Current Environmental Health Reports (2024) 11:4–17
https://doi.org/10.1007/s40572-023-00427-2

REVIEW

The Application of Nature-Based Solutions for Urban Heat Island Mitigation in Asia: Progress, Challenges, and Recommendations

Logaraj Ramakreshnan[1] · **Nasrin Aghamohammadi**[2,3,4]

Accepted: 22 December 2023 / Published online: 3 January 2024

Abstract

Purpose of Review Unprecedented urbanization in Asia affects the net radiation and energy flux of urban areas in the form of urban heat islands (UHI). The application of nature-based solutions (NbS) via urban green and blue infrastructures is a promising approach to mitigate UHI via urban boundary condition modifications, which affect the energy balance. This narrative review discusses the application of green and blue infrastructures in the Asian context by highlighting its progress, challenges, and recommendations. This review is descriptive in nature and includes perspectives on the discussed topics.
Recent Findings Studies on the application of green and blue infrastructures in UHI mitigation are still scant in Asia. Their cooling performance is greatly influenced by their types, size, geometry, surface roughness, spread (threshold distance), temporal scales, topography, pollution levels, prevailing climate, and assessment techniques. Distinct urban characteristics, climatic conditions, environmental risks, lack of awareness and expertise, lack of policy and government incentives, and limited scientific studies are the major challenges in their implementation of UHI mitigation in Asia.
Summary Although green and blue infrastructures are associated with urban cooling, more in-depth experimental work and multidisciplinary research collaboration are paramount to exploring its implementation potential in Asia and other countries that share similar urban and environmental characteristics.

Keywords Built environment · Blue infrastructure · Heat mitigation · Green infrastructure · Nature-based solutions · Urban heat island

Introduction

Urbanization, catalyzed by the growth of gross domestic product (GDP), is a global megatrend that serves as a major anthropogenic driver of environmental change. According to the World Urbanization Prospects 2018 report, the world is experiencing a huge wave of urban expansion with 55% (4.2 billion) of the population concentrated in the major cities, which is projected to elevate up to 68% (6.7 billion) by 2050 [1]. As a consequence, future growth of the urban population is expected to occur in Asia bringing huge social, economic, and environmental transformations. The conversion of rural areas to urban landscapes results in a substantial decline of green spaces, elevation of low-albedo artificial surfaces as well as disruption of energy and water balances (urban fluxes) that increase the urban temperatures in the form of urban heat island (UHI) effects [2–4]. In addition, the loss of forest and green cover during the land conversion process leads to the emanation of a vast amount of heat-trapping greenhouse gases into the atmosphere [5]. Continual haphazard urbanization has the potential to result in negative consequences on the climate, human health, ecological well-being, economic stability, and governance system [6, 7].

Environmentally sensitive urbanization is therefore essential to mitigate the UHI phenomena, environmental degradation, climate externalities, and other potential

---

✉ Nasrin Aghamohammadi
Nasrin@curtin.edu.au

[1] Institute for Advanced Studies, University of Malaya, 50603 Kuala Lumpur, Malaysia

[2] School of Design and the Built Environment, Curtin University, Kent Street, Bentley 6102, Australia

[3] Department of Social and Preventive Medicine, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia

[4] Centre for Energy Sciences, University of Malaya, 50603 Kuala Lumpur, Malaysia

health impacts [8–10]. In view of this, the application of nature-based solutions (NbS) in the planning, designing, and retrofitting of the cities is a prospective pathway for mitigating UHI while slowing further calefaction, supporting biodiversity, and securing ecosystem services [11–14]. Hence, its application in the mitigation of UHI with concern to the challenges for their implementation and prospects warrants further discussion, especially in the context of the Asian region. Furthermore, heterogeneous spatial characteristics, diverse vegetation, and various climate zones affect the heat mitigation services provided by natural infrastructures [15, 16]. For instance, a stronger cooling effect of greeneries is recorded in the semi-arid and semi-humid zones compared to arid, humid, and extremely humid zones with respect to different vegetation types in each zone [15]. Due to the varying performance of green and blue infrastructures on urban heat mitigation, the present study reviewed the current progress, challenges, and prospects associated with the application of NbS in the UHI mitigation agenda of the fast-growing Asian region based on available scholarly studies.

Approach

A non-systematic literature review was performed based on the peer-reviewed articles published from 2003 to 2023 in the Asian region using the Web of Science. The literature search was focused on the studies that provided quantitative estimates of the NbS application on UHI mitigation in terms of urban green and blue infrastructures. A Boolean search was performed using a combination of keywords such as “urban heat island,” “heat island,” “urban heat,” “heat budget,” “cool island,” “nature-based solutions,” “nature-based designs,” “blue-green,” “green systems,” “urban greenery,” “urban vegetation,” “urban forestry,” “urban park,” “green roof,” “green wall,” “living wall,” “street tree,” “blue body,” “urban lake,” “urban river,” and “wetland.” Other keywords such as “health,” “mental,” “psychological,” “emotion,” “respiratory,” “cardiovascular,” “mortality,” “wellbeing,” “heat stress,” “heat cramp,” “thermal comfort,” and “physical activity” were used in combination with the aforementioned terms to search for review articles that provided a summary of potential health benefits of NbS application in UHI mitigation agenda. This was done to emphasize the salutogenic role of green and blue infrastructures that provide multiple contributions toward the environment, health enhancement, and economy (healthcare) through its potential application in the Asian region. Meantime, the challenges and potential recommendations for its application were suggested based on the authors’ perspectives on the discussed topics.

Urbanization and UHI Intensity (UHII) in Asia

Asia is one of the fast-urbanizing regions (1.3% annually) and home to 20 megacities with inhabitants of more than 10 million people [1, 17]. Seven out of the world’s ten largest urban centers in 2015 are located in Asia, which hosts approximately 13% of urban populations as shown in Fig. 1. Haque et al. [18] hypothesized that the majority of the fragmented or diffused patches of built-up areas would coalesce and result in more aggregated urban landscapes in Asia by 2030.

The rapid growth of the Asian cities accelerated the urban temperatures compared to their rural peripheries in the form of UHI. In Tokyo, Japan, the seasonal average UHII for the compact and super high-rise, high-rise, mid-rise, and low-rise urban areas were 3.1 °C, 4.1 °C, 5.8 °C, and 8.3 °C, suggesting the relative heat storage capacities of morphologically diverse urban areas [4]. In Delhi, India, an increase of 4.8–5.1 °C in land surface temperature (LST) was recorded over two decades (2000–2020), which corresponds to a one-fifth decrease in its vegetation cover and fallow lands [19]. The increasing urbanization in Shanghai, China, registered nighttime UHIIs which are 0.4 °C greater than that of daytime [20]. The UHII recorded the day and night in Dhaka, Bangladesh, was nearly 7.0 and 5.0 °C, which was increasing at a rate of 0.03 °C/year and 0.02 °C/year during 2001–2017 [21]. Despite these high magnitudes, the behavior of UHII was observed to vary with the spatial heterogeneity of continents and climate zones [22], which could influence the efficiency of NbS in UHI mitigations.

NbS and the Applications in UHI Mitigation in Asian Context

NbS refers to an umbrella concept of ecosystem-based approaches that work in ally with nature to address multiple environmental, economic, and societal challenges [11–14]. The conventional UHI mitigations usually focused on the minimization of solar radiation absorption by urban structures, air flow enhancement in urban areas, and integration of cooling elements into the built environment [23]. However, the application of NbS in UHI mitigation could range from engineered solutions (i.e., green walls, hydroponic green roofs) to the use of more naturally managed ecosystems (i.e., wetlands, lakes, forests). Some mitigation strategies exert a direct impact on a structure or individual by modifying the urban boundary conditions via convective and radiative loads. Meantime, some strategies have an indirect impact by modifying

