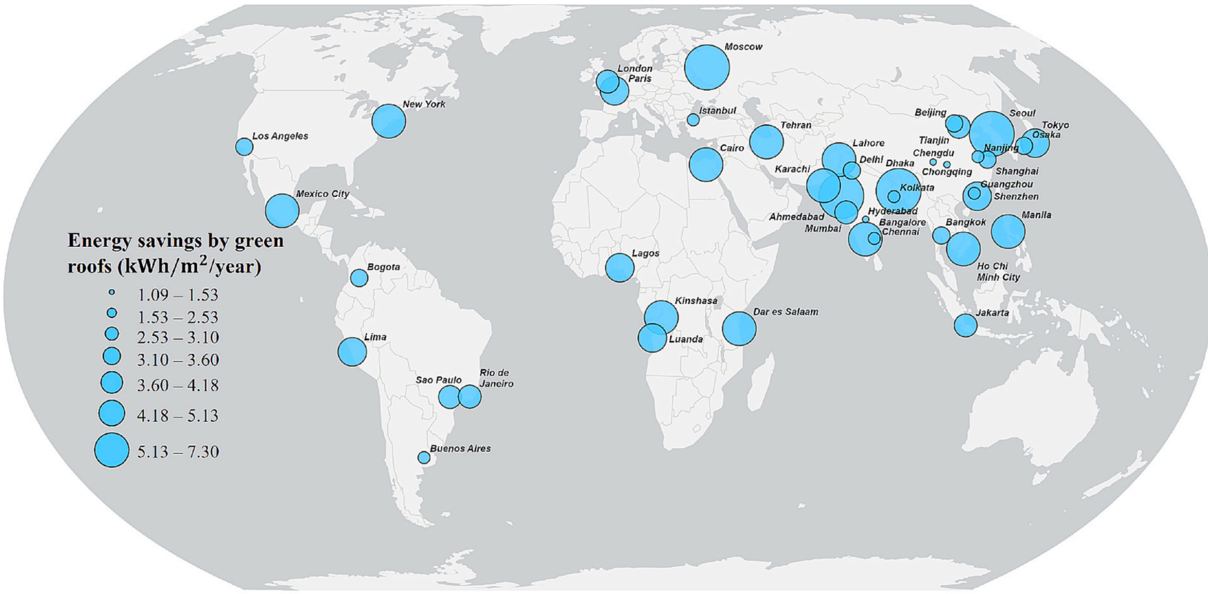


Fig. 6. Building energy-reduction effects by cool and green roofs: (a) cool roof cooling energy savings in ten urban layouts; (b) cool roof heating energy savings in ten urban layouts; (c) green roof cooling energy savings in ten urban layouts; and (d) green roof heating energy savings in ten urban layouts; (e) spatial patterns of energy savings by cool roofs in 43 megacities; (f) spatial patterns of energy savings by green roofs in 43 megacities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(f)

Fig. 6. (*continued*).

installation actually leads to an average increase of heating energy consumption at 0.01 kWh/m^2/year across all urban layouts.

Cool roofs exhibit the most significant cooling energy reduction in sparsely built layouts, followed by large low-rise layouts. Relatively high cooling energy reduction amounts were also observed in other relatively open urban layouts such as heavy industry and open high-rise layouts. Similarly, green roofs demonstrate the highest energy-saving potential in the heavy industry layout, followed by large low-rise and sparsely built layouts. The relationship between building height and cooling energy savings by both roof types in different urban layouts is positive, as evident in Fig. 6(a) and (c). Regarding the reduction of heating energy by roofs (Fig. 6(b) and (d)), no consistent patterns were found between urban layouts and energy-saving performance. Fig. 6(e and f) presents the spatial patterns of the energy-saving effects by cool roofs and green roofs. As shown in Fig. 6(e), regions with high energy-saving efficiency by cool roofs are clustered in South Asia, including cities like Bangalore, Dhaka, and Ahmedabad, with average energy-saving values exceeding 40 kWh/m^2/year. Notably, cities with low to middle latitudes, such as Mexico City, Sao Paulo, and Kinshasa, also demonstrate remarkable cool-roof performance in terms of energy savings, with values higher than 30 kWh/m^2/year. Green roofs, while generally less effective in terms of building energy savings compared to cool roofs, still have notable energy-saving effects, particularly in regions with higher latitudes. Areas with high efficiency by green roofs were identified in East and South Asia, North Europe, and North America (Fig. 6(f)). In cities with mid to high latitudes, significant energy-saving effects by green roofs were observed. For example, Moscow, Seoul, and Tehran showed energy-saving values of 5.7, 5.5, and 4.8 kWh/m^2/year, respectively.

