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REVIEW ARTICLE

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Unlocking rooftop potential for sustainable cities: A systematic review

Abstract The utilization of rooftop space offers various benefits to cities and their residents, such as urban heat island mitigation, energy saving, and water management. However, a comprehensive understanding of these benefits and their regional differences is still lacking. We reviewed 97 articles published between 2000 and 2022 to evaluate the efficiency of various rooftop engineering approaches, including green roofs, white roofs, solar roofs, blue roofs, and wind turbine roofs. The main findings are as follows: (I) As of 2020, there are ~245 billion m^2 of rooftop space worldwide, equivalent to the land area of the UK. About 29%–50% of these rooftops are suitable for utilization. (II) Effective use of rooftop space can cool cities by ~0.60°C, meet ~44% of city energy demand, reduce runoff by ~17%, and save ~23% of building water demand. (III) Climate and building types influence the efficiency of rooftop engineering, with mediterranean climates and low-rise buildings offering the most favorable conditions. This review provides a comprehensive evaluation of global rooftop resources and their potential benefits, offering valuable guidance for cities to adopt differentiated rooftop strategies.

Keywords rooftop engineering, review, urban heat island mitigation, energy saving, water management

1 Introduction

The rapid growth of urban areas has placed significant burdens on the thermal environment, hydrological systems, and energy systems of cities (Chen et al., 2016; Chapman et al., 2017). The Sustainable Development Goals outlined by the United Nations necessitate that cities mitigate negative impacts such as urban heat island (UHI) effects and flooding on human health, improve living conditions, and provide essential water and energy services. As integral systems, cities hold the key to achieving sustainable development by optimizing their limited resources.

Roofs, comprising 20%–30% of urban land (Besir and Cuce, 2018), represent a valuable supplement to land resources and play a crucial role in promoting sustainability, particularly in cities with limited land availability. The utilization and retrofitting of rooftops, known as rooftop engineering, has attracted significant attention in recent years (Santamouris, 2014; Besir and Cuce, 2018; Shafique et al., 2018). These approaches enable the regulation of buildings and surrounding environmental conditions without the need for additional land, making them an appealing choice. Currently, only approximately 10% of rooftop space globally is utilized, primarily on newer and larger buildings in Europe, North America, and Southeast Asia (Vijayaraghavan, 2016; Dong et al., 2020; Zuo et al., 2022). There are five main types of rooftop engineering: green roofs, which involve the use of vegetation and soil layers to provide insulation and reduce cooling loads by up to 70% (Mihalakakou et al., 2023);

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white roofs, which are coated with white paint to reflect solar radiation and mitigate UHI effects by 0.4°C–0.6°C (Oleson et al., 2010; Zhang et al., 2016); solar roofs, which are equipped with photovoltaic (PV) panels to harness solar energy and meet 17%–62% of regional electricity demand (Gernaat et al., 2020; Molnár et al., 2022); blue roofs, which incorporate storage or drainage facilities to manage stormwater; and wind turbine roofs, which integrate small wind turbines to harness wind energy and generate electricity. The benefits of rooftop engineering include various aspects, including energy, urban heat island mitigation, water management, air quality improvement, biodiversity conservation, and urban agriculture (Table 1). These benefits have been extensively researched and validated through theoretical and experimental studies.

The effectiveness of rooftop engineering can be influenced by climate conditions and building characteristics. On a regional scale, latitude affects the angle of solar elevation, thereby influencing the optimal tilt angle for PV panels and the efficiency of electricity generation. Climate conditions also impact the evaporation and heat dissipation of green roofs (Morakinyo et al., 2017), and determine whether white roofs result in an energy penalty. At the building scale, factors such as plot ratio, building density, average building height, and building spacing can influence the potential contribution of PV roofs to electricity generation (Tian and Xu, 2021) and wind turbine roofs (Lu and Ip, 2009; Ledo et al., 2011; Gagliano et al., 2013). This information suggests that the benefits of the same rooftop engineering solution can vary significantly in different regions and built environments. A previous review summarized the existing types of rooftop engineering and their suitability in different climate zones, including an assessment of their economic cost payback period (Abuseif and Gou, 2018). However, this review did not provide an estimation of rooftop resources nor consider the impact of building characteristics. Therefore, there is still a need for a comprehensive review to guide the large-scale utilization of rooftops.

In this context, we present a comprehensive review of the utilization of rooftops and their associated benefits, with a specific focus on three key areas: (I) A comprehensive overview of rooftop resources, including their total area and distribution. (II) The benefits of the five most common rooftop engineering strategies, including white roofs, green roofs, solar roofs, blue roofs, and wind turbine roofs, in terms of energy conservation, UHI mitigation (specifically a 2-m temperature reduction), and water management. (III) Assessing the suitability of different types of rooftops for utilization. Through this review, our aim is to provide scientific evidence that will help unlock the untapped potential of rooftops.

2 Methods and material

2.1 A framework for analysis

Figure 1 presents the fundamental framework employed for this review. Initially, we analyze the area and distribution of rooftop resources across different climate zones (Fig. 1(a)) and building type zones (Fig. 1(b)). Subsequently, we gather relevant information on the benefits and cost payback periods associated with different rooftop engineering strategies through a thorough review of published articles. We then consider the influence of varying climatic and building conditions and evaluate the suitability of different rooftops for utilization. Finally, we provide recommendations for practical applications based on our findings.

2.2 Criteria for article selection

To conduct this review, we utilized the “Web of Science” as our search database. Our search parameters included

Table 1 Rooftop engineering and potential benefits

Aspect	Benefits	Green roofs^a	White roofs^b	Solar roofs^c	Blue roofs^d	Wind turbine roofs^e
Energy	Reduce cooling consumption	++	++	+	+	
	Reduce heating consumption	++		++	+	
	Generate electricity			++		++
	Save water pumping energy				+	
UHI	UHI mitigation	++	++	+		
Water	Rainwater retention	+			++	
	Converse water use				++	
Biodiversity	Preserve biodiversity	+				
Air	Clean the air	+				
Food	Provide vegetables and fruits	+				

Notes: a: Dvorak and Volder, 2010; Wang et al., 2022a. b: Gilabert et al., 2021; Wijesuriya et al., 2022. c: Taha, 2013; Liu et al., 2019. d: Tjandraatmadja et al., 2013; Sharifi and Yamagata, 2015. e: Vallejo-Díaz et al., 2022.