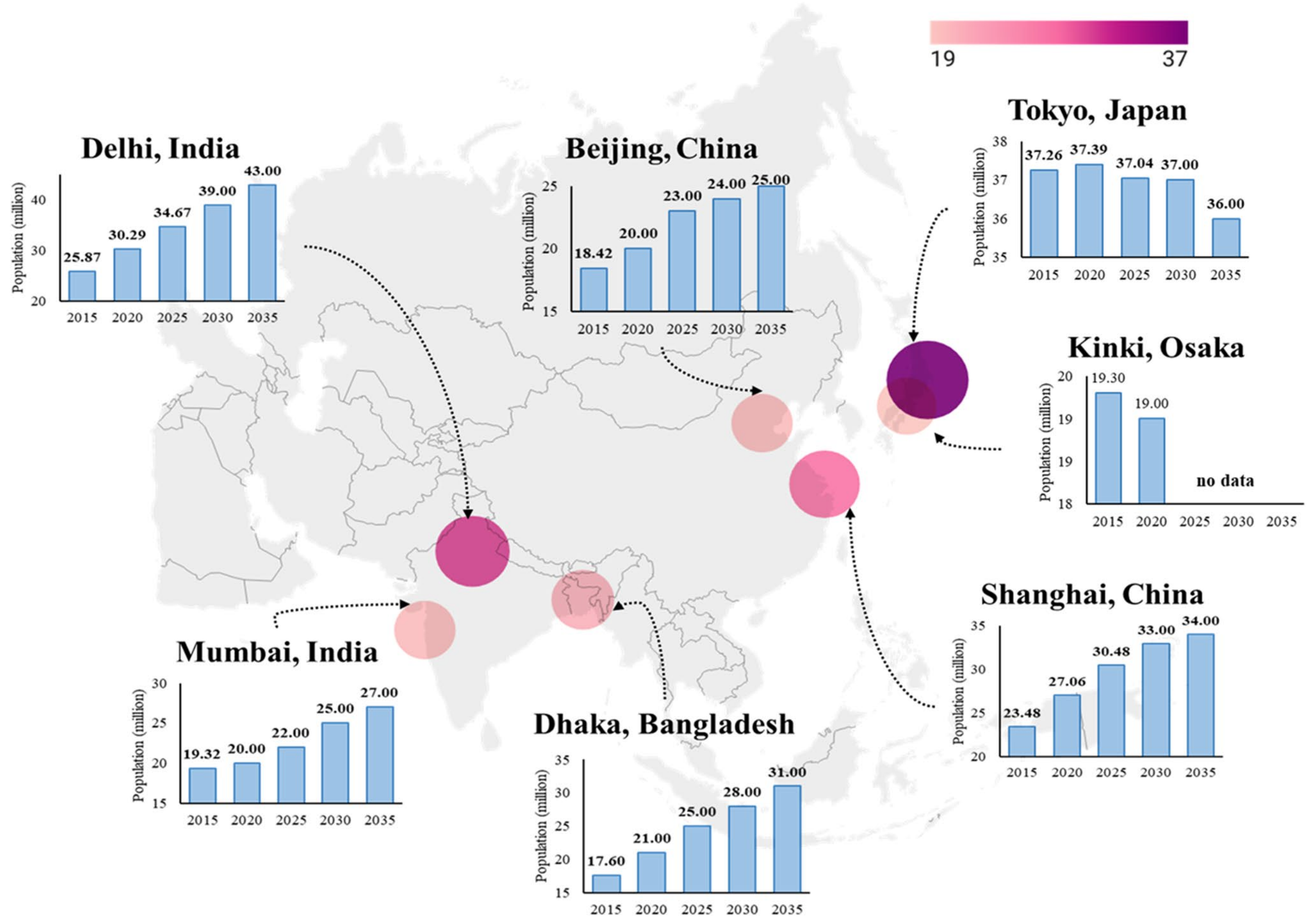


Fig. 1 World's seven largest urban agglomerations in 2015 with population estimates and projections up to 2035. **Data source**: United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision (File 11a: The 30 Largest Urban Agglomerations Ranked by Population Size at Each Point in Time, 1950–2035), Online Edition

the ambient conditions (i.e., temperature, humidity) surrounding a structure or individual, which, in turn, affects its energy balance [24]. The energy flux comparison by land cover types in Yongin-si, South Korea, spotlighted that the most vital ecosystem cooling service mechanism was the generation of the latent heat flux from evaporation (water bodies and swamps) and transpiration (forest and grassland) [25]. Nevertheless, one of the downsides of incorporating greeneries and blue space in urban areas is that it can elevate the local attractiveness that invites more urban development to the area, which, in turn, exacerbates the UHI [26]. For instance, in Seoul, South Korea, the proximity of Gyeongui Line Forest Park encouraged the gentrification process, which elevated new developments and housing prices in the area [27]. Similarly, the price of housing units in "Forest City," a green city concept built on four man-made islands in Malaysia, increased due to the incorporation of green elements into the urban designs [28]. Despite this, the application of NbS in urban development can contribute to decreased energy consumption and heat mitigation.

Green Infrastructure

Incorporating vegetation in urban areas is one of the ecologically friendly measures to resolve the UHI effects [15, 29, 30]. Green infrastructure can take many forms such as urban forests, urban parks, gardens, woodlands, green walls or façades, green roofs, and street trees, which provide varying ecosystem services to the urban environment such as microclimate modifications, carbon sequestration, reduced surface runoff, flood relief, sustainable drainage, aesthetic values, and salubrious passive recreations [31, 32]. Green infrastructures modify the microclimate based on three underpinning mechanisms such as (i) shading which reduces the solar insolation by building components, (ii) increased albedo which reduces the long-wave exchanges among the urban infrastructure, and (iii) increased evapotranspiration which influences the sensible and latent heat fluxes [15, 33–35]. In addition, urban vegetation canopies can also improve surface roughness to generate mechanical turbulence and thereby enhance convective heat loss [36, 37]. From a broader perspective, the benefit of adding more vegetation into urban areas is two-fold such as improvement of building energy balance and occupant thermal comfort levels as well as improvement of the outdoor environment and pedestrian thermal comfort levels [13]. Notwithstanding this, mixed reviews are reported in the literature on the efficiency of cooling by the transpiration process and shading by vegetation. Huang et al. [38] argued that tree transpiration has a pronounced impact on air temperature compared to shading, whereas Koch et al. [39] reported vice versa. Based on these scenarios, it should be noted that the cooling performance of both of these mechanisms depends on the tree species, morphology, coverage, and their physiological responses to heat [38]. In tropical Singapore, the influence of evapotranspirational cooling on thermal comfort enhancement is reported to be less effective compared to tree shading due to low humidity gradients [40]. However, this can vary in other settings depending on environmental variables such as wind speed, air temperature, vapor pressure, soil moisture, solar radiation reaching the canopy, and carbon dioxide concentration [38]. Despite these challenges, the integration of greenery systems in four scales, namely individual building level, street level, neighborhood level, and microscale level, is anticipated to further shape the extent of cooling effects and other corresponding ecosystem services experienced by the urban areas and city dwellers [41].

Urban Forests and Parks

Urban forests are small enclaves of ecosystems in the urban landscape that buffer ground cooling by providing a divergent outflow of cool air toward the surrounding areas [42]. Tree size, height, crown closure, leave area index, species composition, etc. are called the three-dimensional spatial arrangement of the urban forest, which strongly advocates the exchanges of evapotranspiration and energy between a forest ecosystem and atmosphere [43]. Urban forest landscape elevates the dew deposit and nocturnal relative humidity in the urban areas, which play a significant role in UHI amelioration [44]. Even though urban areas recorded high anthropogenic water vapor emissions, the magnitudes of the water vapor emissions from the urban park in Sakai, Osaka, Japan, were high and comparable to that from a planted forest due to the oasis effect [45]. This indicates that the urban vegetation, including soils, could play an important role in water vapor emissions, and dissipation of surface energy as latent heat, thus reducing the warming effects caused by the UHI phenomenon [46]. Such characteristics enable most of the urban forests, as a stand-alone ecosystem, to generate their own microclimate and impart resilience to climate change. In the Asian region, a plethora of investigations dealing with urban forests or parks is focusing on their cooling effects, characterized by the types of forests [47], tree architecture [34, 43, 48–50], forest or park configurations [51–56], forest size or amount [57, 58], threshold distances [6, 42, 43, 47, 51–53, 58], geographical attributes [59], and the energy balance between vegetation and man-made structures or atmosphere [32, 33].

Selection of urban forest types is crucial to optimize the extent of the cooling effect that varies according to the distance from each type of forest, known as a threshold distance. Tang et al. [47] described that the cooling intensities of different forests in Changchun city, China, were only within a certain threshold distance such as landscape forest (3.2 °C; 125 m), ecological public welfare forest (0.2 °C; 150 m), and attached forest (0.6 °C; 5 m). Tree architecture such as crown closure, leave area density (LAD), height, and basal area were also reported to influence the cooling effect [43]. By changing the characteristics of LAD per plant from 4% trees to 60% trees, Tamaskani Esfehankalateh et al. [34] identified an approximate reduction of 3.0–5.2 °C in air temperature during summertime in Seongnam, South Korea. LAD has a high correlation with the drag coefficients (0.5–0.9) of common subtropical trees [50] compared to trees in temperate areas (0.1 to 0.3) [60], providing better cooling performances in the Asian region. By manipulating the tree canopy densities in Bhopal, India, Ali and Patnaik [48] reported that the air temperature under the dense canopy ($> 70\%$) was 2.1 °C lower than that of the open canopy ($< 40\%$). They recorded a mean radiant temperature (T_{mrt}) difference of 4.6 °C between the canopies, suggesting a 10% increase in tree canopy density could lower the T_{mrt} by 0.6 °C. Multiple layered canopies of woodland in Hong Kong are able to record a maximum cooling of -4.1 °C in summer compared to other surfaces [49]. However, the extent of woodland cooling beyond its perimeter was not reported in the study.

In terms of the spatial configuration of urban forests, Wang et al. [56] suggested that UHI attenuation can be maximized by increasing the urban forest patches. In 0.9 km^2 of Olympic Forest Park, Beijing, China, Amani-Beni et al. [51] reported that LST dropped by 0.4 °C with a 10% increase in the green space and by 0.15 °C with a 1 km decrease in distance to the edge of the park. In another study, Amani-Beni et al. [6] observed lowered air (1.0–3.5 °C) and surface (1.7–4.8 °C) temperatures in the same park where a 10% increase in the green space was related to an air temperature drop by 0.16 °C. The urban green space gradient with relatively smaller size forest patches produces more cooling effects [54]. Therefore, it is necessary to improve the spatial arrangement of the existing forest patches instead of increasing their coverage. On the other hand, Zhou et al. [55]

reported that the aggregated distribution of forest patches with increased shape complexity provided a much stronger cooling effect up to 7.8 °C compared to the fragmented distribution. In contrast, some studies reported that patched configuration could induce hot spots within the forest areas [53]. Besides the patched arrangement, the line arrangement of the forest also demonstrates a significant cooling performance. Kim et al. [52] reported that the Gyeongui line forest developed along abandoned railway tracks in Seoul, South Korea, reduced the surface temperature within a marginal distance of 300.4 m from the forest, which resulted in reduced residential and commercial buildings' energy consumption.

