# DOCTORAL DISSERTATION

Research of Green Roof Implementation and Impact on Outdoor Thermal Performance at Pedestrian and Near-surface Level in Subtropical Area

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## Abstract

Green roof is an effective measure to save limited land and solve urban heat island (UHI) problem. However, the thermal performance of green roof is a complex engineering which would be influenced by the plant shape, vegetation type, green scale, green coverage ratio, building morphologies, layout style, geographical position, weather condition and so on. Meanwhile, green roof implementation (GRI) provides multifaceted of environment benefit such as extending roof longevity, air purification, water runoff control, water purification, urban infrastructure improvement, but it is limited by several barriers, such as technological support and policy guide. Therefore, green roof implementation should consider both science fundamental feasibly and market principle cost-benefit.

This dissertation would be conducted in Hangzhou City of subtropical area, analyze the green roof market by drivers, motivations, barriers is to complement and promote green roof research, furthermore, analyze the green roof market by different area, age group and gender in China. Then, through two studies of numerical simulation, outdoor thermal environment of green roof is improved by building morphologies and green-roof configurations in different scenarios. Lastly, near-surface thermal performance of green roof and virginally reveal its characteristics in different weather and period. The main works and results can be summarized as follows:

***Chapter 1, Research background of the study***, firstly presents the current UHI problem in worldwide situations, then puts forward to several countermeasures, furthermore, gradually leads to the topic of this dissertation regarding on green roof strategy as one of the important countermeasures, then, provides the relatively previous researches in green roof implementation of thermal mechanism, buildings morphology, green-roofs layout, promotion explore to find the gaps in all literatures. Lastly, the purpose of this dissertation to complement the gaps is explained.

***Chapter 2, A review of drivers, motivations, barriers on green roof implementation,*** aims at conducting a systematic review for identifying the influencing factors- drivers, motivations, and barriers to GRI. Specifically, 217 published works, in which 164 entirely for GRI and 53 partially for GRI, from 2000 to 2019 were reviewed. Based on the review, it was found that the there are three types of drivers to GRI, namely policy pressure, market pressure (e.g., customers demand, award or certification, cost-benefit demand), and innovation and technology advancement. Extensive factors such as energy efficiency, urban heat island mitigation, extending roof longevity, air purification, water runoff control, water purification, urban infrastructure improvement, noise reduction, biodiversity improvement,

recreation, and aesthetics, property value increase, and employment improvement may motivate people to implement green roof techniques. The barriers that may hinder GRI include lack of government policy, unsound technological development, high initial cost and long payback period, and individual unwillingness. Suggestions on how to overcome GRI barriers were proposed, namely: increasing governmental policies and support, improving technical innovation, encouraging long-term view, and increasing education and dissemination. Moreover, this section presents some recommendations for sustainable GRI cases. Overall, this chapter is significant in the development and implementation of green roof in both academic and practical perspectives.

***Chapter 3, Methodology selection and feasibility analysis in China,*** firstly, specifically selected in Hangzhou City of Southern China as the research site, which belongs to hot summer and cold winter area. Later, approach for this dissertation is screened and introduced, in detail, comparing with other software or test principles. Lastly, it analyzes the index frequency of green roof by Baidu Index in China, and the main findings are below：(1) in the three levels of spatial scale of large district-province-city, the index volume corresponding to the three levels are East China, Zhejiang Province and Hangzhou City respectively which is the highest in hot rank. (2) The age group who are more curious about green roof is between 20 and 29 years old, among which males are slightly higher than females by 12%. (3) through the analysis of the hot rank of related words, users who are interested in green roof concentrates on the construction mode and related technologies, such as stainless-steel tank and reclaimed water.

***Chapter 4, Impact of morphological characteristics of green roofs on pedestrian cooling in subtropical area.*** For better cooling performances, this section is essential to reasonably configure green roofs, especially in real and complex neighborhoods. Therefore, the aim of this section is to investigate the impact of morphological characteristics of green roofs on pedestrian cooling in real and complex neighborhoods. In specific, based on an ENVI-met model, this study studied the effect of greening layout, coverage ratio, vegetation height, and building height on pedestrian air temperature reduction in the tropical city of Hangzhou, China. Results indicate green roofs could generate moderate effects on pedestrian air temperature reduction (around 0.10–0.30 °C), while achieving a cooling performance of 0.82 °C. Green roofs in upwind zones were able to generate the most favorable cooling performance, while green roofs in downwind zones made slight differences to pedestrian thermal environments. Green roofs with a low coverage ratio were not useful for lowering pedestrian temperature, and a greening coverage ratio of 25–75% in upwind zones was effective cooling scope in real neighborhoods. Locations that were horizontally close to green roofs enjoyed better cooling performances. Increasing vegetation height could strengthen cooling effects of green roofs, while an increase in building height weakened the cooling performance. Nevertheless, higher building height could enhance pedestrian cooling performances because of building shading effects. In addition, because of wind effects and building shading, building height limits for the cooling performance of green roofs could be higher than 60 m. And the layout of orientation array of green roof along the wind direction is more comfortable to expand the cool resource at the same ratio of green roof.

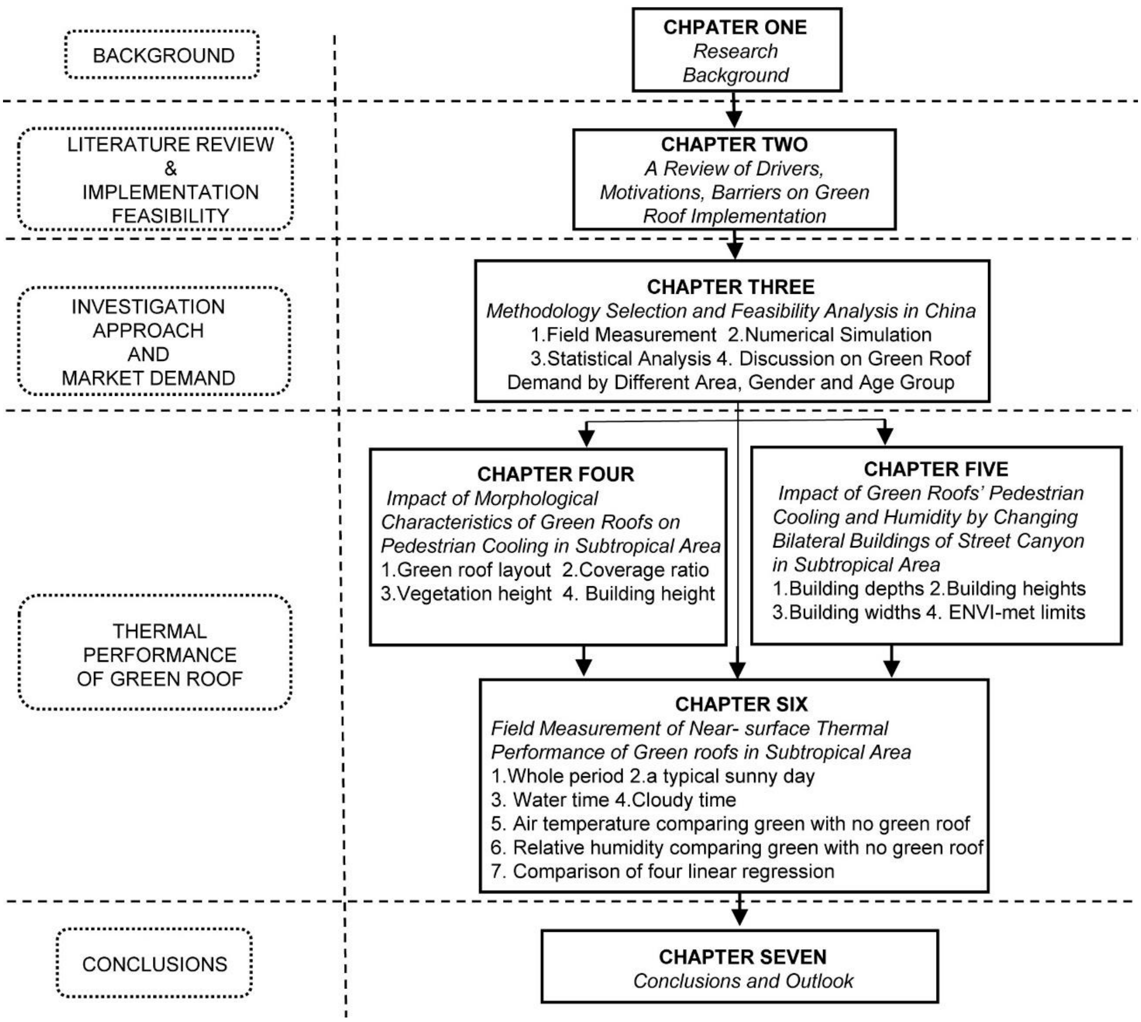
***Chapter 5, Impact of green roofs' pedestrian cooling and humidity by changing bilateral buildings of street canyon in subtropical area,*** is to explore the optimal and cost-benefit GRI strategy to mitigate the UHI effect. This section focused on the thermal performance of morphological characteristics of buildings with and without green roofs at pedestrian level in street canyon. There are four experimental tests in the Wangma community, Changqing Street, Shangcheng District Hangzhou City, China. Then the simulation software of ENVI-met is employed to simulate and verify the appropriate parameter which wind speed is 1.5 m/s. Afterwards, this section analyzed the microclimate in street canyon by aspect ratio of real environment at the pedestrian level (1.4m). Lastly, by changing building heights, depths, and widths on the both sides of street canyon, the simulation results find (1) the building depth covered green roof has a limited value at 24 meters; (2) The lower the height, the better the cooling effect, and the height is more than 42 meters which will be the limit value; (3) The cooling effect of green roof which is limited in 108 meters of building width could not change obviously in street canyon at the pedestrian level. However, the humidifying effect does which is the wider the more humid. (4) the limitations of software have been discussed.

***Chapter 6, Field measurement of near-surface thermal performance of green roofs in subtropical area,*** investigates the near-surface thermal performance of green roofs. In specific, based on the field measurement in a city with subtropical climate, chapter six compared the cooling and humidifying effects of three types of green roofs, including *Pomegranate*, *Bermuda grass* and *Sedum lineare*, on a typical sunny day. Afterwards, the test investigated the influence of watering activity and weather condition on the thermal performance of green roofs. Results indicate that the *Pomegranate* generally had the best cooling and humidifying effects by up to 3°C and 7.2%, followed by *Bermuda grass* and *Sedum lineare*. When air temperature of bare roof was more than 35°C, *Bermuda grass* presented insignificant cooling performance. *Sedum lineare* was the worst in providing cooling and humidifying effects, and even it severely intensified the thermal pressure in the peak period. However, the thermal performance of green roofs depended on the time in a day. *Sedum lineare* and *Bermuda grass* could also generate better cooling and humidifying effects, compared with *Pomegranate* before sunrise. Watering played a vital role in changing the diurnal near-surface thermal performance of green roofs, while the influence could not sustain for more than 10 minutes. Cooling performance of *Pomegranate* did not vary with cloudiness condition, while the cooling performance of *Bermuda grass* and *Sedum lineare* could be significantly enhanced under cloudy conditions. Overall, this section can help to understand the thermal environment at the urban green canopy layer and inform designers and architects to reasonably select rooftop plants for cooling.

***Chapter 7, Conclusion and outlook*** have been presented.

**Framework of the Dissertation**

# Research of Green Roof Implementation and Impact on Outdoor Thermal Performance at Pedestrian and Near-surface Level in Subtropical Zone



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# *Chapter 1*

## ***Research Background***

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**1 Current problem and Countermeasure**

**1.1.1 Issue and Challenge**

In recent years, rapid urbanization leads to the continuous increase of urban population, according to the report of America, the population of city will be predicted to increase up to 67% by 2050[1-3]. The global speed of urbanization is faced with unprecedented environmental pollution and deterioration challenges so that it is restricted to the efficiency of urban growth. The environment issue mainly reflected on urban heat island (UHI), urban waterlogging, scarcity of energy and green land, bio-diversity disappearance and so on [4, 5]. In these issues of rapid urbanization, the UHI problem which means the urban area is much hotter than the suburb area as shown in figure 1-1 is prominent to deteriorates comfort conditions of habitants.

According to the latest data released by NASA, the global average temperature in June was 0.93℃ above the past standard temperature, which had broken the previous record of 0.82℃ set in 2016 [6]. Notably, Europe experienced a heat wave in June, 2019, with 13 places in France exceeding the hottest temperatures on record. In gallargues-le-montueux, France, the top temperature is up to 45.9℃, 3.2℃ higher than the previous log in 2003. In addition, the melting season is coming earlier than usual in the arctic, especially in Greenland. Based on recent environment research, areas near the arctic are experiencing record temperatures, this is unprecedented temperatures on Ellesmere Island in the region reached 20℃ at noon, while the Canadian military signal intelligence station of CFS Alert recorded 21℃ (the last time it reached 20℃ was in 1956), compared with an average of 7℃ in July. That's equivalent to a temperature of 42℃ in Toronto. Earlier, local authorities reported that Canada was warming twice as fast as the rest of the world.

Unfortunately, but it is true that the earth is much more and more hot. As a result, heat island also intensifies the current energy problem of urban areas, endanger the vulnerable population like elders and sick people in summer[7]. If nothing is done to slow the rise in global temperatures, some 350 millions europeans could suffer a climate crisis by 2100, with "99% of deaths due to extreme heat" [6]. The scientists calculated that for every 2℃ increase in global temperatures, there would be a 5,400% increase in deaths from warmer temperatures, a 3,780% increase in deaths from coastal flooding, and a 138% increase in deaths from forest fires and a 20% increase in deaths from storms[8].

Furthermore, in recent years, the increasing phenomenon of UHI is mainly reflected in the influence of urban climate on building energy consumption, which leads to the significant increase of air conditioning and cooling energy consumption of buildings in summer. As early as 1973, Watanabe et al. used satellite remote sense to observe the surface temperature

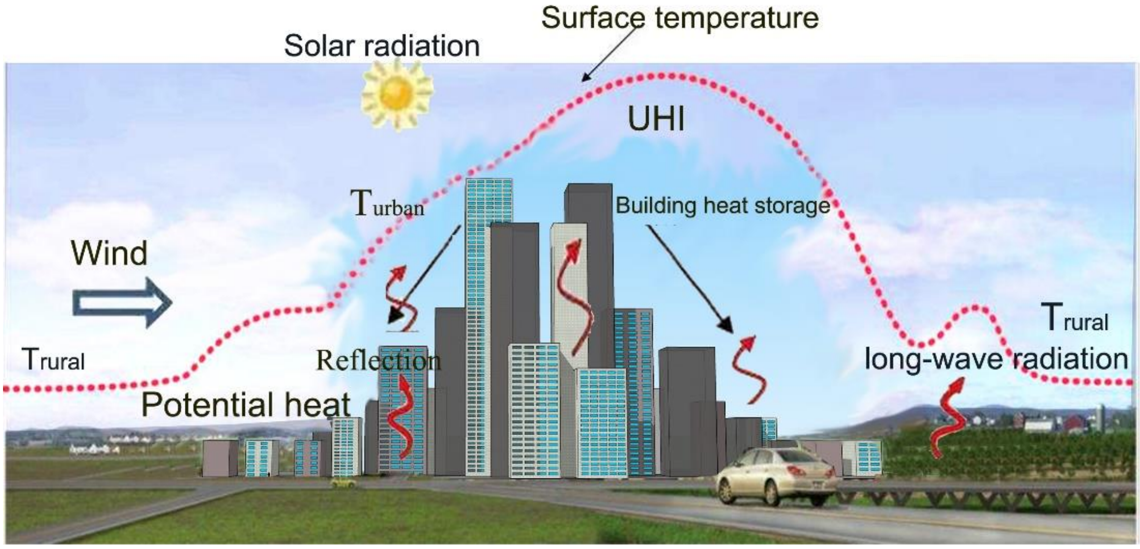


**Figure 1-1** Urban heat island

distribution and thermal environment in Tokyo (Japan), and drew a distribution map of energy consumption based on the government's field survey [9]. After analyzing the heat island, they found that the region about 10 percent higher energy per unit area than surrounding areas because of its UHI intensity. After that, M. Santamouris et al. analyzed the meteorological data of 30 weather stations in urban and suburban areas of Athens and 10 different districts, and found that the urban heat island intensity of Athens in summer exceeded 10℃ [10]. By comparison, the cooling load of urban homes is almost twice that of suburban ones, and the peak demand from cooling is three times higher. Due to the high temperature of outdoor air, the minimum energy efficiency of air conditioners is reduced by 25%. Meanwhile, the winter heat load of downtown buildings is 30 percent lower than that of the suburbs [10]. Akbari et al. studied the electricity consumption records of large cities with a population of more than 100,000 in the United States and found that when the temperature increases by 1℃, the maximum load of electricity will increase by 1.5%~2% [11] . A comparison of 40 years' worth of meteorological data shows that summer temperatures in these cities have risen by an average of 0.4℃to 0.8℃, which means that 3 to 8 percent of electricity is now used to compensate for the side effects of urban heat islands [11]. Tso C.P. observed the phenomenon of urban heat island in Singapore and found that the urban temperature increased by about 1℃ which lead to tremendous extra electricity [12].

However, the causes of UHI effect are constituted by multiple of thermal disadvantages which are described in figure 1-2. Through the analysis of heat factors in UHI, the main culprit comprises a large number of artificial heat, buildings, roads and other high heat storage and green space reduction.

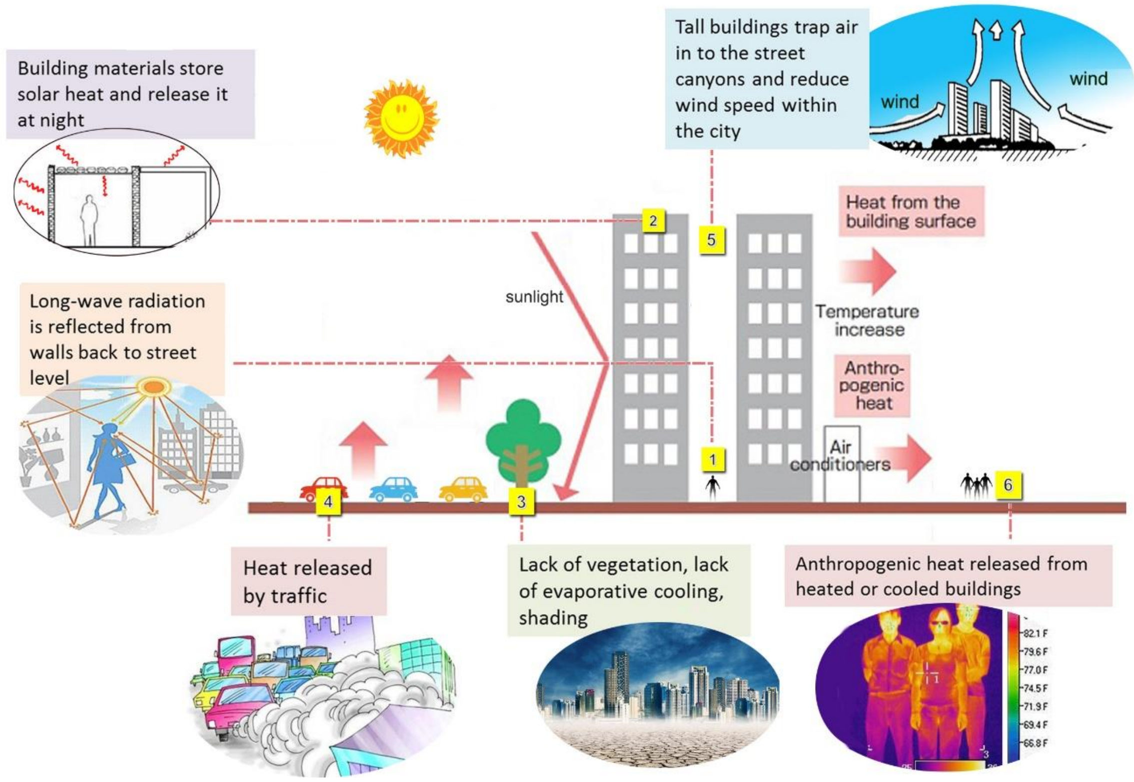


**Figure 1-2** The causes of UHI

### 1.1.2 Countermeasure

To solve the UHI, many countermeasures have been put forwards as shown in figure 1-3.

(1) Adopt green urban planning and design concepts. Researchers will adopt ecological and rational energy planning, urban development models, transportation planning and green space system planning, and adjust the urban industrial structure. Using new building materials to improve the reflectivity of sunlight; use outdoor building materials that can reduce heat and energy consumption and reduce heat island intensity; advocate permeable ground pavement to install material.

(2) Reduction of artificial heat. Urban residents need to be taught the concept of environmental protection into a conscious action. The change of residents' daily life style will be a long-term and meaningful work, which can directly reduce the waste heat of transportation, air conditioning and industrial production. In addition, researchers should improve the efficiency of energy use, carry out clean production, or develop and utilize new types of efficient and environment-friendly energy.

(3) Protection of urban wetlands and water bodies. Constructed wetlands should be constructed in cities and the area of original urban wetlands and water bodies should be protected to avoid being swallowed up by urbanization.

(4) Increment of Urban green land and forest. A large number of studies have shown that

urban vegetation, water body and wetland are important components of urban ecosystem, which can reduce the environmental pressure of the city, reduce the heat island effect, and finally realize the benign cycle of urban ecosystem[13]. Urban vegetation absorbs a lot of heat from the environment through transpiration, reducing the ambient air temperature and increasing air humidity. At the same time, a large amount of carbon dioxide absorption in the air, curb the greenhouse effect. In addition, plants can hold dust in the atmosphere, reducing the concentration of total suspended particulate matter in the urban atmosphere. When the vegetation coverage rate of an area reaches 30%, urban green space will obviously weaken the heat island effect [14]. On the contrary, vegetation reduction is the primary contributing factor to the formation of urban heat island. Therefore, the measure is key to alleviate the heat island effect are to strengthen urban greening and improve the thermal properties of the urban underlying surface.

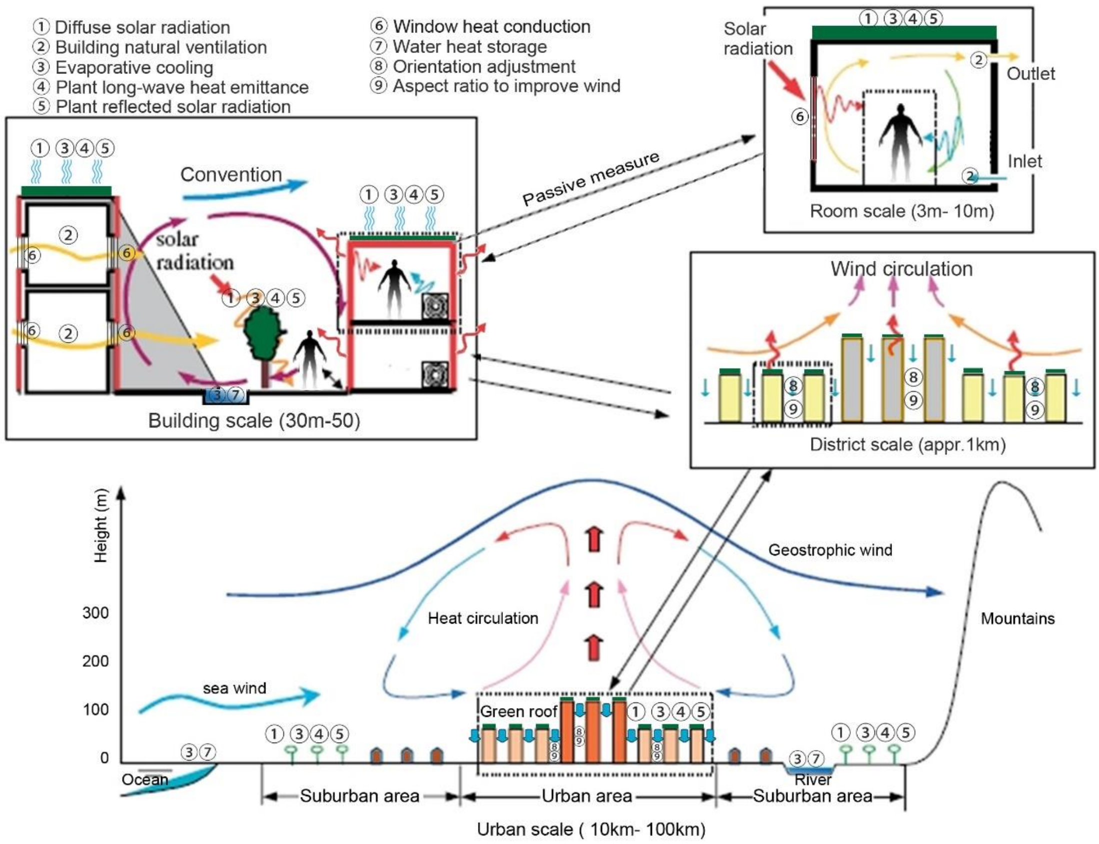


**Figure 1-3** The countermeasure of UHI ( Revised on [15])

### 1.1.3 Green Roof Strategy to Mitigate the UHI

Green roof mainly affects air temperature through the following two aspects:

(1) The transpiration of plants converts strong solar radiation into latent heat of vaporization and reflects or absorbs the received solar radiation, indirectly reducing the air

temperature around the building [16-18].

(2) Greenery, such as trees, provides enough shade to shield the walls and roofs from solar radiation, thereby reducing the temperature range of the envelope[19, 20].

The results by monitoring of two residential buildings in Sacramento, California in the United States in summer showed that proper planting of trees could save 30% of the energy consumption of air conditioning, about 3.6~4.8 degrees/day[21]. Taha simulated the environment temperature and annual electricity consumption of air conditioning changed due to large-scale planting of trees in ten cities. The simulation results showed that trees could reduce the environment temperature by 0.3℃~1℃ at 2 PM, and even reach 3℃ for some cities[22]. The fluctuant value for green roof impacted on air temperature decrease is in line with the theory that each city can obtain result distinctly according to different climate zones if all the surrounding buildings are greening[23].

The green roof which is shown in figure 1-4 is one of the more effective ways to increase the green area or overall green quantity, especially in the case of urban land scarcity and building density is relatively high, which is more important. Due to roofs can form up to the 35%-50% of the urban land area [24, 25], the use of these usually neglected surfaces could be an effective strategy to mitigate the negative impacts of urbanization[26]. Green roofs offer a natural and sustainable way to cover building envelopes with vegetation to bring multiple environmental benefits, which is more and more popular to be focused in the world. Green roof should be deployed on building envelopes to boost thermal comfort and shading-effects on roof surfaces. Shading-effect on roof surfaces is an important solution to sustain thermoregulation in buildings. Therefore, thermal comfort occurs in the buildings due to the evapotranspiration, photosynthesis and shading effects of vegetation on the roof surfaces. Green roofs provide decline in the urban heat island effects and the enormous growth in thermal benefits of the buildings[7]. Moreover, green roofs contribute to less energy consumption and minimize the money to expenditure for thermal comfort[27]. Furthermore, with a 42% tree cover in the city, the improvement of the air quality is more or less 1%. Air pollution removal by urban trees and shrubs in the United States, the greater the area of plant and tree cover, the more air may be filtered by the vegetation[28]. An investigation evaluated the thermal effects of vegetation at both the urban and building scales[29]. The UHI effect was monitored in four areas of New York City, USA, and an average temperature difference of 2℃ was found between the most vegetated and the least vegetated areas. Green roofs showed a potential for decreasing the use of energy for cooling and heating and, as a consequence, reducing peak energy demands as shown in figure 1-5. Green roof could suppress noise, create friendly living and leisure space, and improve the aesthetics of buildings [30, 31]. The main process of green roof to alleviate the UHI effect is shown in figure 1-5.

**Figure 1-4** The field investigation of green roof

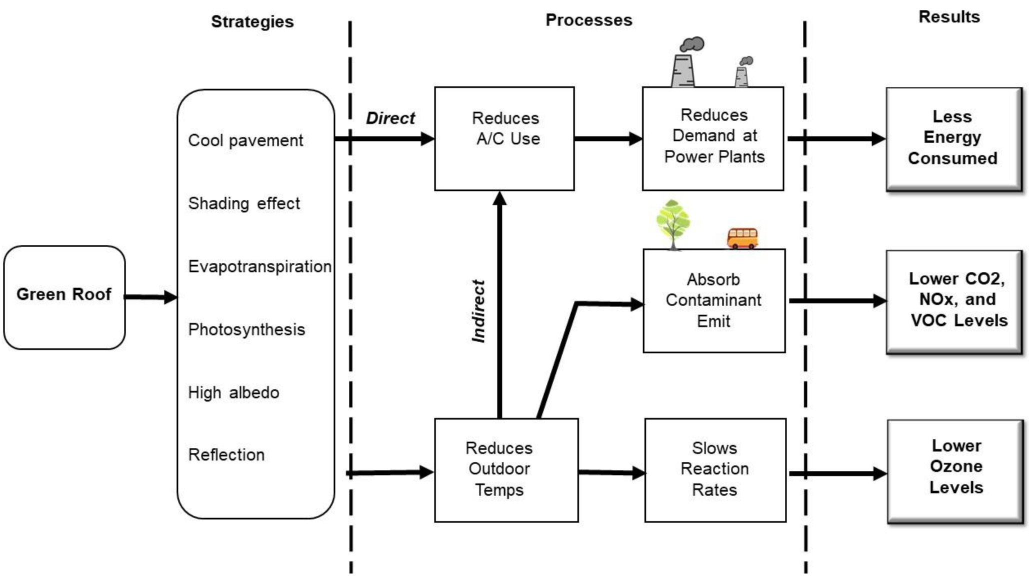


**Figure 1-5** The strategies of Green roof to solve UHI

## 1.2 Research Background of Green Roof

### 1.2.1 Classification of Green Roofs

Green roofs including two types of extensive green roof and intensive green roof are vacant vertical space with plants in their final layer[32, 33], which is based on vegetation type, construction material, management and allocated usage. So far, green roof is not strictly and clearly classified in the world, and table 1-1 reports the popular criteria of comparison between intensive green roof and extensive green roof. More details will be involved in figure 1-6.

**Table 1-1** Two main types of green roof systems[34-38]

| Types of Green Roof | Soil Depth(cm) | Lightweight (kg/m2) | Plant Options | Maintenance |
|---|---|---|---|---|
| Extensive Green Roof | 8-16 | 60-200 | Limited plant species options | Lower maintenance, nutrient, and irrigation requirements; Only 10 -20% organic matter in the soil |
| Intensive Green Roof | 16 or more | 120-500 | Many more plant options including trees and shrubs | Requires irrigation, fertilization, and regular maintenance |


**Figure 1-6** The configuration of intensive green roofs and extensive green roofs

### 1.2.2 Composition of Green Roof

As usual, there are eight layers that construct the green roof, respectively included plant medium, growing substrate, filtration layer, root barrier layer, water storage layer, drainage lay, waterproofing layer, roof construction, as shown in table 1-2.

**Table 1-2** Composition of green roof [39-41]

| NO. | Lays introduce | Practical function |
|---|---|---|
| 1 | Plant medium | Multiple plant types provide biodiversity, aesthetic, shade and insulation |
| 2 | Growing substrate | Provide fertilizer and support the load of upper plants |
| 3 | Filtration layer | To prevent loss of substrate by rain |
| 4 | Root barrier layer | Prevent root overgrowth and puncture roof, avoid the damage of building structure layer |
| 5 | Water storage layer | Store rainwater for plant absorption in dry weather, delaying and reducing rain floods |
| 6 | Drainage layer | Discharge redundant water (including water, spray, irrigation and rain) |
| 7 | Waterproofing layer | The roof's final barrier prevents rainwater from penetrating into the interior |
| 8 | Roof construction | Belong to building envelope and support the all load |

### 1.2.3 Historical Development of Green Roofs

Green roofs can be traced back as far as the gardens of Babylon and the Roman Empire, i.e. they grew trees on top of buildings[42]. Jim indicated technological revamping of materials and skills since the 1960s has primed and popularized green roof applications. The modern reinforced concrete technology invented in the 1850s allowed construction of multi-storey buildings with extensive flat roofs[43]. Nowadays, the world leader in green roof technologies is Germany where Guidelines is initially established for the planning, Execution and Upkeep of green-roof Sites which issued by Forschungsgesellschaft Landschaftsentwichlung Landschaftsbau (FLL). More details, the historic process, could be summarized in figure 1-7.

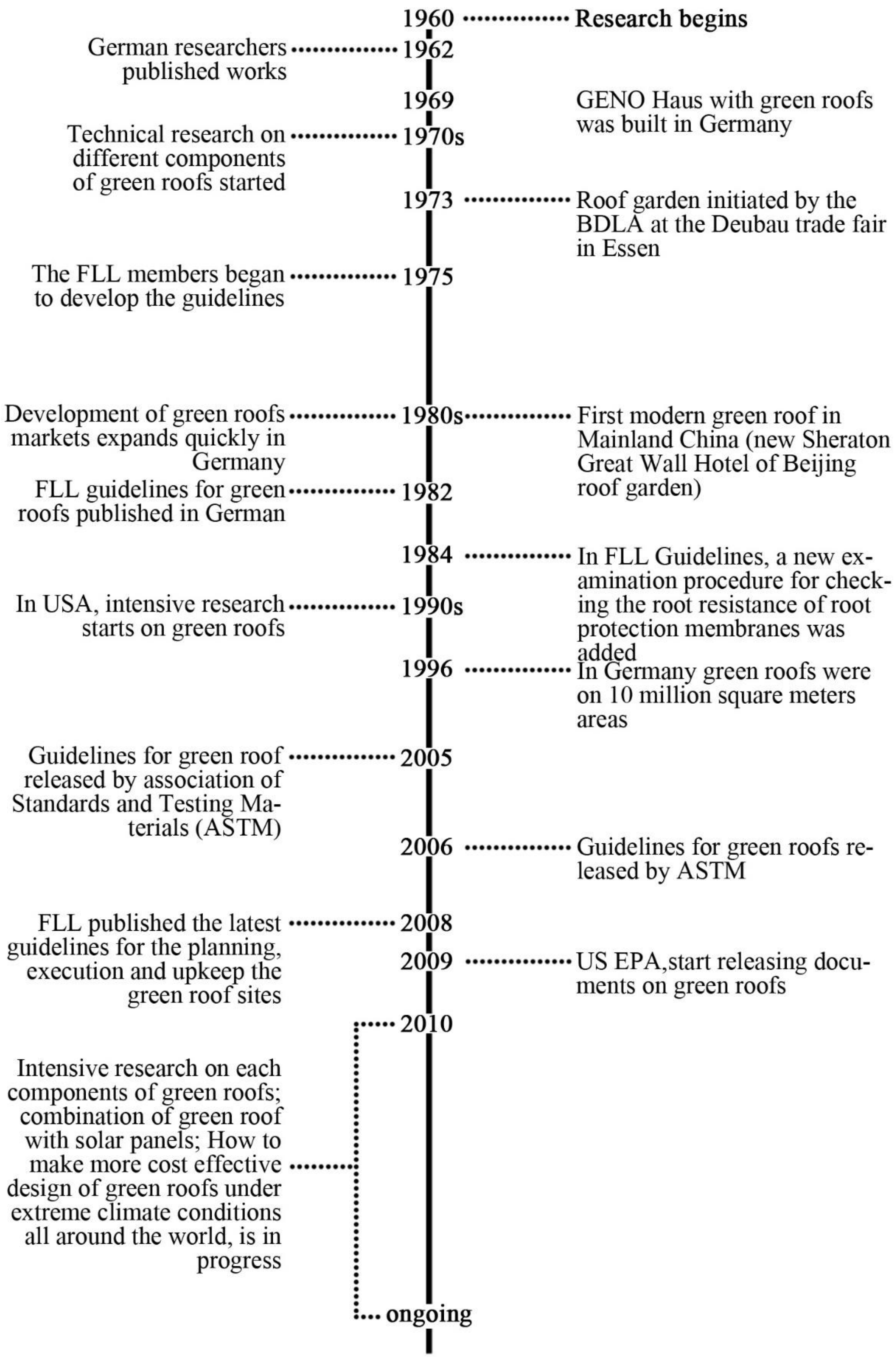


**Figure 1-7** Historic development of green roof (Revised on [38, 42-44])

### 1.2.4 Heat Insulation by Plant and Substrate Impact on Thermal Performance

Common shading components mainly reduce indoor radiation heat gain through heat transfer, without involving latent heat exchange process[17]. In the process of shading, evaporation of water, photosynthesis, transpiration, evapotranspiration are generally believed to play a great role in the heat insulation and cooling effect [17].The latent heat and sensible heat exchange between vegetation and air are realized by heat transfer. By on-site measure and analysis, plant absorb and transfer the solar heat which is major way to eliminate the solar radiation and it is helpful to reduce the roof temperature and heat flux[18]. Similarly, a study pointed out when the moisture content of green roof substrate is sufficient, the indoor heat flux can be greatly reduced, and even the heat flow can be reversed from house to outdoor in summer, comparing with traditional insulation roof [45]. However, when the substrate layer is dry, penetrating heat can also be reduced 60%[45]. Therefore, it can be seen that plants can dissipate solar radiation by either roof substrate or roof plant for heat insulation. While, several researchers found that for roofs with insulation measures, greening and cooling have no obvious energy saving effect [46-48]. This is mainly because when the thermal resistance of the envelope reaches the critical value, it is of little significance to increase the thermal resistance for the heat transfer of the envelope.

### 1.2.5 Ecological Characteristics of Plant Impact on Thermal Performance

As a means of cooling effect of green roof, it is affected by plant species, leaf area index (LAI), substrate type and thickness, moisture content in substrate layer, climate conditions, building envelope structure and conservation management and so on. Most studies demonstrate that leaf area index (LAI) play a decisive role to plant species, which is because LAI directly affect the size and scope of the covered building area, thus determining the amount of solar radiation that can be blocked. Several plant studies found the larger LAI is, the stronger the cooling ability will be, especially when LAI>3 is involved[49, 50]. Besides, the substrate layer not only directly affect the plant growth but also reduce the heat entering the indoor as a thermal resistance, especially its heat storage ability can slow down the temperature fluctuation of building surface[17]. An investigation indicates that inorganic substances are used in the substrate layer of building roof, which has a significant cooling effect and a small fluctuation for roof temperature[51]. Due to air temperature and relative humidity determine the content of water evaporation, the drier the climate, the green roof can bring better energy saving and alleviate UHI effect [23]. In addition, an analysis of transpiration and photosynthesis of the contribution of heat insulation by Crassulacean Acid Metabolism (CAM) plants demonstrates that photosynthetic energy accounted for 5% ~ 38% of transpiration[52]. Interestingly, the stomatal of CAM plant is closed when the surrounding temperature is too high to protect himself, so CAM plant, such as sedum, is popular to be used in green roof.