3.5. Relationship between urban layout and cooling intensity of cool and green roofs

A sensitivity analysis was conducted to identify the relationship between urban layout and the cooling effect of cool and green roofs. In this analysis, building coverage/density and building height were considered as representations of urban layout. The findings are depicted in Fig. 7, where Fig. 7(a–d) demonstrates the interaction between building height and cooling intensity in both open and compact layouts. Fig. 7 (e–h) shows the relationship between building coverage and cooling intensity in layouts with low to moderate and high building heights.

In the open layout scenario (Fig. 7(a) and (b)), building coverage was set to 30 %, while in the compact layout scenario (Fig. 7(c) and (d)), building coverage was increased to 60 %. Each of these scenarios in Fig. 7(a–d) incorporated 12 data points. A series of scenarios were constructed for each urban density layout, with varying building heights ranging from 9 m to 70 m, covering low, mid, and high buildings. A fixed gap of 3 m was used for building heights under 30 m (i.e., 9 m, 12 m, 15 m, 18 m, 21 m, 24 m, 27 m, and 30 m) and a fixed gap of 10 m for building heights over 30 m (i.e., 40 m, 50 m, 60 m, and 70 m).

In the low height layout (Fig. 7(e) and (f)), buildings ranged from 3 m to 9 m in height. In the mid-high layout (Fig. 7(g) and (h)), building height ranged from 9 m to 18 m. In each of analyzed scenarios in Fig. 7 (e–h), eight data values were included. To evaluate the impacts of building coverage on cooling intensity, scenarios with varying building coverage ratios between 10 % and 72 % were simulated for each building height layout: a fixed gap of 10 % was applied for ratios below 60 % (i.e., 10 %, 20 %, 30 %, 40 %, 50 %, and 60 %) and a fixed gap of 6 % for ratios above 60 % (i.e., 66 % and 72 %). Please note that all simulations included in Fig. 7 were performed under the same weather conditions, i.e., moderate weather conditions with an air temperature ranging from 17 °C to 28 °C and relative humidity ranging from 45 % to 75 %.

As previously also discussed, the cooling effect at the pedestrian level becomes less pronounced as building height increases (Fig. 7(a) and (c)). This pattern aligns with existing research [48,49]. Cooling intensity tends to decrease with increasing building height primarily due to the larger volume of air below the roof level that needs to be cooled. However, the cooling extent varies slightly in open and compact layouts. In Fig. 7(a), almost no discernible cooling effect can be observed at the pedestrian level when cool roofs are applied to buildings in an open layout with building height exceeding 63.6 m. Conversely, in compact layouts (as shown in Fig. 7(b)), the cooling effect of cool roofs diminishes when being applied to buildings with height exceeding 58.1 m.