The cooling performance is also influenced by the size of the parks. By investigating 33 parks of different sizes in Changchun, China, Ren et al. [57] revealed that the maximum summertime cooling intensity (8.9 °C) was recorded for the largest park (324.6 ha) which decreases with the size of the park. Similarly, Lee and Park [42] identified that the cooling effects were highly dependent on the size of the urban forests in Seoul, South Korea, which can reach up to 300 m threshold distance from the urban forests. By using a time-series of remotely sensed imagery of Beijing, China, from 1990 to 2007, Huang and Ye [58] reported that the vegetation coverage of more than 60% was effective in decreasing LST within a threshold distance of 90–120 m.

The energy balance between vegetation, man-made structures, and atmosphere is another factor studied to elucidate the cooling performance of urban forests. Kuang et al. [33] described that the Olympic Forest Park in China registered a maximum seasonal average net radiation flux (238.7 ± 94.8 W/m^2) in summer daytime, which was approximately 59.0 W/m^2 higher than that on a nearby building roof due to albedo differences. They also expounded that the cooling effect of the park was more pronounced when there was no external horizontal advection by the wind, whose speed was opposed by aerodynamic impedance. Lee et al. [32] reported that the Seoul Forest Park in South Korea reduced the UHI intensity by 0.6 °C in summer compared to the adjacent high-rise urban areas due to the larger thermal capacity of the vegetation and permeable soils. The geographical attributes also influence the cooling effect of urban vegetation. The cooling performance of urban forests was reported to be different for coastal cities and negatively correlated with the distance from the coastline [59].

Masutomi et al. [61] forecasted that the amplification of urban tree coverage to 30 m^2 per capita could reduce 0.4–0.5 °C of air temperature in Tokyo, Japan. Besides UHI mitigation, urban forests offer a multitude of health and social benefits such as thermal comfort, social activities, leisure, and education [56]. Using six healthy male university students (aged 22.0 ± 1.0 year) with similar body weights and heights, Ren et al. [62] found that the street with the highest tree cover (75%) registered lower physiological equivalent temperature (PET), systolic blood pressure, diastolic blood pressure, and pulse rate compared to the street with 3% tree cover, suggesting enhanced thermal comfort level and physiological parameters. Similar effects were also reported in Damascus, Syria [63] and Shenyang, China [64].

Green Walls and Façades

Green walls refer to all systems which enable the greening of a vertical surface of buildings [65] and are categorized as green facades or living walls based on their systems and construction characteristics [66, 67]. They barricade or reduce the thermal energy flowing into the building interior through shading and evaporative cooling mechanisms, translating into cooling load reduction and energy savings [68]. When applied at the street scale, the combined system of vegetation and soil in green walls or façades can provide evaporative cooling effects and improve the thermal comfort of pedestrians in the area [3].

The majority of studies devoted to green walls or façade intervention on urban cooling in the Asian region are based on parametric simulations rather than real-scale, in situ experimentations. This can be attributed to the difficulty of finding a large-scale, facade-greening project, and a control case with similar design characteristics in the Asian context. The utilization of numerical tools such as energy balance models (or urban canopy model) and computational fluid dynamic model (i.e., ENVI-met, Fluent) [3] or integrated models (often with building energy models) [69, 70] mostly dominated the literature. On an important note, many studies have widely relied on ENVI-met which simulates atmosphere-building-plant-soil interactions based on the fundamentals of fluid mechanics and heat transfer [71]. Capturing the cooling performance of a single-green wall or façade in a large city environment was not feasible, which further motivated the researchers to investigate the combined effects of more than one type of urban greening option in their models. The impact of combined strategies, including other factors such as albedo reduction of building walls and sidewalks, on UHI mitigation is anticipated to be higher due to the synergistic benefits [72]. Since the simulation of a few scenarios encompassing both green walls and roofs is mostly used in the same studies, it is quite difficult to discuss studies focusing on green walls alone in this region.

A plethora of studies explored the cooling performance of green walls by comparing the buildings enveloped with and without green walls. By using a coupled hygrothermal transfer model, He et al. [69] discovered that the green envelope of office buildings in Shanghai, China, decreases sensible heat with a maximum indoor temperature difference of 0.34 °C between buildings with and without them under free-floating conditions. Basher [73] recorded 0.94 and

1.3 °C reductions in the indoor temperature and T_{mrt} from a green wall set up on the balcony area of a residential building in Penang, Malaysia. Similarly, living walls exhibited improved thermal performance in reducing the temperatures of external wall surface, internal wall surface, and internal air temperature by 10.2 °C, 3.3 °C, and 2.1 °C in tropical Sri Lanka [74].

The green walls are also reported to provide better thermal insulation to the buildings, resulting in a smaller heat gain throughout the day or heat loss at night. Under heating conditions, the average heat flux of the room with no green wall was 3.1 W/m^2 larger than that of the room with a green wall, which corresponds to 1.22 times of energy consumption in Hunan, China [75]. Lee and Jim [8] identified that the green wall accommodated with *Lonicera japonica* climbers with 0.24 LAI in Hong Kong, China, can shield the buildings against insolation up to 497 W/m^2 behind the canopy and 356 W/m^2 in the indoor space, with the average daily energy saving of 0.226 kWh/m^2 (USD 75.8). In Iran, Karimi et al. [76] identified that the thermal transmittance of the wall is reduced in buildings with living green walls due to material layers, compared to buildings with direct green facades. They reiterated that the prior selection of appropriate construction methods and plant species is pivotal for optimizing their performance on UHI reduction.

Concerning the types of green walls, Wong et al. [68] discovered that the modular panel with the vertical interface and inorganic substrate can reduce the ambient temperature up to 3.3 °C at a distance of 0.15 m in Singapore. Their study emphasized that the physical structure of the green walls, substrate type, composition, depth, and moisture content have a dominant impact on the performance of different types of green walls in the tropical region. The building characteristics were also reported to influence the performance of green walls. Peng et al. [3] found that low-rise, high-density urban blocks in Nanjing City, China, experience the maximum cooling benefit due to the highest ground and canopy cooling intensity per unit greening area, suggesting its potential in pedestrian-level microclimate enhancement. Likewise, in English Bazar Municipality, India, the compact low-rise and open mid-rise buildings covered fully (100%) with green walls were reported to reduce the peak-hour air temperature by 1.33 °C and 2.6 °C, respectively [71]. Even though the green walls reduce the temperature by 0.39–0.75 °C in the summer and 0.39–1.26 °C in winter in Tehran, Iran, the cooling effect was only observed at a distance of 0–0.5 m from the building, suggesting the influence of a threshold cooling distance from the green walls [77].

A number of studies also reported contradictory findings on the cooling performance and UHI reduction potential of green walls in the Asian context. Li and Zheng [70] evaluated the performance of vertical greening on a building according to the actual window-to-wall ratio (rather than a fictitious model without windows) and reported 0.56 °C of cooling effect in summer, which is far less than the values reported in most of the studies. Their findings cautioned that the role of vertical greening in indoor temperatures could be not as strong as suggested in the previous studies. Contradictory findings are reported in other subtropical regions where green façades seem to reflect more radiation toward urban canyons and exacerbate the outdoor thermal comfort levels, which draws attention to the sensitive plantation of building walls that might trap heat [78].

Green Roofs

Green roofs are the roofs of buildings partially or completely covered with different kinds of vegetation over a waterproofing membrane. Since roofs make up 20–25% of the overall urban surface areas [29], converting the unused, impervious parts of building rooftops for vegetation is a practicable solution to re-establish the vanishing urban green cover [79]. Green roofs are classified into three main types such as extensive, semi-intensive, and intensive green roofs with respect to their level of complexity in terms of weight, system build-up height, substrate layer, maintenance, cost, plant types, and irrigation [29, 80, 81]. Installation of green roofs into a rooftop brings three changes such as amplifying the thermal mass, adding porous substances with moisture holding capacity that increases the specific heat capacity as well as increasing the thermal conductivity when the green roof substrate is moist. Nonetheless, these changes are highly dependent on green roof types defined by plant communities, biomass structure, foliage cover, transpiration rate, substrate composition, thickness, and moisture content [82].

The studies on green roofs in the Asian region are mostly based on observations conducted by installing test specimens on the roof surface. Deng et al. [83] reported that the LST of tree-accommodated roofs in Guangzhou and Foshan cities in China is approximately 10–15 °C lower than other artificial roof types. The average air temperature of the hydroponic green roofs (30.3 °C) in Osaka and Kyoto was 2.5 °C lower than the air temperature recorded in the bare roofs (32.8 °C), with a 15% reduction in heat influx during daytime and a 16% reduction in heat outflux during nighttime [84]. In another similar study, greater air and surface temperature reductions were reported by the hydroponic green roofs with respect to net radiation and latent heat fluxes compared to conventional roofs [85]. In the tropical city of Singapore, Yang et al. [86] compared the performance of cool roofs (accommodated with materials that reflect sunlight and absorb less solar energy) and green roofs (use soil and vegetation as insulation) on UHI reduction. They identified that cool and green roofs reduce heat gain by 15.5 KWh/m^2 (37%) and 13.1 (31%) KWh/m^2, respectively for the whole of a summer day. Despite their cooling performance, sufficient exposure to sunlight and the longevity of the rooftop structures were critical for a successful green-roof retrofit in the tropical region [87].