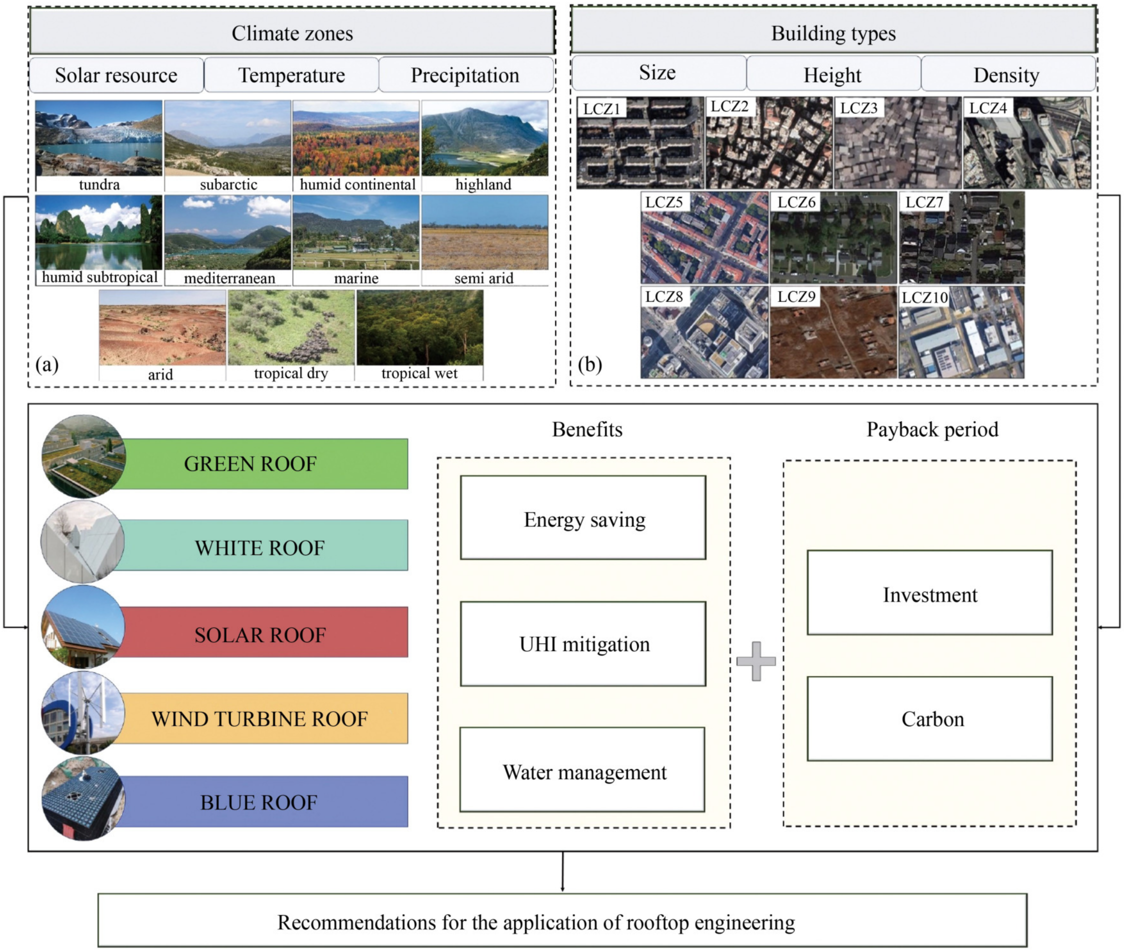


Fig. 1 A framework for review; (a) Different climate zones (source: Wikipedia); (b) Remote sensing images of typical areas of different building types. LCZ1 refers to compact high-rise buildings, LCZ2 refers to compact mid-rise buildings, LCZ3 refers to compact low-rise buildings, LCZ4 refers to open high-rise buildings, LCZ5 refers to open mid-rise buildings, LCZ6 refers to open low-rise buildings, LCZ7 refers to lightweight low-rise buildings, LCZ8 refers to large low-rise buildings, LCZ9 refers to sparsely built buildings, LCZ10 refers to heavy industry buildings (source: Google Maps).

the terms "green roof," "solar roof," "photovoltaic roof," "cool roof," "reflective roof," "white roof," "roof tank," "blue roof," or "wind turbine roof," along with keywords such as "urban heat island," "temperature," "energy," "electricity," "rainwater," "stormwater," or "runoff" in the abstracts. We restricted the publication year between 2000 and 2022, selected "environmental science ecology" as the research direction, "articles" as the document type, and included only the core collection of the Web of Science database. Furthermore, we excluded journals from MDPI and Hindawi. The initial screening yielded a total of 4182 documents.

To be included in this review, papers had to meet the following criteria: (I) The topic should be related to the benefits that rooftops can generate, such as UHI mitigation, energy saving, water management, economic, or carbon payback period. (II) The research should use appropriate indicators and scales. When evaluating the cooling effect, we mainly focus on pedestrian perception, so data should be measured at a height of two meters above ground. When discussing the energy supply potential of solar roofs, their contribution to regional electricity demand should be considered. On the other hand, wind turbine roofs primarily contribute to the electricity demand of a building. When considering the runoff mitigation effect, the reduction of entire regions should be taken into account, rather than solely focusing on single buildings.