### 1.2.6 Albedo of Green Roof Impact on Thermal Performance

The plant albedo is the reflection coefficient that dictates the reflectivity of the surface to the solar energy incident on a green roof surface[53]. Roof temperature is also significantly affected by roof color and materials. Green roofs are mediums that combat heat island and increase the albedo of urban areas. Green roofs reflect between 20% and 30% of solar radiation, and absorb up to 60% of it through photosynthesis, which means that a percentage below 20% of the heat is transmitted to the growing medium [54]. An investigation illustrates that the correlations between the internal temperatures and the plant varieties and found that vegetation abundance is effective in adjusting land surface temperature[54]. However, the most competitive passive cooling technique like reflective paints cannot lead to temperatures lower than ambient [55].

Recently, a test compared two test rooms with air conditioning and quantified the decreased thermal losses for the room with the green roof [64], without being able to define if a green roof over performs a cool roof [56]. The bare roof albedo of 0.15, comparing with 0.30 of green roof, renders 75% higher heat storage[57]. The albedo of green roof ranges from 0.7 to 0.85 which is much higher than albedo of a typical, 0.1-0.2, bitumen, tar, and gravel roofs[58]. So green roofs are regarded as a medium that can reduce the temperature of a roof which can reduce the temperature of a black roof from 80.0°C to 27.0°C [58]. The efficiency of green roofs has been regarded as equal to the brightest possible white roofs.

Another study was conducted to analyze effects of green roofs in heat island by observing recent vegetated and reflective surfaces in LANDSAT images of Chicago in USA. Results show that applying green roofs and other vegetation forms in this city from 1995 increases the city's albedo, up to 0. 016 [59]. Likewise, citywide Normalized Difference Vegetation Index (NDVI) rises up to 0. 007. This finding along with counts of pixels with increased albedo and NDVI suggest that green roofs are very important in preventing heat island however, the reflective strategies are more useful than the vegetative methods[59].

A review of ten simulation studies indicates that green roofs can increase the city's albedo whereby, 0.1 increase of the albedo can decrease the average ambient temperature around 0.3 K and decreases the peak ambient temperature around 0.9 K [60]. Data correlate quite well in a linear regression given below indicating that an albedo change of 0. 1 in urban areas decreases the average ambient temperature by 0. 3 K. It is found that for an albedo change of 0.1 in urban areas the peak ambient temperature decreases by 0. 9 K.

## 1.3 Overview of Green Roof Implementation and Outdoor Thermal Performance

### 1.3.1 Market Status of Green Roof Implementation

As a consequence, multiple efforts have been made to counteract these problems and guarantee resilience and livability in cities. For instance, many cities have outlined plans towards transitioning into sustainable cities or into low-carbon eco-cities with resilient homes by alleviating environmental, economic, and social impacts and by minimizing resource utilization [61]. Moreover, multi-sectional sustainability programs have been initiated such as city forests for urban greening [62], sponge city for urban flooding mitigation [63], sustainable transport systems for mitigating transport impacts [64], sustainable building for environmentally-friendly building sector [65]; some of them have been implemented. Nevertheless, existing efforts have largely been insufficient to deal with the challenges that cities are and will potentially be facing. It is therefore essential to explore more pragmatic and feasible strategies for the creation of healthy and comfortable living spaces, whilst guarding against environmental deterioration. The loss of open spaces coupled with the demands on greening has ushered in the philosophy of green roof (GR) where rooftops are being utilized as alternative space for planting vegetation [66, 67].

Also referred to as eco-roofs [68], living roofs [69], and roof gardens [70], green roof can be categorized into extensive GR (EGR) and intensive GR (IGR), depending on the chapter 1.2.1. The EGR, a roofing type with extensively low vegetation (less than one meter in height), is usually simple and lightweight due to its thinner growing substrate [71]. It does not require much additional loads on the buildings and has strong possibilities of being widely adopted [72]. However, the plant species are significantly limited by temperature, wind speed, solar radiation, and water availability [73]. In comparison, the IGR is usually more complex, requiring deep growing substrate for planting high vegetation (more than one meter), resulting in considerable additional load on buildings. However, the deep growing substrate allows a variety of vegetation species for planting [74].

Adding a green roofing system has been acknowledged as an ecological and sustainable approach to improving the urban and built-up environment. Aside from being an alternative in enhancing the urban landscape, GR can perform a variety of roles in several aspects. For instance, GR can help reduce roof surface temperature [75] and the ambient temperature at the pedestrian level [76, 77] as a result of evapotranspiration and shading effects of plants [17]. A study summarizing the existing cooling effect of GR indicated that the ambient temperature could witness a reduction of 0-2 ℃ in average value and that GR can lower peak temperature by 0-3℃ [78]. Aside from ambient temperature reduction, the additional insulation layer provided by GR can help regulate indoor temperature (i.e., cooling in summer and warming in winter), which results in energy-saving benefits [79]. Also, the green roofing system has become an essential component of green infrastructure that helps reduce stormwater runoff [80, 81]. It is indicated that the green roof was capable of delaying the roof water discharge, resulting in decreasing the peak rate by up to 78% compared with traditional roofs [82]. The green roofing system has been highly recommended for urban flood management and has been integrated in various countries, including the USA, the UK, New

Zealand, Australia, Canada, and China [63]. In addition, green roof can alleviate air pollution [83], reduce urban noise [84], enhance biodiversity [85], provide additional recreation places [84], and prolong the lifespan of roof membrane [86]. There are also a number of sensory benefits from plants, albeit non-quantifiable, which can significantly improve health and well-being [87].

Green roof implementation (GRI) can directly or indirectly address critical urban issues and further promote sustainability. However, existing studies have primarily considered the environmental, energy, and ecological aspects of green roof. In comparison, very limited studies have targeted at the factors affecting GRI in terms of applicability and feasibility. For instance, Rowe [67] highlighted the benefits of green roof in pollution abatement and suggested that future research should focus on implementation issues (e.g., plant selection, planting substrate development, and greywater usage) and on the associated technical, economic, and political issues concerning green roof applications. Shafique et al. [88] made a review on the green roof benefits, while also underscoring the associated implementation challenges such as the initial construction and maintenance cost, constrained local research, lack of inter-industry cooperation, and other technical issues. Ziogou et al. [89] confirmed the positive energy and environmental benefits generated by green roof retrofitting in Cyprus, while also concluding that retrofitting was still not cost-efficient due to the initial installation costs. Ascione et al. [86] evaluated the technical and economic feasibility and concluded that GR did not outperform conventional counterparts in areas with insufficient rainfall due to added costs for irrigation. Moreover, the initial installation investments of green roof became difficult to offset even in climates with adequate rainfall [86]. This is in line with the argument that green roof would be difficult as a cost-effective alternative due to the additional costs from installation, maintenance, and electricity needed for watering [90].

Green roof can be a promising approach to improving urban environmental quality and enhancing sustainability. But the implementation is much more complicated, considering that the benefits derived from green roof come with various technical, social, economic and political concerns. On the one hand, GRI is primarily propelled by the individual's motivation to improve the natural environment; on the other hand, GRI could be part of a communal strategy towards realizing a sustainable environment, given its impact on human health, economic activities, social behavior, biodiversity, and aesthetics. Therefore, the success of GRI is largely dependent on being able to recognize and understand the intricacies of implementation. And although there have been extensive studies emphasizing the importance of promoting GRI and with a few contributing towards understanding possible factors influencing implementation, there have been limited studies mainly focused on reporting the drivers, motivations, and barriers to GRI.

Generally, drivers are boot in policy, economy, society, technology, and innovation pressure for GRI. Drivers have the potential to reshape public and household behavior towards adopting GR. Motivations can be considered as the primary goals that different stakeholders want to achieve through GRI. At the same time, the motivational factors can be transformed into their profits and benefits in the real practice. Barriers are the elements hindering GRI, so that they should be overcome during GRI promotion. Currently, four types of obstacles affect GRI including governmental policies, technological level, costs, and individual willingness. Among them, government policies have a direct effect on the GRI, but lack of demonstrable evidence significantly hinders their usage [91].

Green roofs have been acknowledged as an effective means to create healthy and comfortable living spaces while guarding against environmental deterioration. There have been extensive studies focusing on the GR performance in energy, environmental, and ecological aspects. However, the topic of GRI that covers technical, economic, political and social issues has rarely been investigated.

### 1.3.2 Market Exploration of Green Roof Implementation in China

Comparing with several developed countries, because of the limit on infrastructure investment, construction techniques and materials, while the insufficiencies of related laws and regulations, at present, China is laggard in research and practical work. In recent years, whereas, due to the technological advancement on construction, and more attention on green roof, more and more green roof been constructed. The government also published policies to pave the step-by-step way for construction of green roof. As a result, many excellent examples in the green roof development have been built in Beijing, Guangdong, Chongqing, Shanghai, and megacities in Zhejiang Provinces. Chinese green roof development is tentative and following a relatively stable development model [92]. For Chinese government, the implementation plan of green roof is usually political action from top to bottom. Without supportive policies, green roofs are thus unlikely to move from niche to regime level in the near future [93]. Therefore, there is a gap in how to preferentially implement and feasibly promote green roof from bottom-up perspective as shown in figure 1-8.

The big data of the internet provides a new way to integrate and screen the useful information through artificial intelligence, which form a bottom-up statistical result and derive a cost-effective plan[94]. A large number of historical data from the cloud server and real-time index data about complicated information of green roof would bring infinite possibilities for us to effectively grasp market and implement green roof. And sustainable urban design will be revolutionized if big data is used for the exploration of multiple design possibilities rather than the validation of the final design [95]. These possibilities are based on the additional outcomes of subjective consciousness, while the words of related index are help to peek at the additional market differentiated from top-down policy and regulation [96, 97]. Big data can help government decision makers and planners to understand the past and present about land use situation and better allocate social resources [95]. Utilizing the big data analyzing to guide the green roof implementation, the results are targeted and diversified. Meanwhile, due to the object of big data has immediacy and diversity, its research for green roof is a kind of quantitative cognition and embodied in multifaceted aspects of survey (such as space dimension, time dimension, content) which perform a bottom-up, fair and open data support, promoting the green roof implementation by mass basis. In addition, data-driven greenspace planning shows that big data is not only a technology change, but also an innovation of concept and model [97].

Based on the big-data investigation of the word “green roof” of index frequency, it is available to explores the green-roof attention in China, and provides references for green roof implementation and develop the land market of China. In addition, according to analyzation of the related words of green roof as heat rank, the additional market of green roof and potential value behind big data are further explored.

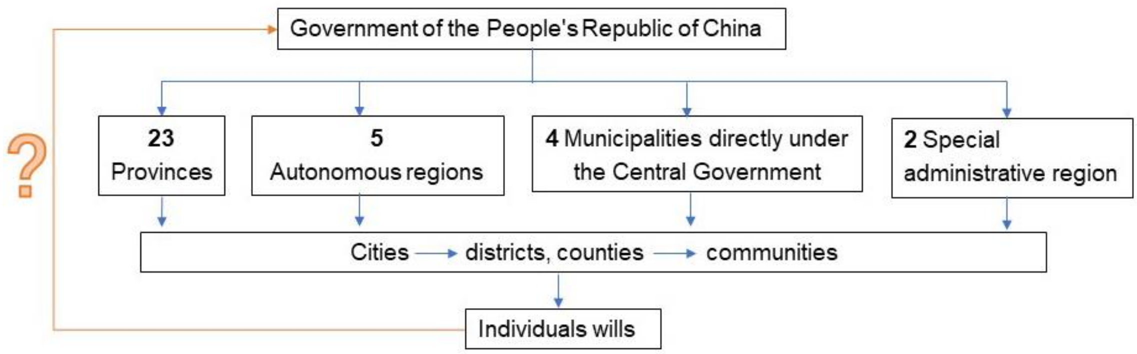


**Figure 1-8** Traditional ways of green roof implementation

### 1.3.3 Impact of Green-Roofs Layout on Thermal Performance

Through an investigation in Singapore, it finds that near-surface temperatures are all lower than non-green parts in roof garden by different types of plant, namely grass, shrub, bush and tree, their the average cooling temperature is the lowest and up to 3℃ [98]. It is to say, the variations for different species of green spaces change from each other, therefore, the thermal performance is also different.

An analysis from experimental measurement results showed that the plant of cooling and humidifying effect have little correlation with transpiration, however they have a close relationship with leaf area [99]. For this reason, shading plays the important role in providing the cooling effect and could be much more useful than other cooling course such as transpiration and photosynthesis [100, 101]. Likewise, the thermal performance of green roof is proportional to the green space, which is the larger for green space, the better the cooling and humidifying effect. However, because of the variety of configurations that make up the green roof by plant morphology, canopy density, leaf texture, and the size of leaves, the cooling results are different [39]. Under different paving configurations, lawns, shrubs, grasses, and green land all have a cooling and humidifying effect, while double layer structure of bushes and grass has a much better effect in cooling and humidification, compared with single layer [92]. A comparison on humidification effects for different types of green spaces and found that roofs covered with bushes and grass has the highest relative humidity, and compared to non-green space, the daily average humidity increased by 23.1%. Shrub and grass are second to bushes and grass, which increased by 7.7%. For turf space the relative humidity only increased by 5.4%. For shrub and grass or turf areas, the increase is insignificant. Humidifying effect is not only related to the structure but also the area of the green space. In other words, when the greening area reaches a certain size, then environmental benefits would be obvious [92]. And cooling rate is proportional to the ratio of urban green area[76]. In addition to the direct or indirect cooling effect brought by the green roof, to the surrounding environment, moisturized substrate release large amount of water vapor into the air and the moisture level increases near the green roof [17].

Cool material, urban greenery, water bodies and urban design that can weaken heat source strength and promote excess urban heat dissipation are primary strategies and techniques for urban cooling [102-104]. Among them, green roof, namely planting vegetation on building rooftops, is thought as an effective approach due to evapotranspiration and shading effects [16, 105, 106]. Moreover, green roof, known as the garden or forest replacing the dark and exposed concrete surfaces, is conducive to energy and carbon reduction through increasing mass and thermal resistance value [107-109]. Figure 1-9 exhibits the cooling mechanism of green roof, where solar heat gain can be reduced by leaves, followed by conversion of absorbed solar heats to latent heats by evapotranspiration, and the reduction of absorbed radiation resulting in lower surface temperatures and less emitted longwave radiation, thereby reduced air temperatures [106, 108]. To better utilize green roof for urban cooling, various studies have been carried out to examine factors that can influence the cooling potential of green roof [74, 110-112]. It is shown that the cooling performance varies with climates and geographic conditions. In hot-humid climates (e.g., Hong Kong), the cooling performance underperformed that in hot-dry climates (e.g., Cairo). Likewise, green roofs in warm-humid climates (e.g., Tokyo) and temperate climates (e.g., Paris) also witnessed weakened cooling efficiencies [113]. This is because the greenery transpiration is a complex process in relation to various factors within the planetary boundary layer such as solar intensity, wind speed and soil temperature [113, 114]. For instance, in semiarid climates, green roof could reduce the diurnal sensible heat flux by 150 W/m2 and lower the planetary boundary layer height by 700m [107]. Nevertheless, in temperate continental climate of Chicago, the inclusion of green roof could reduce surface temperature, but it also reduced wind speed and atmosphere dynamics [108]. Moreover, in subtropical oceanic climate of Baltimore-Washington metropolitan area, cooling performance of green roof varied with soil moisture, and the cooling performance was negligible when soil moisture was close to its wilting point [109].

Nevertheless, in the same climate, cooling performances of green roof vary with roof structures. Adapting to building types (e.g., single family residential and commercial buildings) with weight, maintenance and irrigation concerns, green roof can be divided into extensive green roof (EGR) and intensive green roofs (IGR), as shown in figure 1-9. Overall, the IGR is characterized by better cooling performances than EGR [113]. A study conducted in Hong Kong indicated that IGR could reduce pedestrian air temperature up to 0.5–1.7℃, compared with the 0.4–0.7 ℃ reduced by EGR [112]. In the same context, another study idealizing the roof height of 20 m also suggested that IGR had higher cooling efficiencies than EGR, with the pedestrian-level air temperature reductions of 0.6℃ and 0.2℃, respectively [111]. In addition, various studies on green roof have evidenced that cooling performance could be enhanced with the increase of green coverage ratio [111, 113, 115].

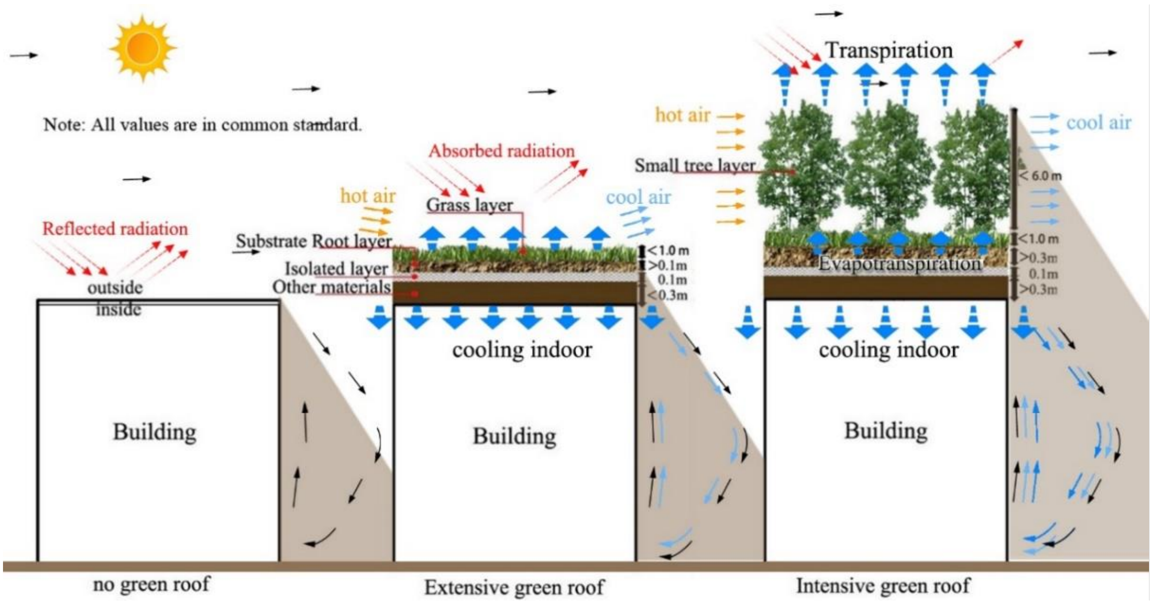


**Figure 1-9** A schematic structure of an extensive green roof and an intensive green roof, and the cooling mechanism in the daytime

Apart from green roof structures, building characteristics and configurations can also influence cooling effects of green roof. Overall, the cooling performance decreases along building height, and the cooling effects on pedestrian air temperature is negligible when building height exceeds 60 m [113]. Meanwhile, the increase of urban density restrains the pedestrian cooling performances, and green roof plays an insignificant role in medium- and high-density neighborhoods [111, 113, 116]. It is also evidenced that building layout and associated green roof arrangement can affect the cooling performance of green roof [117, 118]. For instance, among idealized enclosing-, scattered- and array-shaped neighborhoods, green roof with enclosing layout had the best cooling performance, followed by array layout and scattered layout [118]. Along prevailing wind, arranging green roof in upwind zones could reduce the temperature of the whole neighborhood [118].

Overall, studies have suggested that cooling performance of green roofs depends on both building morphology and green roof structures [119]. However, most studies on comparatively investigating cooling performances of green roof are mainly conducted in idealized neighborhoods. In reality, building morphology is quite complex rather than idealized, which affects the microclimate significantly [120, 121]. It is essential to further investigate the cooling performance of green roofs in real neighborhoods.

### 1.3.4 Impact of Buildings Morphology on Thermal Performance of Green Roof

From the community morphology, green roof can be found that enclosing layout has the maximum air temperature drop, which is up to 0. 5 ℃ at ground of pedestrian level. From the perspective of the uniformity of regional environmental temperature distribution, the regional thermal environment of scattered layout is better than enclosing and array layout as a whole. Centrally arranging the green roofs upwind can effectively reduce the air temperature of the whole region [39].

For a city morphology which has a high building-height-to-street-width (H/W) ratio, such as Hong Kong, the present study reveals that green roof is ineffective for human thermal comfort near the ground [14]. It is agreement with that reflective or green roofs are installed in high-rise buildings and the expected climatic impact and mitigation potential is very limited [60].

The lower building of cooling benefits of green roof is more obvious than the taller. Height of buildings could influence outcome of green roof in a city area by potential temperature and mean radiant temperature [122]. Sometimes, the taller buildings temperatures are lower due to their shading effect [14]. The aspect ratio (building height to street width) also plays an important role on the cooling effect of green roof influencing street canyon, which directly influence the design choices in relation to street usage [123]. An analysis that the effect of building-height-to-street-width (H/W) ratio on cooling effect of green roof demonstrated that the benefit of the cooling effects is low when the H/W ratio exceeds 1 [124], and it presented that vegetation could reduce the outside air temperature of the street canyon by 0. 8 ℃. Adjust the layout of buildings, for example, reduce the barriers caused by the mutual obstruction between buildings and increase the roof roughness, is helpful to improve the wind speed and effectively reduce the roof temperature[125]. Besides, several studies illustrated the effect of building layout on the microclimate of green roof. The main building layouts can be categorized into enclosing layout [79, 126], array layout [127], and scattered layout [34, 128]. Especially, the enclosing layout can promote the microclimatic conditions [129]. The cool suspended enclaves depends on building density and the layout pattern and geometry of buildings in conjunction with roads [130].

According to local climate zone (LCZ), numerical simulation of ENVI-met green roof at a pedestrian height of 1. 5m was carried out in 8 sample areas [131]. The results showed that the average temperature drop of the high (compact and open), middle (compact and open) and low (compact and open) building areas at 14:00 was 0.09, 0. 19, 0. 25℃, respectively. And the average temperature drops at 20:00 was 0.4, 0.6, 0. 09℃ indicates that the cooling intensity decreases with the increase of building height. It indicates that compared with the building layout intersecting with the dominant wind direction, the parallel layout has greater cooling potential.

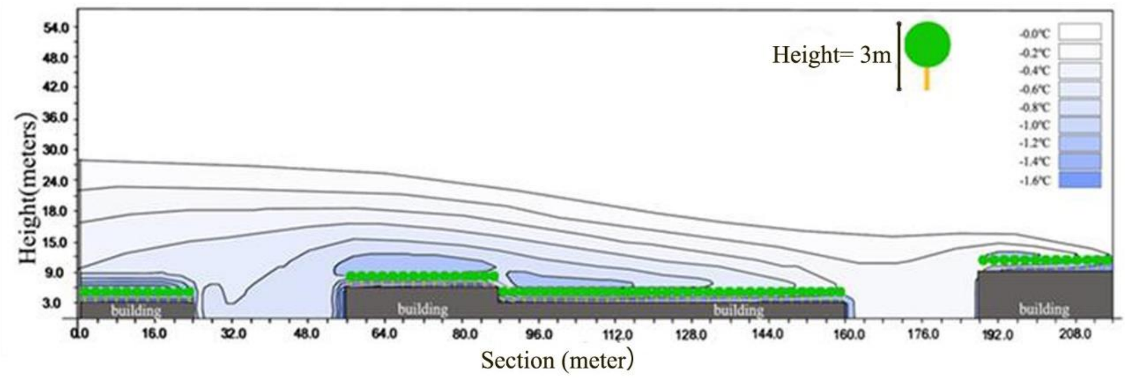


**Figure 1-10** Difference air temperature in ENVI-met simulation. Isoline interval 0.2K( Revised based on [132])

Green roofs not only issues and conduct pioneering works in Germany, recent years, but also develops a simulation software named ENVI-met have been created in Germany which is important application to test landscape arrangement and improve the microclimate research on green roofs as shown in figure 1-10. A study by ENVI-met find that if all surrounding building implement green roof, the building which is much more close to the ground and the best cooling and humidifying effect, the maximum cooling value up to 0.5℃[39]. Furthermore, the ENVI-met is applied to study green roofs in high-density and high-rise area in Hong Kong

[14]. The result demonstrates that the high-rise and high-density area covered by green roofs is not significant to decrease air temperature at the pedestrian level. In addition, a research of albedo increment indicates that green roofs decrease the mean temperature from 0.3 to 3℃ on a city scale and drastically alleviate the UHI effect [60]. On a neighborhood scale, the cooling effect of semi-extensive green roofs ranges between 0.05 and 0.6℃ due to meteorological region and simulation time change [133].

Despite there have been many studies on the microclimate effects of green roofs in city and neighborhood scale, the gap between building morphologies and green roofs to influence microclimate in street canyon could be addressed rarely. Especially, the research of the cooling and humidifying effect at pedestrian level in summer of humid and hot region is negligible, through changing the depths, heights, widths of bilateral building. However, the relationship between buildings on both sides and cooling and humidifying effect of green roof in street canyon at the pedestrian level plays an important role in thermal comfort in city.

### 1.3.5 The Thermal Performance of Green Roof in Field Studies

Green roofs not only fundamentally offer a substantial surface for the implementation of cooling and humidifying strategies in such speedy urbanization context [134, 135], but also strategically work as a supplement to urban greening that can reduce the surface temperature through shading hard surfaces, cool the ambient air through consuming solar heat gain for transpiration and photosynthesis, and provide additional insulation to indoor spaces [38, 75, 113, 136]. Moreover, green roofs are beneficial to the local biodiversity, rainwater collection for irrigation, stormwater and peak flow control, building life span extension and city amenity [137-139]. With the compulsory or voluntary support, the green roofs can take shapes from building scales to the whole city landscapes [61]. It is predictable that the urban boundary layer can transit from building featured one to homogeneous urban green canopy layer (UGCL) according to Oke’s theory, as shown in figure 1-11 [140].

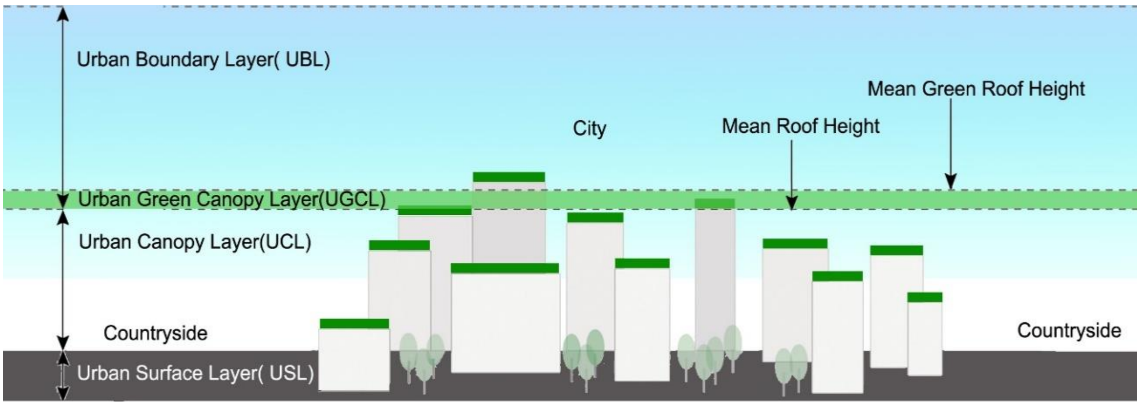


**Figure 1-11** The occurrence of urban green canopy layer (UGCL) based on Oke’s theory [140].

Under this circumstance, the green roofs will have more significant implications on the urban greenery, energy and water demand reduction, and outdoor thermal comfort [140-143]. The effect of green roofs on the thermal variation at city canopy layer could be more notable, in terms of surface heat and moisture transfer, and land-atmosphere interactions in the planetary boundary layer [144].

On the cooling potential, various studies have been carried out to examine the influence of green roof at the pedestrian level, green roof surface level and planetary boundary layer. Morakinyo et al. through numerical simulations, compared the cooling effects of green roof at the pedestrian level in different climates including hot-dry, hot-humid, temperate and warm-humid [113]. Their results indicate that green roof played the most prominent cooling performances in hot-dry climates, followed by hot/warm-humid and temperature climates, as the greenery transpiration varies with the solar radiation, wind velocity and soil temperature [113, 145]. Green roof structure is also a factor affecting the pedestrian cooling performance, where intensive green roof has a better pedestrian cooling performance than the extensive green roof. An experiment in Hong Kong (China) indicated that intensive green roof could lower pedestrian ambient temperature by up to 0.5-1.7 °C, while 0.4-0.7 °C by extensive green roof [146].

For the impact of green roof on planetary boundary layer, studies have indicated that the widespread adoption of vegetative rooftops, because of vegetation evapotranspiration, can lower the height of planetary boundary layer [147]. A study in semiarid climate further evidenced this conclusion that roofing system could reduce the diurnal sensible heat flux by about 150 $W/m^2$ and lower the planetary boundary layer height by 700 m. Comparatively, the nocturnal sensible and latent heat fluxes had been increased by about 4 and 6 $W/m^2$ [144]. Moreover, it is found the implementation of green roof in the city can affect the urban-rural air circulation [148]. Under the condition of low wind velocities, the diurnal urban temperature is much lower because of the evaporative cooling of green roof, so that thermals rising from the rural areas facilitate the urban-rural advective circulations [149]. In comparison, the urban-rural circulations are not obvious in the nighttime when the evaporative cooling effects of green roof are weaker [150].

More studies have been carried out to investigate the thermal performance of green roof to the rooftop surface temperature and even indoor space temperature, because this has a significant implication on the reduction of energy demand for cooling. Table 1-3 presents an overview of the studies that focusing on the thermal performances of green roof to rooftop surface and indoor space. It is shown that most existing studies have focused on the influence of extensive green roof on the rooftop surface and indoor space temperature reduction, and only two cases have explored the effect of intensive green roof. This is because of the high requirements of intensive green roof on the substrate. Moreover, the cooling performance of green roofing has been most concerned in summer, while green roof can also an insulation layer protecting indoor space from cold sources [151]. Across different climate zones, green roof can reduce rooftop surface temperature by more than 10°C [152-156]. Meanwhile, the cooling performance of green roof to the indoor space is also very significant, ranging between 3 and 4°C [46, 153, 157]. Nevertheless, it is also shown that the cooling performance of green roof varies with vegetation types and seasons [158, 159]. Table 1-3 also indicates that existing studies have mostly focused on the temperature reduction resulted from green roof, while the humidifying effects have been scarcely investigated.

**Table 1-3** A summary of the experimental studies on the impact of green roofs on the rooftop surface and indoor space

| NO. | Location | Roof type (species) | Köppen classification (season) | Sensor location | Maximum temperature reduction | Average temperature | RH | Ref |
|---|---|---|---|---|---|---|---|---|
| 1 | Singapore | IGR (Erythrina, Ixora, Raphis Palm, Pandanus, Ophiopogon) | Af (October-November) | between soil surface and vegetation | 15.0°C | <3.0°C↓ | similar | [152] |
| 2. | Queensland, Australia | EGR (Rhoeo, Scaevola, Grevillea Obtusifolia, Helichrysum Italicum, Callistenon Captain Cook, Dianella little jess, Eremophila Maculata) | Aw (summer) | Indoor space | 4.0 °C | - | Green roof: 45-75%<br>Non green roof: 37-73% | [157] |
| 3 | Shanghai, China | EGR (*Sedum lineare*) | Cfa (summer) | a: between roof construction and soil<br>b: Indoor space | a: 16.0°C<br>b: 3.0°C | - | - | [153] |
| 4 | Hongkong, China | IGR (Aquilaria sinensis, Bridelia tomentosa, Camellia honkongensis, Camellia oleifera, Cerbera manghas, Cinnamomum burmanii, Elaeocarpus chinensis, Ligustrum lucidum, itsea monopetala, Sterculia lanceolate, Ternstroemia gymnanthera) | Cfa (summer) | the bottom surface of the vegetation layer | 3.0°C | | | [137, 160] |
| 5 | Taiwan, China | EGR (perennial herb, shrub, vine, and groundcover) | Cfa (spring, summer) | between roof construction and<br>substrate layer | 17.75°C, 12.57°C, 11.55°C, 9.31°C | | - | [154] |
| 6 | Michigan, USA | EGR (Hylotelephium spectabile, Hylotelephium verticillatum, Saxifraga granulate, Sedum acre, Sedum album, Sedum ellacombianum, Sedum floriferum, Sedum kamtschaticum, Sedum pulchellum, Sedum reflexum, Sedum sexangulare, and Sedum spurium) | Cfa (four seasons) | between roof construction and substrate layer | Summer: 20.0 °C<br>Spring/autumn: 5.0°C<br>Winter: <1.0°C | | | [159] |
| 7 | Poitou–Charentes | EGR (Pampa, Toundra) | Cfb (summer) | between roof construction | 20.0°C | | | [155] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | region, France | | | and substrate layer | | | | |
| 8 | La Rochelle, France | EGR (Tundra, Pampa) | Cfb (summer) | between roof construction and substrate layer | 30.0°C | | | [156] |
| 9 | Utrecht, Netherlands | EGR (S.floriferum Weihenstephaner gold, S. album Coral carpet, S. reflexum, S. spurium Fuldaglut, S. sexangulare, S. album superbum) | Cfb (summer) | 15cm above roof vegetation | | 0.2°C↑ | | [158] |
| 10 | Thessaloniki, Greece | EGR (Jasminum nudiflorum, Euonymus japonicus, Euonymus ovalifolius, Phormium, Veronica andersonii, Buxus sempervirens, Vinca major, Berberis thunbergii, Cotoneaster horizontalis and Alyssum maritimum) | Csa (four seasons) | a: soil surface<br>b: between roof construction and substrate layer<br>c:1.8m above roof vegetation | a:＞27°C<br>b: 30°C<br>c:10°C | | | [161] |
| 11 | Loutraki region, Greece | EGR (-) | Csa (summer) | a: soil surface<br>b: indoor | a: 14.0°C<br>b: 3.0°C | b: 2.0°C↓ | | [46] |
| 12 | Athens, Greece | EGR (-) | Csa (April-December) | soil surface | | 5.0°C↓ | | [162] |
| 13 | Calabria, Italy | EGR (-) | Csa (summer) | soil surface | | 6.2°C↓ | | [75] |
| 14 | Chongqing, China | EGR | Cwb (summer) | soil surface | 24.0°C | 3.8–7.2°C↓ | | [163] |
| 15 | Taipei, China | EGR (-) | Cfa (four seasons) | soil surface | Taipei: 29.2°C<br>Chiayi: 32.2°C | | | [164] |
| 16 | Brno-Tuřany, Czech Republic | EGR (Tomato Tree and so on) and IGR | Cfb (winter) | At soil depth of 60cm | | 8.0°C↑ | | [165] |

Overall, existing studies have well explained the cooling potential of green roofs to pedestrian-level ambient temperature, rooftop surface temperature and planetary boundary layer. However, the near-surface level that has an immediate response to vegetation cooling performance has received very limited concerns. Only a case in Utrecht, the Netherlands, has reported that cooling performance of green roof above 15cm of roof surface [158]. Therefore, it is necessary to investigate the near-surface cooling performance of green roofs. In particular, the near-surface thermal performance, for shurb-type vegeation, can indicate the immediate shading and cooling effects of vegetation. In comparison, the near-surface thermal performance for grass-type vegetation can exhibit the immediate combination of vegetation cooling and solar influence.

### 1.4 Contents of this Dissertation

#### 1.4.1 Purpose of this Dissertation

This dissertation would be conducted in Hangzhou City of subtropical area, analyze the green roof market by drivers, motivations, barriers is to complement and promote green roof research, furthermore, analysis the green roof market by different area, age group and gender in China. Then, through two studies of numerical simulation, outdoor thermal environment of green roof is improved by building morphologies and green-roof configurations in different scenarios. Lastly, near-surface thermal performance of green roof and virginally reveal its characteristics in different weather and period. The main research objectives are:

1) **Chapter 2：** In order to strengthen drivers, evade barriers, and enhance motivations towards promoting green roof implementation, chapter seven is designated (1) to provide a comprehensive review towards existing green roof literature, (2) to complement previous reviews regarding the evolution and performance of GR and serves some significant academic and practical purpose.
2) **Chapter 3：** This chapter is a new way to understand land use market and beneficial to improve the successful probability of green roof implementation by bottom- up data support. In short, rely on the big-data analysis, the following three aims of green roof can be studied in this chapter：(1) based on the frequency of analytic visualizations at three spatial scales, put forward the spatial priority of green roof implementation; (2) through analyzing the attention of different genders and age groups on green roof, and put forward the market priority to implement green roof; (3) through analyzing related words of green roof, and predict analytic capabilities for potential market.
3) **Chapter 4：** In order to explore the comprehensive and cost-benefit morphological characteristics of green roof in neighborhood-scale area of typical summer day, therefore, the chapter six aims to investigate the impact of morphological characteristics of green roof on pedestrian cooling in real neighborhoods. In specific, the chapter six is conducted in the summer of a subtropical city, Hangzhou (China), for the following research directions (1) to identify relationships between greening layout and corresponding pedestrian cooling performances, (2) to explore the appropriate coverage ratio of green roof in real neighborhoods, (3) to explore the regulation of vegetation height to decrease pedestrian air temperature, and (4) to examine the impact of building height on green roof's cooling performance in real neighborhoods.
4) **Chapter 5：** In order to hunt for the optimal scope of building morphologies by thermal effect of green roofs at pedestrian level in street canyon, the chapter five aims (1) to conduct a series of delicate feasible design, such as experimental test, verification &

validation, sensitivity analysis, time step and boundary condition settings by simulation software (ENVI-met) to make sure the simulation accuracy. (2) to provide a step-by-step, effective and optimal study to focus on thermal performance of green roof by changing the depth, height, width of bilateral buildings in street canyon to explore comfortable and feasible scope to implement green roof and mitigate the UHI.