Similar to green walls, a number of studies used modelling techniques to simulate different scenarios with varying degrees of vegetation on roofs to identify the maximum cooling potential. Morkinyo et al. [88] reported the outdoor and indoor cooling effects of green roofs range between 0.05 and 0.6 °C and 0.4–1.4 °C, which varies according to the type of green roof, urban density, time of the day, and climate. They revealed that 5.2% of cooling demand reduction was observed in hot-dry climates with full-intensive green roofs. Herath et al. [30] observed a maximum reduction of 1.9 °C temperature for the 100% green roofing combined with 50% green wall retrofit in the Colombo Metropolitan Region, Sri Lanka. By using the Konkuk University in Seoul, Korea, as the simulation area, Park et al. [89] revealed that the combination of different degrees and types of vegetation in green roofs was effective in different urban areas, under which the sky view factors should be 0.5–0.7. In Japan, Hirano et al. [90] observed a maximum temperature reduction of 0.13 °C for a 100% rooftop greening scenario, which corresponds to a CO_2 reduction of 2.93 kg-CO_2/d compared to the 50% rooftop greening case (1.47 kg-CO_2/d). By using three case studies in Hong Kong, Tam et al. [91] demonstrated that other parameters such as moisture retention of deeper soil and shadow effects of high foliage density influence the cooling performance of the green roofs.

Even though a few studies explored the appropriate vegetation types in green roofs, no firm conclusion has been made on the best type to provide an optimum cooling effect in the Asian context. Jim [92] reported that the transpiration of C3 (Peanut) vegetation delivers more cooling effect compared to the CAM (Sedum) vegetation in the humid-tropical climate, characterized by their density, LAI, and surface of foliage elevated above the soil. In another city with a subtropical climate, the bottom temperature of the perennial herb, shrub, vine, and groundcover green roofs is reported to be lower than the bare rooftop temperature by 17.8 °C, 12.6 °C, 11.6 °C, and 9.3 °C, respectively [93]. Nonetheless, more investigations are needed on the selection of suitable vegetation types for a maximum cooling effect in the Asian region.

Blue Infrastructure

The physical properties of urban water bodies such as high heat capacity, low water surface reflectivity, and high evaporative latent heat enable them to adjust the air and land temperatures by means of heat and water vapor exchange in the horizontal direction [94]. During the evaporation process, the thermal energy is absorbed from the surroundings as the water turns from liquid to gas, which provides a cooling effect to the surroundings. Lake breeze circulation that occurs at urban waterfront provides natural cooling for urban open-air performance in summer [95]. Nevertheless, unlike the widely explored performance of green infrastructure on UHI mitigation, studies pertaining to blue infrastructure cooling effects are still nascent. Furthermore, the distance between water bodies and urban areas, the amplitude of temperature drops, and potential modulating factors that influence the performance of water bodies still warrant further investigation, especially in the Asian context.

The field observations of Murakawa et al. [96] revealed that the Ota River flowing through Hiroshima City, Japan, provided cooling effects up to 5 °C for at least a few hundred meters horizontally and more than 80 m vertically. Other than the river breeze of the Ganges, Barat et al. [97] discovered that the surface UHI intensity of Kanpur and Patna in India was influenced by complex land cover and wind speed and direction. Similarly, Saaroni and Ziv [98] reported a temperature drop of 1.6 °C due to the maximum wind speed effect from the lake at the Mediterranean urban park in Tel Aviv, Israel, at midday within the range of 40 m. However, they reported increased heat stress during the late afternoon and evening due to latent heat cooling from the evaporation causing the water to became warmer than the surrounding surfaces. Based on satellite datasets of lakes and rivers in Shanghai, China, Du et al. [94] identified that the water-cooling island (WCI) effect was prominent at 0.74 km from the water body with a temperature drop of 3.3 °C and temperature gradient of 5.2 °C/km. Of note, the WCI effects were positively correlated with the proportion of vegetation around them. Wang et al. [99] found that the distance of 0.01–0.02 km from the Yangtze River Delta, China, exerts a relative influence on surface UHI, which then decreases when the distance is less than 0.025 km. Lin et al. [100] observed an 11.3% depression of surface UHI intensity in the Pearl River Delta Metropolitan Region with a 10% increase in water-body coverage due to ex situ cooling spillover within an envelope of 100 m effective cooling distance. Zhang et al. [101] studied the inter-relationship between the restored Xixi wetlands in Hangzhou, China, and the summertime UHI effect and demonstrated a maximum temperature reduction by 1.5 °C with the recovery of 50 km^2 of wetland.

Despite the size and distance from waterbodies, the cooling performance also depends on a number of other factors. Sun et al. [102] reported that the cooling performance of wetlands in Beijing, China, correlated with the landscape shape index (LSI) of the wetlands and wetland location in relation to the downtown. Similar to urban forests [55], the aggregated wetland patches of larger sizes exhibit lower and more stable LST compared to the fragmented wetland patches of small sizes in Fuzhou city, China [103]. The rapid urban expansion at the expense of wetlands is reported to reduce the wetlands' ability to modify the local microclimate, thus resulting in poor cooling performances. By applying the concentric zone model to Hangzhou city, China, Xue et al. [104] reported that the cooling efficiency increased with blue-green landscape density and therefore recommended 40–70% of their coverage in urban planning. By investigating the relationship between urban morphology and water bodies' microclimatic regulation, Zhou et al. [95] reported that the floor area ratio can suppress the water's cooling ability in the downtown and main windway areas by 28.7% and 20.6%. By employing the growth regression tree model, Jiang et al. [105] studied the blue-green synergistic cooling of the riparian buffer along 18 river channels in Shanghai. They identified that river widths larger than 30 m have a notable role in decreasing the surface temperature within the distance of 260 m from the riverbank. By means of a mobile measurement near the Yangtze River in Wuhan during a hot and humid summer day, Wang et al. [106] observed the cooling effect of the river up to 3.55 °C within 1741 m from the riverbank.

The Health Benefits of Urban Green and Blue Infrastructures

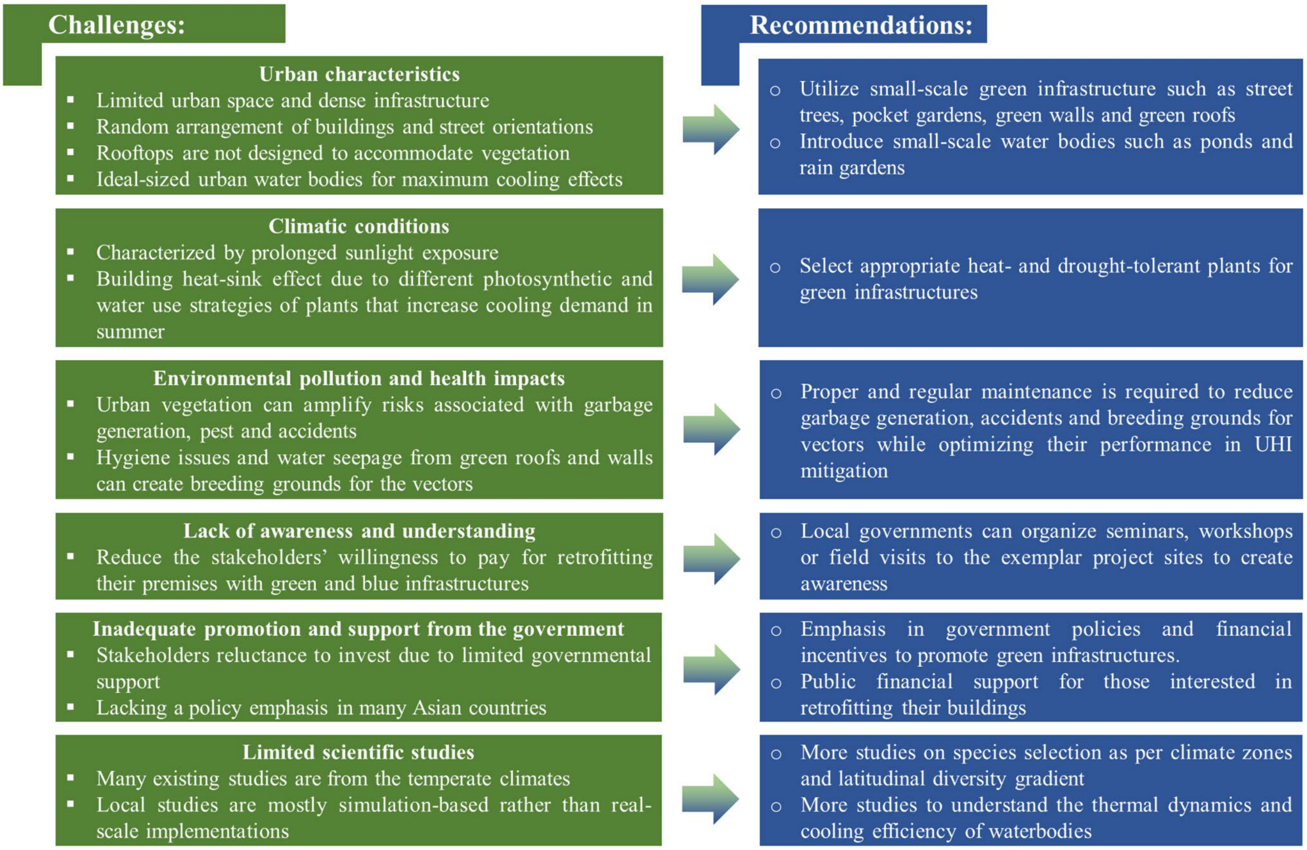
Benefits to humans are one of the key considerations in every application of NbS [107]. Green and blue infrastructures are regarded as therapeutic landscapes which provide space for physical activity and social interactions that enhance urban health. A systematic review of 61 studies encompassing cross-sectional, prospective, experimental, ecological, and birth cohort studies reported that the ecosystem services of green and blue infrastructures can enhance the physical and psychological health of urban dwellers by decreasing heat exposure, air pollution, and noise [108]. In a comparative review of 25 UHI mitigation studies, the impact of urban vegetation on thermal comfort enhancement is reported to be even more significant compared to high-albedo materials, which increase the re-radiation of sun to pedestrians [109]. Essentially, Hami et al. [110] reviewed that the vegetation selection, their arrangement and distribution as well as connectivity as a network are crucial to maximize their effect on thermal comfort improvement.