Based on the above criteria, we followed a systematic filtering procedure. In step 1, we screened the articles based on titles and abstracts to remove records that were not relevant, resulting in the selection of 524 records. In step 2, we conducted a full-text assessment to identify research with specific and comparable results, leaving us with 63 articles. Additionally, we want to give an overview of the distribution patterns and stock of rooftops. To achieve this, we performed a snowball search of the reference list and conducted related field searches, supplementing the review with an additional 34 papers in step 3. Using this selection methodology (Fig. 2), a total

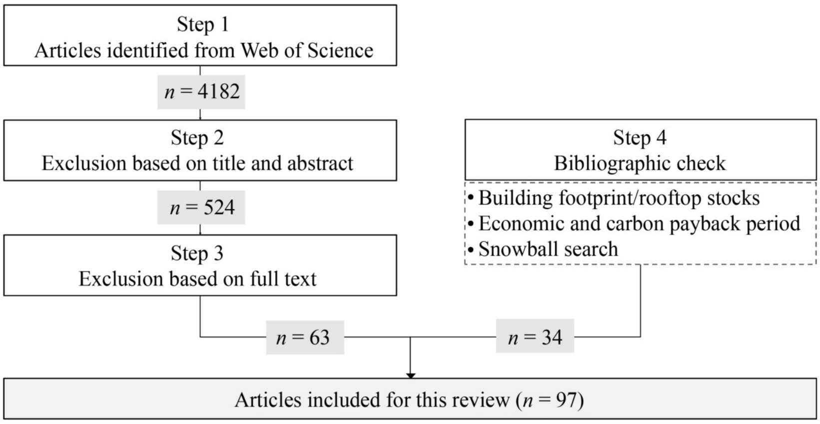


Fig. 2 Methodology of literature selection.

of 97 papers were reviewed for this study.

2.3 Rooftop resource estimation methodology

In this study, rooftop resources were evaluated based on the buildings' footprint, the equipment occupation and engineering feasibility were not taken into account. Our data provides an overview of rooftop resources as of approximately 2020, covering eight sub-regions, namely Canada and the United States (CAUS), East and Southeast Asia (ESEA), Europe (EUR), Latin America (LAM), Middle East and North Africa (MENA), Oceania (OCE), Russian Federation and Central Asia (RFCA), South Asia (SOA), and Sub-Saharan Africa (SSA). We obtained the average area of building rooftops in each region by integrating data from various research sources. To investigate the distribution of rooftops in different local climate zones (LCZ), we referred to an article in the Journal of the American Planning Association (Wheeler, 2015) and matched architectural textures to LCZ (Fig. 1(b)). Based on the calculated average distribution pattern from these samples, we can estimate the distribution in nine sub-regions. To investigate the distribution of rooftops in different climate zones, we used Microsoft's GlobalMLBuildingFootprints and China's national building GIS data set (Zhang et al., 2022), overlaid with climate zoning layers, to identify the proportion of rooftops in different climate zones and extrapolate the rooftop area in nine sub-regions (see Supporting Information).

3 Results and analysis

3.1 Bibliometric analysis

We analyzed 143 cases of rooftop engineering in 97 reviewed articles. As shown in Fig. 3, green roofs (32.2%) were the most widely studied type of rooftop engineering, followed by solar roofs (22.4%) and white roofs (21.0%). CAUS had the highest number of study cases (31.5%), followed by EUR (23.1%) and ESEA (15.4%).

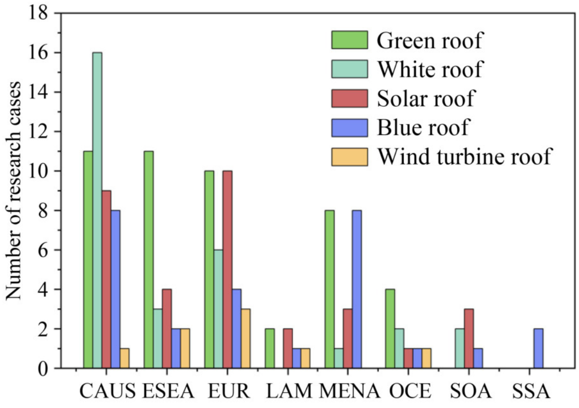


Fig. 3 Distribution of research cases.

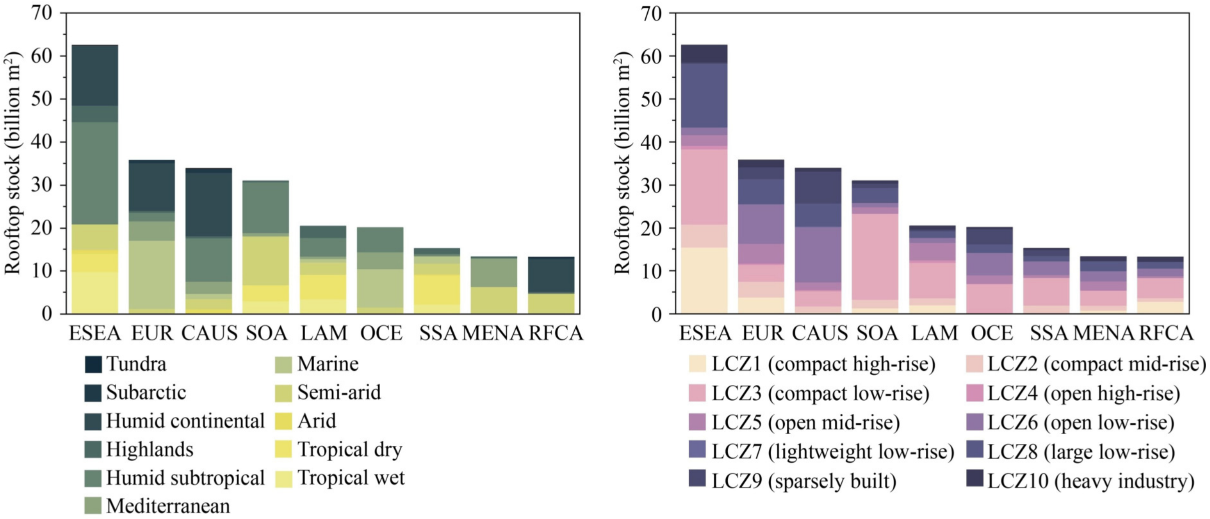
3.2 Overview of rooftop resources

As of 2020, the estimated total area of rooftop space worldwide ranged from 193.9 to 291.6 billion m^2, with an average of 245 billion m^2 (Joshi et al., 2021; Esch et al., 2022; Molnár et al., 2022; Li et al., 2022a), which is equivalent to the land area of the UK. Among these, ESEA had the largest rooftop area (25%), followed by EUR (15%), CAUS (14%), SOA (13%), LAM (8%), OCE (8%), SSA (6%), MENA (5%), and RFCA (5%) (Deetman et al., 2020; Esch et al., 2022; Molnár et al., 2022; Li et al. 2022a; Milojevic-Dupont et al., 2023).