5) **Chapter 6：** For the UGCL cooling, it is essential to understand the near-surface thermal performance of green roofs. For this purpose, chapter six aims to investigate the near-surface thermal performance of green roofs through experiments on three types of green roofs and the bare roof during the summertime of a subtropical city. The objectives are: (1) To understand the near-surface heat reduction performance of *Pomegranate* roof, *Bermuda grass* roof and Sedum lineare roof; (2) To assess the near-surface thermal variations of three types of green roofs on a typical sunny day; (3) To compare the variations of near-surface thermal performance during watering and cloudy conditions; and (4) To investigate the influence of weather condition on the near-surface thermal performance. This chapter is an important way to reveal the cooling and humidifying mechanisms of green roofs and significant to build green roofs (or rooftop gardens) for urban cooling in practice.

### 1.4.2 Framework of this Dissertation

There are seven chapters in this dissertation. Chapter one induces the background why this dissertation to focus on green roof and elaborately illustrates previous literatures and insufficient part, then puts forward the purpose of this dissertation for insufficient part. Chapter two is literature reviews to summary drivers, motivation, and barriers for green roof implementation. Chapter three explains what methodologies will be chosen in the dissertation and analyses the green roof market in China. Both chapter four and five are thermal findings of this dissertation to understand and discover the thermal performance of green-roof configurations and building morphologies by field and simulation research. Chapter six analyzes of the thermal mechanism by three common plants of green roof in different meteorological condition. Chapter seven is conclusion.

- Part one: Research background

Chapter 1, firstly presents the current UHI problem in worldwide situations, then puts forward to several countermeasures, furthermore, gradually leads to the topic of this dissertation regarding on green roof strategy as one of the important countermeasures, then, provides the relatively previous researches in green roof implementation of thermal mechanism, buildings morphology, green-roofs layout, promotion explore to find the gaps in all literatures. Lastly, the purpose of this dissertation to complement the gaps is explained.

- Part two：Literature review and implementation feasibility

Chapter 2, aims at conducting a systematic review for worldwide identifying the influencing factors- drivers, motivations, and barriers to GRI. Specifically, 217 published works, in which 164 entirely for GRI and 53 partially for GRI, from 2000 to 2019 were reviewed. Based on the review, it was found that the there are three types of drivers to GRI, namely policy pressure, market pressure (e.g., customers demand, award or certification, cost-benefit demand), and innovation and technology advancement. Extensive factors such as energy efficiency, urban heat island mitigation, extending roof longevity, air purification, water runoff control, water purification, urban infrastructure improvement, noise reduction, biodiversity improvement, recreation, and aesthetics, property value increase, and employment improvement may motivate people to implement green roof techniques. The barriers that may hinder GRI include lack of government policy, unsound technological development, high initial cost and long payback period, and individual unwillingness. Suggestions on how to overcome GRI barriers were proposed, namely: increasing governmental policies and support, improving technical innovation, encouraging long-term view, and increasing education and dissemination. Moreover, this section presents some recommendations for sustainable GRI cases. Overall, this chapter is significant in the development and implementation of green roof in both academic and practical perspectives.

- Part three：Methodology selection and market demand

Chapter 3, firstly, specifically selected in Hangzhou City of Southern China as the research site, which is belongs to hot summer and cold winter area. Later, approach for this dissertation is screened and introduced, in detail, comparing with other software or test principles. Lastly, it analyzes the index frequency of green roof by Baidu Index in China, and the main findings are below：(1) in the three levels of spatial scale of large district-province-city, the index volume corresponding to the three levels are East China, Zhejiang Province and Hangzhou City respectively which is the highest in hot rank. (2) The age group who are more curious about green roof is between 20 and 29 years old, among which males are slightly higher than females by 12%. (3) through the analysis of the hot rank of related words, users who are interested in green roof concentrates on the construction mode and related technologies, such as stainless-steel tank and reclaimed water.

- Part four：Thermal analysis by simulation scenarios & field measurement

Chapter 4, for better cooling performances, is essential to reasonably configure green roofs, especially in real and complex neighborhoods. Therefore, the aim of this section is to investigate the impact of morphological characteristics of green roofs on pedestrian cooling in real and complex neighborhoods. In specific, based on an ENVI-met model, this chapter studied the effect of greening layout, coverage ratio, vegetation height, and building height on pedestrian air temperature reduction in the tropical city of Hangzhou, China. Results indicate green roofs could generate moderate effects on pedestrian air temperature reduction (around 0.10–0.30 ℃), while achieving a cooling performance of 0.82 ℃. Green roofs in upwind zones were able to generate the most favorable cooling performance, while green roofs in downwind zones made slight differences to pedestrian thermal environments. Green roofs with a low coverage ratio were not useful for lowering pedestrian temperature, and a greening coverage ratio of 25–75% in upwind zones was cost-effective in real neighborhoods. Locations that were horizontally close to green roofs enjoyed better cooling performances. Increasing vegetation height could strengthen cooling effects of green roofs, while an increase in building height weakened the cooling performance. Nevertheless, higher building height could enhance pedestrian cooling performances because of building shading effects. In addition, because of wind effects and building shading, building height limits for the cooling performance of green roofs could be higher than 60 m. And the layout of orientation array of green roof along the wind direction is more comfortable to expand the cool resource at the same ratio of green roof.

Chapter 5, is to explore the optimal and effective GRI strategy to mitigate the UHI effect. This section focused on the thermal performance of morphological characteristics of buildings with and without green roofs at pedestrian level in street canyon. There are four experimental tests in the Wangma community, Changqing Street, Shangcheng District Hangzhou city, China. Then the simulation software of ENVI-met is employed to simulate and verify the appropriate parameter which wind speed is 1.5 m/s. Afterwards, this section analyzed the microclimate in street canyon by aspect ratio of real environment at the pedestrian level (1.4m). Lastly, by changing building heights, depths, and widths on the both sides of street canyon, the simulation results find (1) the building depth covered green roof has a limited value at 24 meters; (2) The lower the height, the better the cooling effect, and the height is more than 42 meters which will be the limit value; (3) The cooling effect of green roof which is limited in 108 meters of building width could not change obviously in street canyon at the pedestrian level. However, the humidifying effect does which is the wider the more humid. (4) the limitations of software have discussed.

Chapter 6, firstly investigates the near-surface thermal performance of green roofs. In specific, based on the field measurement in a city with subtropical climate, it compared the cooling and humidifying effects of three types of green roofs, including Pomegranate, Bermuda grass and Sedum lineare, on a typical sunny day. Afterwards, chapter six investigated the influence of watering activity and weather condition on the thermal performance of green roofs. Results indicate that the Pomegranate generally had the best cooling and humidifying effects by up to 3℃ and 7.2%, followed by Bermuda grass and Sedum lineare. When air temperature of bare roof was more than 35℃, Bermuda grass presented insignificant cooling performance. Sedum lineare was the worst in providing cooling and humidifying effects, and even it severely intensified the thermal pressure in the peak period. However, the thermal performance of green roofs depended on the time in a day. Sedum lineare and Bermuda grass could also generate better cooling and humidifying effects, compared with Pomegranate before sunrise. Watering played a vital role in changing the diurnal near-surface thermal performance of green roofs, while the influence could not sustain for more than 10 minutes. Cooling performance of Pomegranate did not vary with cloudiness condition, while the cooling performance of Bermuda grass and Sedum lineare could be significantly enhanced under cloudy conditions. Overall, this chapter can help understand the thermal environment at the urban green canopy layer and inform designers and architects to reasonably select rooftop plants for cooling.

- Part five：Conclusion and outlook

Chapter 7, Conclusion and outlook have been presented.

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# *Chapter 2*

## ***A Review of Drivers, Motivations, Barriers on Green Roof Implementation***

# Chapter 2： A Review of Drivers, Motivations, Barriers on Green Roof Implementation

**A Review of Drivers, Motivations, Barriers on Green Roof Implementation…................2-1**

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## 2.1 Introduction

This chapter is organized by the following steps. First, a comprehensive investigation of green roof implementation (GRI) drivers, motivations, and barriers provides the necessary proficiency in recognizing the various factors affecting the GRI. It provides the foundation towards a comparative assessment on the impact of the different GRI factors on the public and private sectors. A critical review on the drivers, motivations, and barriers can offer reasonable suggestions, which decision-makers can use in developing policies that encourage green roof (GR) adoption. For the following sections, Section 2.2 introduces the methodology for the identification of drivers, motivations, and barriers. Section 2.3 reports the existing studies on the GR from around the world, which includes the research on drivers, motivations, and barriers to the GRI. Section 2.4 and Section 2.5 presents recommendations and the implications for comfortable GR cases. Finally, Section 2.6 gives the summary for this review.

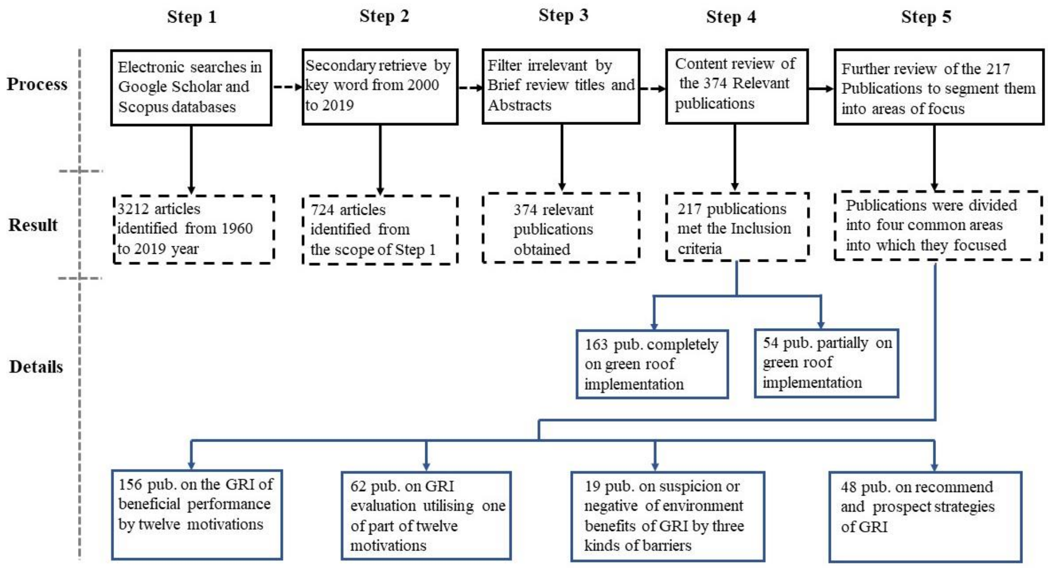


**Figure 2-1** Search strategy process

## 2.2 Research method

Aiming at presenting a comprehensive review towards existing GR literature, this chapter conducted an electronic search process for all possible GR publications on July 30, 2019, as shown in figure 2-1. The database this chapter depended on were Google Scholar and Scopus [1]. During the electronic search process, this chapter used the appropriate Boolean operator and relevant keywords (*i.e.*, “cooling roof”, “vegetative roof”, and “green roof”), resulting in 3212 publications from 1960 to 2019. Nevertheless, many of them were irrelevant to the application of GR. Therefore, the search was limited to works published from 2000 to 2019 with keywords “green roof implementation” or “green roof review”, resulting in 724 publications. A further examination on both titles and abstracts of these publications allowed us to determine the suitability for inclusion of each publication in this review [2]. According to the principle that all publications should cover at least one keyword in title and abstract, this chapter screened 374 possible publications.

The content review was conducted among remaining publications to verify whether they truly analyzed GRI. It is found that majority of the papers satisfied the criteria, resulting in 217 publications that totally (163) or partly (54) focused on GRI. In specific, remaining publications included 185 journal papers, 26 conference papers, three theses and three textbooks (Table 2-1). An in-depth review was conducted to classify the remaining publications into four overlapping categories (figure 2-1). The first group focuses on GRI's performance analysis in applications such as UHI mitigation, energy-saving functions, and runoff control using experimental tests and simulations. A total of 156 published works explicitly described 12 categories of GRI benefits. The second category is composed of 62 published works partly providing GRI benefits. Moreover, these publications emphasize the role of government in advocating for GRI. The third group comprises 19 published works, providing the general critique and discussion of the disadvantages and shortcomings of GRI. The last group comprises 48 studies and discusses recommended strategies for the implementation and sustainable use of green roofing system. Due to content overlaps, the total number from the four research topics is greater than 217.

**Table 2-1** Summary of selected articles

| Type of publication | Inclusion criteria | | Number |
|---|---|---|---|
| | Focused entirely on GRI | GRI as part of larger scope research | |
| Journal articles | 145 | 40 | 185 |
| Conference | 17 | 9 | 26 |
| Dissertation | 0 | 3 | 3 |
| Textbook | 1 | 2 | 3 |
| Total | 163 | 54 | 217 |

### 2.3 Results

This section mainly reports the findings on the drivers, motivations and barriers to the GRI. Journal papers rather than conference papers, dissertations and books provide complete research and have undergone extensive review by experts often through a blind reviewing process, so that this research will mainly focus on journal articles. The number of identified articles each year ranges from 1 to 34 (see figure 2-2), and has been on a trend of growth since 2000, despite some fluctuations. Note that the number of papers for 2019 is an incomplete tally since the number represents only those that have been available online by July 2019. In about 20 years period (2000-2019), there could be an annually published number of 1.9 and 15.5 for the first (2000-2009) and the second half (2009-2019) period, respectively. This stark difference exhibits the growing concerns on GRI research. Figure 2-3 and figure 2-4 presents the sources and number of journal or conference papers. Journal papers had a proportion of 85.25% (185 out of 217) of the database for next-step analysis, and 11.98% (26 out of 217) were conference papers. The number of the journal and conference papers for analysis was large, having the potential to provide people with extensive GRI information. The 185 articles analyzed case studies from 36 countries, 15 of which are from developing countries and 21 from developed countries (see figure 2-5). Most papers were about China (36), the United States of America (26) and Italy (16), while ten papers covered at least two countries (e.g., Germany and Italy, Italy and USA, China and USA).

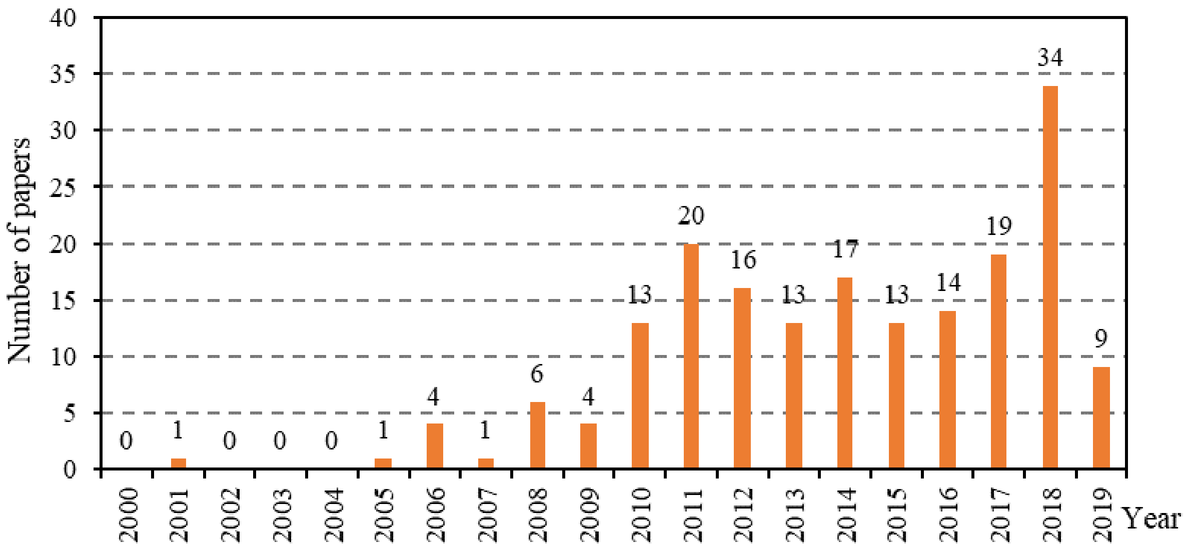


**Figure 2-2** Number of relevant papers published yearly from 2000 to 2019

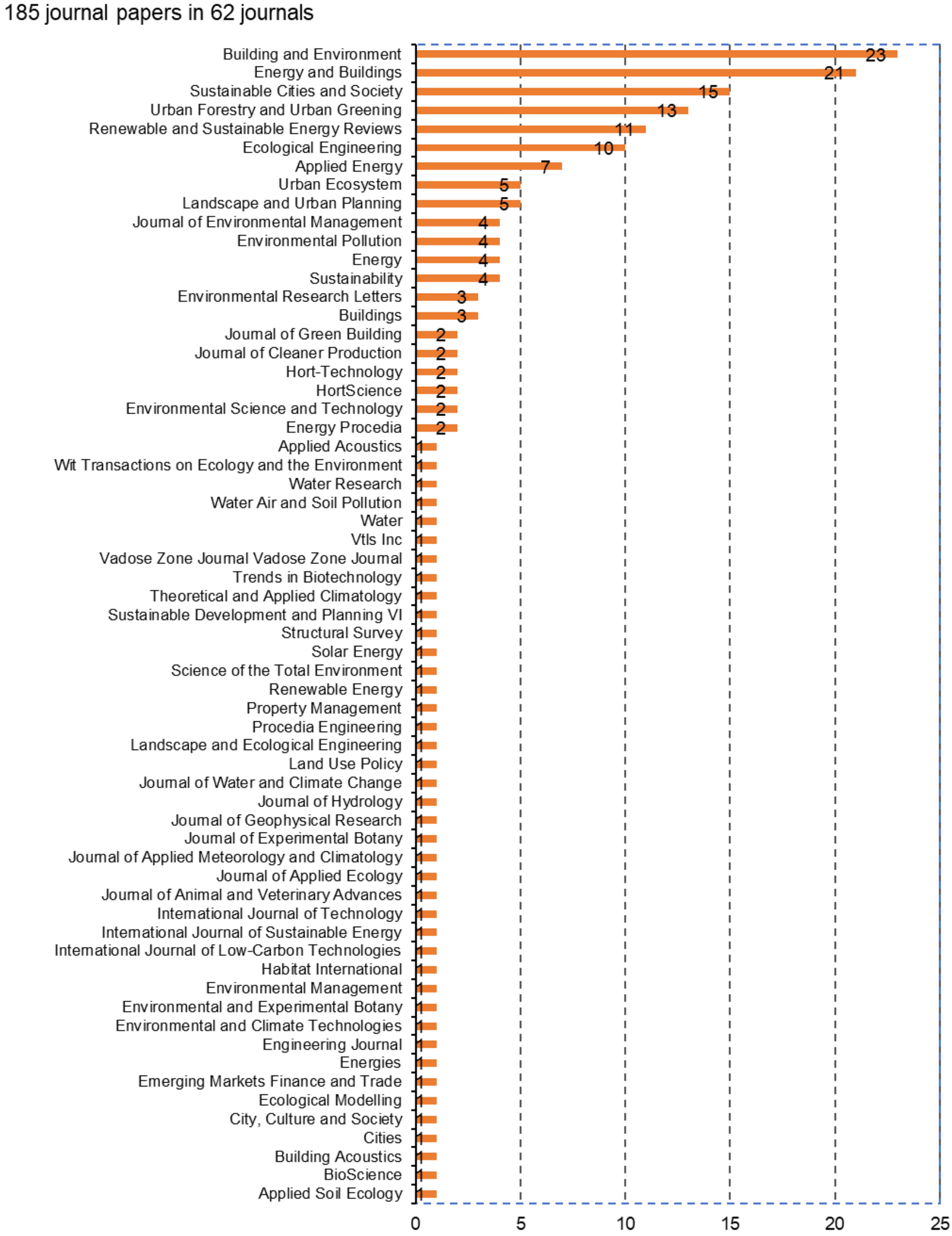


**Figure 2-3** The sources and number of the selected papers in journals

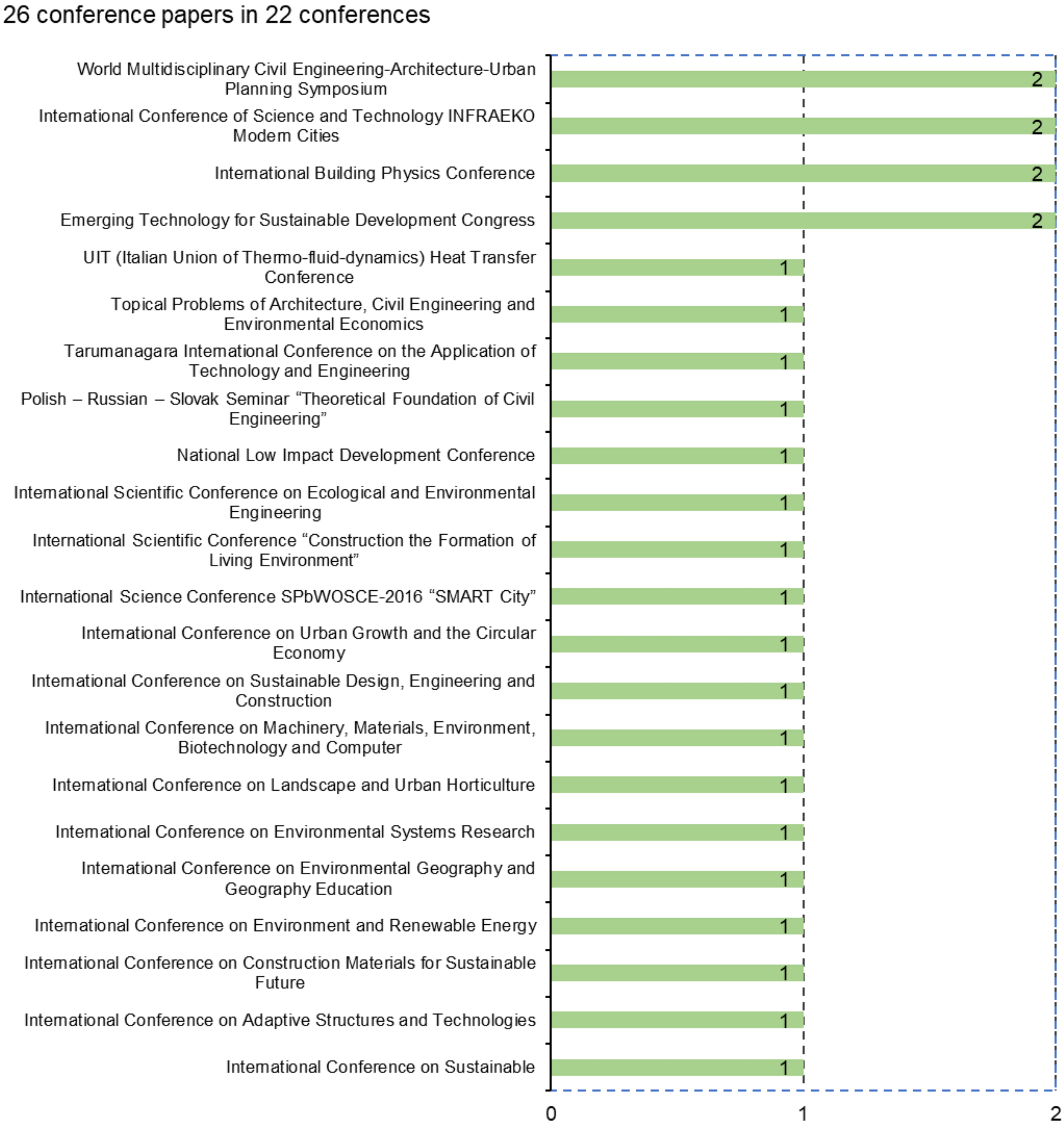


**Figure 2-4** The sources and number of the selected papers in conferences

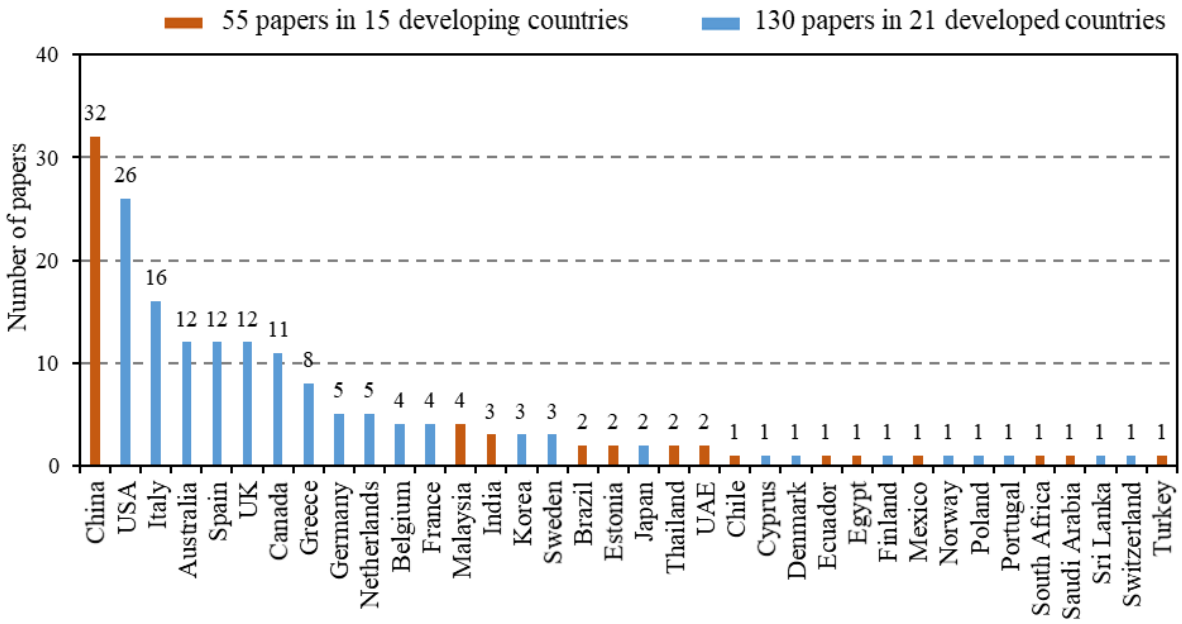


**Figure 2-5** Distribution of selected journal papers by country

First, according to the content analysis among 54 papers, three kinds of drivers on policy, market, and innovation and technology were identified. Second, 12 categories of motivations were verified based on 106 papers. Third, four aspects of barriers, including government policy, technology level, high short-term costs and long returns, and individual unwillingness were summarized based on 24 papers. It should be noted that some papers could consist of several different categories. Most motivations appeared to be modes of sustainable strategies, such as efficient energy use, urban heat island (UHI) mitigation, runoff control, and infrastructure cost reduction, aimed at emphasizing the positive effect of GRI in the urban environment transformation (*e.g.*, becoming comfortable and livable buildings and cities) [3-5]. Moreover, according to the external effect and internal effect theories, GRI should be induced from external pressures and by internal advantage, and not based solely on political strategies. Market needs and technological benefits are other forms of pressure pushing GRI. But these became their own separate categories in order to fully characterize GRI's overall desire, namely: (i) to build a decent reputation and achieve government confidence; (ii) to achieve better public and private opportunities; and (iii) to increase efficiency and benefits from more innovations.

### 2.3.1 GRI drivers

#### 2.3.1.1 Policy pressure

Table 2-2 exhibits the GRI drivers and other basic properties. With a variety of problems associated with urbanization and economic development, the government without any doubt could recognize the GR benefits and thereby propose relevant regulations to exploit their environmental benefits [6]. Green roofing systems could be further compelled to be economically and socially responsible, primarily due to compulsory policies, regulatory guidelines and initiatives [7]. The majority of pioneering work on GR was from Germany, where the guidelines for planning, execution, and upkeep of green-roof sites was published by Forschungsgesellschaft Landschaftsentwichlung Landschaftsbau (FLL) in 1995 [8]. The original version of GRI (2008) required policies to be publicly listed in Berlin including those related to environmental, social, and technology aspects. FLL's Report found that government strategies have greater awareness of green roofing systems compared to private sector [9, 10]. A possible explanation could be that the short-term benefits of GRI are not as perceptible and the installation costs may be too restrictive [11]. Existing evidence has verified that policy pressure could be an effective driver, especially in developed countries. The case of "Leadership in Energy and Environment Design" (LEED) advocated by the USGBC has become the most influential and internationally recognized standard in the assessment of green building (GB) and building sustainability, including GR. For the city of Toronto, Canada, the government has legislated the GRI by setting critical specifications (*e.g.*, environmental preservation, water efficiency, health improvement and public engagement for better wellbeing) [12]. For China, the context of developing country, its government issued the

**Table 2-2** Classification of drivers of GRI

| Drivers | Elements | References |
|---|---|---|
| Policy pressure | Mandatory policies, regulations, guidance, requirement, or initiatives | [6, 9-15] |
| Market pressure | i). Customers (sometimes known as project investors, municipal department, owners or end-user) demand or pressure | [6, 9, 16-18] |
| | ii). Award or certification: | [19-21] |
| | differentiation of market projects (e.g., meeting evaluation standards for GB) competitor pressure, e.g., competitors' GRI strategies | |
| | iii). Cost benefit (or joint venture)'demand or pressure | [10, 11, 22-26] |
| Innovation and technology advancement | Innovation and technology advancement | [16, 17, 27] |

initiative of sponge city, in which the GR-related techniques can be observed for runoff control [28]. In China, some provincial or city level governments have also implemented GR specifications to enhance the proportion of urban greening [28]. In addition, the Chinese Government released the Evaluation Standard for Green Building to accelerate GRI in the Chinese construction industry [29]. However, there have been studies claiming that GRI is difficult to reach the specified standards, especially in current era with rapid urbanization, as demonstrated by the constructing more building for improving housing affordability [14]. Nevertheless, the government should start to consider addressing the environmental problems by providing GR-related supportive policies, otherwise the urban environment could be keeping deteriorating in the near future [10].

#### 2.3.1.2 Market pressure

High-quality of life and personal satisfaction are the key determining GRI promotion given the current degree of urbanization and environmental degradation [30]. The end-users who could plant, play, and relish time on rooftops require a communal space to release their frustrations and relieve themselves of pressure [31, 32]. In some instances, GRI is incorporated as part of the contract conditions in green building projects [29] . The benchmark in new developing green buildings has been driven mainly towards safer and better quality GR products and implementation services, which have been advanced by a number of assessment standards (*e.g.*, LEED from USA, Three Green Star from China) [29]. Moreover, the requirements for emerging GRI schemes may also oblige among different groups of stakeholders to consider communal benefits and multifarious interests (e.g., revenues, policy update, participation upgrade, and individual moral management). Achieving satisfactory GR performance to draw the attention of possible users is also a critical issue requiring future studies. By this proactive approach, it has potential to form a market driven GRI atmosphere and then real practice. The example in the Kuala Lumpur, Malaysia showed that a potential to push GRI is its effective influence in the decision-making process [33]. Previous studies have shown the importance of considering UHI mitigation, energy-saving function, stormwater retention, and recreational space provision in the decision-making market [33-35]. Another essential proactive measure is the analysis of GRI needs and preferences as it pertains to the implementation process. In terms of GRI pioneering practices, the use of certifications (*e.g.*, GB certifications) and recognitions may advocate for more GR systems to emulate or follow successful models to acquire competitive advantage with regards to legitimacy [36]. In summary, the existence of market pressure is capable of advocating for greater acceptance of green roofing systems (*e.g.*, the benefits of end-users, society and environmental preservation).

#### 2.3.1.3 Innovation and technology advancement

Innovation and technology advancement is another factor driving GRI, particularly on the aspects of energy preservation and runoff control. For example, GRI use can indirectly benefit from research in various applications, including energy efficiency improvements, carbon emission reduction, and solar energy collection [16, 37, 38]. These developments provide sustainable solutions and appropriate retrofitting upgrades to the existing buildings [34, 39]. Interestingly, retrofitting GR of old buildings can be cost-effective, particularly considering that most old buildings have poor insulation and consume more energy (for cooling and warming the building) [40, 41]. The innovation and improvements from green roofing systems provide a viable escape from continued constriction brought by traditional roofs and deliver various other advantages [42, 43]. From the financial perspective, innovation and technology advancement are efficient to decrease the investment in relation to electric consumption and drainage [11, 22]. A study in Toronto, Canada demonstrated that the GR retrofitting could lead to the reduction of building energy demand by up to 3%, while the most significant was to create comfortable indoor spaces for occupants' living [44]. In addition, GRI is driven by potential benefits that would be amplified with the development of new materials, methods, and technologies, which will be further discussed in the next section.

### 2.3.2 GRI motivations

#### 2.3.2.1 Energy efficiency

Table 2-3 lists the motivations for GRI. When GRI results in better energy-saving performance, public desire, and personal behavior to obtain economic profits become one of motivational factors for GRI. Previous researches have indicated that plants and vegetation in rooftops can reduce energy usage in air-conditioning between 25% to 80% in summer [45], especially for hot climates that could witness the reduction of cooling load by 32-100% [46]. Within the context of Athens, Greece, Santamouris et al. administered the combination of experimental and numerical study on the GR system over a nursery school building [47], revealing that GR could result in a dramatic electricity reduction for summertime cooling and a 6-49% decrease for the whole building. The effect was even more apparent for top floor electricity consumption, ranging between 12% and 87%. In addition, the GR had negligible effect on the wintertime electricity consumption for heating [48]. If individuals and governments focus on energy-saving strategies, they will be more motivated to consider installing green roofing systems. By reducing electric consumption, the vast potential to cut costs and alleviate the energy crisis for cities can lead to significant economic benefits [37, 40, 49], which would be part of the optimal GRI performance .

**Table 2-3** The motivations for GRI

| No. | Motivations | References |
|---|---|---|
| 1 | A way to increase energy efficiency | [13, 21, 48, 50] [11, 19, 23, 24, 37, 45, 51] |
| 2 | A way to mitigate UHI effects | [19, 21, 24, 25, 37, 50-55] |
| 3 | A way to prolong roof longevity | [11, 23, 24, 50, 56-58] |
| 4 | A way to purify air pollutants | [11, 19, 21, 23, 24, 26, 37, 50, 59-61] |
| 5 | A way to control runoff | [11, 19, 21, 23, 25, 53, 54, 62] |
| 6 | A way to clean hydrological conditions | [25, 26, 37, 50] |
| 7 | A way to improve urban infrastructure | [24, 63] |
| 8 | A way of sound insulation for noise reduction | [21, 37, 50, 53] |
| 9 | A way to increases biodiversity | [19, 21, 24, 64-66] |
| 10 | A way to provide a recreational place and urban aesthetics | [6, 11, 19, 24, 37, 53, 67] |
| 11 | A way to enhance property value | [18, 24, 68] |
| 12 | A way to improve employment | [6] |

#### 2.3.2.2 Urban heat island (UHI) mitigation

GR has also been regarded as an important approach to mitigating UHI phenomenon. For example, an increase in albedo by the use of GR (0.7-0.85), could lower the ambient temperature by 0.3-3°C, compared with the traditional roof materials such as bitumen, tar, and gravel roofs that only have the albedo of 0.1–0.2) [69]. In analyzing the effects of GR at a community-scale using simulation software (e.g., ENVI-met), several studies have concluded that GRI could mitigate local temperatures by 0.2-1.4℃, especially at the downwind direction [70-72]. The strategy has turned out to be more effective in lowering the ambient temperatures in hot climates to more liveable and comfortable conditions [72, 73].

#### 2.3.2.3 Roof longevity prolongation

A properly installed and well-maintained GR provides added insulation and waterproofing that can result in better roof longevity. GRI helps prolong the life span of roofing systems, which can extend their utility by more than three times longer compared with traditional roofs [58]. In practice, there have been many manufacturers guarantee the life expectancy of the waterproofing membrane can be two times longer than its usual life span [11]. If the waterproofing layer of traditional roofing could endure approximately 10 to 20 years, moreover, GR would last more than 50 years [49, 57] The reduced maintenance costs as a result of lengthening the roof's life span should also not be neglected [58].

#### 2.3.2.4 Air purification

GR acts like biological filters that can improve air quality by partly absorbing vehicular exhaust and industrial emissions. Significant reduction in $CO_2$, $NO_X$, sulfur compounds and particulate matter (PM) from GR can result in a substantial decrease in risk from pulmonary and cardiovascular diseases [74]. According the study in the context of Chicago, USA, the GR with the area of 19.8 ha was capable of removing 1675 kg of airborne pollutants annually [59]. Another study has also suggested that if every building in Toronto installed a GR, the city would see the reduction of airborne pollutants by up to 58 tons [60]. A Manchester experiment found that by installing 50 ha (15.3%) of GR in the city center, 2.3% (± 0.1%) of the city's 9.18 tons of annual $PM_{10}$ input could be absorbed. The improvements in air quality make the average net present value of GR 24.5% to 40.2% lower than traditional roof [75]. A study found that considerable economic benefits derived from air purification could value up to USD895~ USD3392 (mean = USD2140) for every 2000 $m^2$ of installed GR [76].

#### 2.3.2.5 Water runoff control

GRI can significantly reduce water runoff, which is a valuable function, especially in urban areas [63]. The ability to retain water depends on the substrate properties (such as the depth and composition), precipitation and climatic conditions [77]. Vegetation also contributes to the retention of rainwater [78], with a fraction of water retained by the leaves while a portion is eliminated by evapotranspiration [79]. This helps in decreasing the peak water level and reduces the risk of flooding during extreme weather events. The retention capacity is measured by the volumetric gap (%) between water falling on GR surface and that removed (adsorbed and evaporated) and is usually expressed in annual terms. The rate varies from 40% to 80% [80] and is about 52% in the Mediterranean areas [81]. This includes the effect of stormwater retention in reducing the combined sewer overflows that many cities, especially the metropolitan, are suffering from. For instance, Toronto was estimated to save $46.6 million in infrastructure if GR would be utilized for combined sewer overflow (CSO) reduction [82].