Recent studies have found a negative correlation between building height and the cooling effect of green roofs at the pedestrian level [45,50,51]. However, our results demonstrate significant variations in the cooling performance of green roofs with building heights with different urban densities. In open layouts (Fig. 7(b)), we observed a

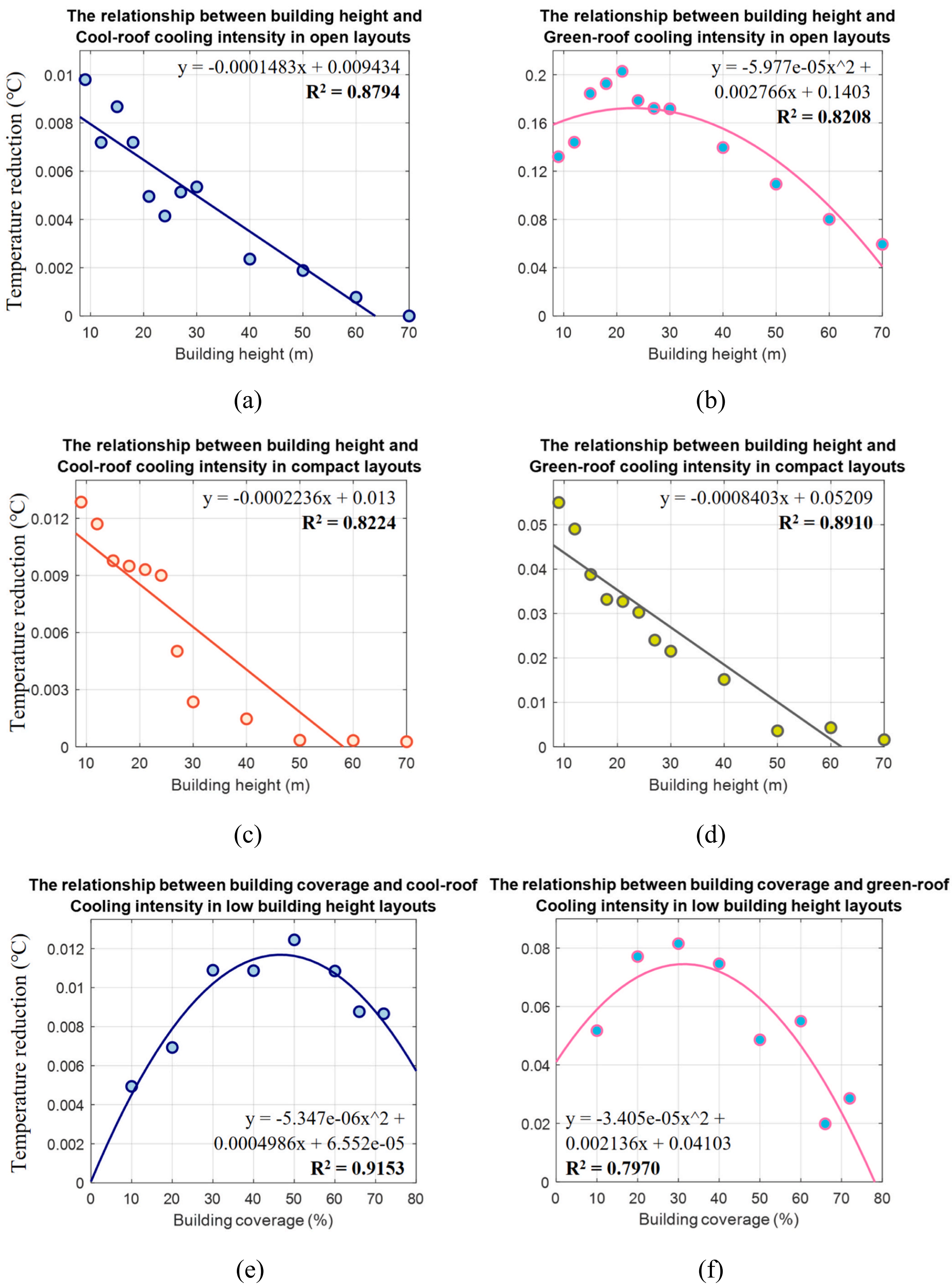

The relationship between building height and Cool-roof cooling intensity in open layouts
y = -0.0001483x + 0.009434
R² = 0.8794
Temperature reduction (°C)
Building height (m)
(a)
The relationship between building height and Green-roof cooling intensity in open layouts
y = -5.977e-05x^2 + 0.002766x + 0.1403
R² = 0.8208
Building height (m)
(b)
The relationship between building height and Cool-roof cooling intensity in compact layouts
y = -0.0002236x + 0.013
R² = 0.8224
Temperature reduction (°C)
Building height (m)
(c)
The relationship between building height and Green-roof cooling intensity in compact layouts
y = -0.0008403x + 0.05209
R² = 0.8910
Building height (m)
(d)
The relationship between building coverage and cool-roof Cooling intensity in low building height layouts