(I) Distribution of rooftops in different climate zones

As depicted in Fig. 4(a), the majority of world rooftop resources are concentrated in humid subtropical (24%), humid continental (19%), and semi-arid (16%) regions. These sub-regions can be classified into two categories based on the climate condition of rooftops.

(i) Rooftops in ESEA, EUR, CAUS, and OCE experience more humid climate conditions. ESEA rooftops are predominantly found in humid subtropical and humid



(a) (b)

Fig. 4 Stock and distribution of rooftop resources.

continental regions, while EUR rooftops are mainly distributed in marine and humid continental regions. CAUS rooftops are primarily located in humid continental and humid subtropical regions, and OCE rooftops are mainly distributed in marine and humid subtropical regions. (ii) Rooftops in LAM, SOA, SSA, MENA, and RFCA exhibit a variety of climate conditions. LAM rooftops are mainly distributed in tropical dry and humid subtropical regions. SOA rooftops are predominantly found in humid subtropical and semi-arid regions. SSA rooftops are primarily located in tropical dry and semi-arid regions. MENA rooftops are mainly distributed in Mediterranean and semi-arid regions. Lastly, RFCA rooftops are mainly distributed in humid continental and semi-arid regions.

(II) Distribution of rooftops in different LCZs

LCZ3 is the most common type, accounting for 30% of all buildings. These sub-regions can be further categorized into four main groups based on the built environment condition of the rooftops.

(i) ESEA, SOA, and RFCA exhibit more compact construction, with LCZ3 being the dominant type in SOA, and LCZ3, LCZ1, and LCZ8 being dominant in both ESEA and RFCA. (ii) CAUS, on the other hand, tends to have more sparse construction, with LCZ6 and LCZ9 being dominant. (iii) OCE, SSA, and LAM have more low-rise buildings. OCE is mainly dominated by LCZ3, LCZ6, and LCZ8, while SSA is predominantly comprised of LCZ3 and LCZ6. LAM is primarily characterized by LCZ3 and LCZ5. (iv) EUR and MENA display a variety of building types. In EUR, LCZ6, LCZ8, LCZ5, LCZ3, LCZ1, and LCZ2 are all dominant, while MENA is primarily dominated by LCZ3, LCZ6, LCZ8, and LCZ5.

3.3 Benefits and costs of rooftop engineering

3.3.1 Benefits of making sustainable cities

(I) Green roofs

Benefits of green roofs, as reported in the literature, include energy savings, UHI mitigation, and water management. Extensive green roofs have the potential to reduce temperatures by 0.10 °C–1.5 °C (with an average of 0.60 °C) at a height of 2 m above ground level during summer days, and intensive green roofs have a slightly higher maximum cooling effect of 1.51 °C (Rosenzweig et al., 2009; Li et al., 2014; Sharma et al., 2016; Imran et al., 2018; Žuvela-Aloise et al., 2018; Lalosevic et al., 2018; Dong et al., 2020; Cheng et al., 2020; Zuo et al., 2022). We use the term "utilization ratio" (UR) to describe the proportion of rooftops that are equipped with rooftop engineering. The cooling effect is more significant in areas where the UR is higher than 80% and experiences hot summers (Fig. 5(a)). Extensive green roofs are expected to save 2.00%–9.45% of a building's energy consumption throughout the year (Wong et al., 2003; Jaffal et al., 2012; Refahi and Talkhabi, 2015; Berardi, 2016; Naing et al., 2017; Movahed et al., 2020; Algarni et al., 2022). The greatest energy savings were observed in locations where the annual average temperature exceeded 30°C. However, regions with temperate climates also reported significant energy savings (Fig. 5(b)). The stormwater reduction potential of extensive green roofs ranges from 0.63% to 15.6%. It performs best in regions with annual precipitation below 750 mm, and the efficiency declines rapidly as rainfall increases (Fig. 5(c)) (Mentens et al., 2006; Versini et al., 2016; Zhou et al., 2019; Liu et al., 2022a; Chen et al., 2022; Twohig et al., 2022; Fu et al., 2022; Cristiano et al., 2023).