#### 2.3.2.6 Water purification

The capacity of GR to isolate pollutants, thereby improving water quality, has recently received much attention in research [83, 84]. The GR, as a filter layer, reduces acid rain damage by raising the pH level (from 5-6 to 7-8), which results in a positive impact on urban water quality[26, 85]. According to Graham and Kim's simulation experiments, if all buildings in Vancouver install GR in the next 50 years, the water system will return to its natural hydrological conditions[86]. Roofing materials (e.g., impermeable film, asphalt, adhesives, drains, and grooves) are themselves potential sources of pollution, including metals (aluminum, copper, zinc, iron, etc.) and plastic materials [78, 87, 88]. A study found that heavy metals in runoff come from different urban rooftops, but the least metal content comes from GR (except for Zn) [89] which is probably due to plant absorption [61]. In general, the use of GR has positive effects on the improvement of water quality [26, 85].

#### 2.3.2.7 Urban infrastructure improvement

The retention capability of GR is also an important consideration to improve the resilience of building system stormwater and urban flooding, because of less water draining through the system [90, 91]. GR can reduce stormwater or flooding pressure on city drainage networks and avoid the harm from urban waterlogging. Based on the findings of a two-year measurement in Seattle, USA, the installation of GR reduced the need for stormwater infrastructure, which could benefit the city an estimated savings of \$39-100/$m^2$ or between \$100-324/$m^2$ for IGR system [23]. Overall, it is essential to count the urban infrastructure improvement, especially for rainwater and urban flooding management, as a motivational factor [92].

#### 2.3.2.8 Sound insulation and noise reduction

The potential of GR to provide sound absorption and noise insulation has often been proposed in multiple studies [93, 94]. According to field measurement, it is found that the GR could reduce noise by 5-13 dB during its transmission at low and mid frequencies, and by 2-8 dB at high frequencies [95]. In addition, a study compared the sound transmission loss in GR with different substrate depths and in the conventional roof type [94]. The GR with smaller substrate depth (75 mm) had less consistency in thermoluminescence increases while the GR with a deeper substrate (150mm) was more robust. It is reported that the GR with deeper substrates could increase transmission loss by 5-13 dB at low and mid frequencies and less than 6 dB at higher frequencies [94]. Additionally, based on the experiments, it is concluded that GR can dramatically lower the noise scale in cities because of the high absorption coefficient of the added GR layer [96, 97]. This sound absorption benefit becomes more evident in low-rise dwellings as the added GR layer is under the direct exposure to noise sources, making it a predominant absorptive surface.

#### 2.3.2.9 Urban biodiversity improvement

Compared with other roof systems, GR are uniquely designed to promote biodiversity and provided habitats for small animals in urban areas [98, 99]. Green zones can serve as ecologic “suspending island” to provide settlement and aid in the movement of wildlife species [100]. Replacing impervious surfaces with GR attracts small animals and insects and directly generates new spaces for wildlife [101]. GR can be used to save in restoration and conservation costs towards promoting biodiversity [102]. A study in the Friuli-Venezia Giulia Region (Italy) found that a protected area of 1786 $km^2$ would require an investment of about EUR40.19 million to preserve, rehabilitate and improve lands as natural habitat [103]. Although GR does not offer precisely the equivalent level of biodiversity like other forms of green realms, the conservation cost can still be significantly reduced by as much as 40% and 80% for IGR and EGR, respectively [35].

#### 2.3.2.10 Civic beauty and recreational place

Aside from the various economic motivations, GR also provides a variety of recreational, aesthetic, and psychological value to cities [31, 100]. For example, the use of different species of vegetation can create rooftop landscapes for beautification and provide a unique recreational space for inhabitants. The addition of color adds aesthetic value and improves the city's "fifth surface" beauty. People are more likely to prefer buildings covered with plants (GR and green walls) [104]. In one study conducted among the visitors of a sparsely vegetated GR at the center of Helsinki, multiple perceived benefits were identified [31]. The results showed GR provided visual and other sensory experiences, improved aesthetic and leisure value, and increased desire to explore. Also, roof gardens provide conducive space for mental relaxation and energy recovery, giving psychological rehabilitation for people working under considerable stress [31, 32]. Among those who visited the roof garden multiple times, the most common reasons include: take the children out to play (29.3%), fitness and exercise (20.7%), meeting friends (13.8%) and meditation (12.1%) [31].

#### 2.3.2.11 Property value increase

GR, particularly in high-end tourist areas, can increase property due to aesthetic improvements and enhanced accessibility of green spaces. Previous studies have concluded that GR was able to increase real estate value, which ranged from 3.6% [68] to 20.0% [12]. The difference in value effect was dependent on the GR category: at 2–5% for EGR and 5-

8% for IGR, respectively [18]. There is also indirect evidence attributing increased property value on GR.

#### 2.3.2.12 Employment opportunity

Although employment and income generation can be somewhat limited [105], GR can, directly and indirectly, create architectural and engineering jobs (e.g., design, construction, maintenance, and research). In one study where 50% of the buildings in the district were being retrofitted with GR, 1374 new jobs were created over 10 years [106]. Another study conducted in a residential area in the Western coast of Turkey showed  also tried to analyze the money and employment opportunities that would be generated if all rooftops in a condominium complex were converted into GR [107].

### 2.3.3 GRI barriers

#### 2.3.3.1 Lack of government policy

Table 2-4 exhibits four types of barriers and eleven subtypes of barriers to GRI, and their impacts are presented through the bold arrow in figure 2-6. Governmental policy should be the most powerful aspect, as aforementioned as the policy pressure, determining the GRI promotion. However, some studies have claimed that inefficient government policies may hinder societal enthusiasm towards GR construction[108-110]. This could draw the lessons of green building construction. For instance, previously the green buildings were voluntary in China, developers and private individuals in building industry were hesitated to adopt the green building technologies, although they were well informed with the environmental impacts of traditional building industry [108, 110]. Inadequate attention towards updating the local GRI feedback report is also considered a major barrier [111]. In Europe, some rules and regulations issued by local governments are oblivious towards the economic benefits of GRI [7, 49]. In addition, private companies are typically unwilling to take on GR projects without the necessary guidance and support from the government [112]. The mentioned evidence, therefore, reflects the lack of governmental policies for GRI promotion.

#### 2.3.3.2 Unsound technology development

There are several limiting factors on the technological side of GRI. For example, it is reported that in Australia where the government has recognized the GR significance in improving environmental quality, the gap between scientific data availability and GR feasibility to localized conditions has been a major barrier limiting the EGR prevalence [113]. In analyzing stormwater retention, the roof slope, vegetation type, and accessibility variable were shown

**Table 2-4** Summary of optional barriers for GRI to existing buildings

| Perspectives | Barriers | References |
|---|---|---|
| Government policy | Lack of incentive from the government towards developers | [37, 108, 114, 115] |
| | Lack of incentive from the government toward owners | [108, 115, 116] |
| | Lack of update from laws and regulations | [110] |
| Technology level | The old age of existing buildings; Weak structural loading for applying extensive GR system | [41] |
| | The weak affordability of extensive roof to withstand wind load | [108] |
| | The roof area of a high-rise building is small while lots of building services have been installed. | [108] |
| | The combination of green plants on the roof will breed bacteria and mosquitoes, which will disturb the high-level residents. | [110] |
| | Roofing materials (impermeable film, asphalt, adhesives, drains, grooves, etc.) are themselves potential sources of pollution, including metals (aluminum, copper, zinc, iron, etc.). | [61, 87-89, 117] |
| | It also was limited in scope to considering summertime conditions by calculating sensible flux between various roof treatments and the urban environment. | [37] |
| Non-transparent return | Increase of design/ construction /maintenance/ Irrigation cost | [11, 23, 37, 45, 76, 118] |
| | Lack of complete cost evaluation of GR performance by a life cycle | [6, 22] |
| Individual willing | Lack of awareness on extensive GR system in public and private sectors | [108] |
| | Lack of promotion from the government and social communities among the public and private sectors | [9, 20, 119] |
| | Lack of individual willing to pay | [120] |

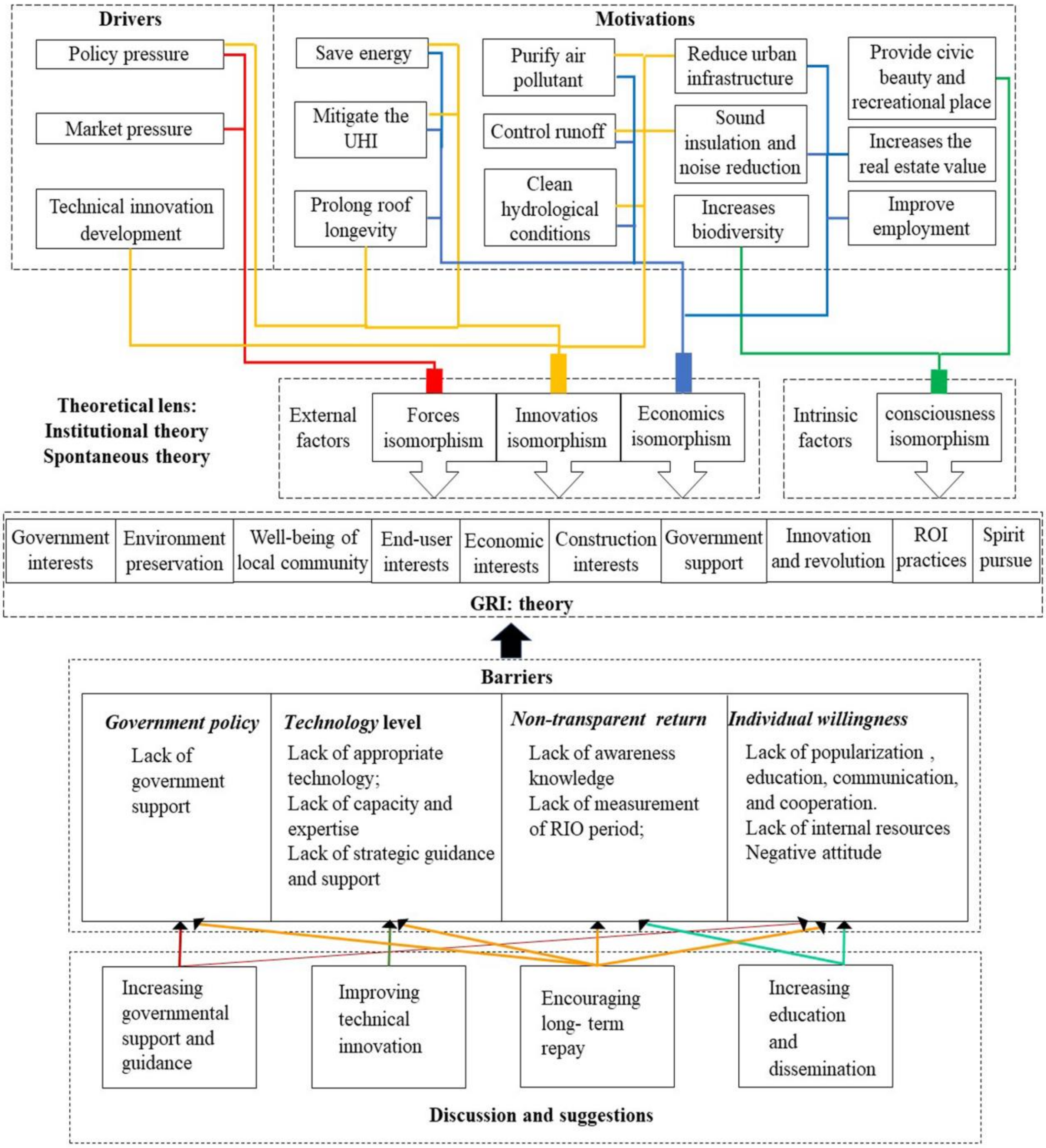


**Figure 2-6** The theoretical perspective of this study

to be critical factors in the decision-making process [33]. High-level architectural designs can turn out to have low-end configuration, due to unsuitability of planting medium and/or plant configuration with the building material. For green roofing systems, the selection of waterproof material is an optional choice among variety of kinds of waterproof materials. For the old age of existing buildings, only light structural loading can be used for applying extensive GR system, while the extensive roofs that always have light weight is weak to withstand wind load. Meanwhile, for high-rise or tall buildings, roofs are sometimes installed with building service facilities, leaving limited spaces for planting vegetation [108]. Green plants on roofs may breed bacteria and mosquitoes, which will disturb residents living near the rooftop [110]. Roofing materials, if they are not properly adopted, can become a source of pollution, including metals (*e.g.*, aluminum, copper, zinc, iron, etc.) [61, 87-89, 117]. In addition, existing studies about the GR impact on built environment are not enough, due to the limitation in experimental conditions and improper numerical platform for heat flux variation analysis under different roof treatments in summer [37].

#### 2.3.3.3 Non-transparent return

Market pressure can significantly influence the implementation of green roofing systems (**Section 2.3.2.2**). However, many GR benefits in terms of environmental protection, biodiversity improvement and the most important wellbeing improvement are difficult to be weight by economic profits, forming a barrier to the use of GR among the developers and private. Thus, the GR valuation cannot be considered as a straightforward process, which can be further complicated by limited suitable materials and inaccurate auditing approaches [82, 121]. When looking only at direct expenditures, the cost of GR, from design, construction, maintenance, and irrigation, would be about three to six times more expensive than conventional roofs [11, 15, 23, 45, 76]. Moreover, knowledge and information gap regarding the return on investments (ROI) for GRI could result in unpopularity [122]. Moreover, predicting ROI in different regions could be very problematic. For example, a study at the University of Maryland found that in one project, it took only seven years to fully recover the costs [11]. In Hong Kong SRA, replacing the ordinary bare roofs with GR were estimated to take about 10 years to recover the costs [123]. In Singapore, research based on the theory of life cycle cost found that although extensive GR were more cost-effective, the cost recovery cycle was estimated at 15 years [45]. A study in Canada determined that the recovery cycle of GR could up to 10 years when using the net- present value method [24]. In Ann Arbor, Michigan, seventy-five campus roofs from the University of Michigan were analyzed, and the researchers found that  the cost of traditional roofs would surpass the costs of GR beyond 40 years [76]. A simulation-based analysis on European GR by Ascione et al. concluded that it would take 143 years to recoup costs; while in southern Europe, costs will not be recovered [49]. In addition, during the stages of construction, operation, and management, it is essential to consider the GRI barriers of added maintenance expense and technical nodus [108].

#### 2.3.3.4 Individual unwillingness

Many architects and developers are reluctant to include roof gardens in their building projects, mainly because residents may not appreciate or use roof gardens, leading to wasteful and redundant space. This highlights the importance of greater public understanding and positive attitude towards roof gardens [124]. In general, the infrequency of useful case studies makes it hard to explicitly demonstrate the benefits from GRI [110]. In Australia, there is growing awareness towards the concept of GR, but there are still only few examples and little information readily available [113]. Another study found that aside from deficient incentives, the general lack of awareness serves as a major barrier hindering people to retrofit their building for GR in Melbourne [34].

## 2.4 Discussion and suggestions

The findings on the factors influencing the implementation of GR – drivers, motivations, and barriers – provide an opportunity to further analyze "how to use these findings for GRI?". This perspective of questioning has been widely used to investigate which GRI should be adopted. Meanwhile, the Institutional Theory and the Spontaneous Theory are appropriate to explain drivers and motivations of GRI are. These approaches, particularly the Institutional Theory, have been used to examine GRI cases around the world. For example, Forschungsgesellschaft Landschaftsentwichlung Landschaftsbau (FLL) in 2002 developed the Guidelines for the Planning, Execution, and Upkeep of Green-Roof Sites, which has been implemented in Germany and even in other countries [125]. The LEED developed by the U.S. Green Building Council (USGBC) became the most influential standard in the assessment of GB and building sustainability (including GR) and has been recognized internationally [126]. Integrating government policies, theoretical research, and market needs, has become extremely useful in identifying the drivers and motivations from both the external pressure-induced and advantage-induced perspectives. As shown in figure 2-6, the impact the GRI barriers on the GRI theory is illustrated, accompanying with a series of recommendations in counterbalancing them.

The first synergistic process is in relation to the measures executed by relevant decision-makers who can drive government, construction enterprises, and end-users to implement GR [127]. Drivers in aspects of policy, market and innovation and technology advancement, can be regarded as synergistic forces. The synergistic isomorphism process could be generated from the economic and environmental problems, such as economic loss caused by the UHI and urban waterlogging. However, it should be noted that when the synergistic forces are too weak to push GRI, they may become a set of barriers proposed in the aspect of governmental policy (*e.g.*, lack of governmental support, lack of legislation of the GR) [21]. The second synergistic process is innovation isomorphism [127]. It refers to comprehensively taking into consideration high technology's desire in obtaining attractive advantages with regards to the applicability and accuracy of expanding GRI (and vice versa) [27]. For the third synergistic isomorphic process, investors (both public or private) continue to preserver in emulating or creating successful GRI practices to avoid economic loss [127]. This is directly verified by the motivation to draw lessons from GRI success exemplars, existing energetic findings, and patterns in different regions. When aiming at GRI benefits (*e.g.*, saving energy, economic bonus, good image, friendly environment, and incentive policy benefits), communities and the private institutions would be more motivated to adopt GRI using successful cases to achieve similar outcomes. Clearly, aside from external institutional drivers, internal technological drivers can be the important element promoting GRI. The final synergistic process is individual consciousness [127]. Individual consciousness motivates people to perform organizational behaviors to be perceived as being compliant [108]. In summary, the GRI can be regarded as a cooperative process with multiple factors influencing the individual's decision-making process.

Some countries and cities are highly determined to learn and develop GRI due to its apparent economic and environmental values; others may lack the motivation, or have the unwillingness or inability to overcome barriers, which lead to their poor GRI performance. Some positive drivers and motivating factors may become barriers to GRI (*e.g.*, reluctant choice, insufficient scientific research, expertise and expenses). Regarding the willingness to pay, there could emerge several categories of motivations characterized by different levels of self-determination. The intrinsic cluster (or intrinsic emotional need) is the most inherent type of motivation, referring to the personal behavior of engagement for him/herself [127]. As a result, intrinsic motivation could view GRI as a promising activity, and the organizations may conduct in GRI projects for their own sake [31]. At this point, the GRI could be motivated. Nevertheless, for most cities, GRI is not completely intrinsically provoked but includes some other extrinsic motivations [10].

### 2.4.1 Increasing governmental policies and support

Since GRI is subjected to mandatory regulatory practices due to its environmental and economic impact, some aspects of GRI are still significantly dependent on the support (*e.g.*, incentives) and guidance (*e.g.*, regulations) from government agencies [10]. For example, a regulation in Tokyo, Japan, specifies GR installation in private buildings whose built-up areas exceed 1000 $m^2$ and in public buildings exceeding 250 $m^2$ that the GR installed has to be more than 20% of the whole rooftop area [128]. Government agencies and other relevant stakeholders must regularly update existing policies in responding to environmental problems. Government institutions can give incentives for construction companies or private individuals for developing and maintaining GR or impose penalties for lack of compliance.

Since international green building standards, such as LEED and BREEAM, have not adequately (in a voluntary way) defended specific index related to the GRI, governmental agencies should develop their own GRI indicator system for real estate agents, designers, engineers and owners to evaluate GR performance. Furthermore, climatic conditions should also be considered in developing GR evaluation system. Due to regional and climatic differences, no single scheme can work for all scenarios [49]. A comprehensive and methodical GR evaluation system is necessary to help in supervising compulsory and spontaneous GR behavior, and also provide some indication as to the direction of GR development in construction enterprises. It is critical to customize GRI specifications at the local level depending on their specific needs (e.g., financial situation, climatic conditions, native vegetation). Considering a variety of international policies are stimulating green buildings and GR use, pilot strategies and programs could be adopted to high-energy consumption buildings for better environmental benefits [129, 130].

### 2.4.2 Improving technical innovation

It is critical for enterprises or institutions to develop and research that promotes efficiency and innovation in GR technologies (*e.g.*, screen comfortable plant types of accessibility, reduce runoff pollution from GR construction materials), which will further enhance their performance and increase their sustainability [18, 27]. The volume of recycled materials at the substrate layer should be considered carefully [131] and the substrate of recycled glass performed towards neutralizing acid rain [132]. Furthermore, Hybrid Photovoltaic (PV)-GR has become an emerging trend that provides additional benefits and improves PV electrical yield [16]. The performance of rooftop photovoltaics is dependent on the module temperature and surrounding conditions (i.e. colder temperatures can facilitate PV performance) [133]. Also, an economic approach that considers the various perspectives must be developed to provide an objective economic assessment of the benefits from GR [89].

### 2.4.3 Encouraging long-term view

Compared with conventional buildings, GR could be more conducive in the long term rather than from a short-term perspective [22, 134]. This evidences the significance to offset the high initial investment of GR through the life cycle costing approach. It has often been stressed that GRI should be view on a long-term perspective. Some studies have criticized existing GRI as being short-sighted, as many governments offer the incentives (e.g. tax abatements) in the temporary and short-term form [22, 135]. In comparison, once the GR projects were finalized, owners might have no chance to enjoy the equivalent amount of financial benefits from subsequent abatement [22, 135]. A study indicated that most people indicated that their greatest interest regarding GR was whether the existing incentives would be stable and long enough for them to recover the initial cost [122]. As a result, incentives should be delivered methodically and from a long-term view [22]. For instance, a structured and strategic GRI development plan can focus on tax abatement and subsidies, which could be offered during different phases of GR implementation, including design, installation and regular maintenance [50]. On the other hand, GRI initiative may at first comprise small efforts that counterpoise present resources, rather than demanding additional ones. For example, through software simulation, the ROI may be established more clearly, which could be used in facilitating market standardization. In summary, developing an approach that assesses the long-term costs and benefits of GR provides a more effective means towards promoting GRI.

### 2.4.4 Increasing education and dissemination

In the future, aiming at encouraging the general public to accept and implement the GR in practice, it is essential to overcome the problem of lack of awareness and knowledge of GRI. By educating and training the public about local standards and specifications, environmental situations and and GR technology, the awareness of using GR can be enhanced. It is also a sound measure to inform people with GRI experience from actual cases and strengthen their environmental awareness. In addition, GR can be used to support the achievement of higher sustainability labels (GR has been listed as a promising item in LEED or BREEAM) [29]. Building an environment-friendly platform or a themed website can help deliver the useful information on GR to public [89]. It would be beneficial for the public to understand passive cooling strategies and improve building quality to jointly promote GRI. Added value on building quality and commercial price can be derived from the installation of GR, including passive cooling for upper layers, as confirmed in the literature [136]. Informing the public of potential savings and benefits from different roofing solutions can also be used towards promoting GRI [49]. Building platforms for strategic cooperation among individual organizations can reduce obstacles that constrains government resources and credibility, which could then help facilitate GRI [137].

Government agencies and advocacy groups need to strive towards disseminating effective information to both building owners and their tenants. Information should be customized to the values and priorities of stakeholder groups, which would include financial and wellness information provided to owners and tenants. If building owners are willing to pay more for green features, the costs of GR may become more competitive [20]. For instance, a survey in Beijing, a city plagued by UHI problems, showed how the locals were willing to pay an annual fee up to 148.582 RMB (22.446 USD) for UHI mitigation [120]. This provides strong argumentation that individual willingness can potentially become a strong asset for GRI. Therefore, more effort is needed to improve individual awareness in preserving the built environment.

## 2.5 Recommendations

Although there is general agreement that a set of environmental benefits can be derived from GR, other concerns in terms of maintenance issues, require further review. For example, conventional GR planted with sedum were hypothesized to have less retention and detaining capabilities in cold climates [49]. Further investigation should be conducted on whether planting more native species could help increase GR performance [54, 66]. Also, GR materials such as light-weight plastic, root barrier and drainage layers, would have to be studied more rigorously, and provide codified standards into their production and use.

Moreover, two types of GR systems should be taken into consideration in use. There have been a simplified green home model for design and practice, as shown in figure 2-7, where the green home modules should been developed to include GR system, water storage element, solar panel, and space for other components [37]. In most cases, the modules could be pre-installed with substrate and vegetation, integrating well with aged and new dwellings. In addition, it could offer a range of flexibility to shift part of GR, in case of amendment and could be shifted to any part of the GR or other dwellings. Nevertheless, it is essential to consider the investment and ultimate disposal of modules [37]. The second type is the agriculture roof, which has more obvious economic benefits. Due to the high construction and operation costs and low input-output ratio, rooftop agriculture has largely been a public welfare project [26]. One such example is the Beddington Zero Energy Development (BedZED) in England, which is a highly innovative scheme that comprises housing, workspace units, and community facilities. Its principal objective is to be ‘carbon neutral’ which is implemented using a wide range of sustainable features. The solution to maintaining the indoor temperature is to grow a large amount of a semi-succulent plant called "jingtian" that covers the roof. "Stonecrop" helps prevent indoor heat losses during winter and improves

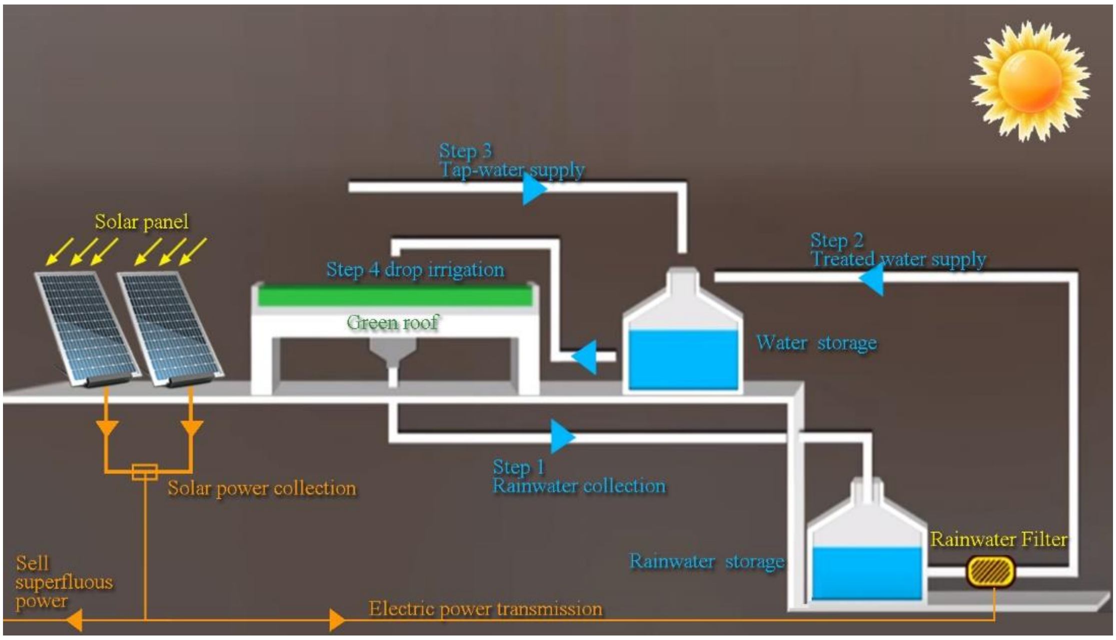


**Figure 2-7** Schematics of a proposed green home, adapted from [37]

the image of the whole ecological village. According to Chinese statistical data, the income of rooftop vegetables per mu (666.7m$^2$) can reach up to 20-40 thousand RMB. In some areas the total added value and household savings can add up to billions in RMB. Since slum and old buildings would greatly benefit from the energy-saving [41], more attention should be paid towards retrofit research for sustainable projects. In addition, there should be more focus on improving policies and public information on greenhouse technology [110].

### 2.6 Summary

This chapter conducted a comprehensive review towards existing GR literature for the identification of drivers, motivations and barriers to the GRI. Through this study, this chapter identified the policy, market and innovation and technology advancement drivers to GRI. At the same time, 12 motivations that may be drawn by different stakeholders for economic profits were also obtained. In addition, the GRI underwent four categories of barriers such as lack of government policy, unsound technological development, high initial cost and long payback period, and individual unwillingness. The typical barriers consisted of lack of governmental support, lack of GR research and demonstration projects, lack of precise analysis of ROI, and lack of GR knowledge and awareness. On this basis, some suggestions were preliminary presented from the perspective of governmental agencies, research institutions, end-users, public and private sectors, for GRI promotion. Nevertheless, in the future much more efforts are required to explore and evidence the significance of the identified drivers, motivations and barriers for GRI, thereby promoting the GRI in practice.

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*Chapter 3*

# *Methodology Selection and Feasibility Analysis in China*

**Chapter 3: Methodology Selection and Feasibility Analysis in China**

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### 3.1 Introduction

According to the regional division of climate zone, the global climate zone can be divided into figure 3-1. Based on previous researches, Alexandri and Jones concluded that Riyadh（Saudi Arabia）, situated in a hot and dry region, would receive the largest temperature mitigation from the use of green roofs by comparing different cities [1]. And, Ascione, F., et al. indicated that GRI in southern Europe is not cost-benefit [2]. the performance of green roof for daytime cooling especially, varies per prevailing climatic condition, this is more apparent with the full-intensive green roof type and follows this order: hot-dry (Cairo), hot-humid (Hong Kong), warm-humid(Tokyo) and temperate (Paris) [3]. For these reasons, we could infer that green roof implementation is much better thermal performance in hot and dry area.

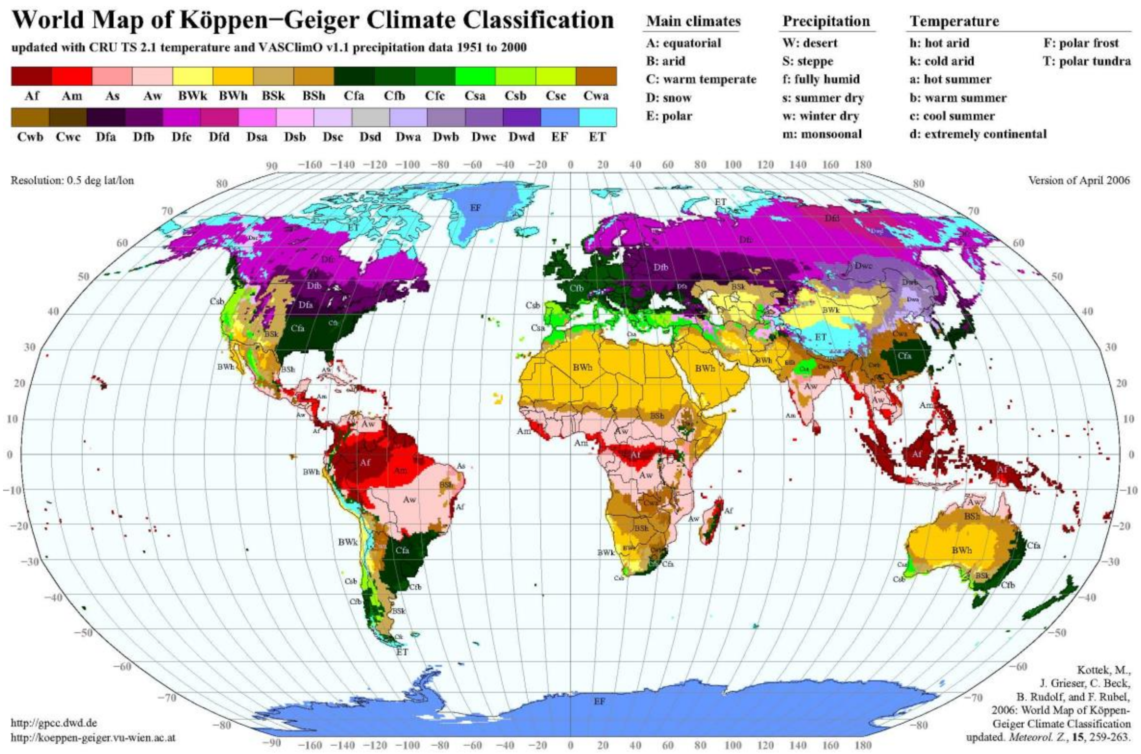

**Figure 3-1** World Map of the Koppen-Geiger climate classification [4]

### 3.2 The Selection of Research Location

There are five climatic zones in China and this dissertation focuses on Hangzhou City, South of China, which is near Shanghai City as shown in figure 3-2. The research location belongs to hot summer and cold winter zone which is a comfortable and feasible climatic zone for green roof research in summer.

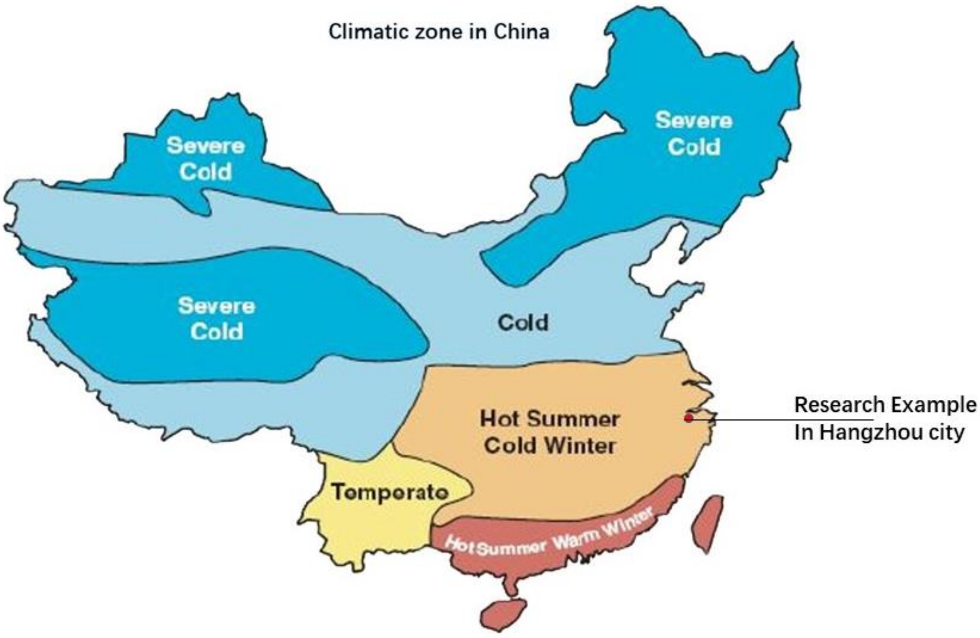


**Figure 3-2** Distribution of climatic zone and research example in China [5]

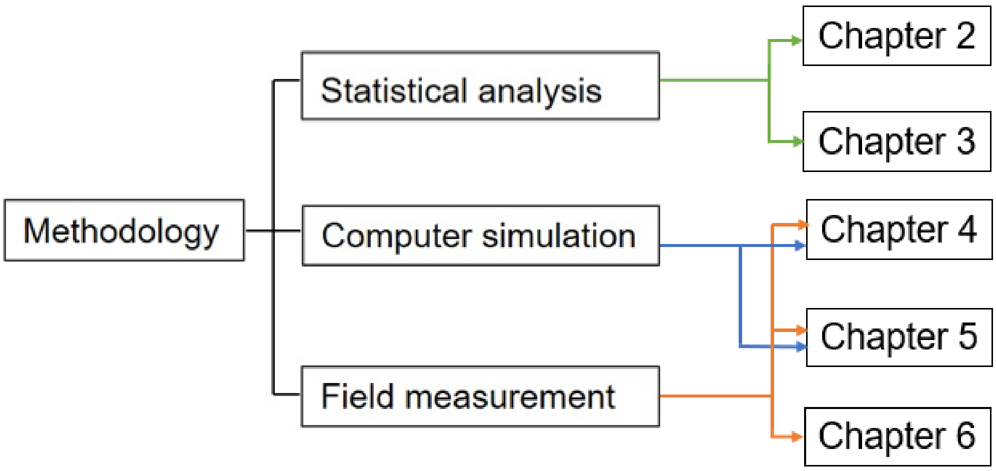


**Figure 3-3** Main methodology in the dissertation

### 3.3 Classification and Selection of Methodology

The research methods of this dissertation are combined and adopted by (1) field measurement, (2) computer simulation (3) statistical analysis. And it is divided into three parts in technological way from different aspects to solve the insufficiencies of previous research. Firstly, this paper expounds the current problems of urban heat island, then put forwards a series of strategic solutions including the main topic of green roof. Afterwards, the new findings of green roof will be elaborately explained and studied. Both Chapter 4 and 5 utilized same methodologies. Chapter 2 and Chapter 3 are partly similar to use statistics which data are collected in different ways. Chapter 6 is in different way as shown in figure 3-3. The main methodologies to be applied in this dissertation is to explore unknown GRI theory, especially, explain how to popularize GRI in manager research, which scope is comfortable and feasible for buildings on both sides of the street to GRI, which scopes of GRI is more cost-benefit and comfortable by GR morphologies variations, what the thermal performance of common plant in roof, in detail, the methods and result will be discuss in following chapters.

### 3.3.1 Field Measurement

In recent decades, with the rapid development of urban climatology and urban boundary layer theory, great progress has been made in the observation and research of urban microclimate. The observation of urban-scale microclimate mainly focuses on the study of the impact of urbanization on heat island, as well as the range, origin and change of heat island intensity. Oke summarized the research progress of urban heat island in the 1980s, especially the observation methods of near-earth air temperature and the variation rules that obtained from the tests [6]. Comparing with the observation method which is summarized by Oke, it can be found that although the great progress in testing methods and instruments over the past 20 years, the methods for testing UHI have not changed significantly. In addition, all conclusions, these approaches have a similar problem -- the inability to accurately distinguish and define the Effects of "Urban Effects" on heat island intensity [7, 8]. The popular methods for testing and analyzing include:

1) the annual variation trend of record values based on urban meteorological stations (as usual, over 20 years) [9, 10];

2) a comprehensive comparison of the annual variation trend between one or more urban meteorological stations and several suburban meteorological stations [11, 12];

3) statistical analysis of one-to-one observation between test values of urban and suburban meteorological stations [13];

4) observation network composed by a central city and its surrounding weather stations [14, 15];

5) weather observation by comparison of horizontal part of urban areas [16];

6) comparison of heat island conditions on weekends and weekdays [17].

In addition, the experiment of Winkler et al. shows the rule of spatial distribution of observation time and measure[18]. So far, most of them adopt satellite, remote sensing, meteorological platform and other research methods from the literature collected. This study of chapter five and chapter six draws lessons from (1) and (5). Chapter four draw on the experience of (2) and (3). The figure 3-4 is main test tools to be utilized in meteorological observation of this dissertation.