The relative effect of greeneries on the deposition, dispersion, and modification of particulate matter (PM_{10} and $PM_{2.5}$) in the atmosphere results in their lowered mass concentrations, which eventually reduce the exacerbation of respiratory or cardiovascular risks [111]. A health impact assessment of 93 European cities revealed that about 1.84% of all-cause mortality for adults aged 20 years and above could be prevented by increasing city tree coverage to 30% [112]. Regardless, Gascon et al. [113] described that evidence on the association between urban greenery and all-cause mortality is limited in their systematic review despite a potential association of reduction in the risk of cardiovascular disease-caused mortality. The urban green space used for physical and social activities is indispensable to promote mental health, especially among vulnerable populations such as older adults [114]. The experiences acquired by humans from their interaction with green roofs [115] and walls [116] including their access, use, and aesthetic values reported to have notable roles in promoting psychological well-being among city dwellers. Nonetheless, other reviews provided inconclusive evidence on the causal relationship between urban greeneries and mental health due to a limited number of studies and the heterogeneity in exposure assessments [117]. The aesthetic values of blue infrastructures are also reported to be associated with emotional benefits [118]. A meta-analysis of 8 randomized controlled trials demonstrated improved physical and mental health among younger adults due to green and blue physical activity interventions regardless of the intervention intensity or their sociodemographic characteristics [119]. While the existing evidence affirms the beneficial impacts of green and blue infrastructures on health, more landscape approach-based investigations are needed to explore their potential in addressing both UHI and urban health issues.

Challenges and Recommendations for Implementing NbS via Urban Green and Blue Infrastructures to Mitigate UHI in Asia

There are six unique challenges identified for the application of green and blue infrastructures to mitigate UHI in Asia (Fig. 2).

Firstly, the direct adoption of NbS from a western context may not always fit the unique urban attributes of Asia [87], characterized by limited urban space and dense infrastructure [49, 120, 121]. In this case, utilizing small-scale green infrastructure such as street trees, pocket gardens, green walls, and green roofs could be viable options to resolve UHI issues [25]. However, green wall or roof retrofits could not substitute for ground-level green spaces that can generate spillover cooling effects to the surrounding built-up areas. The random arrangement of low- to high-rise buildings and street orientations in Asian cities inhibit the solar insolation and natural ventilation that could affect the growth and longevity of the plants incorporated into the green infrastructures [87]. Since most of the rooftops are not designed to accommodate vegetation during the construction process, green roof retrofit is highly dependent on the availability of adequate roof space, structural suitability, and its loading capacity [87, 91]. Besides, constructing ideal-sized water bodies that deliver maximum



Challenges:

Urban characteristics
- Limited urban space and dense infrastructure
- Random arrangement of buildings and street orientations
- Rooftops are not designed to accommodate vegetation
- Ideal-sized urban water bodies for maximum cooling effects

Climatic conditions
- Characterized by prolonged sunlight exposure
- Building heat-sink effect due to different photosynthetic and water use strategies of plants that increase cooling demand in summer

Environmental pollution and health impacts
- Urban vegetation can amplify risks associated with garbage generation, pest and accidents
- Hygiene issues and water seepage from green roofs and walls can create breeding grounds for the vectors

Lack of awareness and understanding
- Reduce the stakeholders' willingness to pay for retrofitting their premises with green and blue infrastructures

Inadequate promotion and support from the government
- Stakeholders reluctance to invest due to limited governmental support
- Lacking a policy emphasis in many Asian countries

Limited scientific studies
- Many existing studies are from the temperate climates
- Local studies are mostly simulation-based rather than real-scale implementations

Recommendations:

- Utilize small-scale green infrastructure such as street trees, pocket gardens, green walls and green roofs
- Introduce small-scale water bodies such as ponds and rain gardens

- Select appropriate heat- and drought-tolerant plants for green infrastructures

- Proper and regular maintenance is required to reduce garbage generation, accidents and breeding grounds for vectors while optimizing their performance in UHI mitigation

- Local governments can organize seminars, workshops or field visits to the exemplar project sites to create awareness

- Emphasis in government policies and financial incentives to promote green infrastructures.
- Public financial support for those interested in retrofitting their buildings

- More studies on species selection as per climate zones and latitudinal diversity gradient
- More studies to understand the thermal dynamics and cooling efficiency of waterbodies

Fig. 2 Challenges and recommendations for implementing urban green and blue infrastructures to mitigate UHI in Asia

cooling effects could be a challenge in Asian cities. Introducing small-scale water bodies such as ponds and rain gardens may resolve this issue [25].

Secondly, the effectiveness of the green and blue infrastructures is highly dependent on the Asian climatic conditions [88, 122, 123]. Most of the Asian region is characterized by prolonged sunlight exposure, and therefore selecting appropriate heat-tolerant plants is crucial for green infrastructures [67, 123]. For instance, even though drought-resistant *Sedum* was widely used in extensive green roofs in cold climates [124], its application in hot climates warrants further consideration owing to its low thermal resistance value [125, 126]. The selection of C3, C4, or CAM vegetation with different photosynthetic and water-use strategies in green walls and roofs was reported to generate various heating and cooling effects according to the diurnal scales [121, 127]. This generates a building heat-sink effect that warms indoor air and heightens the electricity consumption for cooling purposes in summer [92]. To resolve this issue, vegetation that has the ability to withstand long radiation and drought can be incorporated into the green infrastructures [73, 77]. Tropical forest trees with diverse trunk and branching structures, scale of leaves, and high heat-tolerant properties can be incorporated into urban parks for maximum cooling effects [128–130].

Thirdly, environmental pollution and the associated health impacts could be another challenge for the successful implementation of green and blue infrastructures in UHI mitigation. Urban trees with frequent leave shedding and the huge root system can amplify risks associated with garbage generation, pest, and accidents [131]. The hygiene issues and water seepage due to poor maintenance of green roofs and walls can create breeding grounds for the vectors that heighten the incidence of infectious diseases in the cities. Therefore, proper and regular maintenance of these infrastructures is deemed essential to optimize its performance in UHI mitigation.

Fourthly, the lack of awareness and understanding about NbS as a holistic concept to tackle multiple environmental issues, including UHI, is another prohibiting factor for its wide-scale implementation in Asia [132, 133]. The cost associated with the construction and maintenance of green and blue infrastructures makes the developers and building owners pay less attention to incorporating them into their premises. Increased awareness is essential to increase the stakeholders' willingness to pay for retrofitting their premises with green and blue infrastructures [134]. The local governments can organize seminars, workshops, or field visits to the exemplar project sites to create awareness on the benefits of these infrastructures in UHI mitigation.

Fifthly, inadequate promotion and support from the government is another limiting factor for the incorporation of green and blue infrastructures in Asian cities. Stakeholders are reluctant to invest in green and blue infrastructures due to large capital and maintenance costs, which could be incentivized by the governments through policy emphasis [91]. Many Asian countries have promulgated the concept of NbS in their policies to combat UHI such as the “Urban Forest” projects (in Malaysia and Singapore) [3], Gross Floor Incentive Scheme (in Singapore) [135], and the 2030 urban master plan strategy (in Seoul, South Korea) [52]. However, such policy emphasis is still lacking in many other Asian countries. To overcome this, government policies and financial incentives should have become an essential consideration to promote green infrastructures. Public financial support can be provided for the public who are interested in retrofitting their buildings with green walls or roofs.

Lastly, there are limited scientific studies to support their implementation from policy, technical, economic, and social perspectives. Many existing studies are from the cold, temperate climates, whereas the local studies are mostly simulation-based rather than real-scale implementations. Despite the well-known efficiency of urban greenery in heat mitigation, the cooling magnitude is highly dependent on the vegetation type, size, and quantity. Due to the varying distribution of vegetation as per the climate zones and latitudinal diversity gradient, more studies need to be devoted to the species selection in green retrofits for effective heat mitigation in the Asian context. Besides, more studies are needed to comprehend the thermal dynamics and cooling efficiency of waterbodies with respect to the topography, land use patterns, urban configurations, and meteorological variables.

Limitations

This review has several limitations in terms of literature search and interpretation of findings. This review is qualitative in nature, and the reviewed articles are summarized to narrate and inform the readers regarding the progress of the NbS application for UHI mitigation in Asia by highlighting the areas that warrant further improvements. Since a systematic review approach was not applied and only one major publication database was used, it lacks the inclusion of all the published studies for an exhaustive discussion. In addition, no assessments of the quality, validity, or risk of bias in the context of selected studies were presented in this review.