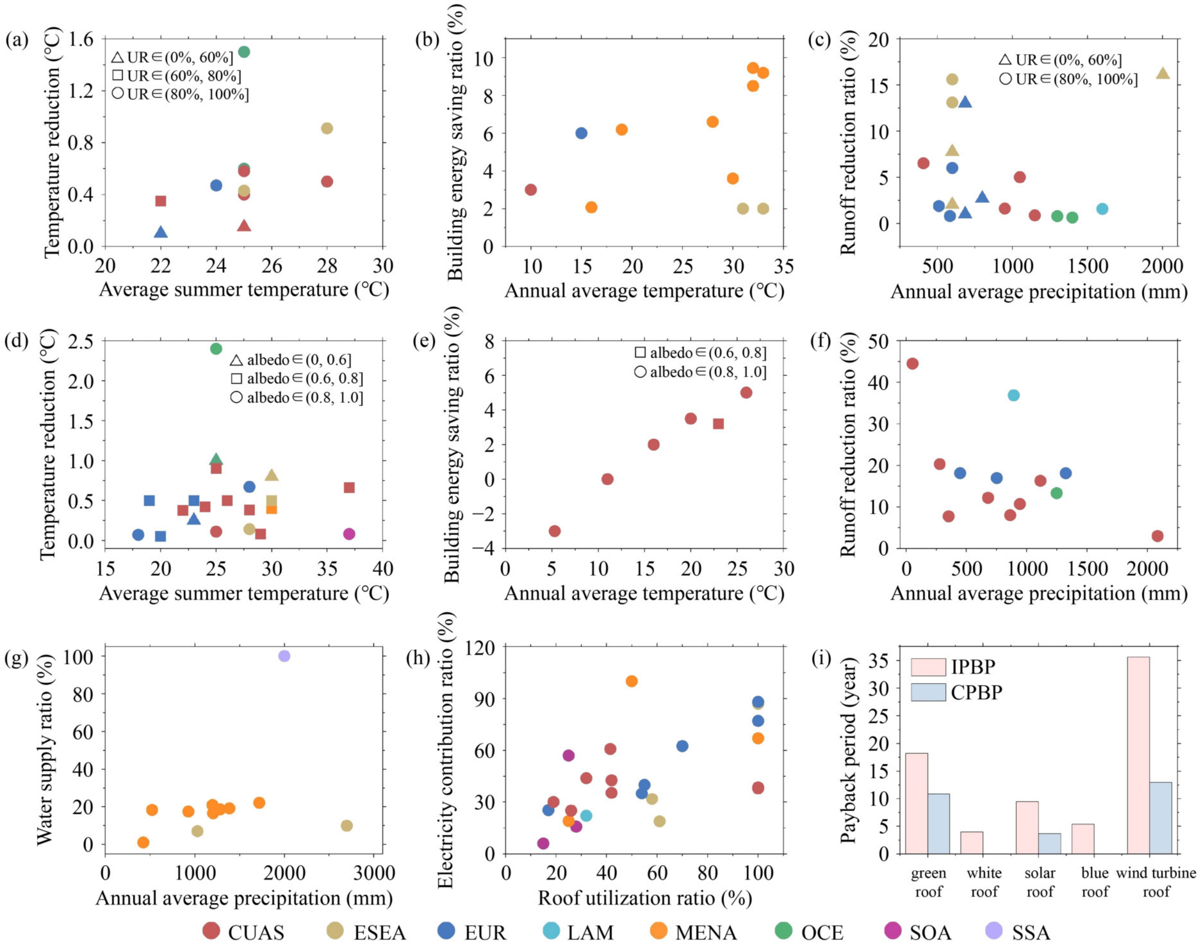


Fig. 5 Benefits and costs of rooftop engineering: (a) Tow meters above ground temperature reduction potential of extensive green roofs on summer days; (b) Building energy saving potential of extensive green roofs; (c) Regional stormwater reduction potential of extensive green roofs; (d) Tow meters above ground temperature reduction of white roofs on summer days; (e) Building energy saving potential of white roofs; (f) Regional stormwater reduction potential of blue roofs; (g) Water saving potential of blue roofs; (h) The proportion of regional electricity that can be supplied by solar roofs; (i) The investment payback period and carbon payback period of rooftop engineering.

(II) White roofs

Benefits of white roofs reported in the literature include energy savings and UHI mitigation. According to multiple studies, white roofs are expected to lower temperatures by an average of 0.51 °C (ranging from 0.07 °C to 2.4 °C) two meters above the ground during summer days (Li et al., 2014; Cao et al., 2015; Vahmani et al., 2016; Zhang et al., 2016; Imran et al., 2018; Žuvela-Aloise et al., 2018; Macintyre and Heaviside, 2019; Broadbent et al., 2020; He et al., 2020; Lynn and Lynn, 2020; Jeong et al., 2021; Gilabert et al., 2021; Macintyre et al., 2021). While there is a positive correlation between higher summer temperatures and cooling effects in EUR and ESEA, no significant correlation was found in CUAS (Fig. 5(d)). The energy-saving efficiency of white roofs is dependent on the annual average temperature. If the annual average temperature exceeds 20 °C, building energy savings of 3%–5% can be achieved. In regions where the annual average temperature is 10 °C–20 °C, energy savings range from 0 to 2%. Energy penalties may occur when the annual average temperature falls below 10 °C (Jo et al., 2010; Wijesuriya et al., 2022) (Fig. 5(e)).

(III) Blue roofs

Blue roofs have the potential to reduce stormwater by an average of 17% (ranging from 3.0% to 44.5%) (Litofsky and Jennings, 2014; Cristiano et al., 2023). However, the stormwater reduction benefit decreases with increasing rainfall (Fig. 5(f)). Additionally, blue roofs can provide 23% (ranging from 1% to 100%) of water demand. In the MENA, they can meet 17% of the water demand, while in ESEA with taller buildings, they can meet 8% of the water demand. In regions like SSA with abundant rainfall and lower water demand, blue roofs can meet all water demand (Chaimoon 2013; Nthuni et al., 2014; Saidan et al., 2015; Kolavani and Kolavani, 2020; Nguyen et al. 2021) (Fig. 5(g)).

(IV) Solar roofs

Benefits of solar roofs, as reported in the literature, include energy supply and UHI mitigation. Solar roofs have the potential to supply 17%–100% (with an average of 44%) of regional electricity demand (Wiginton et al., 2010; Strzalka et al., 2012; Singh and Banerjee, 2015; Molin et al., 2016; Campos et al. 2016; Kurdgelashvili et al. 2016; Margolis et al. 2017; Rodríguez et al. 2017; Assouline et al., 2018; Gagnon et al., 2018; Dehwah and Asif, 2019; Liu et al., 2019; Kouhestani et al., 2019; Phillips et al., 2019; Mishra et al., 2020; Walch et al., 2020; Yang et al., 2020; Yildirim et al., 2021; Liu et al., 2022b; Nasrallah et al., 2022; Talut et al., 2022; Sun et al., 2022; Wang et al., 2022b). Solar roofs in the MENA, SOA, and CAUS have demonstrated the best performance in terms of energy supply, attributed to their abundant solar energy resources and low-rise building features. In contrast, in ESEA, where solar resources are generally moderate and there is a larger number of mid-to-high-rise buildings, the energy supply benefits are not as significant (Fig. 5(h)). Furthermore, PV panels with high conversion efficiency can absorb more solar radiation, thereby helping to reduce the temperature by 0.2 °C two meters above the ground (Taha, 2013).

(V) Wind turbine roofs

The installation of wind turbines on the rooftops of urban buildings with normal wind resources (2–3.4 m/s) can generate approximately 1153–1916 kWh of electricity per year (Karthikeya et al., 2016; Vallejo-Díaz et al., 2022), which accounts for approximately 40% of a household's annual electricity consumption (Gagliano et al., 2013). Additionally, installing wind turbines on the rooftops of urban buildings with better wind resources (≈ 7 m/s) can generate approximately 99206.9 kWh of electricity per year (Rezaeiha et al., 2020).