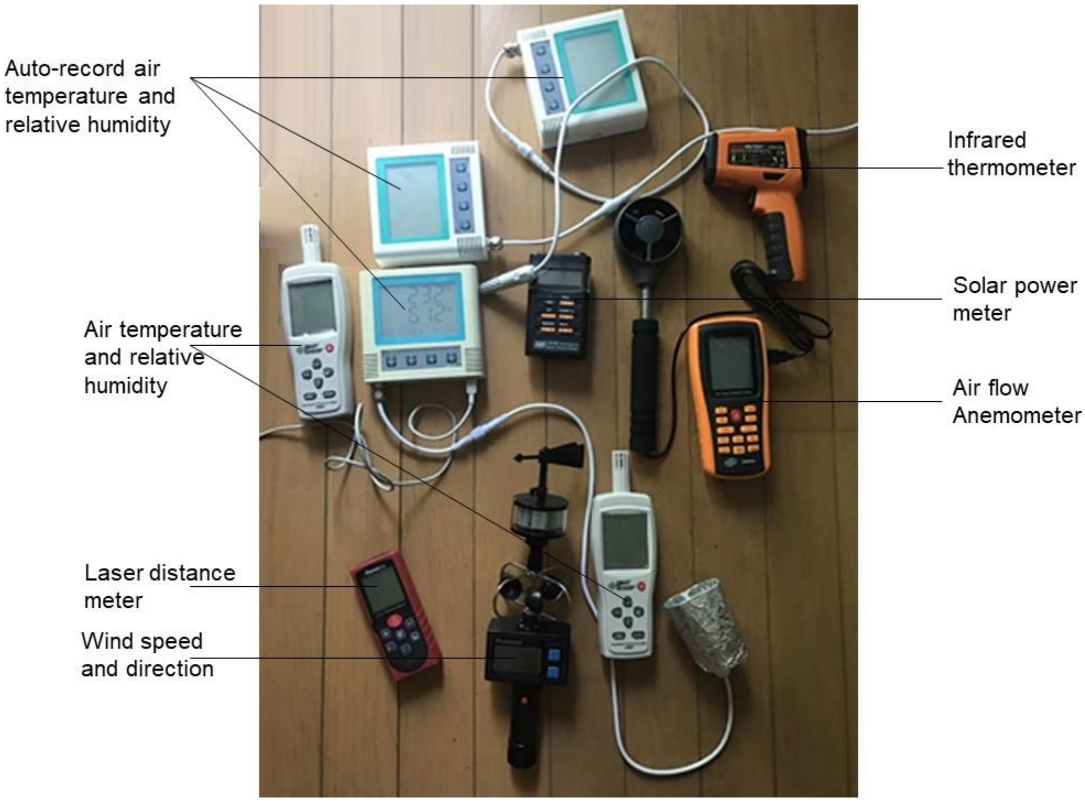


**Figure 3-4** Test tools in this dissertation

### 3.3.2 Numerical Simulation

On the basis of summarizing previous researches, scientists from various countries developed many simple and convenient software to predict outdoor thermal environment and building energy consumption by using powerful computer cluster technology. Some of the software is also integrated with other database or analysis software, such as Geographical Information System (GIS) and Computed Fluid Dynamic (CFD). The applications span all stages of urban planning and building design, from predicting building energy consumption and outdoor environments to evaluating human thermal comfort and health. At the same time, the situation of different climate areas is studied through comparing with the field measured data, wind tunnel experiments and other methods, so as to further check these tools to ensure the accuracy of the results.

Through assessing and comparing with the simulation tools as shown in table 3-1, chapter five and chapter six are employed by the software, ENVI-met. In this dissertation, ENVI-met is of version 4.3.1 winter, an urban three-dimensional micro-climate software, based on computational fluid dynamics and thermodynamics developed by Bruse and Fleer of the University of Bochum of Germany, is used. It is mainly used to simulate the impact of different types of urban underlaying, such as green roofs, walls and road materials, on the micro-environment, and to evaluate landscape design schemes. from the literature collected, its application scope is mainly at the level of large and medium-sized cities, and only for the simulation and evaluation of several typical underlying surface types. However, for areas with smaller scale, such as single building, residential community and street park, its report is relatively few.

**Table 3-1** The analysis of software application in thermal simulation

| Simulation tools | Scale | Principles and effects |
|---|---|---|
| CitySim | A large-scale dynamic building | The heating and cooling needs of buildings for the design and retrofit stages. |
| SOLENE | Microclimate in urban situations | Simulating the urban environment and having the possibility to define freely the envelope materials and quantify the efficiency of a large number of envelopes in a realistic urban environment. |
| EnviBatE | Between buildings indoor and outdoor at the district scale | Modeling heat fluxes and air renewal depending on the type of flux and the geometry. |
| SUNtool | Architectural design and environment | Optimizing the sustainability of master plans by simulating the urban microclimate and the flow of energy, water, and castoff. |
| AUSSSM | Urban heat island | Predicting the intensity of heat islands from the perspective of planning and design, using the principles of urban meteorology. |
| EEP | Medium-scale urban areas | Simulation of building energy consumption, traffic pollutant dispersion, and health conditions. |
| ENVI-met | Environmental micro-climate in small areas | Layout of landscape greening and improving the environmental microclimate. |

Michael Bruse, founder of ENVI-met, used the software to introduce that green roofs could reduce the ecological footprint of our cities by decreasing air temperature [19]. The ENVI-met software includes 5 sub-projects of atmosphere, radiation, soil, plant and architecture. The module has a horizontal range of 0.1-1.0 km, a vertical range of less than 200.0 m, a horizontal resolution of 0.5-5.0 m, a simulation duration of less than 2 days and a maximum time step of 10 seconds. It is mainly used to simulate the interaction among the surface of buildings, vegetation and air in a small-scale space in urban areas. The user interface of ENVI-met software is simple. Users only need to set the boundary conditions according to the actual situation of the study area to simulate the micro-climate parameters, such as air temperature, ground temperature, average radiation temperature, humidity, wind speed and wind direction. Generally, ENVI-met software is widely used in evaluations of planning programs of urban, architectural and landscape design of human settlements[20-22]. This software consists of three independent sub-models and nested grids. The sub-models include three-dimensional main model, soil model and one-dimensional boundary model. The model structure is shown in figure 3-5. The three-dimensional main model is divided into three parts: the horizontal coordinate x, y and the vertical coordinate z. The characteristic parameters, such as greenery, building and underlying surface structure, are all set in the three-dimensional main model. To ensure the accuracy of the simulation, the one-dimensional boundary model extends the 3D main model boundary to the atmospheric boundary layer of 2500.0 m, and then transforms the initial conditions into the actual simulation boundary conditions required by the 3D main model. The soil model is a one-dimensional model, ranging from the underlying surface to the ground surface of 1.75 m. It is mainly used to calculate the transpiration of plants, the wet transfer process of root system in soil and the change of temperature and humidity on the underlying surface. There are many governing equations involved in the ENVI-met sub-model, and the principle can be found in the literature [23]. ENVI-met numerical simulation includes two basic calculation steps, model construction and boundary condition setting. The calculation of model construction needs to define the latitude, longitude and type of research area, including buildings, greenery and underlying surface. In ENVI-met, Plants were simplified into one-dimensional rectangles depending on their height, and these shapes were assigned standardized leaf area index (LAI) and root area index (RAI) by species. The interaction between leaves and surrounding air can be expressed as three parameters: direct heat transfer heat flow, evaporation intensity of surface water and transpiration intensity of plants. Therefore, through such a simplified method, not only can simulate small vegetation, such as grassland and crops, but also can simulate towering trees [24].

Recently, With the newest version – ENVI-met 4.4.1 summer– there will be no more size limitations for model area outputs in LEONARDO. Only system setup will influence the allocated memory. In model area, computer can now use telescoping combined with splitting: The lowest grid box is split into 5 subcells to get more information about the conditions close to the surface and telescoping is used to increase your model area height while at the same time saving computational time. Besides, it strengthens the function of green roof and vertical green. Next version, it will open new simulation function of rain time.

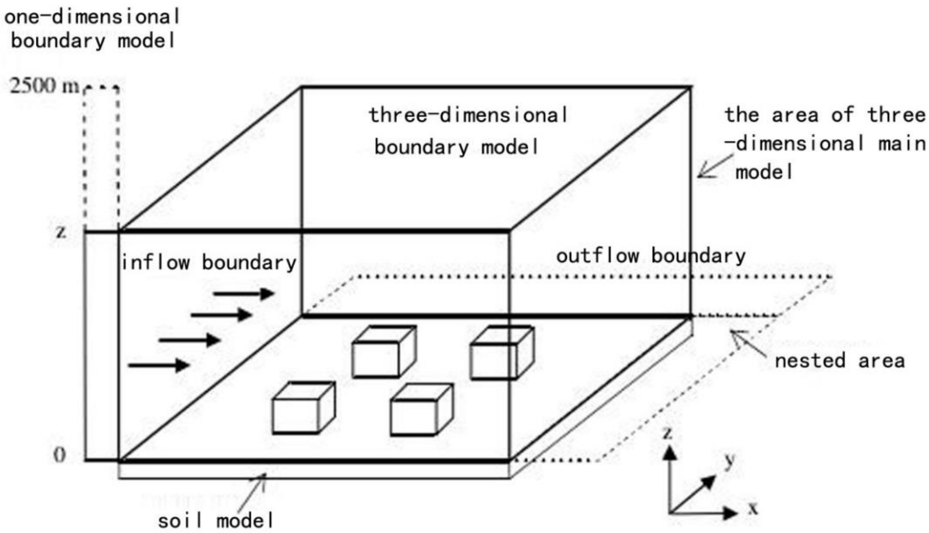


**Figure 3-5** The diagram of the structure of ENVI-met model

### 3.3.3 Statistical Analysis

Everything in the world has two aspects: quality and quantity. When individuals want to understand the essence of things, they must master the regulation of quantity. The method of statistical analysis is to conduct mathematical statistics and analysis through various data and materials obtained through investigation, so as to form a quantitative conclusion. Statistical analysis is a research method, which is helpful to analyze and study the quantitative relations of obstacles, drivers, scope and degree of GRI, is beneficial to recognize and reveal the mutual relations, change laws and development trends between ideality and reality, and achieve the comfortable and logical interpretation and prediction for GRI promotion.

literature screening mainly focuses on chapter two, which collected the theories such as the key words of green roof, roof garden, ecological roof, from Google Scholar, Scopus, Baidu Scholar and so on. Through literature collection and collation, multi-angle analysis and comparison are carried out to summarize theoretical and academic views, draw lessons from relatively mature relevant experience and advanced technical methods to summarize strategies and methods. Especially, this study compares with previous research of thermal performance in green roof. Nowadays, literature information can be converted in the visual format that can be identified by the literature analysis software, which is helpful for literature screening. Such as, the main information distribution of whole literatures is analyzed in software of Citespace as shown in Figure 3-6.

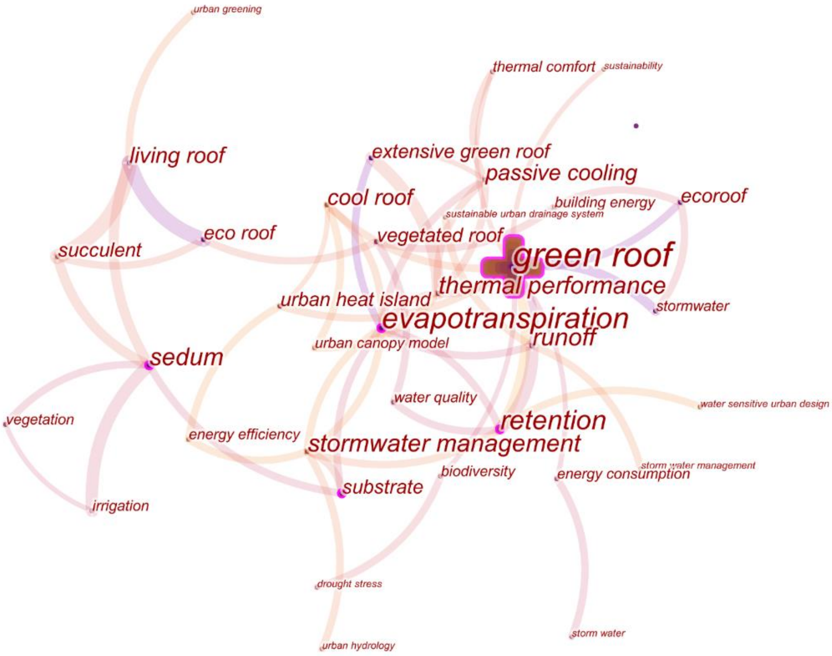


**Figure 3-6** The key words in screening literatures in software of citespace

### 3.4 Green roof market in China

### 3.4.1 Methodology

The sources of big data derived on the internet are mainly defined by target users, comprehensive division of user demands, and enhancement of interaction and communication with users so as to establish an effective feedback mechanism for users[25]. The interaction between users and search engine can provide users with useful information and valuable index by using cloudy server[26]. Since 2010, when GOOGLE withdrew from the Chinese market, Baidu, the local search engine, has occupied more than 60% of the Chinese search engine market [27]. Baidu Index, launched by Baidu company in January 2011, analyzes the data based on the behavior data of netizens among massive index data. Baidu Index collect many data information by users who utilizing the Baidu server, such as user registration data, reader survey information, clicks of digital resources, papers of scientific researchers and so on. Baidu Index can dig these large amounts of related resources through machines and tools. In a word, Baidu Index utilize data-mining technology and a series of network tools to calculate index information and frequency after users are tracked. Therefore, it is helpful to explore and promote the explicit and implicit market demand. In this study, I input keywords of green roof and utilize the functions such as search frequency and distribution characteristics, as shown in figure 3-7, to analyze the dynamic green roof market in China.

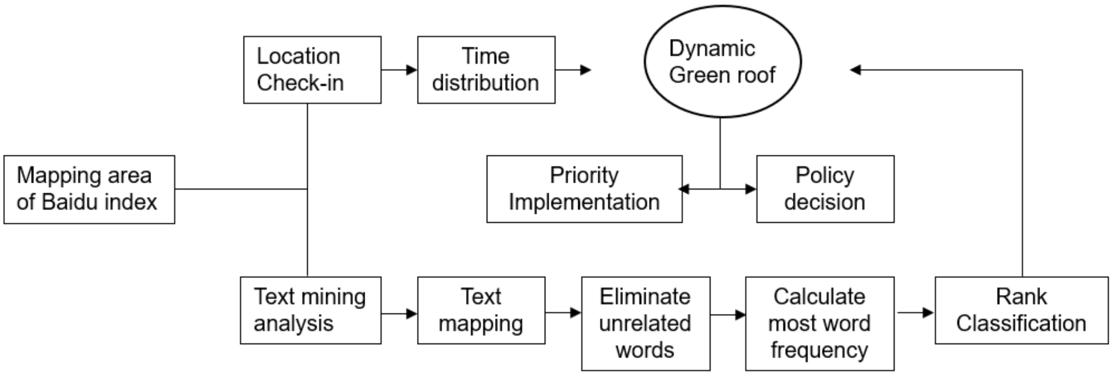


**Figure 3-7** The analysis flow of green roof by Baidu Index

### 3.4.2 Discussion on Green Roof Demand by Different Area, Gender and Age Group

3.4.2.1 Demands of Green Roof in Different Large Districts of China

China is divided into seven large districts from north to south. The index frequency of green roof is indicated by the color from dark blue to light blue from high to low, which is followed by East China, South China, Central China, North China, Southwest China, Northwest China and Northeast China, as shown in figure 3-8 (statistic time: from July 1, 2013 to October 25, 2019). According to top ten regions by big-data statistics, East China is the highest, followed by Central China and South China and so on, while East China is twice as much as the second one. Since East China is located in hot summer and cold winter, which is agreement with that green roof is more suitable in dry and hot areas[28]. In winter, green roof also provides a certain thermal insulation effect[29], so this could be another reason for hot index in East China. As a result, in China's seven large districts, east China should be the most priority and possibility to promote green roof implementation from bottom-up data support.


**Figure 3-8** The index frequency of green roof in seven large regions of China

#### 3.4.2.2 Demands of Green Roof in Different Provinces of China

China has 23 provinces, 5 autonomous regions, 4 municipalities directly under the national government and 2 special administrative regions, among which Guangdong province has the highest index frequency as shown in Figure 3-9 and belongs to the hot summer and warm winter climate zone, followed by Zhejiang and Jiangsu Province and so on. Generally speaking, the top three provinces are located in the south of China, which is closely related to the climate zone belonging to the hot summer [30]. According to the Chinese population data of 2018 year published by the National Bureau of Statistics of China(NBSC) on 2019 year [31], as shown in table 3-2, Guangdong Province is 113.46 million, Jiangsu province is 80.51 million, and Zhejiang Province is only 57.37 million. From the population statistic, the population of Zhejiang Province and Shanghai province is less than 1/2 and 1/4 of that of Guangdong Province, but the index value is more than 1/2 and 1/3 of Guangdong Province respectively, which indicates that the locals of Shanghai and Zhejiang province are more interested in green roof. The Chinese government could carry out a trial implementation of green roof in the two provinces, which provides a solid theoretical basis for promoting the popularization of green roof.

#### 3.4.2.3 Demands of Green Roof in Different Cities of China

As shown in figure 3-10, Beijing, Shanghai and Guangzhou City, the three mega-cities, are among the top-three index in city scale, which may be related to the phenomenon that in recent years, the heat island in each megacity is serious and the green roof has the beneficial function of cooling and humidification to mitigate the UHI [30, 32]. In addition, Chongqing city, located in the top tenth , is a hot summer and warm winter area and also belongs to China's high humidity area which maintains 70-80% all year round, so green roof focus on the cooling effect rather than humidifying effect [33]. From the relationship between urban population and the index volume, except Beijing, Shanghai and Guangzhou, Hangzhou ranks the fourth in city scale and is also the top 10 cities with the lowest population as shown in table 3-3. Hangzhou City has less than half the population of Beijing and Shanghai, but has more than half the index volume of Beijing and Shanghai, indicating that among the top ten cities in China, people in Hangzhou pay more attention to green roof and the market potential is infinite. It should be related to a series of green policies issued by Hangzhou government in recent years, such as ecological city and sponge city, which potentially paved the way for popularization of green roof.

**Table 3-2** The population in the ten provinces as hot rank (Dec. 31st, 2018)

| No. | Province | Population(million) | No. | Province | Population(million) |
|---|---|---|---|---|---|
| 1 | Guangdong | 113.46 | 6 | Sichuan | 83.41 |
| 2 | Zhejiang | 57.37 | 7 | Shanghai | 24.24 |
| 3 | Jiangsu | 80.51 | 8 | Shandong | 100.47 |
| 4 | Beijing | 21.54 | 9 | Fujian | 39.41 |
| 5 | Henan | 96.05 | 10 | Hebei | 75.56 |

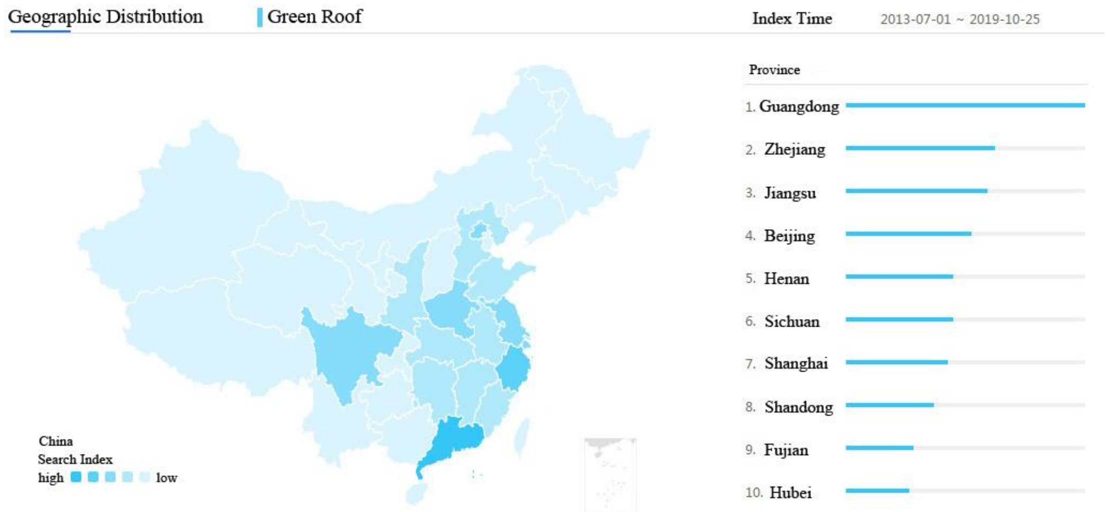


**Figure 3-9** The index frequency of green roof in top ten provinces of China

**Table 3-3** The population in top ten cities of China as hot rank

| No. | City | Population(million) | No. | City | Population(million) |
|---|---|---|---|---|---|
| 1 | Beijing | 21.54 | 6 | Chengdu | 16.3 |
| 2 | Shanghai | 24.24 | 7 | Zhengzhou | 10.13 |
| 3 | Guangzhou | 14.90 | 8 | Xi’an | 10.00 |
| 4 | Hangzhou | 9.80 | 9 | Wuhan | 11.08 |
| 5 | Shenzhen | 13.02 | 10 | Chongqing | 31.02 |


**Figure 3-10** The index frequency of green roof in top ten cities of China

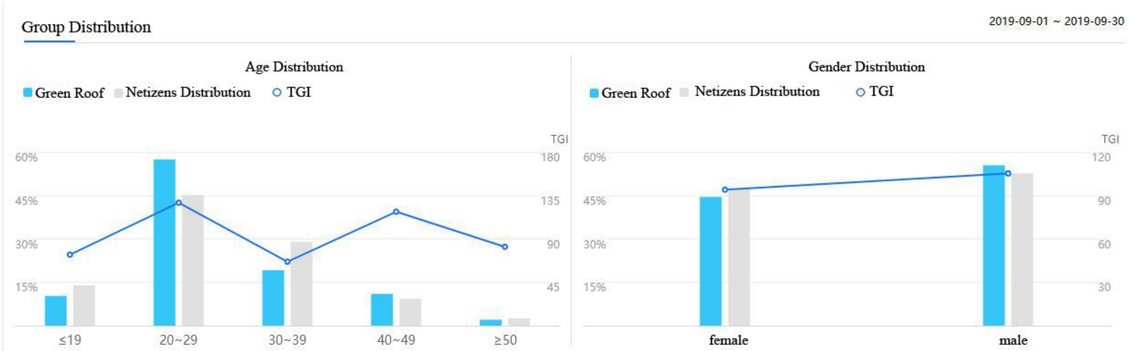


**Figure 3-11** The index frequency of green roof and netizens distribution

3.4.2.4 Index Distribution of Green Roof by Age Group and Gender in China

According to the analysis of TGI (Target Group Index) and index frequency as shown in figure 3-11, the age distribution of retrieval users is mainly between 20 and 29 years old, reaching nearly 60%, which is about 15% higher than TGI, which is consistence with the result that Chinese netizens is almost junior [34]. The grey part is based on the 43rd report of CINIC (China Internet Network Information Center), and it indicates that the young generation pays more attention and accessibly accepts green roof. This trend will change the traditional concept of green roof in China as time goes on, and green roof market would be more and more popular in future. From the perspective of gender, men pay more attention to green roof than women, so from the perspective of market promotion, publicity should be more preferable towards men. Overall, young man would be main market for green roof, which should be probable that green roof is a labor activity for men.

3.4.2.5 Potential Demands of Green Roof by Related Words

Related words are other words to be input for search at the same time, such as waterproof of green roof, vegetation of green roof, maintenance of green roof. Among them, waterproof, vegetation, maintenance that these words are related words. Due to the time limit of Baidu Index, only one week's related-word index can be counted. As shown in figure 3-12, this section extracts seven days' index data from December 3 to 9, 2018 to analysis related-word of green roof. Through the related-word heat rank, it is helpful to reverse dig potential demand for green roof and to participate in green roof implementation to avoid common mistakes and make full preparations in advance. Due to move away from the core word, green roof, the relationship of green roof goes from strong to weak (deep blue to light blue) which means the liveness goes down. Through analysis, it is found that the highest frequency of relevant index is stainless steel water tank, which may be the unknown products could be found but it could infer potential market demand. Furthermore, it is valid to build relevant company in local area in time. Orange indicates that the index frequency is increasing, indicating that the market heat is increasing. Similarly, the increasing index of plastic box located in top two is probably due to the increasing market demand for planting boxes. In addition, such as reclaimed-water system, plant wall and roof garden design, all related heat words provide a more diffuse and diversified market for green roof implementation.

### 3.4.3 Suggestions on Green Roof Implementation by Baidu Index

Big data as a new way to collect the bottom-up information for land use and resource allocation has shown its great potential in quantitative research from the tracks of internet search. Furthermore, the arrival of the new data era provides an opportunity for green roof by bottom-up data support, which carry out scientific research of visualization results and brings an optimal and accessible way to instruct green-city construction in China. Through index rank of Baidu Index, the land use of green roof would be suggested that Chinese government should encourage the green roof implementation in these regions by priority-first levels. All things about green building should promote works in all areas by drawing upon the experience gained on a key point [35]. For this reason, government could set up a pilot program and a good impression to drive nationwide green-roof trend because these areas are accessible and interesting for locals. Furthermore, due to the junior person pay more attention to green roof, the green roof activities should strengthen the residential communities with high ratio of young people, it will be much more bottom-up and spontaneous behaviors to occur, substituting for these traditional top-bottom orders. Besides, the area or community owns high ratio of young population should be encouraged and disseminated firstly. In addition, the guide process of green roof implementation ought to be given priority to the young males. Finally, government or local enterprises could complement related-word products (stainless-steel tank and reclaimed water) and build hot-point product company by related-word rank of green roof, which is not only beneficial to increase the employment post but also is helpful to avoid blind area in green roof market.


| Related words | Hot degree | Related words | Search rate |
|---|---|---|---|
| 1. stainless steel tank | | 1. Hefei company registration | |
| 2. roof garden | | 2. plastic box | |
| 3. reclaimed water | | 3. Shenzhen central park | |
| 4. plant wall | | 4. Hefei decoration company | |
| 5. roof garden design | | 5. stainless steel tank | |
| 6. intelligent water | | 6. timberwork | |
| 7. sedum lineare | | 7. green rooftop | |
| 8. fruit wholesale website | | 8. roof garden | |
| 9. Alibaba logistics | | 9. sedum lineare | |
| 10. vertical green | | 10. urban green | |

**Figure 3-12** The index frequency of related words of green roof

### 3.5 Summary

This chapter explains that the research site is specifically selected in Hangzhou City of Southern China, because it is based on previous researches and belongs to hot summer and cold winter area. Later, three approaches for this dissertation are screened and adopted by (1) field measurement, (2) computer simulation (3) statistical analysis, respectively. In detail, the chapter from 4 to 8 are classified. In addition, these three methodologies are compared with other software or test principles, which provides efficient and diversified methodologies could be further applied in this dissertation. Such as, the software of ENVI-met is more suitable in green roof research than others.

In addition, this chapter analyzes the index frequency of green roof by Baidu Index, and the main findings are below：(1) in the three levels of spatial scale of large district-province-city, the index volume corresponding to the three levels are East China, Zhejiang Province and Hangzhou City respectively which is the highest in hot rank. (2) The age group who are more curious about green roof is between 20 and 29 years old, among which males are slightly higher than females by 12%. (3) through the analysis of the hot rank of related words, users who are interested in green roof concentrates on the construction mode and related technologies, such as stainless-steel tank and reclaimed water.

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*Chapter 4*

# ***Impact of Morphological Characteristics of Green Roofs on Pedestrian Cooling in Subtropical Area***

## Chapter 4: Impact of Morphological Characteristics of Green Roofs on Pedestrian Cooling in Subtropical Area


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## 4.1 Introduction

The remainder of this chapter is structured as follows. Section 4.2 introduces the basic information of the study area and Section 4.3 describes the field measurement, and settings and calibration of the ENVI-met model. Section 4.4 analyzes and discusses the impact of greening layout, coverage ratio, vegetation height, and building height on the cooling performance of green roofs, Section 4.5 puts forward the limitation and outlook of this research, and Section 4.6 summaries this chapter. Overall, this study adds the knowledge of how building morphology and green-roof structure influence microclimate simultaneously. The comparative and scientific assessments of green roof cooling performance in real neighborhoods can practically instruct urban planners and policy-makers to choose effective cooling strategies and techniques.

## 4.2 Study Area

This study was conducted in the context of Hangzhou, the capital city of Zhejiang Province, China (figure 4-1). Hangzhou is the center of the Hangzhou metropolitan area in the Yangtze River Delta. The city has a population of more than nine million, covering an area of 16,596 km$^2$.

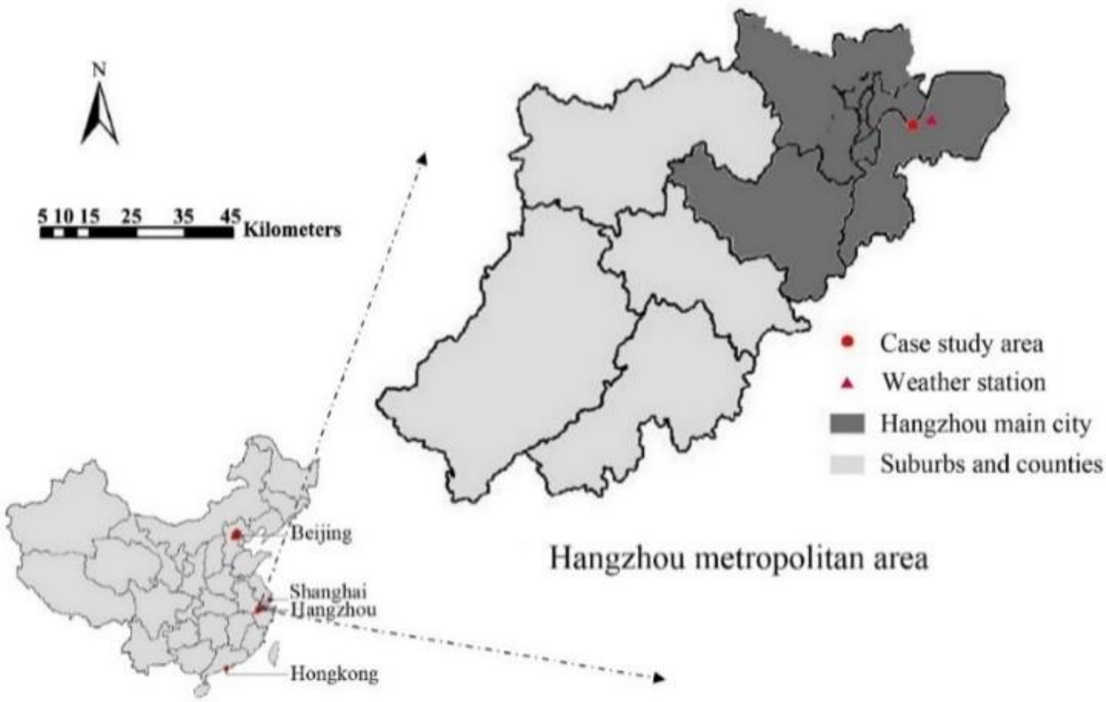
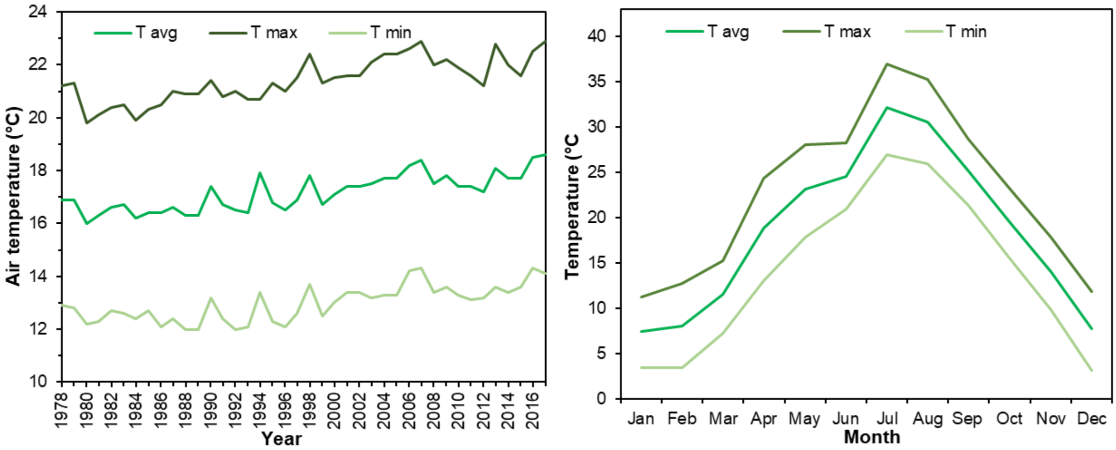



**Figure 4-1** Location of Hangzhou city and the fixed weather station

In the past years, Hangzhou City has witnessed a rapid urbanization trend. Its urbanization ratio reached 75.3% by 2016 [1, 2]. In recent years, Hangzhou has been undergoing the problem of temperature increase. According to the long-term meteorological data collected at the fixed weather station (figure 4-2a, Xiaoshan international airport with the elevation of 43 m), its average temperature has increased more than 1 °C in the past 40 years.

Located at 30°15′39″ N and 120°15′26″ E, Hangzhou is characterized by the subtropical climate. Hangzhou has four distinctive seasons every year. Apart from the hot temperature, its summer (June, July and August) is quite humid as the southeast wind can bring a large amount of vapor, and thereby rich precipitation, from the adjacent East China Sea. In particular, the year of 2017 was the hottest year in the past 40 years, as shown in figure 4-2a. From figure 4-2b, it is observed that July was the hottest month, where the average daily temperature was more than 32 °C. Moreover, the daily minimum and maximum air temperatures were 27 °C and 36 °C, respectively. Overall, the regional climatic conditions make the summer outdoor spaces extremely unfavorable.




(**a**) (**b**)

**Figure 4-2** (**a**) Meteorological condition of Hangzhou City (1978–2017) (**b**) Weather condition of Hangzhou in the year of 2017. (Note: T avg: average air temperature, T max: average maximum air temperature, T min: average minimum air temperature)

### 4.3 Data and Methodology

This study draws upon field measurements and numerical simulation (based on the computational tool of ENVI-met) to perform the comparative analysis of the impact of green roof morphological characteristics on neighborhood cooling. Figure 4-3 presents the framework of this study. The field measurements were applied to measure the pedestrian microclimatic conditions of the case study area that was 6 km away from the fixed weather station (figure 4-1). These field data collected were utilized to calibrate and validate the numerical model established in the ENVI-met software [3], based on which the microclimates under different scenarios were predicted through changing parameters.

### 4.3.1 Field Measurements

Field measurements were carried out around a clothing industrial area consisting of several buildings, as shown in figure 4-4. Building heights range between 3 m and 15 m and the average height of buildings is about 10 m. The case study area is seriously insufficient in greenery. There is one willow, four camphor trees and small-scale lawn at the entrance of the factory and the rest land is primarily occupied by traffic land. On the rooftop of these buildings, some scattered pocket green can be observed on cement roofs which have strong reflective and thermal storage capacity.

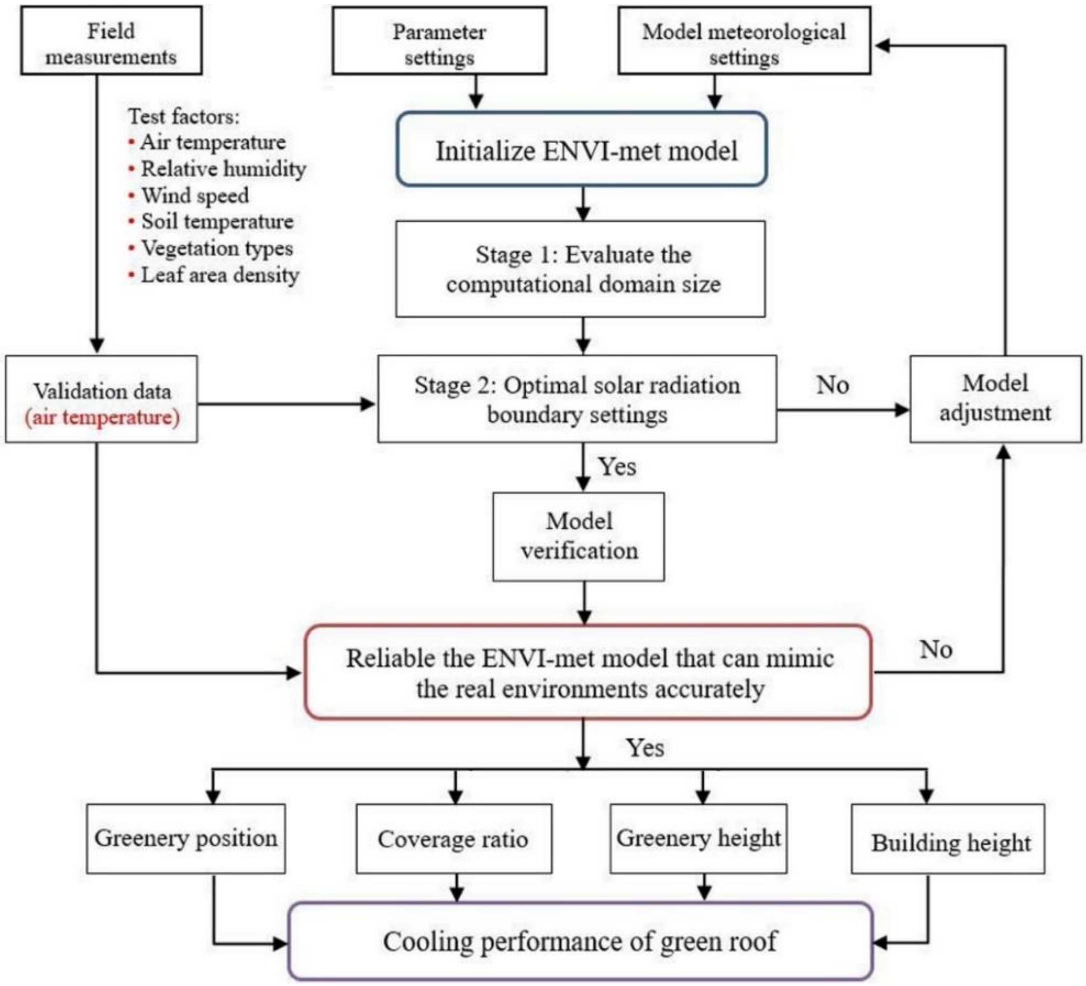



**Figure 4-3** A framework for comparative analyzing cooling performance of green roofs under different scenarios

The study area is used for industrial purpose, so that it is generally operated in the daytime. It is practically meaningful to concentrate on the diurnal microclimates and pedestrian cooling performances of green roofs. Specifically, field measurements were conducted between 8:00 and 20:00 h local time on 29 June 2018. During this period, all buildings were in normal operation. Specifically, this chapter conducted microclimate (including air temperature, relative humidity, wind speed, and wind direction) measurements at five points (in the middle of the road), as presented in figure 4-4. The spatial distribution followed the direction of summertime prevailing wind, in order to examine the possible influence of wind on air temperature. All the equipment (as shown in table 4-1) was set at the height of 1.4 m above the ground through tripods. Meanwhile, the temperature and relative humidity sensors were covered by aluminum alloy sleeves wrapped in aluminum foil to exclude solar radiation [4], as shown in figure 4-4. All the data were recorded every five minutes. Meanwhile, soil temperature was recorded by handheld infrared thermometer (figure 4-4).