Concluding Remarks

This narrative review investigated the application of NbS in UHI mitigation via urban green and blue infrastructures in the Asian context by highlighting the challenges and recommendations for its implementation. The findings suggested that the NbS-based UHI mitigation studies are still limited in the Asian region. The cooling effects of both green and blue infrastructures are anticipated to be influenced by their types, size, geometry, surface roughness, spread (threshold distance), temporal scales (diurnal and seasonal), topography, pollution levels, prevailing climate, and the assessment techniques used in the studies. These attributes largely affect the horizontal and vertical thermal exchange between these infrastructures and the buildings or atmosphere. The findings also suggest that the environmental capital and cooling efficiency of urban green and blue infrastructures could be maximized by employing them in combination rather than in isolation. When applied together, the urban green and blue infrastructures could provide synergistic cooling and other ecosystem services to the urban areas. The urban and building characteristics, climatic conditions, environmental pollution, lack of awareness and expertise, lack of policy and government incentives as well as limited scientific studies are the major challenges associated with the implementation of urban green and blue infrastructures in Asia. Nevertheless, these challenges provide opportunities for more in-depth real-scale experimental work and multidisciplinary research collaboration to explore its implementation in Asia.

Acknowledgements The authors would like to extend their gratitude to Universiti Malaya for providing the opportunities and space to conduct this study.

Author Contribution LR: conceptualization, methodology, investigation, writing—original draft, and writing—review and editing. NA: supervision, conceptualization, and writing—review and editing.

Declarations

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest The authors declare no competing interests.

References

1. United Nations. Department of Economic and Social Affairs, Population Division. World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.
2. Oke TR, Mills G, Christen A, Voogt JA. Urban climates. Cambridge University Press; 2017.

3. Peng LL, Jiang Z, Yang X, He Y, Xu T, Chen SS. Cooling effects of block-scale facade greening and their relationship with urban form. Build Environ. 2020;169:106552.
4. O'Malley C, Kikumoto H. An investigation into heat storage by adopting local climate zones and nocturnal-diurnal urban heat island differences in the Tokyo prefecture. Sustain Cities Soc. 2022;83:103959.
5. Sadatshojaei E, Heidari S, Edraki Z, Wood DA, Ismail AF. Carbon sequestration alternatives for mitigating the accumulation of greenhouse gases in the atmosphere. In: Pirzadah TB, Malik B, Bhat RA, Hakeem KR, editors. Bioresource Technology: Concept, Tools and Experiences. 2022;443–65.
6. Amani-Beni M, Zhang B, Xie GD, Odgaard AJ. Impacts of the microclimate of a large urban park on its surrounding built environment in the summertime. Remote Sens. 2021;13(22):4703.
7. Heaviside C, Macintyre H, Vardoulakis S. The urban heat island: implications for health in a changing environment. Curr Environ Health Rep. 2017;4(3):296–305.
8. Lee LS, Jim CY. Energy benefits of green-wall shading based on novel-accurate apportionment of short-wave radiation components. Appl Energy. 2019;238:1506–18.
9. Connolly C, Ali SH, Keil R. On the relationships between COVID-19 and extended urbanization. Dialogues Human Geogr. 2020;10(2):213–6.
10. United Nations-Habitat (2022). COP27 Presidency Sustainable Urban Resilience for the Next Generation (SURGe). Accessed at https://unhabitat.org/sites/default/files/2022/09/cop27_sustainable_cities_initiative.pdf
11. Augusto B, Roebeling P, Rafael S, Ferreira J, Ascenso A, Bodilis C. Short and medium-to long-term impacts of nature-based solutions on urban heat. Sustain Cities Soc. 2020;57:102122.
12. Girardin CA, Jenkins S, Seddon N, Allen M, Lewis SL, Wheeler CE,...& Malhi Y (2021) Nature-based solutions can help cool the planet - if we act now. Nature, 593, 191–194.
13. Hayes AT, Jandaghian Z, Lacasse MA, Gaur A, Lu H, Laouadi A,...& Wang L (2022) Nature-based solutions (NBSs) to mitigate urban heat island (UHI) effects in Canadian cities. Buildings, 12(7), 925.
14. Xing Y, Jones P, Donnison I. Characterisation of nature-based solutions for the built environment. Sustainability. 2017;9(1):149.
15. Su Y, Wu J, Zhang C, Wu X, Li Q, Liu L,...& Chen X (2022) Estimating the cooling effect magnitude of urban vegetation in different climate zones using multi-source remote sensing. Urban Climate, 43, 101155.
16. Yu Z, Yang G, Zuo S, Jørgensen G, Koga M, Vejre H. Critical review on the cooling effect of urban blue-green space: a threshold-size perspective. Urban Forest Urban Green. 2020;49:126630.
17. International Monetary Fund (2022). GDP, current prices. Accessed at https://www.imf.org/external/datamapper/NGDPD@WEO/OEMDC/ADVEC/WEOWORLD
18. Haque SJ, Onodera SI, Shimizu Y. An overview of the effects of urbanization on the quantity and quality of groundwater in South Asian megacities. Limnology. 2013;14(2):135–45.
19. Singh P, Sarkar Chaudhuri A, Verma P, Singh VK, Meena SR. Earth observation data sets in monitoring of urbanization and urban heat island of Delhi, India. Geomat Nat Haz Risk. 2022;13(1):1762–79.
20. Shen Z, Shi J, Tan J, Yang H. The migration of the warming center and urban heat island effect in Shanghai during urbanization. Front Earth Sci. 2020;8:340.
21. Uddin ASM, Khan N, Islam ARM, Kamruzzaman M, Shahid S. Changes in urbanization and urban heat island effect in Dhaka city. Theoret Appl Climatol. 2022;147(3):891–907.
22. Li L, Zha Y, Zhang J. Spatially non-stationary effect of underlying driving factors on surface urban heat islands in global major cities. Int J Appl Earth Obs Geoinf. 2020;90:102131.
23. Aleksandrowicz O, Vuckovic M, Kiesel K, Mahdavi A. Current trends in urban heat island mitigation research: observations based on a comprehensive research repository. Urban Climate. 2017;21:1–26.
24. Malys L, Musy M, Inard C. Direct and indirect impacts of vegetation on building comfort: a comparative study of lawns, green walls and green roofs. Energies. 2016;9(1):32.
25. Park CY, Park YS, Kim HG, Yun SH, Kim CK. Quantifying and mapping cooling services of multiple ecosystems. Sustain Cities Soc. 2021;73:103123.
26. Zhong W, Schröder T, Bekkering J. Biophilic design in architecture and its contributions to health, well-being, and sustainability: a critical review. Front Archit Res. 2021;11:114–41.
27. Kwon Y, Joo S, Han S, Park C. Mapping the distribution pattern of gentrification near urban parks in the case of Gyeongui Line Forest Park, Seoul. Korea Sustain. 2017;9(2):231.
28 Avery E, Moser S. Urban speculation for survival: adaptations and negotiations in Forest City, Malaysia. Environment and Planning C: Politics and Space; 2022. p. 23996544221121796.
29. Besir AB, Cuce E. Green roofs and facades: a comprehensive review. Renew Sustain Energy Rev. 2018;82:915–39.
30. Herath HMPIK, Halwatura RU, Jayasinghe GY. Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. Urban Forest Urban Green. 2018;29:212–22.
31. Gunawardena KR, Wells MJ, Kershaw T. Utilising green and bluespace to mitigate urban heat island intensity. Sci Total Environ. 2017;584:1040–55.
32. Lee K, Hong JW, Kim J, Jo S, Hong J. Traces of urban forest in temperature and CO2 signals in monsoon East Asia. Atmos Chem Phys. 2021;21(23):17833–53.
33. Kuang W, Li Z, Hamdi R. Comparison of surface radiation and turbulent heat fluxes in Olympic Forest Park and on a building roof in Beijing. China Urban Clim. 2020;31:100562.
34. Tamaskani Esfehankalateh A, Ngarambe J, Yun GY. Influence of tree canopy coverage and leaf area density on urban heat island mitigation. Sustainability. 2021;13(13):7496.
35. Wong NH, Tan CL, Kolokotsa DD, Takebayashi H. Greenery as a mitigation and adaptation strategy to urban heat. Nat Rev Earth Environ. 2021;2(3):166–81.
36. Caplan JS, Galanti RC, Olshevski S, Eisenman SW. Water relations of street trees in green infrastructure tree trench systems. Urban Forest Urban Green. 2019;41:170–8.
37. Zhao L, Lee X, Smith RB, Oleson K. Strong contributions of local background climate to urban heat islands. Nature. 2014;511(7508):216–9.
38. Huang J, Kong F, Yin H, Middel A, Liu H, Zheng X,...& Wang D (2022) Transpirational cooling and physiological responses of trees to heat. Agricultural and Forest Meteorology, 320, 108940.
39. Koch K, Ysebaert T, Denys S, Samson R. Urban heat stress mitigation potential of green walls: a review. Urban Forest Urban Green. 2020;55:126843.
40. Chow WT, Akbar SNABA, Heng SL, Roth M. Assessment of measured and perceived microclimates within a tropical urban forest. Urban Forest Urban Green. 2016;16:62–75.
41. Priya UK, Senthil R. A review of the impact of the green landscape interventions on the urban microclimate of tropical areas. Build Environ. 2021;205:108190.
42. Lee PSH, Park J. An effect of urban forest on urban thermal environment in Seoul, South Korea, based on Landsat imagery analysis. Forests. 2020;11(6):630.
43. Ren Z, He X, Pu R, Zheng H. The impact of urban forest structure and its spatial location on urban cool island intensity. Urban Ecosystems. 2018;21(5):863–74.