3.3.2 Cost payback period

This review examines the investment payback period (IPBP) and carbon payback period (CPBP). They should be compared to the lifespans of rooftop engineering, which typically range from 20 to 30 years. White roofs have the shortest IPBP, at 4.0 years (Jo et al., 2010; Blackhurst, 2020; Rawat and Singh, 2022), followed by blue roofs and solar roofs, with IPBPs of 5.4 years (Nthuni et al., 2014; Bashar et al., 2018; Kim et al., 2021) and 9.5 years (Sorgato et al., 2018; Zhao et al., 2019; Fuster-Palop et al., 2021; Turi et al., 2023), respectively. Wind turbine roofs have the longest IPBP, at 35.6 years (Gagliano et al., 2013; Karthikeya et al., 2016; Almutairi et al., 2017), followed by green roofs, with an IPBP of 18.2 years (Clark et al., 2008; Refahi and Talkhabi, 2015; Ávila-Hernández et al., 2020; Mahdiyar et al., 2021). In terms of economic benefits, white roofs offer the greatest advantage, followed by solar roofs and blue roofs, while green roofs are also viable but wind turbine roofs are not expected to offset their costs. In terms of CPBP, solar roofs have the shortest period at 3.7 years (Battisti and Corrado, 2005; Lamnatou and Chemisana, 2015; Li et al., 2022b), followed by green roofs and wind turbine roofs at 10.9 years (Kuronuma et al., 2018) and 13 years (Mithraratne, 2009), respectively (Fig. 5(i)).

4 Discussion

4.1 Recommendations for the application of rooftop engineering

Based on the results (Fig. 5), we can categorize the benefits of rooftop engineering into five levels. We then assessed the suitability of different types of rooftop engineering in each region, based on the climatic and building conditions.

4.1.1 Solar roofs and green roofs are the most recommended rooftop engineering

When prioritizing energy considerations, it is important to take into account the potential of solar roofs and wind turbine roofs for generating clean electricity. Solar roofs have broader applicability and a shorter payback period compared to wind turbine roofs due to the greater availability of solar resources as opposed to wind resources. Additionally, the installation of wind turbine roofs requires strict requirements and may result in higher costs if not properly configured (Vallejo-Díaz et al., 2022). White roofs and green roofs also contribute to energy conservation, with green roofs being more effective than white roofs in cold climates due to the thermal insulation provided by the soil layer.

To address UHI concerns, cool roofs and green roofs are recommended, with green roofs offering a slightly higher cooling effect compared to white roofs. Both types of roofs feature a stable cooling mechanism, either through high albedo to prevent excessive warming or through transpiration to dissipate heat. Solar roofs also have a modest cooling effect, which depends on their conversion efficiency (Taha, 2013).

In areas experiencing flooding and water shortages, blue roofs are recommended. Blue roofs, due to their ability to hold more runoff than thin layers of vegetation and soil, are more effective in reducing stormwater than green roofs, particularly when rainfall volume is high. Moreover, rainwater collected from blue roofs can be reused to alleviate pressure on the city's water supply system.

Broadly speaking, green roofs offer the widest range of benefits, while solar roofs provide the most significant advantages. These two types of rooftop engineering are considered to have the greatest potential for sustainable cities, and they were the most commonly implemented in the cases reviewed.

4.1.2 Mediterranean climate provides favorable conditions for rooftop utilization

Figure 6(a) illustrates the potential benefits of various rooftop engineering options for urban sustainability across 11 climate zones. The mediterranean climate zone provides favorable conditions for numerous types of rooftop engineering, such as solar roofs, blue roofs, and green roofs. Arid, semi-arid, highlands, humid continental, and tropical dry climate zones have abundant sunshine resources, making the installation of solar roofs highly advantageous. In areas with tropical wet climates, the installation of blue roofs can yield greater benefits due to the ample precipitation resources. Regions characterized by humid subtropical and marine climates, which experience hot summers and high precipitation levels, can benefit greatly from the installation of green, white, and blue roofs. Conversely, in areas with tundra and subarctic climatic conditions, rooftop engineering generally has limited advantages. The impact of climate on the benefits of these rooftops can be further explored by examining factors such as temperature, precipitation, and solar and wind resources.

(I) Temperature: The temperature has a significant impact on the benefits of roofs in terms of reducing UHI effects and saving energy for building air-conditioning. The cooling benefits of green roofs tend to increase with higher summer temperatures, possibly due to increased transpiration in dry and hot regions (Morakinyo et al., 2017). The most effective regions for cooling are believed to be OCE and ESEA. Some studies have also suggested that the United States and China are suitable regions (Zhang et al., 2016). Additionally, the Middle East, Brazil, EUR, and ESEA have been identified as potential regions (Oleson et al., 2010). Although the results may be controversial, most of the mentioned