**Figure 4-4** On-site field measurement and the spatial distribution of test points

**Table 4-1** Parameters and instruments used during the field measurements

| Item | Instrument | Parameter | Resolution/Range | Frequency |
|---|---|---|---|---|
| Temperature | Cos-03 | Air temperature | ±0.1 °C (−20 °C–60 °C) | 5 min |
| Humidity | Cos-03 | Relative humidity | ±1.5% (0–100%) | 5 min |
| Wind | P6-8232 | Wind speed<br>Wind direction | ±0.9 m/s (0–30 m/s)<br>±0.5° (0–360°) | 30 min |
| Soil | PM 6530D | Soil temperature | ±0.5 °C (−20 °C–60 °C) | 1 h |
| LAI | LAI-2000 | Leaf area density | 2.5 m CEP (50% deviation) | 1 D |

CEP: Circular Error Probable; LAI: leaf area index

In addition, this study collected the leaf area density (LAD) profiles of the greenery based on LAI (leaf area index)-2000 and hemispherical cameras [5, 6]. Specifically, vertical and horizontal profiles of LAD and horizontal canopy structure were measured. The greenery was composed of three-type trees, including Osmanthus trees, sweet viburnum and glossy privet), which flourished and had the similar height of 3 m. Several kinds of herb grass whose height was less than 1 m, were observed on site, as shown in Figure 4-5. The composition of trees and grasses made a good reference of IGR and IGR.

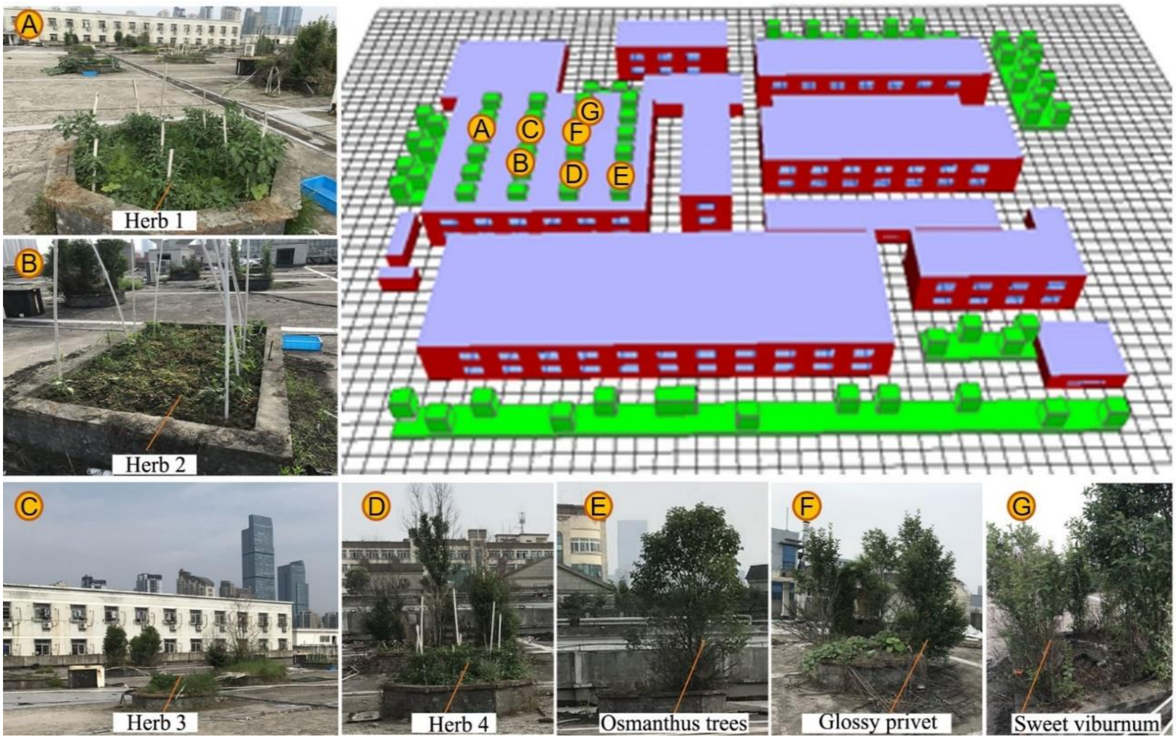



**Figure 4-5** Photos of rooftop vegetation and the initial ENVI-met model

### 4.3.2 Settings and the Calibration of ENVI-met Model

ENVI-met software (version 4.3.1) was adopted to estimate the microclimates in the case study area under different scenarios. this chapter chose to simulate a total amount of 30 h from the 00:00 to 06:00 h of the next morning, in which the first six hours were used to achieve microclimate stabilization. In the numerical model, the distribution of grids in the domain model area (270 m × 240 m × 60 m) was 5 m and 2 m in horizontal ($\Delta x$ and $\Delta y$) and vertical ($\Delta z$) directions, respectively. Measured buildings were coated by concrete roof and red brick wall with several windows. Five nested grids were adopted to discretize the numerical model. The initial micro-meteorological parameters, simulation controlling parameters, and the definitions of the underlying surface and thermal properties of buildings were set to define the initial boundary conditions, as shown in table 4-2.

**Table 4-2** Settings of boundary condition in verified ENVI-met model

| Item | Parameter | Value |
|---|---|---|
| Meteorological parameters | Solar radiation | 0.5; 0.6; 0.8 |
| | Initial wind direction | 45°(SE) |
| | Wind speed at 10 m | 2 m/s |
| | Initial air temperature | 22.0 ℃ |
| | Relative humidity | 71% |
| | Air moisture content (2500.0 m) | 6.5 g·kg$^{-1}$ |
| | Roughness length | 0.1 m |
| Roof | LAD of IGRs | 1.5 m$^2$·m$^{-3}$ |
| | LAD of IGRs | 1.0 m$^2$·m$^{-3}$ |
| | Average albedo of green/roof | 0.2/0.3 |
| Soil | Initial surface temperature/humidity (0–20 cm) | 25.0 °C/50% |
| | Initial temperature/humidity in middle depth (0–20 cm) | 26.0 °C/60% |
| | Initial temperature/humidity in deep depth (>50 cm) | 26.0 °C/60% |

LAD: leaf area density; IGRs: intensive green roofs; IGRs: extensive green roofs

The meteorological parameters such as wind speed, air temperature and relative humidity, were mainly obtained from field measurements. Model roughness length z0 followed the ENVI-met default values and air moisture content at 2500.0 m was set as 6.5 g/kg. The ENVI-met plant model was divided into ten equal layers according to vegetation type, so as to facilitate users to define LAD of each layer, thereby accurately describing different canopy shapes and LAD distribution. The setting of plant height in the study area was based on the field survey data, with 1.5 m2/m3 and 1.0 m2/m3 for IGR and IGR, respectively [7, 8]. The parameters of thermal properties of buildings were based on the “Design standard for energy efficiency of residential buildings in hot summer and cold winter zone” in China [9].

In ENVI-met software, the suggested solar radiation ratio (SRR) is 1.0, representing an ideal weather condition with no cloud. However, in realistic environment, cloud that influences the SRR value can be roughly observed. To calibrate the numerical model, therefore, this chapter conducted the sensitivity analysis of various SRR values, including 0.5, 0.6 and 0.7, to the average air temperatures of the five test points in figure 4-4. As presented in figure 4-6(a), numerical model was much more approaching to the measured thermal environment when

SRR was 0.6. In the scenario of SRR = 0.6, the simulated air temperatures of five test points (8:00–20:00) were compared with the measured air temperatures, as shown in figure 4-6(b). There was a strong correlation between the measured and simulated air temperatures (R2 = 0.8921), meaning the numerical model was in a good agreement with the actual environment [10-13].

### 4.3.3 Accuracy and Uncertainty of the Numerical Model

Except for SRR, which has been mentioned in section 4.3.2, there are some limitations on the setting of surface roughness length and short time scale. The time allowed in ENVI-met model is only between 24 and 48 h, which makes it difficult to obtain the long-term and representative microclimate variation patterns. At the same time, for the wind speed and direction, ENVI-met model adopts less complex input parameters than typical computational fluid dynamics models to mimic real wind fields [14, 15]. It was assumed that approaching wind speed and direction remained constant in a whole day in the ENVI-met model. Nevertheless, the approaching wind keeps changing all the time, thereby leading to the deviation of expected air temperatures. Meanwhile, increasing anthropogenic heat emissions from buildings (for example from air-conditioners) discharged into the street canyons can also elevate outdoor temperatures, which is not reflected in the ENVI-met model. At present, moreover, the ENVI-met model cannot define the substrate layer of the green roof, so the thermal effect of soil is ignored. Particularly, the process whereby the wind blows over the soil, taking away near-surface heat, has been neglected [16, 17].

### *4.3.4 Base Model and Data*

After the calibration of computational model, this chapter performed various simulations with the variations of greening layout, coverage ratio, vegetation height and building height, based on the weather conditions of 7 July 2017. The air temperature ranged from 28 °C to 36 °C, close to the temperature of the hottest month as described in Section 4.2. Herein this chapter simulated roughly light wind conditions, with the wind speed of 2 m/s and summer prevailing wind direction (southeast) [18, 19].. To compare the cooling performance of green roof, this chapter established a base model without any greenery on the rooftop, as shown in figure 4-7. Overall, studied the pedestrian thermal environment (1.4 m) at 15:00 h (the hottest time in a day) in different scenarios. For example, figure 4-7b presents the pedestrian thermal environment of the base case at 15:00 h. Moreover, this chapter investigated the daily average pedestrian temperatures (07:00 to 06:00 h of the next day) at five test points and variations of average pedestrian temperature of five test points. Based on the base case, the cooling performances of different morphological characteristics of green roof can be derived. To obtain the accurate daily temperature from 07:00 to 06:00 h of the next day, the simulation was run six hours in advance. Due to the limited IGR cooling effects, in Sections 4.4.1 and 4.4.2 only IGRs were adopted.

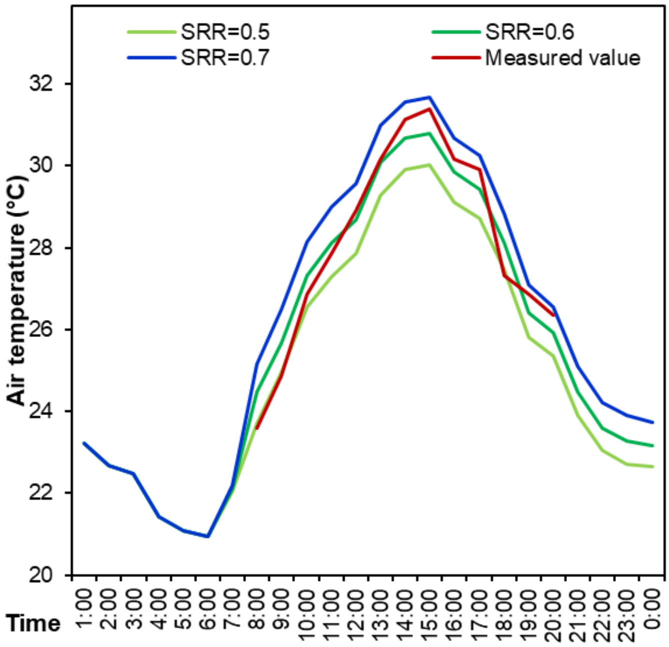



**Figure 4-6** (**a**)

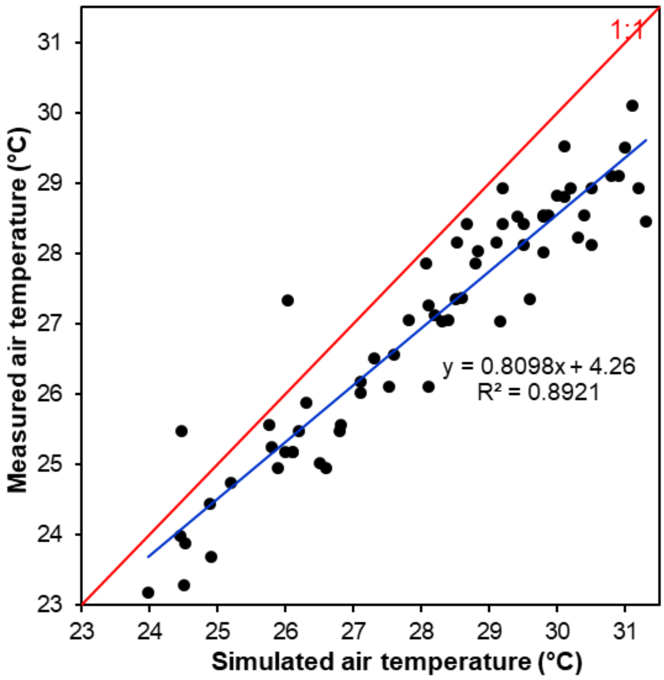



**Figure 4-6** (**b**)

**Figure 4-6** Calibration of ENVI-met model. (**a**) Comparison of measured average air temperature of five points with numerical results in different scenarios of solar radiation, and (**b**) Correlations between measured and simulated air temperatures of five points (from 08:00 to 20:00 h)

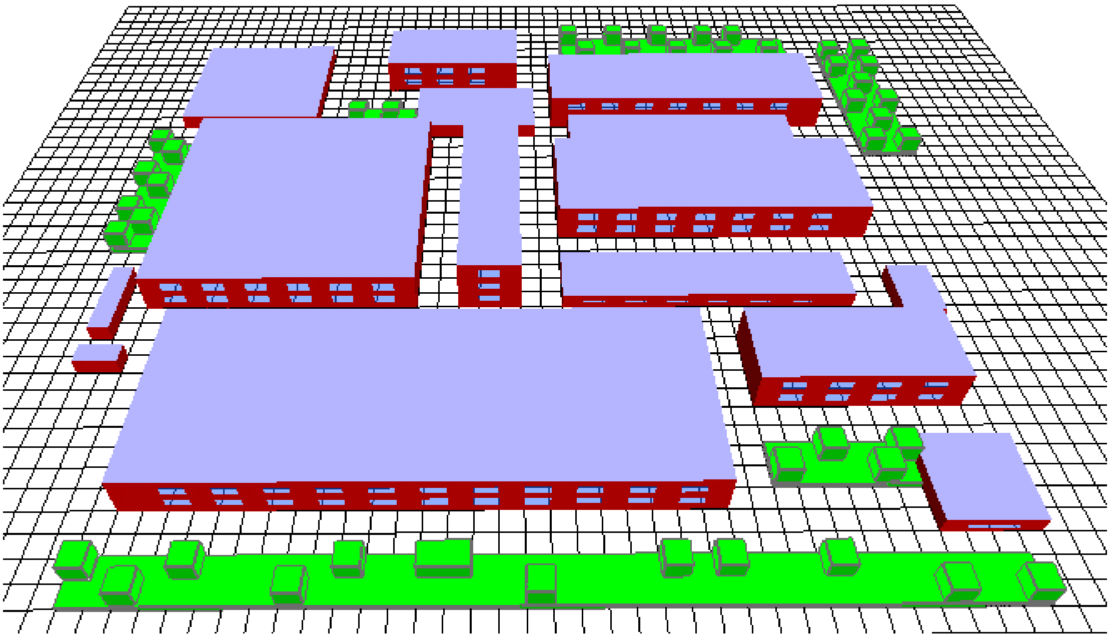


**Figure 4-7** (**a**)

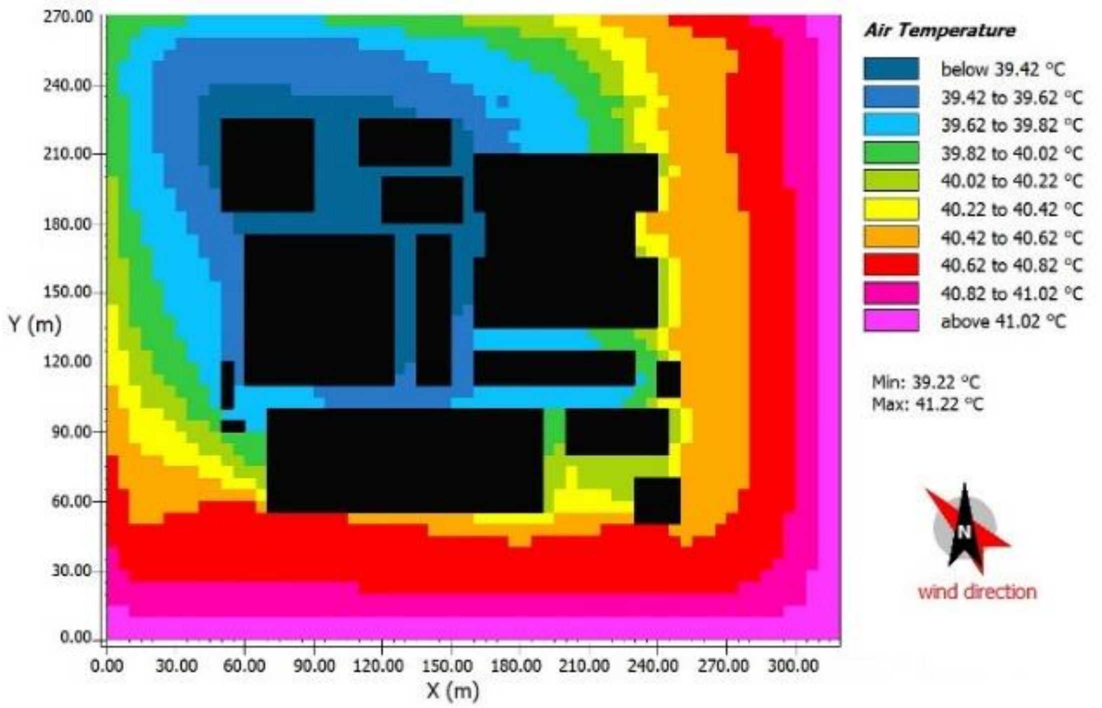



**Figure 4-7** (**b**)

**Figure 4-7** Base case diagram in ENVI-met software: (**a**) Physical model and (**b**) pedestrian thermal environment at 15:00 h

## 4.4 Results and Discussion

### 4.4.1 Effect of Green Roof Layout on Pedestrian Cooling Performance

This section focuses on the cooling performance of five IGR layouts, where the greenery ratio of each scenario is 50%. As shown in figure 4-8a, the IGR layouts were divided into five types: Case-Left, Case-Upper, Case-Right, Case-Bottom, and Case-Wind. In the Case-Wind type, the green roof was set in the upwind zones in order to examine the combining effects of prevailing wind and green roof. On the basis of the base case in Section 4.3.4, the cooling performance of each scenario (at 15:00 h) was obtained and is shown in in figure 4-8b. Overall, the maximum cooling performance of IGR could reach up to 0.26 °C. The Case-Wind type witnessed the best spread cooling effects in the local area, while the Case-Left type exhibited the weakest cooling capability to the local area because the green roof was in the downwind zones. Comparatively, the Case-Right and Case-Bottom types had better cooling performances than the Case-Upper type. This indicates the green layout at the upwind side would effectively reduce the air temperature of the entire area. This result is in a good agreement with the existing conclusions that under the wind effects, green roof with orthogonal arrangement can achieve significant cooling effects in downwind area [20, 21].

figure 4-9 further presents the variations of daily average cooling performance with greening layout. The cooling performance varied dramatically with point location. In particular, the cooling performance were good at point-1, point-2, and point-3, as shown in figure 4-9a. Moreover, Case-Wind and Case Bottom types exhibited the best cooling effects at five test points, as shown in figure 4-9a. At point-1, the cooling performance of green roof followed the order of Case-Wind > Case-Upper > Case-Left > Case-Bottom > Case-Right. This is because point-1 was in the downwind zones in all scenarios and roof greenery could exert

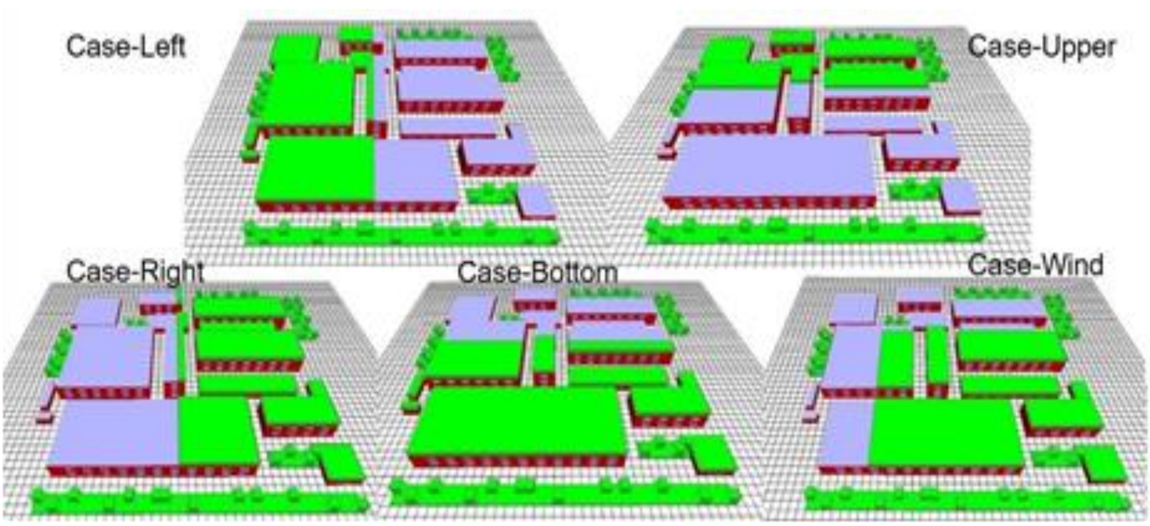



**Figure 4-8 (a)**

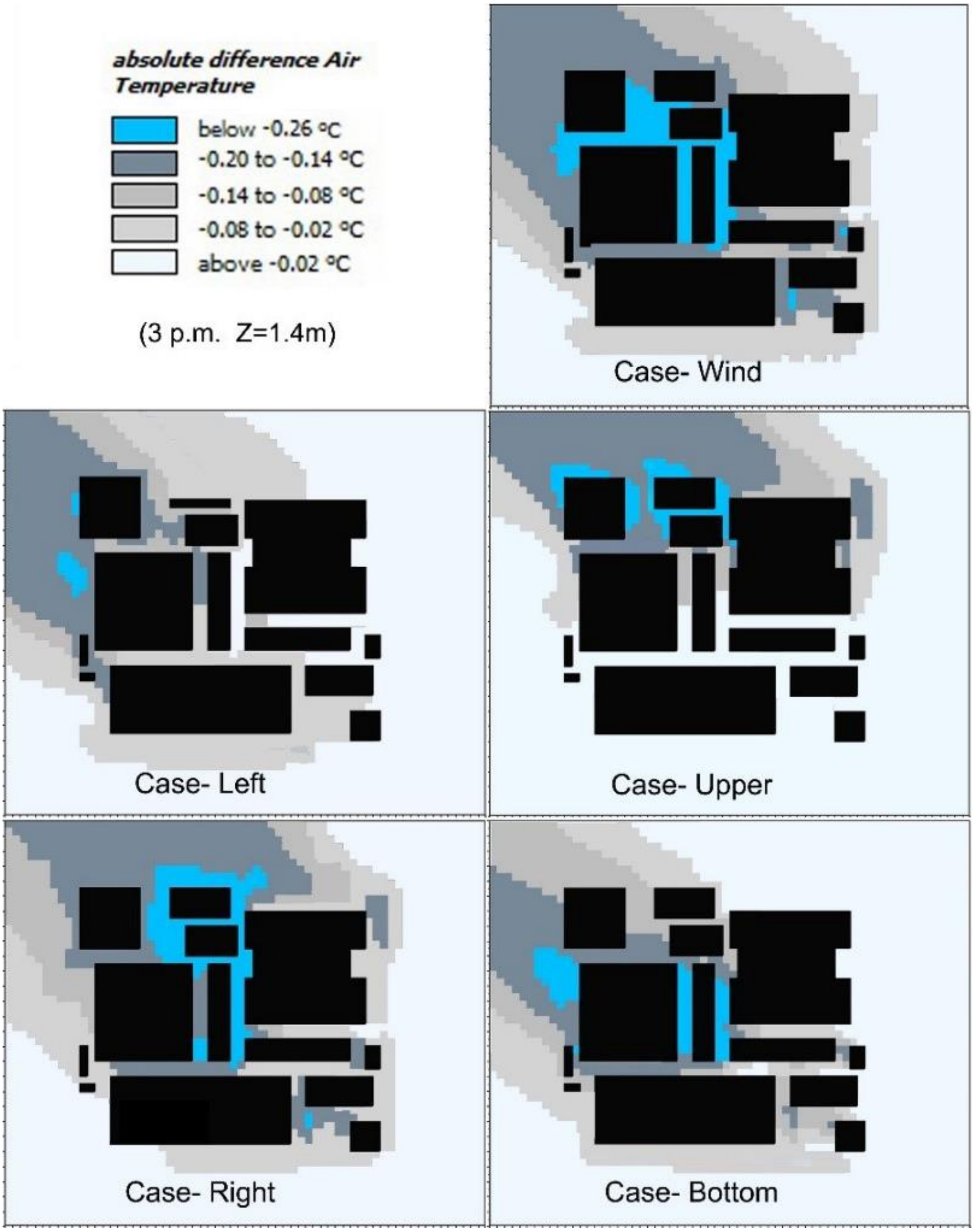



**Figure 4-8 (b)**

**Figure 4-8** Comparison of the impact of greening layout on green roof cooling performance (a) Physical models, and (b) pedestrian air temperature reduction at 15:00 h cooling effects on it. At point-2, the green roof in Case-Wind, Case-Bottom, and Case-Right types exhibited their maximum cooling effects, while the green roof in Case-Up and Case-Left types made slight differences because of the upwind location of point-2. Greenery layout exerted the similar impacts on point-3, but the cooling performances were weaker than that on point-2. In addition, the cooling effects of green roof on point-4 and point-5 were quite weak, no more than 0.1 °C. These indicate that both upwind green roof location and its distance from test points (in downwind areas) are important factors determining the pedestrian air temperature reduction. In other words, downwind areas are much cooler and the location closer to green roof is much cooler.

Moreover, the average air temperature of five test points in all day were calculated to indicate the variations of cooling performances of five scenarios (figure 4-9b). Overall, the diurnal fluctuation of cooling performance was more intense than nocturnal one because the great fluctuation of daytime temperature with solar radiation. The temperature reduction resulted from green roof was stable after 17:00 h, indicating green roof could exhibit a long-time cooling performance in the evening. In the daytime, cooling performance decreased rapidly from the morning time to 14:00 h, at which time cooling performance was negligible. This might be because leaf stomata close at high temperatures, and thereby evapotranspiration stops [22, 23]. Likewise, Case-Wind was the most prominent scenario in decreasing pedestrian air temperature, followed by Case-Bottom, Case-Right, Case-Left, and Case-Upper. Therefore, strategically installing green roof in upwind zones rather than random greening layouts is more efficient for neighborhood cooling.

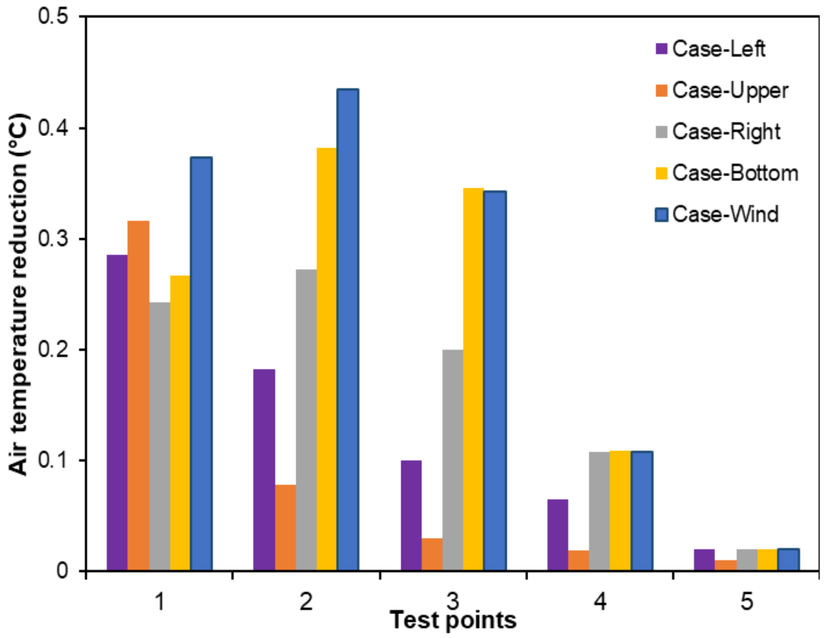



**Figure 4-9** (**a**)

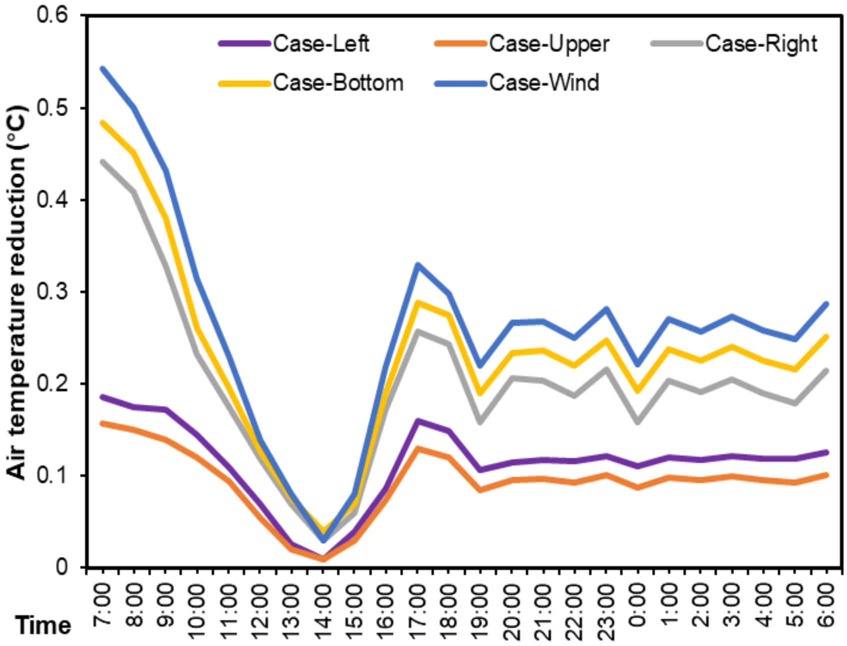



**Figure 4-9 (b)**

**Figure 4-9** Average air temperature reduction in different green roof layout scenarios. (**a**) Daily average air temperatures at five test points, and (**b**) daily variations of average air temperature of five test points from 07:00 to 06:00 h of the next day

### 4.4.2 Effect of Coverage Ratio of Green Roof on Pedestrian Cooling Performance

To further facilitate the application of green roofs, this chapter examined the influence of greening coverage ratio on green roof cooling performances. In particular, five types of IGRs, with the greening coverage ratios of 2%, 25%, 50%, 75%, and 100%, were built, as shown in figure 4-10a. Figure 4-10b presents the cooling performance of each scenario (at 15:00), where cooling performance in Case-2% is negligible and the cooling performance in Case-25% was only about 0.1 °C. With the further increase in greening coverage ratio, the cooling performance was improved and expanded to downward areas simultaneously. For Case-100%, the central area of the neighborhood was cooled up to 0.5 °C. This indicates green roof can form a cool source, like a “cool island”, to isolate the outside heats when the greening area is large enough [11]. In this study, the cooling effects of green roof were not significant as other studies in which cooling performance exceeded 1 °C, which might be due to the larger coverage areas in other studies [24-26].

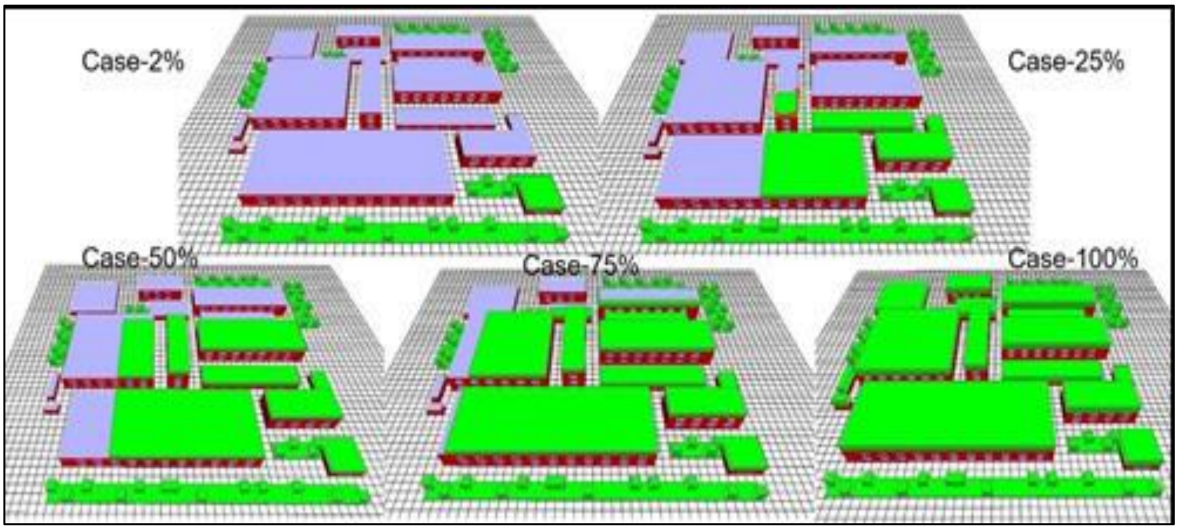
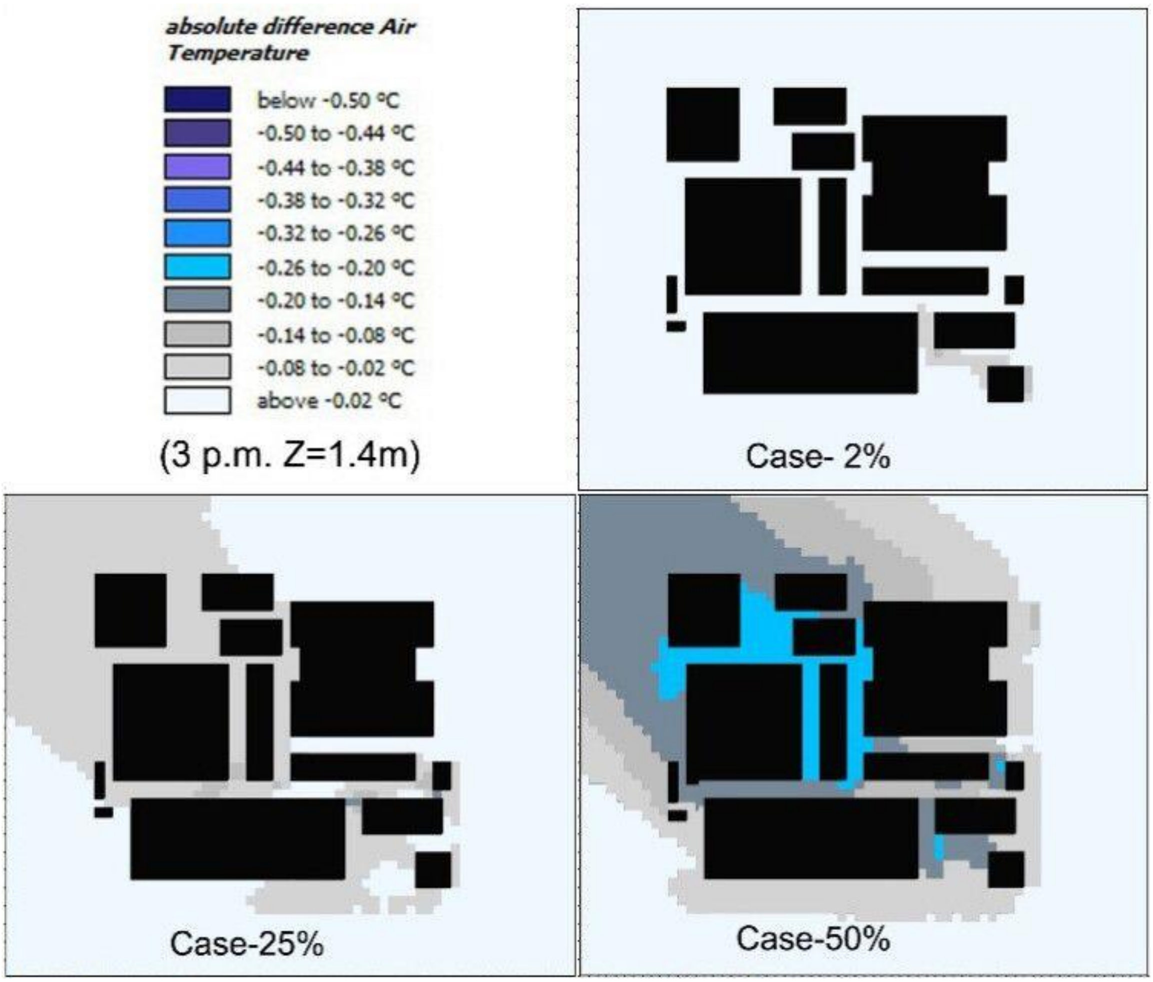

Case-2%
Case-25%
Case-50%
Case-75%
Case-100%

**Figure 4-10 (a)**


absolute difference Air Temperature
below -0.50 °C
-0.50 to -0.44 °C
-0.44 to -0.38 °C
-0.38 to -0.32 °C
-0.32 to -0.26 °C
-0.26 to -0.20 °C
-0.20 to -0.14 °C
-0.14 to -0.08 °C
-0.08 to -0.02 °C
above -0.02 °C
(3 p.m. Z=1.4m)
Case- 2%
Case-25%
Case-50%

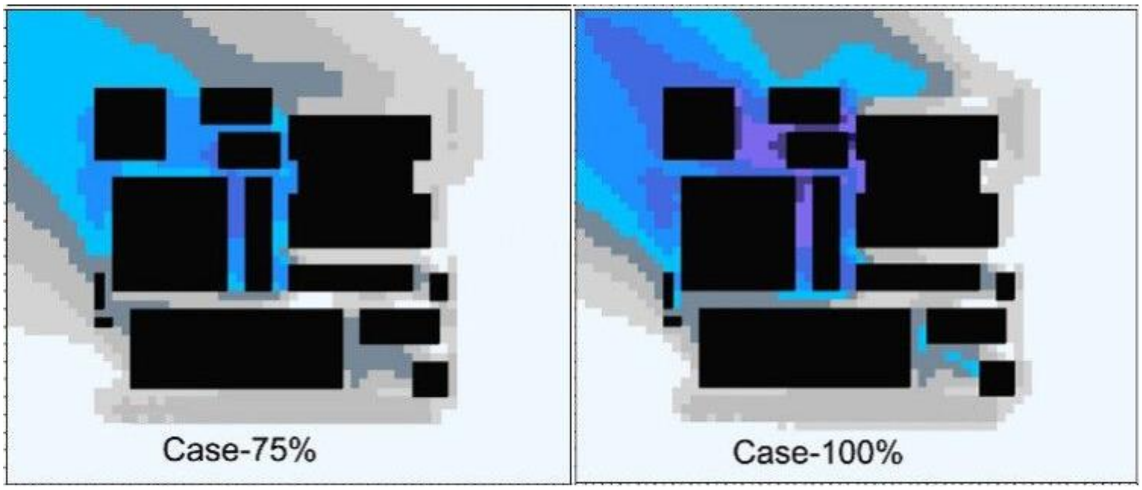



**Figure 4-10 (b)**

**Figure 4-10** Comparison of the impact of greening coverage ratio on green roof cooling performance (**a**) Physical models, and (**b**) pedestrian air temperature reduction at 15:00 h

Likewise, the cooling performances of different types of green roof at five test points were examined, as shown in figure 4-11. In figure 4-11a, a higher greening coverage ratio corresponded to a better cooling performance. Meanwhile, the green roof in all scenarios showed the best cooling performance at the point-1, followed by point-2, point-3, point-4 and point-5. Cooling performance of Case-100% at point-1 exceeded 0.6 °C, while the cooling performances of all green roofs, including Case-100%, at point-5 were less than 0.1 °C consistently. In particular, when the greening coverage ratio was 25%, this study can observe that temperature reduction at point-3 was higher than that at other points. This might be because of its shortest horizontal distance from the rooftop greenery (circled zones in figure 4-11a).