44. Ye Y, Zhou K, Song L, Jin J, Peng S. Dew amounts and its correlations with meteorological factors in urban landscapes of Guangzhou. China Atmos Res. 2007;86(1):21–9.
45. Ueyama M, Taguchi A, Takano T. Water vapor emissions from urban landscapes in Sakai. Japan J Hydrol. 2021;598:126384.
46. Zou Z, Yan C, Yu L, Jiang X, Ding J, Ding J, Qiu G. Different responses of evapotranspiration rates of urban lawn and tree to meteorological factors and soil water in hot summer in a subtropical megacity. Forests. 2021;12(11):1463.
47. Tang Z, Zheng H, Ren Z, Zhang D, Wang P, Zhai C,...& He X (2018) Evaluating environmental equities of urban forest in terms of cooling services using ETM+ and Google data. Journal of the Indian Society of Remote Sensing, 46(2), 287–296.
48. Ali SB, Patnaik S. Assessment of the impact of urban tree canopy on microclimate in Bhopal: a devised low-cost traverse methodology. Urban Clim. 2019;27:430–45.
49. Fung CK, Jim CY. Microclimatic resilience of subtropical woodlands and urban-forest benefits. Urban Forest Urban Green. 2019;42:100–12.
50. Zheng S, Guldmann JM, Liu Z, Zhao L, Wang J, Pan X, Zhao D. Predicting the influence of subtropical trees on urban wind through wind tunnel tests and numerical simulations. Sustain Cities Soc. 2020;57:102116.
51. Amani-Beni M, Zhang B, Xie GD, Shi Y. Impacts of urban green landscape patterns on land surface temperature: evidence from the adjacent area of Olympic Forest Park of Beijing. China Sustain. 2019;11(2):513.
52. Kim K, Yi C, Lee S. Impact of urban characteristics on cooling energy consumption before and after construction of an urban park: the case of Gyeongui line forest in Seoul. Energy Build. 2019;191:42–51.
53. Ren Y, Deng LY, Zuo SD, Song XD, Liao YL, Xu CD,...& Li ZW Quantifying the influences of various ecological factors on land surface temperature of urban forests. Environmental pollution, 2016;216, 519–529.
54. Yao L, Li T, Xu M, Xu Y. How the landscape features of urban green space impact seasonal land surface temperatures at a city-block-scale: an urban heat island study in Beijing. China Urban Forest Urban Green. 2020;52:126704.
55. Zhou W, Cao F, Wang G. Effects of spatial pattern of forest vegetation on urban cooling in a compact megacity. Forests. 2019;10(3):282.
56. Wang XH, Wu Y, Gong J, Li B, Zhao JJ. Urban planning design and sustainable development of forest based on heat island effect. Appl Ecol Environ Res. 2019;17:9121–9.
57. Ren Z, He X, Zheng H, Zhang D, Yu X, Shen G, Guo R. Estimation of the relationship between urban park characteristics and park cool island intensity by remote sensing data and field measurement. Forests. 2013;4(4):868–86.
58. Huang C, Ye X. Spatial modeling of urban vegetation and land surface temperature: a case study of Beijing. Sustainability. 2015;7(7):9478–504.
59. Qi Y, Li H, Pang Z, Gao W, Liu C. A case study of the relationship between vegetation coverage and urban heat island in a coastal city by applying digital twins. Front Plant Sci. 2022;13:861768.
60. Manickathan L, Defraeye T, Allegrini J, Derome D, Carmelie J. Aerodynamic characterization of model vegetation by wind tunnel experiment. In: Proceedings of the 4th International Conference on Countermeasures to Urban Heat Island, Singapore. 2016;1–9.
61. Masutomi Y, Sato Y, Higuchi A, Takami A, Nakajima T. The effects of citizen-driven urban forestry on summer high air temperatures over the Tokyo metropolitan area. J Agric Meteorol. 2019;75(3):144–52.
62. Ren Z, Zhao H, Fu Y, Xiao L, Dong Y. Effects of urban street trees on human thermal comfort and physiological indices: a case study in Changchun city. China J Forest Res. 2022;33(3):911–22.
63. Yahia MW, Johansson E. Landscape interventions in improving thermal comfort in the hot dry city of Damascus, Syria—the example of residential spaces with detached buildings. Landsc Urban Plan. 2014;125:1–16.
64. Miao C, Li P, Huang Y, Sun Y, Chen W, Yu S. Coupling outdoor air quality with thermal comfort in the presence of street trees: a pilot investigation in Shenyang, Northeast China. J For Res. 2023;34(3):831–9.
65. Ávila-Hernández A, Simá E, Ché-Pan M. Research and development of green roofs and green walls in Mexico: a review. Sci Total Environ. 2023;856:158978.
66. Manso M, Castro-Gomes J. Green wall systems: a review of their characteristics. Renew Sustain Energy Rev. 2015;41:863–71.
67. Al-Kayiem HH, Koh K, Riyadi TW, Effendy M. A comparative review on greenery ecosystems and their impacts on sustainability of building environment. Sustainability. 2020;12(20):8529.
68. Wong NH, Tan AYK, Chen Y, Sekar K, Tan PY, Chan D,...& Wong NC (2010) Thermal evaluation of vertical greenery systems for building walls. Building and environment, 45(3), 663–672.
69. He Y, Yu H, Ozaki A, Dong N, Zheng S. A detailed investigation of thermal behavior of green envelope under urban canopy scale in summer: a case study in Shanghai area. Energy Build. 2017;148:142–54.
70. Li J, Zheng B. Does vertical greening really play such a big role in an indoor thermal environment? Forests. 2022;13(2):358.
71. Ziaul S, Pal S. Modeling the effects of green alternative on heat island mitigation of a meso level town, West Bengal. India Adv Space Res. 2020;65(7):1789–802.
72. Park CY, Yoon EJ, Lee DK, Thorne JH. Integrating four radiant heat load mitigation strategies is an efficient intervention to improve human health in urban environments. Sci Total Environ. 2020;698:134259.
73. Basher HS. Thermal performance of edible vertical greenery system in high-rise residential balcony. Int J Integr Eng. 2019;11(9):141–53.
74. Rupasinghe HT, Halwatura RU. Benefits of implementing vertical greening in tropical climates. Urban Forest Urban Green. 2020;53:126708.
75. Xing Q, Hao X, Lin Y, Tan H, Yang K. Experimental investigation on the thermal performance of a vertical greening system with green roof in wet and cold climates during winter. Energy Build. 2019;183:105–17.
76. Karimi K, Farrokhzad M, Roshan G, Aghdasi M. Evaluation of effects of a green wall as a sustainable approach on reducing energy use in temperate and humid areas. Energy Build. 2022;262:112014.
77. Daemei AB, Azmoodeh M, Zamani Z, Khotbehsara EM. Experimental and simulation studies on the thermal behavior of vertical greenery system for temperature mitigation in urban spaces. J Build Eng. 2018;20:277–84.
78. Fahmy M, El-Hady H, Mahdy M, Abdelalim MF. On the green adaptation of urban developments in Egypt; predicting community future energy efficiency using coupled outdoor-indoor simulations. Energy Build. 2017;153:241–61.
79 AK MA, Katoh Y, Katsurayama H, Koganei M, Mizunuma M. Effects of convection heat transfer on Sunagoke moss green roof: a laboratory study. Energy Build. 2018;158:1417–28.
80. Ismail WZW, Abdullah MN, Hashim H, Rani WSW. An overview of green roof development in Malaysia and a way forward. In AIP Conf Proc. 2018;2016(1):020058.