y = -5.347e-06x^2 + 0.0004986x + 6.552e-05
R² = 0.9153
Temperature reduction (°C)
Building coverage (%)
(e)
The relationship between building coverage and green-roof Cooling intensity in low building height layouts
y = -3.405e-05x^2 + 0.002136x + 0.04103
R² = 0.7970
Building coverage (%)
(f)

Fig. 7. The relationship between urban layout and cooling intensity of cool and green roofs, with (a–d) reflecting the effect of building height on the cooling intensity, and (e–h) reflecting the effect of building coverage on the cooling intensity: (a) cool roof cooling intensity in open layouts; (b) green roof cooling intensity in open layouts; (c) cool roof cooling intensity in compact layouts; (d) green roof cooling intensity in compact layouts; (e) cool roof cooling intensity in low building height layouts; (f) green roof cooling intensity in low building height layouts; (g) cool roof cooling intensity in mid-high building height layouts; (h) green roof cooling intensity in mid-high building height layouts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

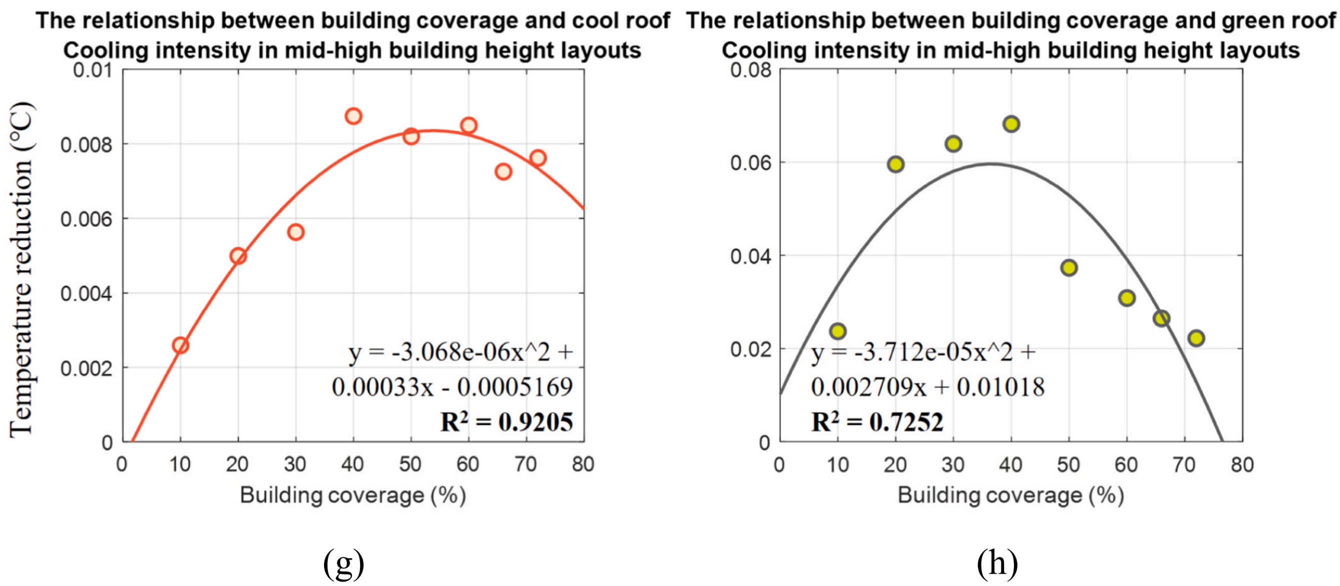


Fig. 7. (*continued*).