As shown in figure 4-11b, the greening only on one building (Case-2%) was not capable of decreasing surrounding air temperature. With the greening coverage ratio increasing to 25% from 2%, the cooling performance increased. However, the cooling performance of green roof was also limited when greening coverage ratio increased to a certain value. It is indicated that cooling performance of green roof in Case-75% was close to that in Case-100%. There was still an increase in green roof cooling performance with greening coverage ration increasing from 50% to 75%. Therefore, the threshold value of 75% for greening coverage ratio in this study is higher than the suggested value of 50% in Mumbai, India[27], on account of constant greening ratio on the ground. Therefore, in practice, the greenery coverage ratio can be set between 25% and 75% for the aspect of effective cooling scope.

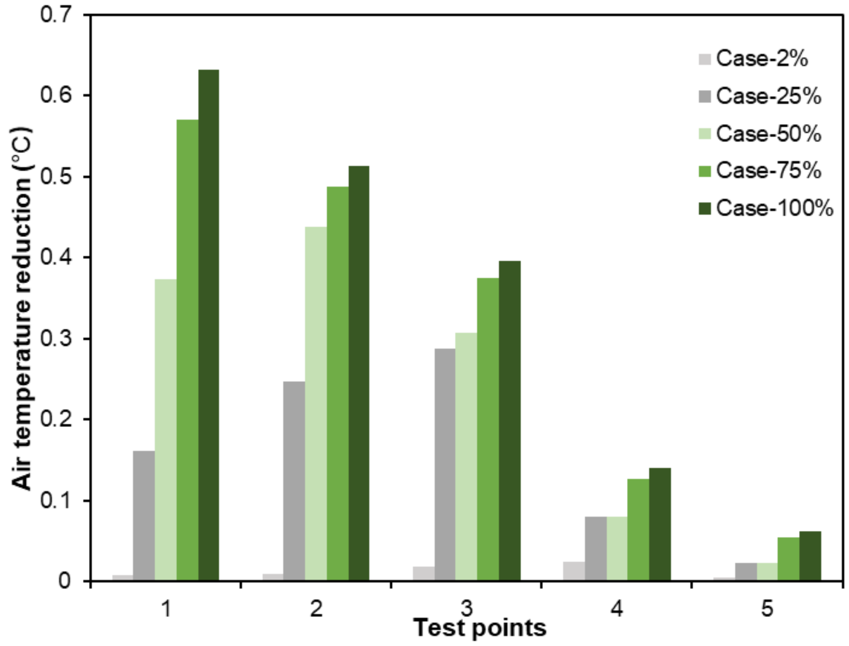



**Figure 4-11** (**a**)

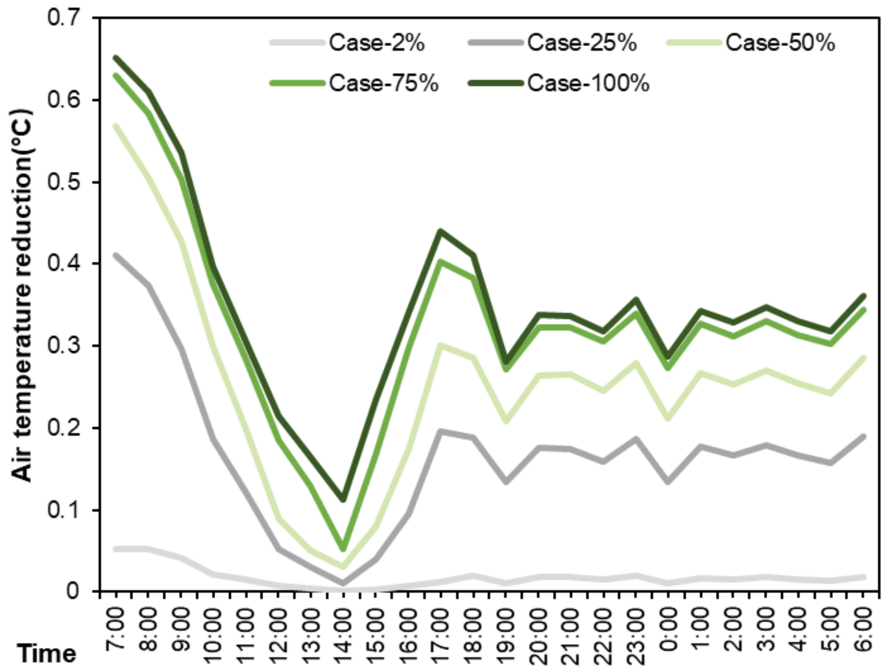



**Figure 4-11** (**b**)

**Figure 4-11** Average air temperature reduction in different greening coverage ratio scenarios (**a**) Daily average air temperatures at five test points, and (**b**) daily variations of average air temperature of five test points from 07:00 to 06:00 h of the next day

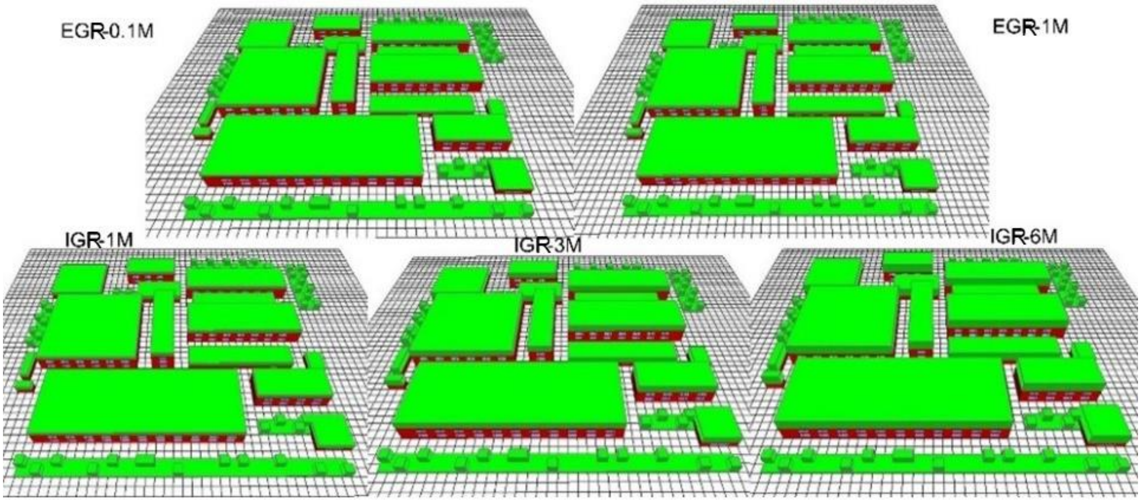
### 4.4.3 Effect of Vegetation Height of Green Roof on Pedestrain Cooling Performance

Figure 4-12a presents the physical model and pedestrian cooling performance at 15:00 h of green roofs with different vegetation heights. There were five types of green roof: IGRs with 0.1 m height grass (IGR-0.1M), IGRs with 1 m height grass (IGR-1M), and IGRs with 1 m, 3 m, and 6 m height trees (IGR-1M, IGR-3M and IGR 6M). The coverage ratios of all roofs were 100%.

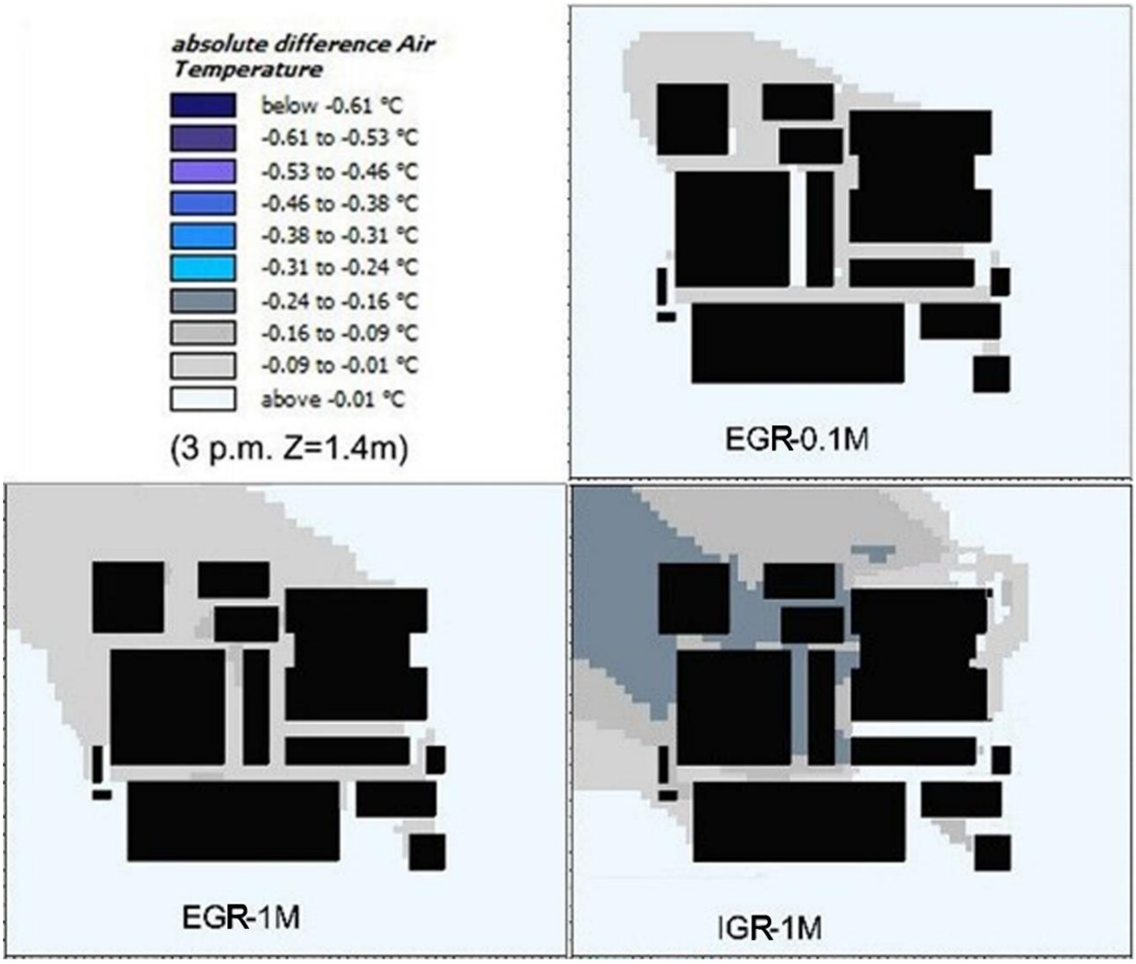
From figure 4-12b, it is observed that IGR-0.1M, IGR-1M, IGR-1M, IGR-3M, and IGR-6M could yield maximum cooling performances up to 0.10, 0.16, 0.24, 0.53, and 0.61 °C respectively, and the surrounding environment would be visibly improved with the increase in vertical greening height. The increase of greening height can not only provide more shade but also enhance the transpiration by foliage, so that heightening vertical greening is also an effective approach to decreasing the local temperature.

According to figure 4-13a, the cooling performances of green roof at five points showed a constant increase with the increasing vertical greening height. The most significant cooling performance of 0.8 °C could be observed at point-1 when the greening height was 6 m. For the IGRs in this study, however, their cooling performances at point-4 and point-5 were negligible, with a temperature reduction of less than 0.1 °C. Comparing IGR-1M and IGR-1M, the cooling performances of IGR-1M were better than IGR-1M at five points, indicating that different types of green roof generated notably diverse cooling impacts on pedestrian-level temperature[11].

Figure 4-13b presents the variations of average temperature reduction of five test points in a day. Apart from the morning time, all types of green roofs witnessed their best cooling performances at 17:00. This is in the agreement with the phenomenon that a higher leaf area index, a denser and more complex vegetation structure of IGR can weaken more heat strength because of foliage solar shading and passive cooling by evapotranspiration [28-31]. For this reason, enhancing cooling air production via evapotranspiration and increasing more shade to prevent direct solar exposure are conducive to alleviate local heat stress. Comparing the cooling performance of different types of green roofs, IGRs exhibited better cooling performance than IGRs, while only a slight increase could be observed from IGR-1m to IGR-1M when considering the average temperature reduction of five test points. However, from IGR-1M to IGR-3M and then IGR-6M, a significant increase in cooling performance could be observed. Cooling performance of IGR-6M was about 0.2 °C higher than that of IGR-3M, which was about 0.2 °C higher than that of IGR-1M, as well. Therefore, for better cooling performance, adopting IGRs with higher heights is suggested.


EGR-0.1M
EGR-1M
IGR-1M
IGR-3M
IGR-6M

(**a**)


absolute difference Air Temperature
below -0.61 °C
-0.61 to -0.53 °C
-0.53 to -0.46 °C
-0.46 to -0.38 °C
-0.38 to -0.31 °C
-0.31 to -0.24 °C
-0.24 to -0.16 °C
-0.16 to -0.09 °C
-0.09 to -0.01 °C
above -0.01 °C
(3 p.m. Z=1.4m)
EGR-0.1M
EGR-1M
IGR-1M

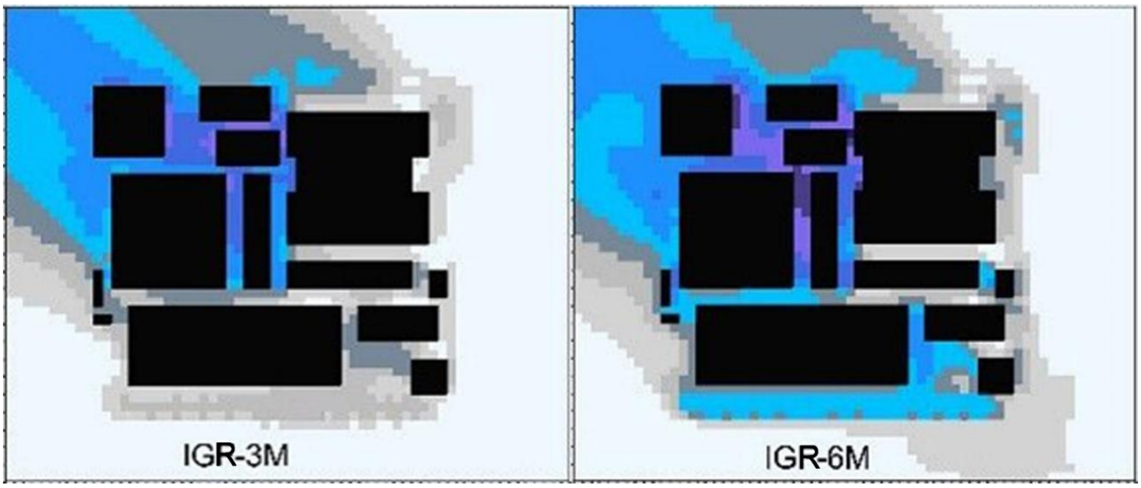



**Figure 4-12** (**b**)

**Figure 4-12** Comparison of the impact of vertical greening height on green roof cooling performance (**a**) Physical models, and (**b**) pedestrian air temperature reduction at 15:00 h.

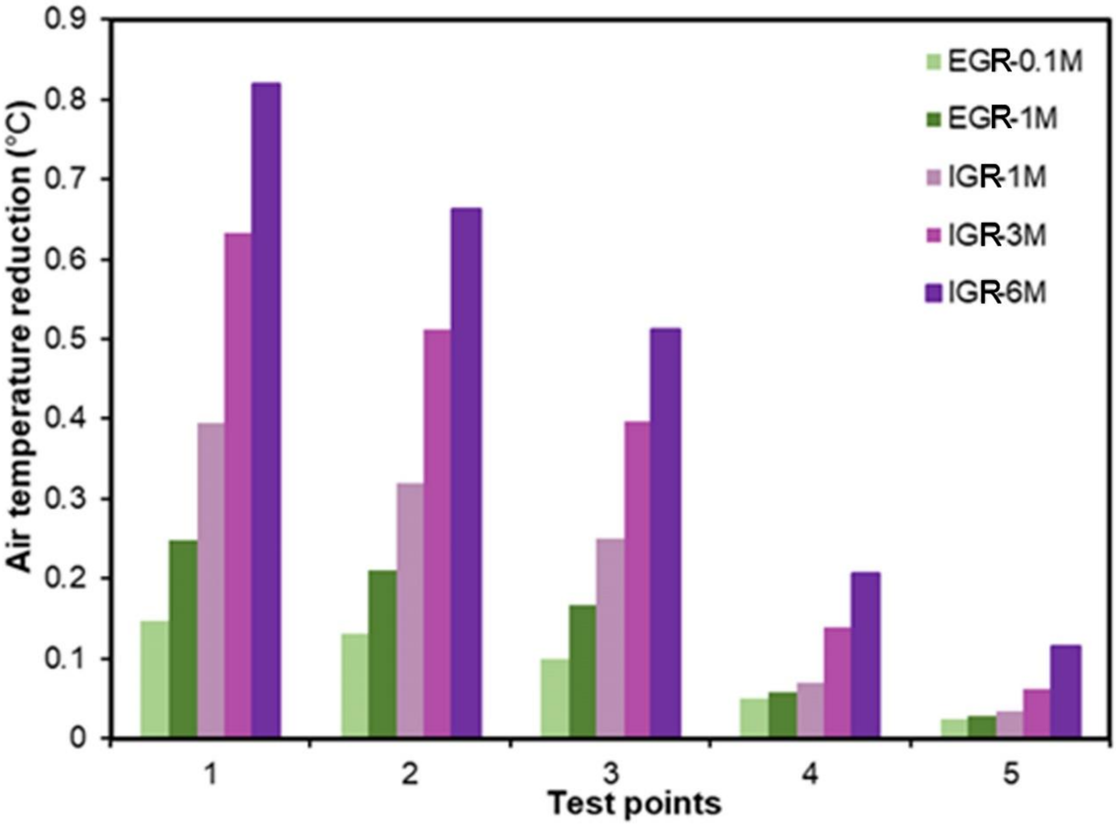



**Figure 4-13** (**a**)

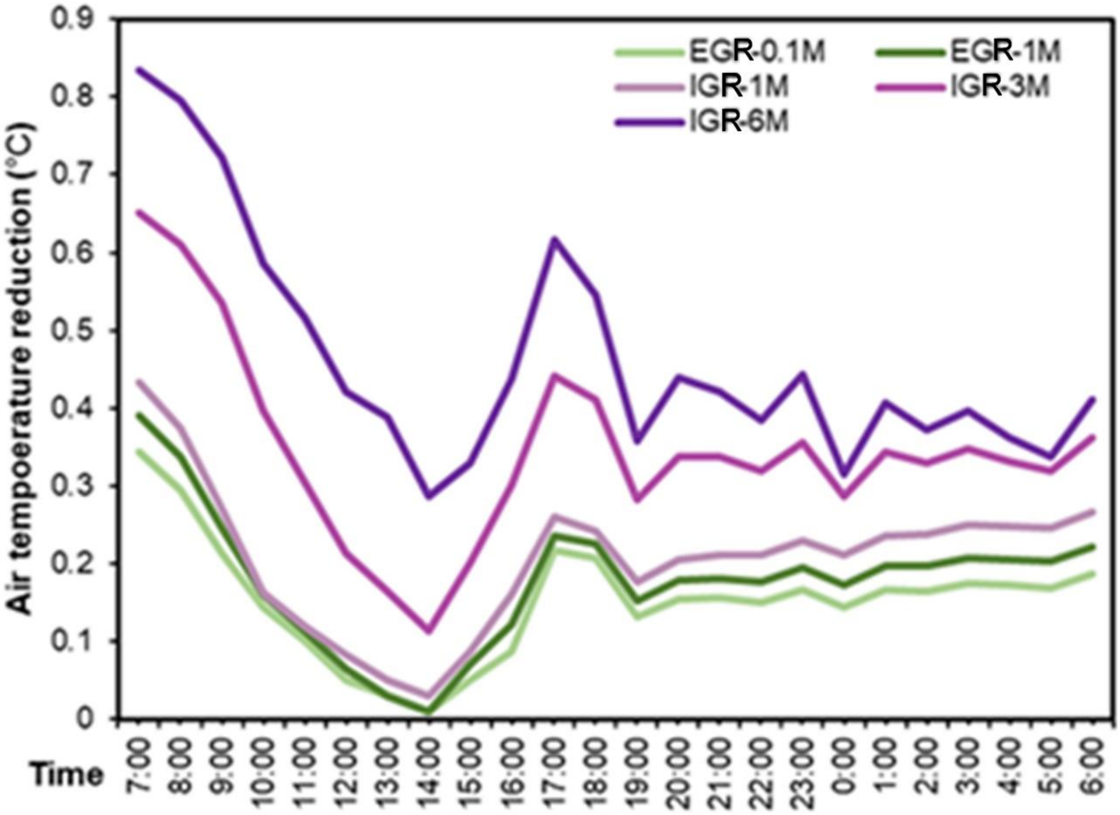



**Figure 4-13** (**b**)

**Figure 4-13** Average air temperature reduction in different vegetation height scenarios (**a**) Daily average air temperatures at five test points, and (**b**) daily variations of average air temperature of five test points from 07:00 to 06:00 h of the next day

Through the analysis of thermal section by different vegetation height as shown in figure 4-14, it could be found that when vegetation height is 6 meters, green roof performs a better cooling area than vegetation height is 1meter in near-surface and pedestrian level. Comparing the thermodynamic diagram of IGR-1M and IGR-6M, the result shows IGR-6M could maximum produce up to 0.5 °C cooling effect and closer to green part better cooling effect, which is agreement with green space is effective cooling source to cure the UHI [22, 23]. While, the cooling performance of plant capony is remarkable comparing with the cooling performance of pedestrian level, which means that green roof is more uesful to improve the thermal environment of city canopy layer. In addition, the cooling performance in downwind direction presents a higher level, and the cooling scope of case IGR-6m is much larger than case IGR-1M.

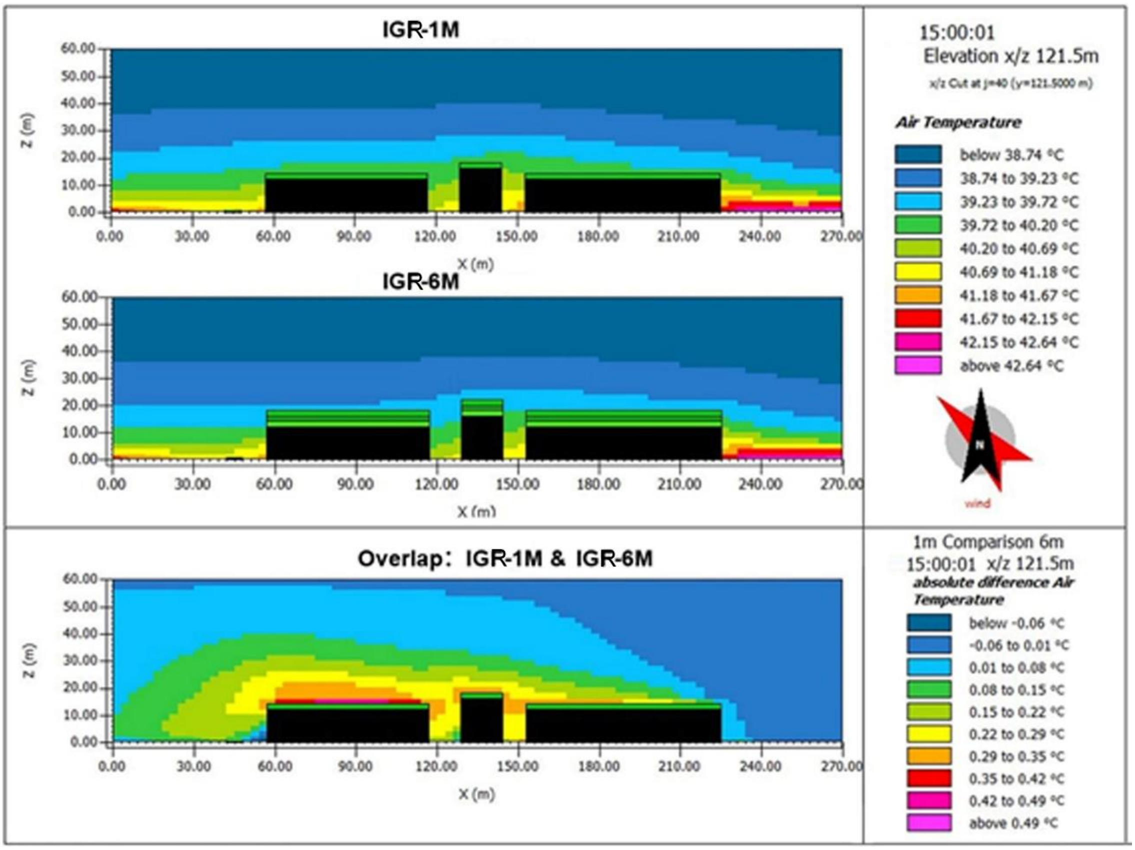



**Figure 4-14** The thermal performance of section plan

### 4.4.4 Effect of Building Height on Green Roof Cooling Performance

This section examines the impact of building height on the green roof's cooling performance. Because of the variation of building height, the dimension of computation domain was altered to 200 m, but the vertical grid (Δz) remained at 2 m. The base case had the average building height of 10 m and covered no vegetation. Afterwards, the same IGRs on three different height building groups were used: E1M-H10 (buildings with average height of 10 m and covered with 1 m grass), E1M-H20 (buildings with average height of 20 m and covered with 1 m grass), and E1M-H30 (buildings with average height of 30 m and covered with 1 m grass). At the same time, same IGRs on four different height building groups were used: I3M-H10 (buildings with average height of 10 m and covered with 3-m trees), I3M-H20 (buildings with average height of 20 m and covered with 3-m trees), I3M-H40 (buildings with average height of 40 m and covered with 3-m trees), and I3M-H60 (buildings with average height of 60 m and covered with 3-m trees), as shown in figure 4-15a.

As shown in figure 4-15b, cooling performances of green roofs gradually faded away as the increase of building height. This is consistent with the conclusions that as the increase in vertical distance from green roof to the ground, the influence of green roof on pedestrian-level thermal environment decreases [32]. It is worth noting with the increase of building height, IGRs showed larger influencing areas in the downwind zones (e.g., the grey zones in E1M-H10 and E1M-H20), which might be in relation to the shading effects of higher buildings. Same trend could be found in IGR scenarios. Due to stronger evapotranspiration and shading effects of IGRs, the cooling areas were larger than that of IGRs. Nevertheless, this trend will be invalid due to the increase of building height, considering the fact that green roofs exert negligible effects on pedestrian air temperature when building height exceeds 60 m [33]. An existing study has suggested that green roofs are not useful in high-rise area for cooling pedestrian air temperature[33]. However, this conclusion may not be valid, as wind can enhance green roof cooling performance in downwind areas. This has also been evidenced in previous studies via remote sensing technology [24, 25].

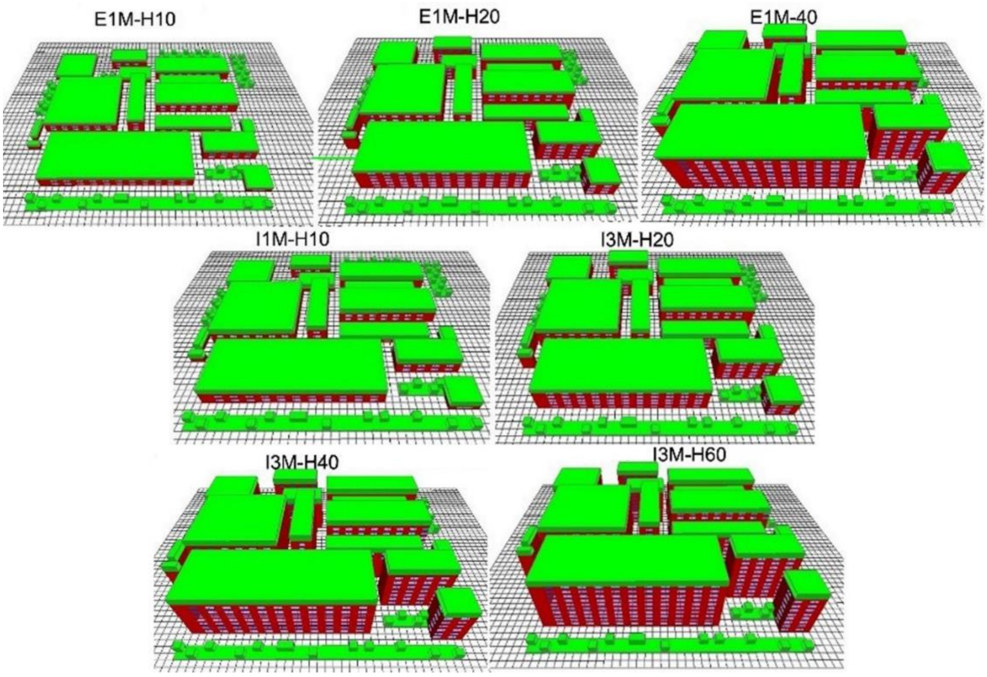
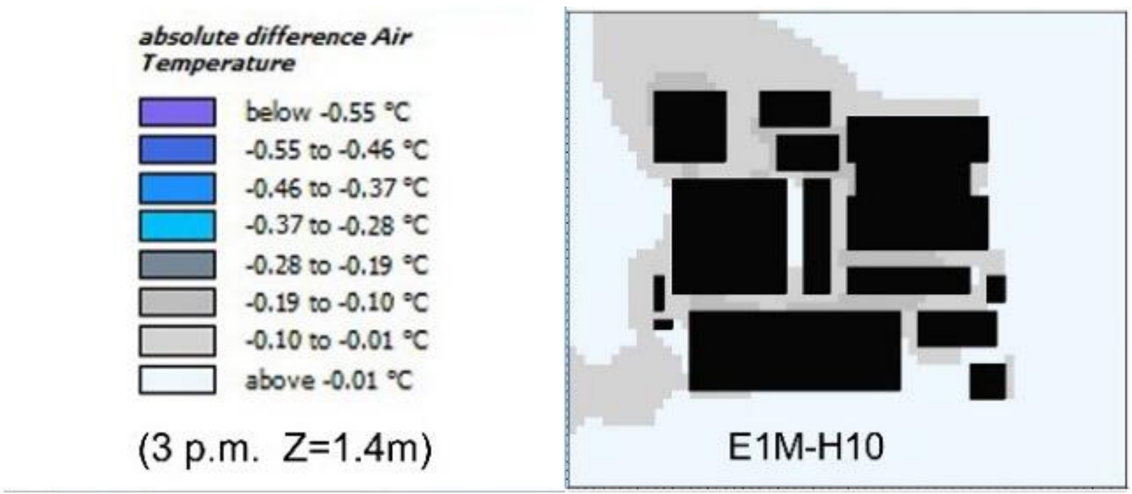



**Figure 4-15** (**a**)



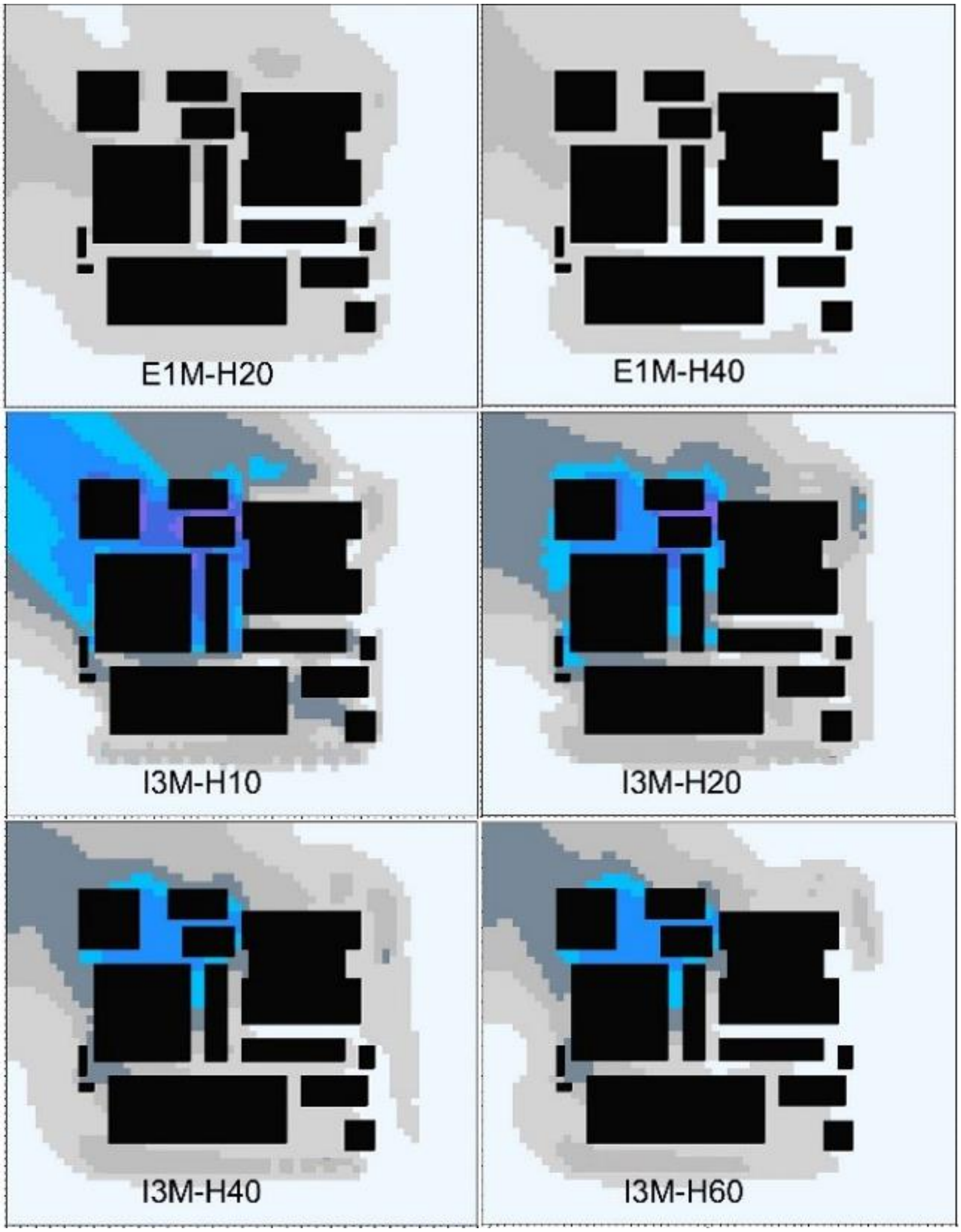



**Figure 4-15** (**b**)

**Figure 4-15** Comparison of the impact of building height on green roof cooling performance (**a**) Physical models, and (**b**) pedestrian air temperature reduction at 15:00 h

As shown in figure 4-15a, the cooling effects of green roof decreased with the increase of building height. At point-1, the cooling effects were gradually weakened by increasing building height, and there were slight differences among the cooling performances of I3M-H10, I3M-H20, and I3M-H40. However, at point-2 and point-3, I3M-H10, I3M-H20, and I3M-H40 showed an increasing cooling performance difference. At other points, the cooling performances of green roofs were negligible. Moreover, cooling performances of different green roofs decreased gradually from point-1 to point-5. In particular, the cooling performance of I3M-H10 at point-1 reached 0.6 °C, while it decreased to negligible (less than 0.1 °C) at point-5. For I3M-H60, it could exert cooling effects on point-1 and point-2, with the values of 0.4 °C and 0.2 °C, respectively, while at point-3, point-4, and point-5, the cooling performances were negligible.