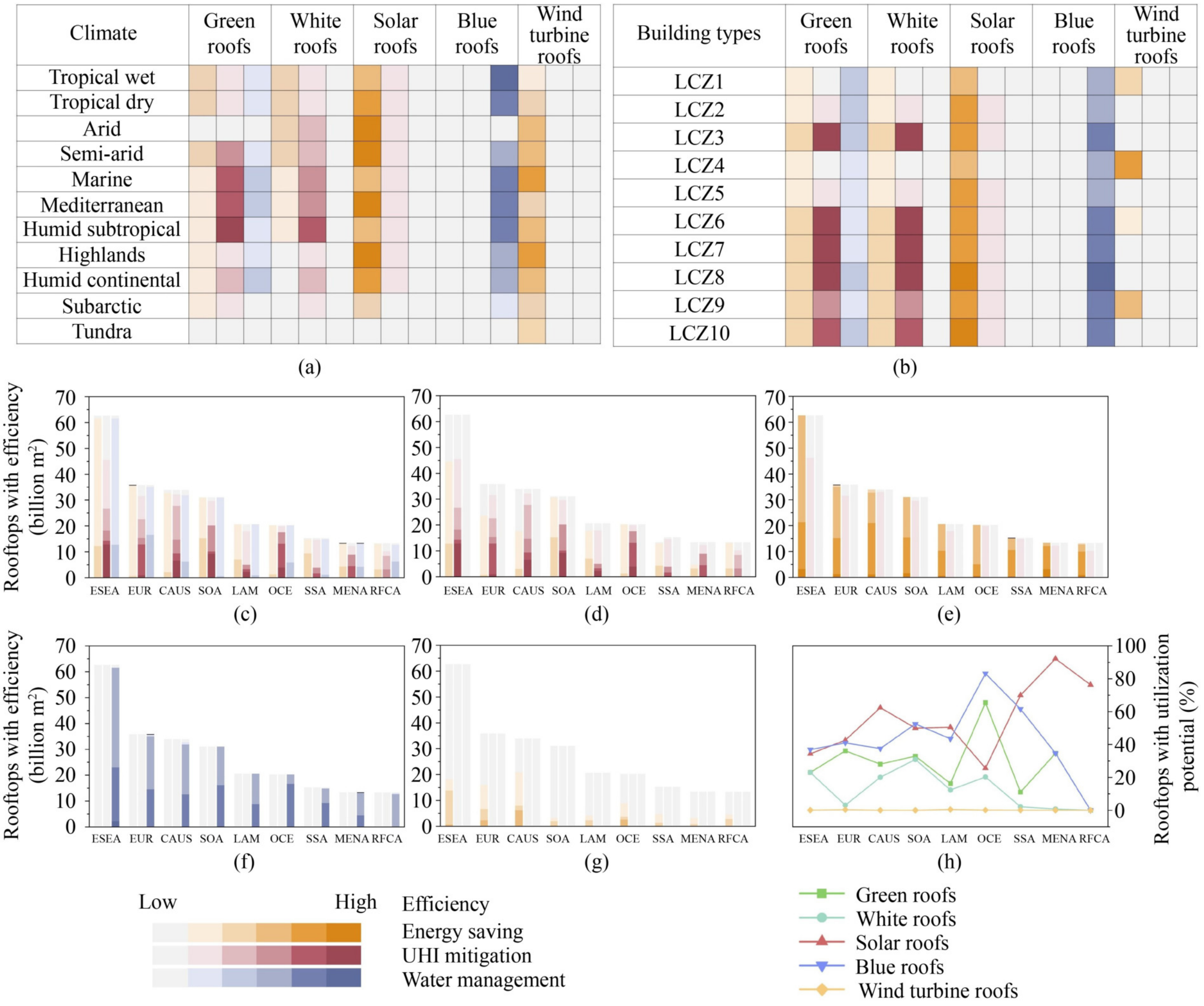


Fig. 6 (a) Rooftop engineering efficiency of different climate conditions; (b) Rooftop engineering efficiency of different building types; (c) Efficiency levels of green roofs; (d) Efficiency levels of white roofs; (e) Efficiency levels of solar roofs; (f) Efficiency levels of blue roofs; (g) Efficiency levels of wind turbine roofs; (h) Rooftops with utilization potential, taking into account climate conditions and building types.

regions are centered around subtropical climate zones, particularly monsoon climate zones, followed by temperate and arid climate zones.

(II) Precipitation: Precipitation plays a crucial role in the benefits of roofs in terms of stormwater management and water conservation. The reduction of stormwater runoff is more significant in cities with annual rainfall of less than 1000 mm. Considering the capacity limitations of the substrate, the benefits may be more pronounced in regions with moderate and evenly distributed rainfall, such as non-monsoon zones in subtropical and temperate regions (approximately corresponding to the eastern parts of EUR and CAUS). Moreover, regions with abundant and evenly distributed precipitation are more suitable for rainwater harvesting for secondary use, such as tropical rainforest climate zones (approximately corresponding to the southern part of ESEA and the central part of LAM), avoiding supply risks and the need for large water storage tanks.

(III) Solar and wind resources: The availability of solar radiation and wind speed are crucial factors affecting the energy capture of solar roofs and wind turbine roofs. Climate zones are correlated with the availability of solar and wind energy resources. Solar resources are abundant in dry climatic zones, followed by temperate monsoon and mediterranean climatic zones. These regions are primarily distributed in OCE, MENA, southwestern parts of CAUS, and southern parts of SSA. On the other hand, wind energy resources are rich in polar climatic zones, subtropical maritime climatic zones, and temperate maritime climatic zones. These regions primarily include coastal areas of Antarctica, EUR, CAUS, and SSA.

4.1.3 Large low-rise buildings are most suitable for rooftop utilization

Figure 6(b) presents the potential benefits of various rooftop engineering options across ten different building types. Certain building roofs are suitable for specific types of rooftop engineering. For instance, LCZ3, LCZ6, and LCZ7 can yield significant benefits through the installation of green, white, and blue roofs, while LCZ8 and LCZ10 can deliver substantial advantages with the installation of solar roofs and blue roofs. LCZ5 and LCZ2 are also suitable for solar roofs and blue roofs. Moreover, certain building types may exhibit a preference for particular rooftop engineering options. LCZ4 is particularly suited to wind turbine roofs, whereas LCZ9 is well-suited to blue roofs. It is important to note that certain building types may not be suitable for rooftop utilization. For example, LCZ1 can accommodate solar roofs, wind turbine roofs, and blue roofs, but the benefits are not significant. The impact of building type on benefits can be examined with building height, building size, building density, and rooftop form.

(I) Height: Building height influences the efficiency of rooftop engineering through its impact on heat conduction, shielding, and building energy/water demand. For green roofs and white roofs, the cooling effect is not significant when rooftops exceed 50 m in height, resulting in limited UHI mitigation (Feng et al., 2022). Consequently, the observed cooling benefits of the OCE in this study may be attributed to its comparatively low building height. Regarding energy and water supply benefits, lower buildings may achieve a higher proportion of supply due to their lower demand (Xu et al., 2023). Thus, although CAUS has a higher unit electricity demand and fewer solar resources compared to LAM, its lower average building height enables it to realize a higher electricity supply potential. For wind turbine roofs, rooftops that surpass the average height of urban areas are preferable to mitigate disturbances and ensure a constant supply of wind energy (Millward-Hopkins et al., 2013; Rezaeiha et al., 2020). As a result, the majority of wind turbine roof cases focus on skyscrapers.