81. Shafique M, Kim R, Rafiq M. Green roof benefits, opportunities and challenges–a review. Renew Sustain Energy Rev. 2018;90:757–73.
82. Jim CY. Diurnal and partitioned heat-flux patterns of coupled green-building roof systems. Renew Energy. 2015;81:262–74.
83. Deng Y, Chen R, Xie Y, Xu J, Yang J, Liao W. Exploring the impacts and temporal variations of different building roof types on surface urban heat island. Remote Sens. 2021;13(14):2840.
84. Tanaka Y, Kawashima S, Hama T, Sastre LFS, Nakamura K, Okumoto Y. Mitigation of heating of an urban building rooftop during hot summer by a hydroponic rice system. Build Environ. 2016;96:217–27.
85. Tanaka Y, Kawashima S, Hama T, Nakamura K. Thermal mitigation of hydroponic green roof based on heat balance. Urban Forest Urban Green. 2017;24:92–100.
86. Yang J, Pyrgou A, Chong A, Santamouris M, Kolokotsa D, Lee SE. Green and cool roofs' urban heat island mitigation potential in tropical climate. Sol Energy. 2018;173:597–609.
87. Wong JKW, Lau LSK. From the 'urban heat island'to the 'green island'? A preliminary investigation into the potential of retrofitting green roofs in Mongkok district of Hong Kong. Habitat Int. 2013;39:25–35.
88. Morakinyo TE, Dahanayake KKC, Ng E, Chow CL. Temperature and cooling demand reduction by green-roof types in different climates and urban densities: a co-simulation parametric study. Energy Build. 2017;145:226–37.
89. Park J, Shin Y, Kim S, Lee SW, An K. Efficient plant types and coverage rates for optimal green roof to reduce urban heat island effect. Sustainability. 2022;14(4):2146.
90. Hirano Y, Ihara T, Gomi K, Fujita T. Simulation-based evaluation of the effect of green roofs in office building districts on mitigating the urban heat island effect and reducing CO2 emissions. Sustainability. 2019;11(7):2055.
91. Tam VW, Wang J, Le KN. Thermal insulation and cost effectiveness of green-roof systems: an empirical study in Hong Kong. Build Environ. 2016;110:46–54.
92. Jim CY. Heat-sink effect and indoor warming imposed by tropical extensive green roof. Ecol Eng. 2014;62:1–12.
93. Huang YY, Chen CT, Liu WT. Thermal performance of extensive green roofs in a subtropical metropolitan area. Energy Build. 2018;159:39–53.
94. Du H, Song X, Jiang H, Kan Z, Wang Z, Cai Y. Research on the cooling island effects of water body: a case study of Shanghai, China. Ecol Ind. 2016;67:31–8.
95. Zhou X, Zhang S, Liu Y, Zhou Q, Wu B, Gao Y, Zhang T. Impact of urban morphology on the microclimatic regulation of water bodies on waterfront in summer: a case study of Wuhan. Build Environ. 2022;226:109720.
96. Murakawa S, Sekine T, Narita KI, Nishina D. Study of the effects of a river on the thermal environment in an urban area. Energy Build. 1991;16(3–4):993–1001.
97. Barat A, Parth Sarthi P, Kumar S, Kumar P, Sinha AK. Surface Urban Heat Island (SUHI) over riverside cities along the Gangetic Plain of India. Pure Appl Geophys. 2021;178(4):1477–97.
98. Saaroni H, Ziv B. The impact of a small lake on heat stress in a Mediterranean urban park: the case of Tel Aviv. Israel Int J Biometeorol. 2003;47(3):156–65.
99. Wang Z, Meng Q, Allam M, Hu D, Zhang L, Menenti M. Environmental and anthropogenic drivers of surface urban heat island intensity: a case-study in the Yangtze River Delta. China Ecol Indic. 2021;128:107845.
100. Lin Y, Wang Z, Jim CY, Li J, Deng J, Liu J. Water as an urban heat sink: blue infrastructure alleviates urban heat island effect in mega-city agglomeration. J Clean Prod. 2020;262:121411.
101. Zhang F, Shao D, Shao Y. Wetlands appraisal method to alleviate urban heat island effect. Pol J Environ Stud. 2014;23(5):1805–12.
102. Sun R, Chen A, Chen L, Lü Y. Cooling effects of wetlands in an urban region: the case of Beijing. Ecol Ind. 2012;20:57–64.
103. Cai Y, Zhang H, Zheng P, Pan W. Quantifying the impact of land use/land cover changes on the urban heat island: a case study of the natural wetlands distribution area of Fuzhou City. China Wetlands. 2016;36(2):285–98.
104. Xue X, He T, Xu L, Tong C, Ye Y, Liu H, Xu D, Zheng X. Quantifying the spatial pattern of urban heat islands and the associated cooling effect of blue–green landscapes using multisource remote sensing data. Sci Total Environ. 2022;843:156829.
105. Jiang Y, Huang J, Shi T, Wang H. Interaction of urban rivers and green space morphology to mitigate the urban heat island effect: case-based comparative analysis. Int J Environ Res Public Health. 2021;18(21):11404.
106. Wang Y, Ouyang W, Zhan Q, Zhang L. The cooling effect of an urban river and its interaction with the littoral built environment in mitigating heat stress: a mobile measurement study. Sustainability. 2022;14(18):11700.
107. Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C,...& Turner B (2021) Getting the message right on nature-based solutions to climate change. Global change biology, 27(8), 1518–1546.
108. James P, Banay RF, Hart JE, Laden F. A review of the health benefits of greenness. Curr Epidemiol Rep. 2015;2:131–42.
109. Taleghani M. Outdoor thermal comfort by different heat mitigation strategies-a review. Renew Sustain Energy Rev. 2018;81:2011–8.
110. Hami A, Abdi B, Zarehaghi D, Maulan SB. Assessing the thermal comfort effects of green spaces: a systematic review of methods, parameters, and plants' attributes. Sustain Cities Soc. 2019;49:101634.
111. Diener A, Mudu P. How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective-with implications for urban planning. Sci Total Environ. 2021;796:148605.
112. Iungman T, Cirach M, Marando F, Barboza EP, Khomenko S, Masselot P,...& Nieuwenhuijsen M. Cooling cities through urban green infrastructure: a health impact assessment of European cities. The Lancet 2023
113. Gascon M, Triguero-Mas M, Martínez D, Dadvand P, Rojas-Rueda D, Plasència A, Nieuwenhuijsen MJ. Residential green spaces and mortality: a systematic review. Environ Int. 2016;86:60–7.
114. Carver A, Lorenzon A, Veitch J, Macleod A, Sugiyama T. Is greenery associated with mental health among residents of aged care facilities? A systematic search and narrative review. Aging Ment Health. 2020;24(1):1–7.
115. Williams KJ, Lee KE, Sargent L, Johnson KA, Rayner J, Farrell C,...& Williams NS. Appraising the psychological benefits of green roofs for city residents and workers. Urban forestry & urban greening, 2019;44, 126399.
116. Goel M, Jha B, Khan S. Living walls enhancing the urban realm: a review. Environ Sci Pollut Res. 2022;29(26):38715–34.
117. Gascon M, Triguero-Mas M, Martínez D, Dadvand P, Forns J, Plasència A, Nieuwenhuijsen MJ. Mental health benefits of long-term exposure to residential green and blue spaces: a systematic review. Int J Environ Res Public Health. 2015;12(4):4354–79.
118. Li H, Browning MH, Rigolon A, Larson LR, Taff D, Labib SM,...& Kahn Jr PH. Beyond "bluespace" and "greenspace": a narrative review of possible health benefits from exposure to other natural landscapes. Science of The Total Environment, 2022;159292.
119. Yen HY, Chiu HL, Huang HY. Green and blue physical activity for quality of life: a systematic review and meta-analysis of randomized control trials. Landsc Urban Plan. 2021;212:104093.

120. Jamei E, Ossen DR, Seyedmahmoudian M, Sandanayake M, Stojcevski A, Horan B. Urban design parameters for heat mitigation in tropics. Renew Sustain Energy Rev. 2020;134:110362.
121. Kim Y, An SM, Eum JH, Woo JH. Analysis of thermal environment over a small-scale landscape in a densely built-up Asian megacity. Sustainability. 2016;8(4):358.
122. Sun T, Grimmond CSB, Ni GH. How do green roofs mitigate urban thermal stress under heat waves? J Geophys Res: Atmos. 2016;121(10):5320–35.
123. Zhang Y, Yin P, Li X, Niu Q, Wang Y, Cao W,...& Li BThe divergent response of vegetation phenology to urbanization: a case study of Beijing city, China. Science of The Total Environment, 2022;803, 150079.
124. Castleton HF, Stovin V, Beck SB, Davison JB. Green roofs; building energy savings and the potential for retrofit. Energy Build. 2010;42(10):1582–91.
125. Coutts AM, Daly E, Beringer J, Tapper NJ. Assessing practical measures to reduce urban heat: green and cool roofs. Build Environ. 2013;70:266–76.
126. Rowe DB, Getter KL, Durhman AK. Effect of green roof media depth on Crassulacean plant succession over seven years. Landsc Urban Plan. 2012;104(3–4):310–9.
127. Cao J, Hu S, Dong Q, Liu L, Wang Z. Green roof cooling contributed by plant species with different photosynthetic strategies. Energy Build. 2019;195:45–50.
128. Kjelgren R, Trisurat Y, Puangchit L, Baguinon N, Yok PT. Tropical street trees and climate uncertainty in Southeast Asia. HortScience. 2011;46(2):167–72.
129. Rashid ZA, Al Junid SAM, Thani SKSO. Trees' cooling effect on surrounding air temperature monitoring system: implementation and observation. Int J Simul Syst Sci Technol. 2014;15(2):70–7.
130. Shahidan MF, Shariff MK, Jones P, Salleh E, Abdullah AM. A comparison of Mesua ferrea L. and Hura crepitans L. for shade creation and radiation modification in improving thermal comfort. Landsc Urban Plan. 2010;97(3):168–81.
131. Sabir MA, Nawaz MF, Rasheed F, Naeem MS, Jaskani MJ. Opinion of urban dwellers varies to manage the urban spaces for urban forestry: a case study of Faisalabad city. Pak J Agric Sci. 2021;58(1):105–13.
132. Wilkinson SJ, Reed R. Green roof retrofit potential in the central business district. Prop Manag. 2009;27(5):284–301.
133. Ismail Z, Abd Aziz H, Nasir NM, Taib MZM. Obstacles to adopt green roof in Malaysia. In: Proceedings of the 2012 IEEE Colloquium on Humanities, Science and Engineering, Kota Kinabalu, Malaysia. 2012;357–61.
134. Zhang G, He BJ. Towards green roof implementation: drivers, motivations, barriers and recommendations. Urban Forest Urban Green. 2021;58:126992.
135. Ansel W, Appl R. Green roof policies: an international review of current practices and future trends. In: International Green Roof Association (IGRA), Nürtingen, Germany. 2010;12–5.