polynomial relationship between building height and temperature reduction by green roofs. The relationship is initially positive for heights lower than 23.1 m, but it subsequently decreases until it reaches 76.8 m. This finding indicates that, in open layouts, green roofs provide a greater cooling effect at the pedestrian level than cool roofs. In areas with low to mid-rise buildings, the cooling impact of green roofs can become more pronounced as building height increases, likely due to diminished shading from nearby structures. In addition, compact layouts demonstrate a similar trend in cooling effect with both green roofs and cool roofs. In Fig. 7(d), the cooling effect of green roofs becomes almost negligible when buildings exceed 62.0 m in height. Overall, both cool roofs and green roofs perform better in open layouts, which can be attributed to their increased solar reflectance and enhanced natural ventilation [51]. Fewer obstructions in open layouts allow these roofs to effectively reflect sunlight and facilitate airflow, enhancing the cooling effect.

The relationship between building coverage and cooling intensity by cool and green roofs is minimally influenced by variations in building height. Similar trends were observed in the relationship between building coverage and cooling intensity at the pedestrian level in layouts with varying building heights. In all scenarios, there is a positive correlation between cooling potentials and building coverage in relatively open layouts. However, as building coverage increases, the correlation shifts to a negative relationship. This finding contrasts with previous studies, which found the cooling effect of roof-level strategies to increase with higher building coverages [45,52,53]. Our results reveal an intriguing insight: when building coverage exceeds a certain threshold, typically around 30 % to 50 % of the total area, the further increase in building coverage results in a decrease in the cooling potentials of roof-level strategies at the pedestrian level. As the building coverage goes beyond this threshold, a significant portion of the ground area becomes shaded, resulting in reduced sunlight reaching the surface. This reduction in solar exposure affects the air mixing between the urban street canyon and the air above the buildings, ultimately impacting the effectiveness of roof-level strategies in providing pedestrian-level cooling benefits.

In the low building height layout (Fig. 7(e)), the maximal temperature reduction by cool roofs was observed at the building coverage ratio of 46.6 %. In the mid-high building height layout (Fig. 7(g)), the highest temperature reduction occurred at the building coverage ratio of 53.8 %. These findings suggest that for cool roofs, approximately half of the building coverage ratio is the most effective in cooling the pedestrian-level environment. In the case of green roofs, as depicted in Fig. 7(f) and (h), the optimal cooling effect was observed at building coverage ratio of 31.4 % and 36.5 % in the low and mid-high building height layout, respectively. Therefore, about 1/3 of the building coverage is deemed most suitable for green roofs to effectively cool down the environment. These findings emphasize the importance of achieving a balance between the enhanced cooling effect through increasing roof coverage and the potential reduction in cooling by the shading effect caused by expanding buildings.

4. Discussion

This study conducted a worldwide investigation into the performance of cool roofs and green roofs for pedestrian-level cooling and building energy savings and examined the relationship between the ambient environment and the mitigation potential of these roof-level strategies. A hybrid approach, which combines a micro-level CFD and a building energy simulation tool, was developed to precisely account for the surrounding meteorological and built environment. We then applied this integrated approach to a total of 43 megacities around the world to understand the cooling and energy-saving patterns of typical roof-level strategies in diverse urban settings and climates.