(II) Size: The size of the building affects the efficiency of rooftop engineering by influencing factors such as installation space, the formation of cold islands, and water collection areas. Larger rooftops tend to yield better UHI mitigation results by forming cold islands. Our findings confirm this relationship, as ESEA and EUR, with larger building sizes, exhibit a greater cooling effect compared to other areas with similar summer temperatures. Additionally, larger rooftops provide more space and convenience for the installation of PV panels, wind turbines, and water tanks.

(III) Density: When considering solar roofs, low-density buildings may be preferable as they can avoid rooftop shading. However, dense buildings can hinder the cooling effects of green roofs and white roofs by preventing air circulation from transmitting cooling effects up to two meters above ground (Morakinyo et al., 2017). There is a study that concludes high-density commercial areas have the most noticeable cooling effect, followed by medium-density residential areas and low-density residential areas, however it should be noted that the temperature is measured above the rooftop (Sharma et al., 2016). For wind turbine roofs, dense buildings result in more air turbulence, while large streets with a width-to-height ratio higher than 1.5 may offer better wind resources (Gagliano et al., 2013). In high-density areas, green and blue roofs are more necessary for stormwater reduction due to the scarcity of vegetated and permeable surfaces (Xu et al., 2020).

(IV) The shape of the rooftop: The shape of the rooftop is correlated with the type of building. Low-rise small rooftops (LCZ3, LCZ6, and LCZ7) may be pitched in EUR, CAUS, and southern ESEA, whereas they tend to be flat in northern ESEA (Xu et al., 2021). Low-rise large rooftops (LCZ8) are generally flat and have less equipment occupying them, providing ample space for utilization. Mid-rise rooftops (LCZ2 and LCZ5) are often pitched in EUR and flat in MENA. Among high-rise buildings (LCZ1 and LCZ4), residential buildings generally have flat rooftops but are heavily occupied by equipment, while skyscrapers tend to have diverse forms. The shape of the rooftop affects light orientation and wind flow patterns. With solar roofs, the shaded side of a pitched rooftop lacks solar radiation, and diversified roof forms lack flat space for photovoltaic installation. Regarding wind turbine roofs, the central region of flat rooftops is considered less turbulent (Lu and Ip, 2009; Ledo et al., 2011; Gagliano et al., 2013).

4.1.4 Global rooftop utilization potential assessment

Considering the climate conditions and building types, approximately 50%, 29%, and 43% of rooftops could achieve moderate to high levels of benefits in energy saving, UHI mitigation, and water management, respectively (Figs. 6(c)–6(g)). Rooftops that provide moderate to high levels of benefits are considered suitable for utilization. Specifically, OCE and ESEA have the largest number of rooftops suitable for green and white roofs; CAUS and ESEA have the largest number of rooftops suitable for solar roofs; ESEA and OCE have the largest number of rooftops suitable for blue roofs; and CAUS has the largest number of rooftops suitable for wind turbine roofs.

As shown in Fig. 6(h), the percentage of rooftops with utilization potential varies with the different types of rooftop engineering. For example, over 90% of rooftops in MENA are suitable for solar roofs, while only around 30% are suitable for green roofs and blue roofs. However, this does not imply that MENA should prioritize solar roofs exclusively; the specific configuration should consider local sustainable development requirements. Nevertheless, MENA, OCE, and SSA generally exhibit high rooftop utilization potential, attributed to a greater proportion of low-rise rooftops in climatically favorable areas.

4.2 Research gap and prospect

Through a systematic review of the literature, we identified several shortcomings in the existing research:

(I) Insufficient research on the nexus of energy, water, and carbon. The city, as a system, is characterized by the interconnectedness of its various elements. However, in the research on rooftop engineering, the benefits often remain disconnected from each other.

(II) Rooftop studies mainly focus on single rooftop engineering, especially in large-scale research. There are few case studies on the combined benefits of various rooftop engineering and their integration with other sustainable infrastructures, such as permeable interlocking concrete pavements (Zhang and Ariaratnam, 2021), roadside green swales (Lu et al., 2023), and urban constructed wetlands (Shah et al., 2023).

(III) Insufficient research on energy, water, carbon, and material footprints from a life cycle perspective. Besides benefits, the feasibility of rooftop engineering still needs evaluation from an ecological perspective.

4.3 Limitation

Our work has some shortcomings:

(I) Uncertainties in the measurement of rooftop area and distribution. This review refers to an article describing building types to estimate the distribution of building types in sub-regions, but some regions have only a single case and may not represent the entire region. We tried to reference other relevant papers, and the patterns of building type distribution are almost identical to reality.

(II) Only some significant benefits of the most common rooftop engineering are considered. To make a better cross-sectional comparison, some insignificant benefits and novel rooftop engineering were not considered. Some older cases are included, but because the parameters and scenarios used are relatively ideal, they remain relevant even in today's technological context. However, due to changes in technology, many variables are unknown, so we need to highlight this issue.

5 Conclusions

This review investigated global rooftop resources and their potential benefits. Our findings indicate that approximately one-third of the world's rooftops are suitable for utilization, providing benefits in UHI mitigation, energy saving, stormwater reduction, and water conservation. However, these benefits are significantly influenced by building types and climate conditions. Generally, it is recommended that priority be given to the rooftops of low-rise buildings in regions with moderate climates, such as the mediterranean climate zone. Rooftops in MENA, SSA, and OCE require more intensive exploitation because most of them have suitable conditions. This study calls for urban planners and other stakeholders to actively promote rooftop utilization and to adopt differentiated strategies in different areas.

Competing Interests The authors declare that they have no competing interests.

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Notations

ANT	Antarctic
CAUS	Canada and the United States
ESEA	East and Southeast Asia
EUR	Europe
LAM	Latin America
MENA	Middle East and North Africa
OCE	Oceania
RFCA	Russian Federation and Central Asia
SOA	South Asia
SSA	Sub-Saharan Africa
LCZ1	Compact high-rise buildings
LCZ2	Compact mid-rise buildings
LCZ3	Compact low-rise buildings
LCZ4	Open high-rise buildings
LCZ5	Open mid-rise buildings
LCZ6	Open low-rise buildings
LCZ7	Lightweight low-rise buildings
LCZ8	Large low-rise buildings
LCZ9	Sparsely built buildings
LCZ10	Heavy industry buildings

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