The findings indicate that the cooling and energy-saving benefits of cool roofs are particularly notable in megacities where solar radiation is abundant and the urban heat island effect is pronounced. As shown in Fig. 3, in regions D (South Asia) and E (Sub-Saharan Africa), the average building energy reductions by cool roofs reached 28 kWh/m^2/year. Cities such as Bangalore, Dhaka, and Ahmedabad, which are typically characterized by hot climates and extensive concrete and asphalt surfaces, can effectively lower pedestrian-level temperatures and conserve energy by implementing cool roofs. This can be attributed to the heat mitigation mechanism of cool roofs, primarily through increased albedo to minimize the transfer of heat from the roof to the interior spaces [54,55]. However, in higher latitudes during winter, increased roof albedo is less effective for heat mitigation due to reduced solar radiation. This decrease in solar heating can lead to higher space heating demands to compensate for the lower solar input [56]. Consequently, cool roofs may not be an ideal choice in cold climatic zones. However, it should also be noted that rooftop snow cover can reduce the impact of roof albedo during winter, thereby mitigating the negative effects of cool roofs on building energy use for space heating [55]. In this study, all simulations were conducted under snow-free conditions. Therefore, the potential effects of snow-covered roofs (SCR) on energy use may require further investigation to fully understand their impact. This information can be used to inspire and guide megacities to create better urban environments within respective locales. Urban planners should prioritize the implementation of cool roofs in hot, sunny megacities with significant urban heat island effects. Additionally, for cities in temperate zones that experience both hot summers and cold winters, it is suggested to implement switchable roof reflectance technology [10]. This involves designing switchable coatings on roofs that can alternate between low and high reflectance according to the heating and cooling seasons, thereby achieving higher effectiveness in HVAC energy savings. Some scholars have also proposed using the metal–insulator transition phenomenon for certain metal oxides on roofs [57]. These materials can change their solar reflectance depending on temperature: when the temperature is below a certain threshold, the material is in an insulator state with low solar reflectance, while in summer, the material transitions to a metallic state with high solar reflectance.

On the other hand, green roofs have the potential to provide additional cooling effects through the shading provided by the plants on the rooftop [58,59]. This is why a more significant cooling effect has been observed for green roofs worldwide. At the city scale, green roofs can achieve a cooling effect of up to 0.80 °C. Green roofs can also provide evapotranspiration-induced atmospheric moisture. However, existing studies have shown that these humidifying effects did not diminish the overall improvement in thermal comfort [60]. Additionally, the critical importance of irrigation to the cooling performance of green roofs has been identified in many studies [61], finding that irrigated green roofs were more effective in mitigating urban heat and reducing building energy use compared to non-irrigated systems. In terms of building energy-saving performance, green roofs make a modest but still effective contribution in most regions, especially in high latitude areas. This effectiveness is attributed to their ability to enhance thermal insulation for buildings, thereby reducing heating energy consumption during cold months [62]. As illustrated in Fig. 6, notable energy-saving effects of green roofs were observed in mid-to-high latitude regions; for instance, Moscow and Seoul recorded energy savings of 5.7 and 5.5 kWh/m^2/year, respectively. Nevertheless, it is important to note that as a form of greenspace, green roofs offer additional benefits, such as storm water retention, air quality improvement, and enhancement of urban biodiversity, along with various aesthetic and economic values [63]. Especially, green roofs serve as valid alternatives to replace lost greenspaces and habitats in modern cities, and foster natural life behaviors [64,65]. Therefore, a comprehensive decision-making process is essential during the implementation of roof-level strategies in the real world. The trade-offs between different mitigation strategies in various regions is important rather than relying on one-size-fits-all approaches.

5. Conclusion

To summarize, this research delivers an in-depth comprehension of the efficacy of two popular roof strategies – green and cool roofs – for temperature regulation and energy conservation of buildings across 43 megacities. The main findings are summarized as below:

(1) In terms of global cooling effect comparison, green roofs outperform cool roofs. Among the 43 megacities studied, the maximum pedestrian-level temperature decrease for cool roofs was recorded in Beijing at 0.23 °C. In contrast, green roofs can provide a cooling effect of up to 0.80 °C in Delhi.
(2) For cooling effect comparison in various urban layouts, both cool roofs and green roofs perform better in open layouts. The effectiveness of cool roofs declines as building height increases, while green roofs show a polynomial relationship between building height and temperature reduction.
(3) In terms of global energy-saving effect comparison, cool roofs significantly decrease building energy use during warm seasons, with savings ranging from 5.4 to 63.8 kWh/m^2/year, whereas energy savings from green roofs range from 1.1 to 7.3 kWh/m^2/year. The highest energy-saving efficiency for cool roofs was observed in Bangalore, while Dhaka showed the highest energy-saving amount using green roofs.
(4) Regarding seasonal variations in energy-saving effects, the highest average energy-saving value by cool roofs, 8.46 kWh/m^2, was recorded during the spring in region D (South Asia). Relatively significant energy-saving effects from green roofs were observed during the warm seasons in regions D and E (Sub-Saharan Africa), and during the relatively cold seasons in Europe and Central Asia.
(5) For energy-saving effect comparison in different urban layouts, there is a positive relationship between building height and cooling energy reductions for both roof types. However, no consistent patterns were found between urban layouts and heating energy-saving performance.

The research findings can guide policymakers and urban planners in formulating strategies tailored to their specific context to combat the urban heat island phenomenon and lessen global energy use. Furthermore, the study offers insights into the functionality of green and cool roofs, promoting the creation of sustainable, comfortable, and energy-efficient urban environments.

6. Future work

This study has several limitations. Firstly, there are some constraints in the microscale model (i.e., ENVI-met) used in the research. It does not consider local-scale advection and vertical mixing within the boundary layer. Moreover, the model may face additional challenges accurately representing vertical mixing within the urban canopy layer [66]. Existing studies also acknowledged that the ENVI-met model has shortcomings in accurately modeling meteorological parameters, especially during the simulation of heat mitigation strategies applied at the roof level [67]. Therefore, some modeling errors are likely to persist. Future research could involve assessing multiple points within a domain and examining additional atmospheric variables to verify the accuracy of ENVI-met simulations, a method also recommended by Crank et al. [67]. Furthermore, it is also helpful to improve the grid resolution in the model domain for realizing a more detailed microscale study.

Secondly, some details in the simulations were simplified given the broad scope of the current study. These primarily include the fixed and idealized designs of the cool and green roofs, and the use of local climate zones (LCZs) for scaling up. In this study, we assumed all buildings in the study areas have cool and green roofs with fixed designs in the optimized scenarios. However, the individual designs of cool and green roofs can vary greatly, while the implementation of roof-level strategies is often constrained by building conditions such as materials and age. Additionally, the study assumes consistent building construction conditions across all LCZs. Since the LCZ system is classified mainly based on properties of surface structure, the differences in the building construction cannot be reflected by LCZs.

Therefore, localized information about building sectors and the urban environment can enhance modeling accuracy in building energy use, as past studies have also suggested [68]. For smaller-scale studies, such as neighborhoods or individual buildings, the granularity or grid size of the model can be adjusted to capture microclimatic variations. Future research should aim to further refine modeling approaches to better capture the complex realities of urban environments and building characteristics, utilizing detailed information and advanced simulation tools. A promising approach may involve developing an updated classification system for urban built environments that considers variations in the thermal environment, urban climate, and building categories. Another possible direction is to conduct localized case studies, incorporating realistic building and environmental parameters to enhance the accuracy and applicability of the model. Additionally, future studies could further expand the application of the model to evaluate the meteorological feedback on building energy use, considering not only roof-level strategies or other mitigation solutions but also human activities that may influence the microclimate, and subsequently affect building energy use. In summary, by improving and applying this novel approach, future research can provide more comprehensive and accurate insights into the interplay between urban environments, building characteristics, and energy consumption, ultimately leading to more effective strategies for energy savings and climate mitigation in diverse urban settings.

CRediT authorship contribution statement

Siqi Jia: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Qihao Weng:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Cheolhee Yoo:** Writing – review & editing, Methodology, Investigation. **James A. Voogt:** Writing – review & editing, Methodology.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115671.

Data availability

Data will be made available on request.

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