Figure 4-16b also shows green roofs with higher building height had weaker cooling effects on pedestrian air temperature. In the night time, I3M-H10 exhibited stable cooling effects around 0.35 °C, about 0.2 °C higher than that of I3M-H-60. Likewise, E1M-H10 generated the cooling performance of 0.2 °C, followed by that of E1M-H20 (about 0.1 °C), and E1M-H40 (about 0.05 °C). At the time of sunrise and sunset, green roofs achieved their peak cooling performance. However, at 14:00 h, lower buildings (E1M-H10 and I3M-H10) exhibited lower cooling performances, as compared with other IGRs and IGRs built on higher buildings. This may be because more solar radiation can enter the bottom of shallow street canyon, while higher buildings can shelter the ground from solar radiation [34]. Therefore, in the daytime, the pedestrian cooling performance of green roofs is affected by both building shading effects and vegetation shading and evapotranspiration effects.

In addition, in the scenario of I3M-H60, it is of interest to observe that cooling performances of green roof at point-1 and point-2 could reach 0.42 °C and 0.24 °C, respectively (figure 4-16a). This result is in contrast with the conclusion that green roofs play a negligible role in pedestrian temperature reduction when building height exceeds 60 m [12]. Likewise, at point-1 and point-2, the cooling performance of green roof could reach 0.2 °C and 0.1 °C in the scenario of E1M-H40 (figure 4-16a). It is concluded that the height limit of buildings upon which green roof is located varies with target locations, which is in relation to the wind effects [20, 21]. Based on the average temperature of five points at 14:00 h (figure 4-16b), this chapter can further conclude that the building orientation, through influencing the pedestrian-level solar exposure, becomes another factor affecting the building height limit, exceeding which green roofs show no differences in terms of cooling performance [34].

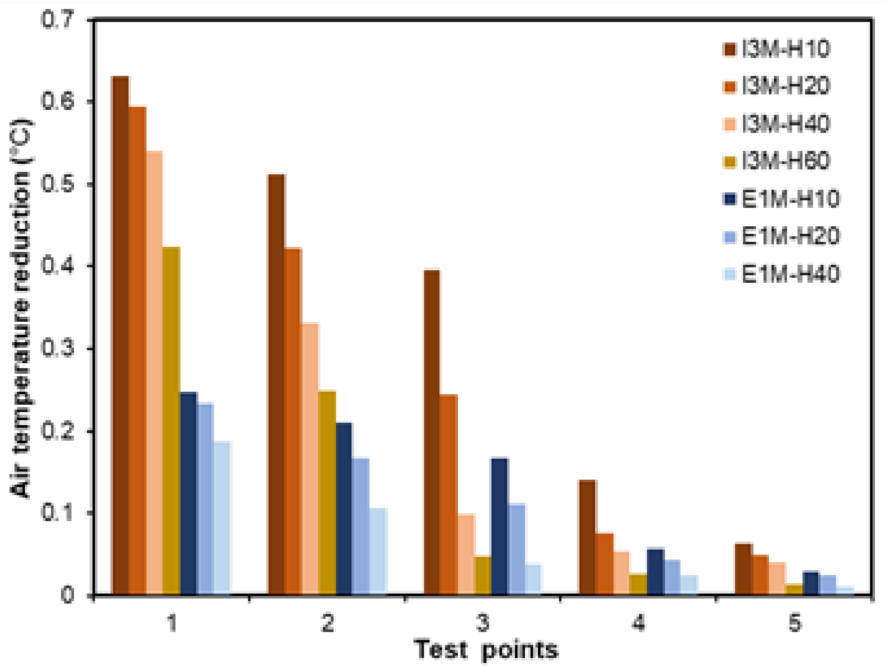



**Figure 4-16** (**a**)

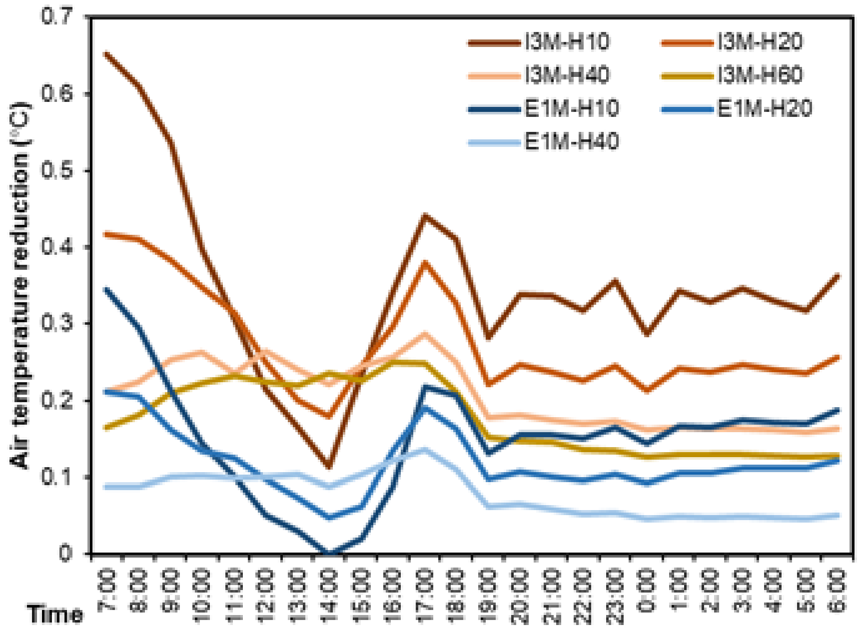



**Figure 4-16** (**b**)

**Figure 4-16** Average air temperature reduction in different building height scenarios. (**a**) Daily average air temperatures at five test points, and (**b**) daily variations of average air temperature of five test points from 07:00 to 06:00 h of the next day

**Table 4-3** A summary of pedestrian cooling performance of green roof in different scenarios

| Scenarios | | Daily Average Temperature (°C) | | | | | Average Temperature of Five Points (°C) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | $T_{24h}$ | $T_{max}$ | $T_{min}$ |
| Layout | Left | 0.29 | 0.18 | 0.10 | 0.07 | 0.02 | 0.13 | 0.29 | 0.02 |
| | Upper | 0.32 | 0.08 | 0.03 | 0.02 | 0.01 | 0.09 | 0.32 | 0.01 |
| | Right | 0.24 | 0.27 | 0.20 | 0.11 | 0.02 | 0.17 | 0.27 | 0.02 |
| | Bottom | 0.27 | 0.38 | 0.35 | 0.11 | 0.02 | 0.22 | 0.38 | 0.02 |
| | Wind | 0.37 | 0.43 | 0.34 | 0.11 | 0.02 | 0.26 | 0.43 | 0.02 |
| Coverage ratio | Case 2% | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 |
| | Case 25% | 0.16 | 0.25 | 0.29 | 0.08 | 0.02 | 0.16 | 0.29 | 0.02 |
| | Case 50% | 0.37 | 0.44 | 0.31 | 0.08 | 0.02 | 0.24 | 0.44 | 0.02 |
| | Case 75% | 0.57 | 0.49 | 0.38 | 0.13 | 0.05 | 0.32 | 0.57 | 0.05 |
| | Case 100% | 0.63 | 0.51 | 0.40 | 0.14 | 0.06 | 0.35 | 0.63 | 0.06 |
| Vegetation height | IGR-0.1M | 0.15 | 0.13 | 0.10 | 0.05 | 0.03 | 0.10 | 0.15 | 0.03 |
| | IGR-1M | 0.25 | 0.21 | 0.17 | 0.06 | 0.03 | 0.15 | 0.25 | 0.03 |
| | IGR-1M | 0.39 | 0.32 | 0.25 | 0.07 | 0.04 | 0.21 | 0.39 | 0.04 |
| | IGR-3M | 0.63 | 0.51 | 0.40 | 0.14 | 0.06 | 0.35 | 0.63 | 0.06 |
| | IGR-6M | 0.82 | 0.66 | 0.51 | 0.21 | 0.12 | 0.46 | 0.82 | 0.12 |
| Building height | E1M-H10 | 0.25 | 0.21 | 0.17 | 0.06 | 0.03 | 0.15 | 0.25 | 0.03 |
| | E1M-H20 | 0.23 | 0.17 | 0.11 | 0.04 | 0.02 | 0.12 | 0.23 | 0.02 |
| | E1M-H40 | 0.19 | 0.11 | 0.04 | 0.02 | 0.01 | 0.07 | 0.19 | 0.01 |
| | I3M-H10 | 0.63 | 0.51 | 0.40 | 0.14 | 0.06 | 0.35 | 0.63 | 0.06 |
| | I3M-H20 | 0.59 | 0.42 | 0.24 | 0.08 | 0.05 | 0.28 | 0.59 | 0.05 |
| | I3M-H40 | 0.54 | 0.33 | 0.10 | 0.05 | 0.04 | 0.21 | 0.54 | 0.04 |
| | I3M-H60 | 0.42 | 0.25 | 0.05 | 0.03 | 0.01 | 0.15 | 0.42 | 0.01 |

### 4.4.5 Cooling Performances in above-mentioned Four Type Scenarios

Above sections have analyzed the impacts of greening layout, coverage ratio, vegetation height, and building height on pedestrian cooling performances of green roofs. Table 4-3 further summarizes the air temperature reduction at five points under different scenarios. From the temperature reduction at five points, it is observed overall that green roofs exerted moderate cooling effects on the environment at the pedestrian level compared with other cooling strategies and techniques of cool pavements, water bodies, and urban forests. Nevertheless, green roofs could also generate the most favorable cooling performance of 0.82 °C at the point-1 in the IGR-6M scenario. Green roofs could generally generate cooling performances of 0.10–0.30 °C at point-1, point-2, and point-3, while the cooling performances were primarily less than 0.10 °C at point-4 and point-5. Meanwhile, temperature reduction generally followed the pattern of point-1 > point-2 > point-3 > point-4 and point-5, except for Case-Right, Case-Bottom, Case-Wind, and Case-25%. This further shows that downwind side is generally the most advantageous part to enjoy the cooling performance of green roofs [20, 21]. From the average temperature of five points, it is found that the cooling performances ($T_{24h}$) were generally low, at around 0.10–0.30 °C. Nevertheless, Case-Wind, Case-100%, IGR-6M, and I3M-H10 were the most favorable scenarios in different categories, with $T_{24h}$ of 0.26, 0.35, 0.46, and 0.35 °C, respectively. For practically enhancing pedestrian cooling performance of green roofs, therefore, it should combine the conditions of wind, higher coverage, higher vegetation height, and lower building height.

### 4.4.6 Effect of Orientation Array of Green roof on Pedestrian Cooling Performance

In order to better utilize green roofs, it is a complementary to design the influence of orientation array on green roof cooling performances. As shown in figure 4-17a, there are four types of angles to be built, with the same greening coverage ratios of 50%. Figure 4-16b presents the cooling performance of each scenario (at 15:00), where thermal performance of maximum and minimum value in four types is similar as shown in green box and the cooling performance in case-GR135 has the lowest value of 40.56°C. That is to say, the layout of orientation array of green roof along the wind direction is more comfortable to expand the cool resource. In other words, it is agreement the cooling performance of Case-GR135 is dramatically increased due to provide a large interfacial contact area and improve the mass transfer processes. The cooling effect is as follows： case-GR 135 > case-GR 180 > case-GR 90 > case-GR 45.

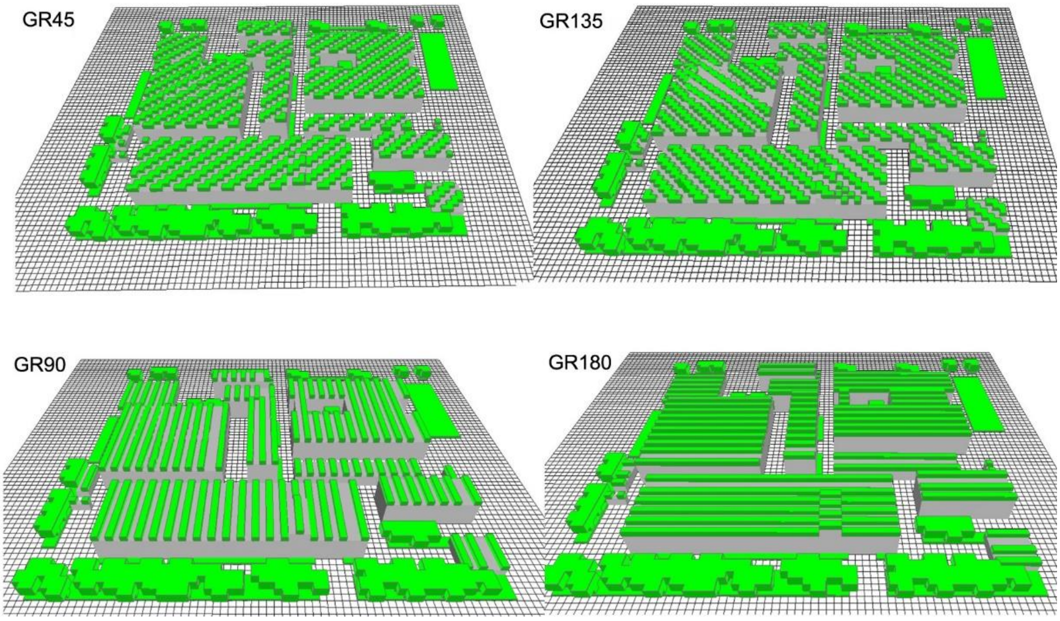



**Figure 4-17** (**a**)

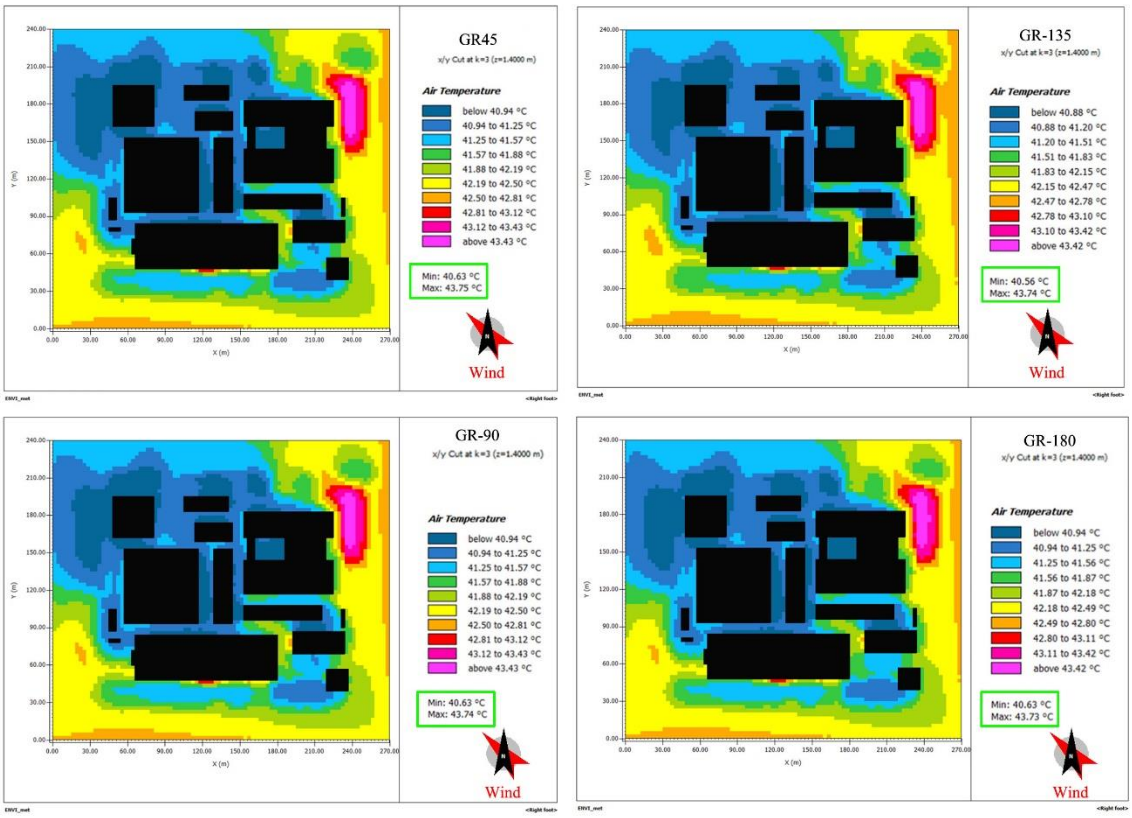



**Figure 4-17** (**b**)

**Figure 4-17** Comparison of the impact of building height on green roof cooling performance (**a**) Physical models, and (**b**) pedestrian air temperature reduction at 15:00 h

### 4.5 Summary

This chapter investigated the effect of morphological characteristics (greening layout, greening coverage ratio, vegetation height, and building height) of green roofs on pedestrian cooling performances in a real neighborhood in the subtropical city of Hangzhou, based on field measurement and numerical simulations. Based on the analysis in this study, the following conclusions can be drawn.

1. Overall, green roofs could generate a moderate cooling performance at the pedestrian level, while the most favorable cooling performance could reach up to 0.82 °C. To better utilize green roofs for pedestrian cooling, it is essential to simultaneously control the wind, greening layout, coverage ratio, vegetation height, and building height.
2. Installing green roofs in upwind zones was favorable for pedestrian-level cooling, while green roofs in the downwind zones could only exert limited cooling effects. Overall, the cooling performance of green roof followed the pattern of Case-Wind > Case-Upper > Case-Left > Case-Bottom > Case-Right.
3. A green roof with a low greening coverage ratio was not useful to improve pedestrian thermal environment. The cooling performance increased with the increasing coverage ratio, but the cooling performance reached a threshold when the coverage ratio increased to a certain value. Nevertheless, a neighborhood with a high coverage ratio could experience a “cool island” in the central area. In addition, the horizontal distance from green roofs to the target location could also influence the pedestrian cooling performance, where a short distance corresponded to a better cooling performance.
4. Vegetation height played a critical role in improving green roof cooling performance. IGRs exhibited better cooling performances than IGRs, and the increase in vegetation height resulted in better cooling performances. The cooling effects of IGR-6M on the whole area could reach 0.5 °C, and more than 0.3 °C at 14:00 h. However, when greening height was under 1 m, the cooling effects of green roofs were insignificant.
5. Building height was also an important factor affecting green roof cooling performance. With the increase of building height, the cooling effects of green roofs generally showed a trend of decrease. At this time, however, buildings and vegetation had combined effects, where higher buildings and vegetation could generate stronger cooling effects at the noon time. Moreover, because of wind effects and building shading, the building height limit for the cooling performance of green roofs was increased.
6. When the green roof is layout by interval type at same ratio, the layout of orientation array of green roof along the wind direction is more comfortable to expand the cool resource at the same ratio of green roof.

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# Chapter 5

# *Impact of Green Roofs' Pedestrian Cooling and Humidity by Changing Bilateral Buildings of Street Canyon in Subtropical Area*

**Chapter 5: Impact of Green Roofs' Pedestrian Cooling and Humidity by Changing Bilateral Buildings of Street Canyon in Subtropical Area**

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## 5.1 Introduction

The chapter 5 is structured as follows. Section 5.2 introduces the basic information of the study area and describes the field measurement, and settings and calibration of the ENVI-met model. Section 5.3 analyzes and discusses the impact of building depth, building height, building width on the cooling performance of green roofs, Section 5.4 puts forward the limitation of simulation software of the ENVI-met and Section 5.5 summaries this chapter. Overall, this study adds the knowledge what the scope of bilateral morphology of building to implement green roof to influence microclimate simultaneously. The comparative and scientific assessments of green roof cooling performance in ideal street can theoretically instruct urban planners and policy-makers to choose effective cooling strategies and cost-benefit scope.

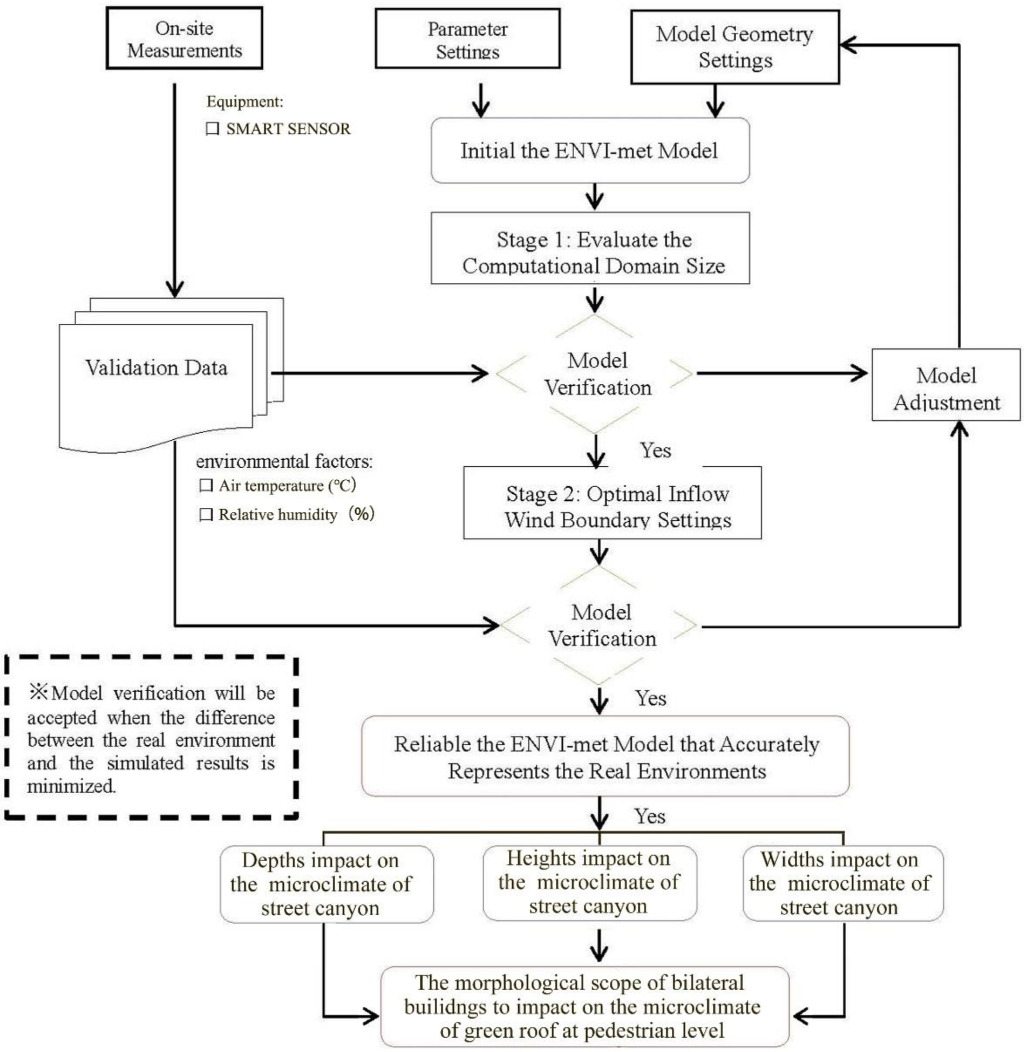


**Figure 5-1** A framework for comparative analyzing microclimate performance of green roofs under different scenarios

## 5.2 Methodology

This study draws upon field measurements and numerical simulation (based on the computational tool of ENVI-met) to perform the comparative analysis of the impact of building morphological characteristics on microclimatic effect in street canyon. Figure 5-1 presents the framework of this study. In briefly, the simulation process could be generalized that the building depth, height and width of both sides of the street canyon which is covered green roofs was derived from the real environment and aspect ratio. Firstly, to explore the limiting depth for microclimatic effect, the building height and width are fixed by only changing the building depth. Next, the depth value of building is fixed, only by changing the height value, the limiting value of building height concerning the microclimate of green roof would be found. At last, the limiting value of width for building covered green roof could be found in the same way.

### 5.2.1 Field Measurements

For this study, ENVI-met sets up a model based on the real condition, and then validates against field test. The subject is a sunny day on September 5, 2017 year in the Wangma Community, Changqing Street, Shangcheng District, Hangzhou City, China. The measured region belongs to the severely meteorological area that the summer is hot while the winter is cold. The selected study area has green roofs and the aspect ratio of building height to street width H/W is 1:1, while the measurement of distribution of the four test sites was run simultaneously in the study area as shown in figure 5-2.

Placement of instrument was put in the hollow tube for smooth wind and it is wrapped by aluminum foil to avoid solar radiation as shown in figure 5-2. The community is located in

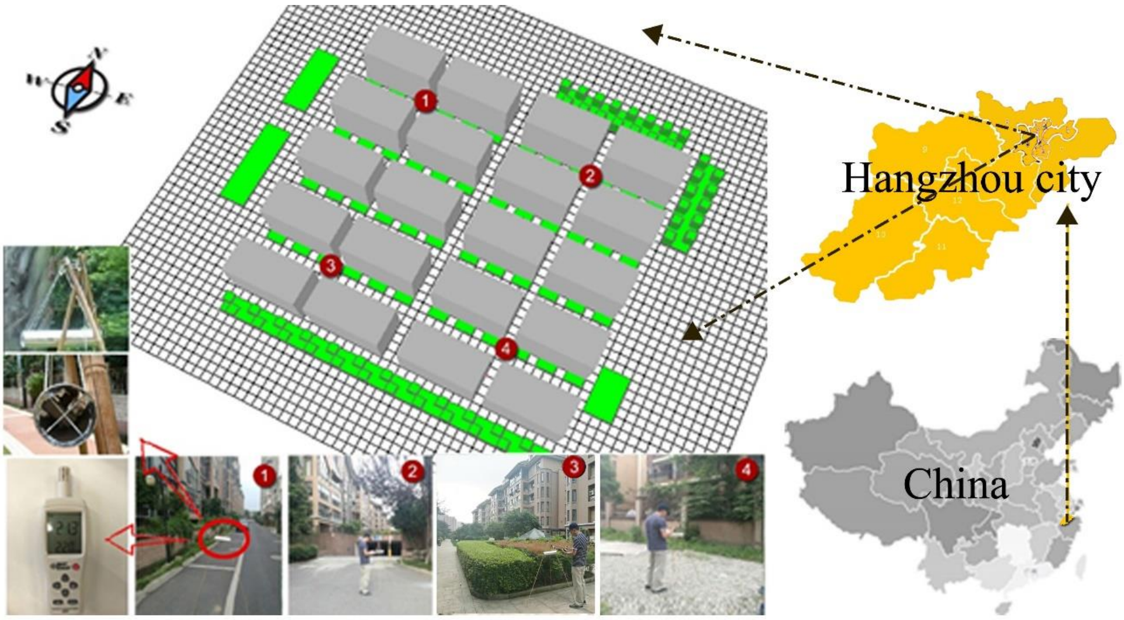


**Figure 5-2** The distribution of the four tests and measured instruments

the city center, with regular road patterns, arranged in the direction of east-west. For the limitations of the software, the community is briefly built by the blocks in ENVI-met simulation coinciding with on-site community environment. SMART SENSOR, an automatic sensor of record for temperature and humidity as shown in figure 5-2, is employed in each test area. There are four monitoring points are set, and the data of air temperature and relative humidity is automatically recorded every 10 minutes. Besides, each instrument is calibrated before the field test.

**Table 5-1** Settings of boundary condition in ENVI-met

| Project | Major parameters |
|---|---|
| Initial wind direction | 45°(SE) |
| Wind speed | 1.0；1.5；2.0 m/s |
| Initial air temperature | 22.0℃ |
| Relative humidity | 71% |
| Air moisture content (2500.0m) | 7g·kg-1 |
| Roughness Z0 | 0.1m |
| Average height of trees | 2.0m |
| Average leaf area density | 2.35m2·m-3 |
| Foliage albedo | 0.75 |
| Average heat-transfer coefficient of walls | 1.0 W·m-2·K-1 |
| Average reflectivity of walls | 0.4 |
| Average heat-transfer coefficient of roofs | 1.0 W·m-2·K-1 |
| Average reflectivity of roofs | 0.3 |
| The soil of initial surface temperature/ Humidity (0-20cm) | 25.0℃/50.0% |
| The soil of Initial temperature/ Humidity at middle depth(20-50cm) | 26.0℃/60.0% |
| The soil of Initial temperature/ Humidity at deep depth (> 50cm) | 26.0℃/60.0% |

### 5.2.2 Settings of the ENVI-met

Based on the software verification of field survey, the number of vertical and horizontal grids in the entire model area was 100 ×60 respectively (the resolution was set at 4.0 m). Five nested grids were provided around the model area. Furthermore, the initial macro-meteorological parameters, simulation controlling parameters and the definition of underlying surface and thermal properties of buildings are needed to set the boundary conditions. The ENVI-met model boundary condition settings in this study are shown in table 5-1. The meteorological parameters come from both the field measurement and the observation data which is from a meteorological website, Underground Weather, in America. Model roughness length Z0 and air humidity at 2500.0 m altitude use ENVI-met default values. The ENVI-met plant model is divided into 10 equal layers according to plant height. Users can define the leaf area density (LAD) of each layer by using the three-dimensional plant modeling tool provided by ENVI-met so as to describe different canopy shapes and leaf area density distribution. At certain altitudes, trees with large LAD represent dense foliage and canopy and produce larger shade area; conversely, if the LAD is smaller, the leaves and canopy are sparse and the shade area is smaller[1]. The setting of plant height in the study area is based on the field survey data. The definition of LAD is based on the measured values of the leaf area index of landscaping plants in Hangzhou [1]. The parameters of thermal properties of buildings are based on the "Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone" in China[2] and the "Design Standard for Energy Efficiency of Public Buildings" (Zhejiang Province Implementation Rules)[3]. In addition, due to the preliminary period of 6-hours simulation is not precise in ENVI-met, the actual time of software verification starts from 0:00 am and ends at 24:00 pm on September 5, 2017.

### 5.2.3 Verification of the Software Accuracy

Krüger et al.[4] compared the results between field surveyed wind velocity of a pedestrian street in Curitiba, Brazil to the ENVI-met simulation. The wind speed measured at a local weather station is used as the initial wind speed, with results showing that the simulation values can match the field measured value fully when the beginning wind speed is not more than 2 m/s (R2=0.80). When the beginning wind speed is more than 2m/s, the simulation values are mildly larger than the measured value (R2=0.70). In Krüger's study, a single wind speed is used for one day instead of per hour. Three values of wind speed (1.0m/s, 1.5 m/s and 2.0 m/s) are applied in the test, followed by a comparison of the measured air temperature and relative humidity. The study carries out a sensitivity test for the wind speed, to determine how different ENVI-met models with diversified wind speed can be employed in a humid-hot climate precisely. In the ENVI-met model, the wind speed is set from 1m/s to 2m/s. As shown in the results in figures 5-3(a) and (b), when the wind speed is 1.5m/s, it is closer to the measured values than the results of 1.0m/s and 2.0m/s.

Through comparing the hourly measured and simulated values at each point from 6:00 to 24:00, the points were at the same position in both the ENVI-met simulation and the field measurement. Previous studies have employed and validated this model for green-roof-related research. For instance, a strong correlation (R2=0.82-0.96) was found between measured and simulated air temperature on rooftops (greened and non-greened)[5, 6] while strong agreement (R2=0.79-0.85) was also noted under tree-shade and/or open-space at the pedestrian level[7, 8] with a 20-25% percent error. In the model, the reasonable correlation between simulated results and measured values with R-square equal to 0.85 in air temperature and 0.84 in relative humidity as shown in figures 5-3(c) and (d), respectively, indicates that the ENVI-met model is reliable for studying the air temperature and relative humidity at the pedestrian level in street canyons in hot-humid regions.

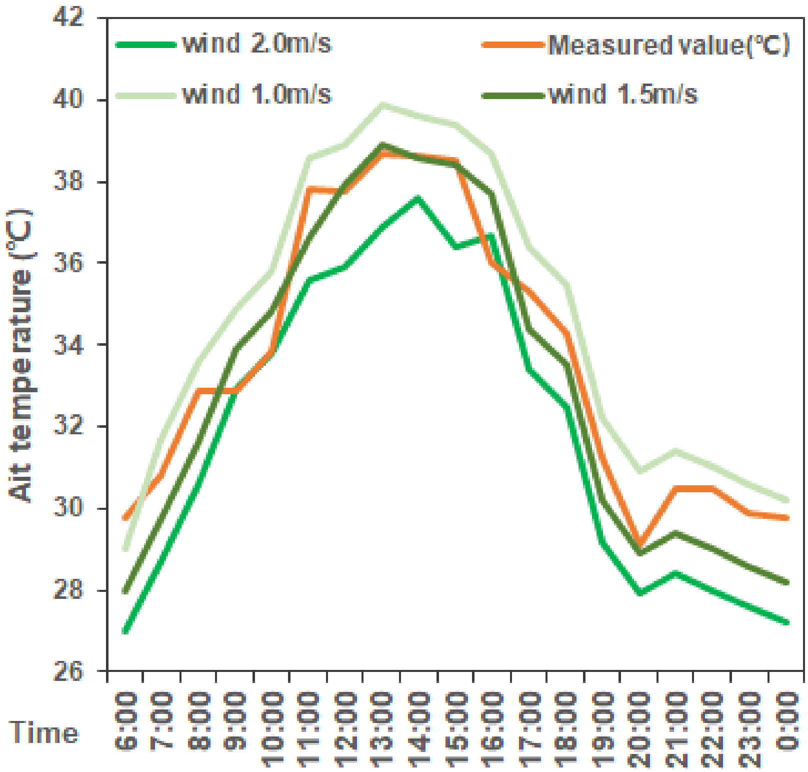


**Figure 5-3 (a)**

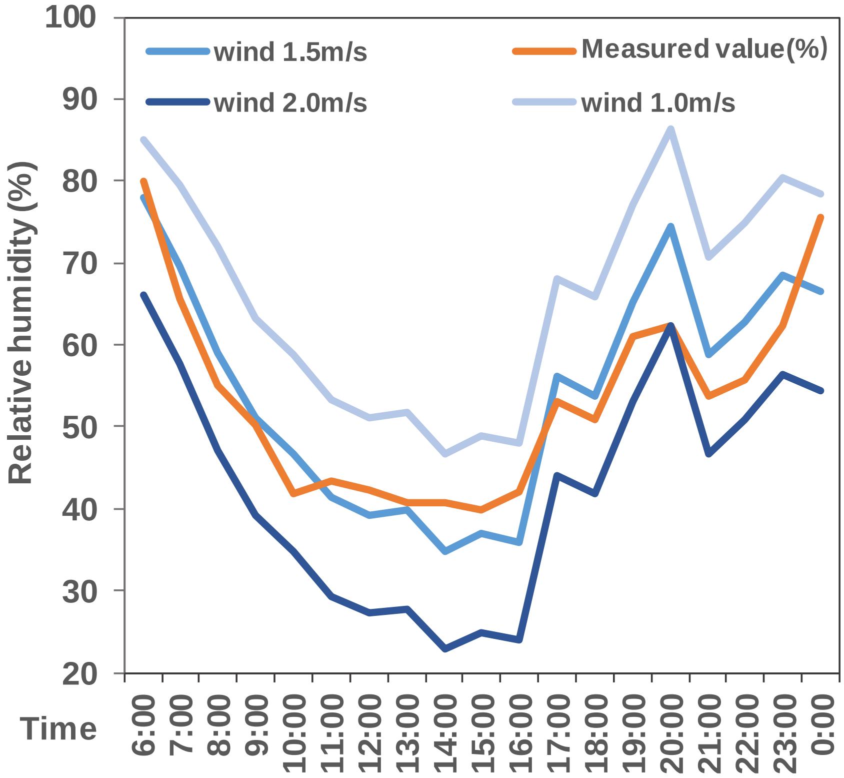


Figure 5-3 (b)

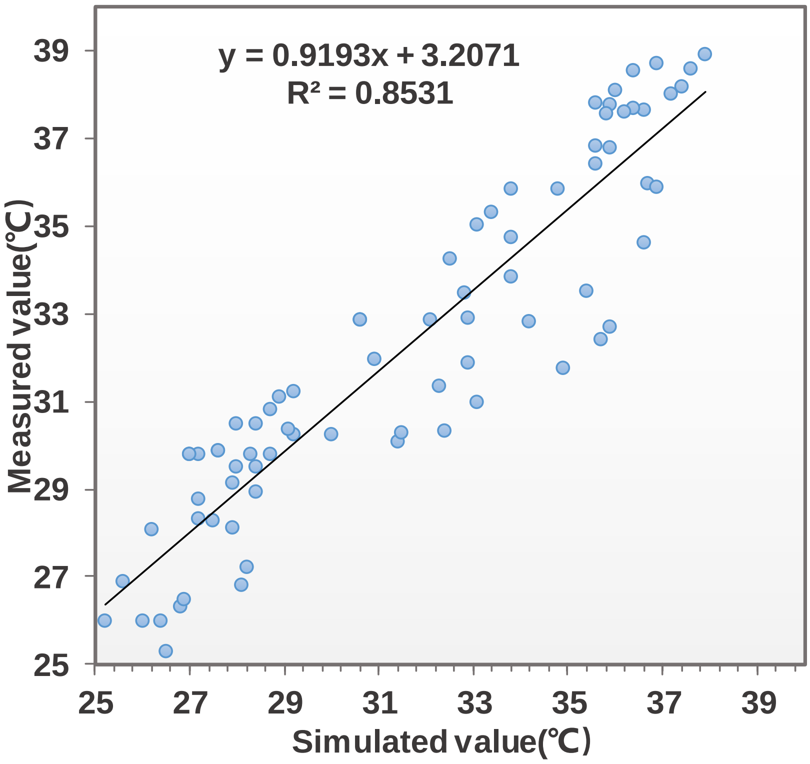


Figure 5-3 (c)

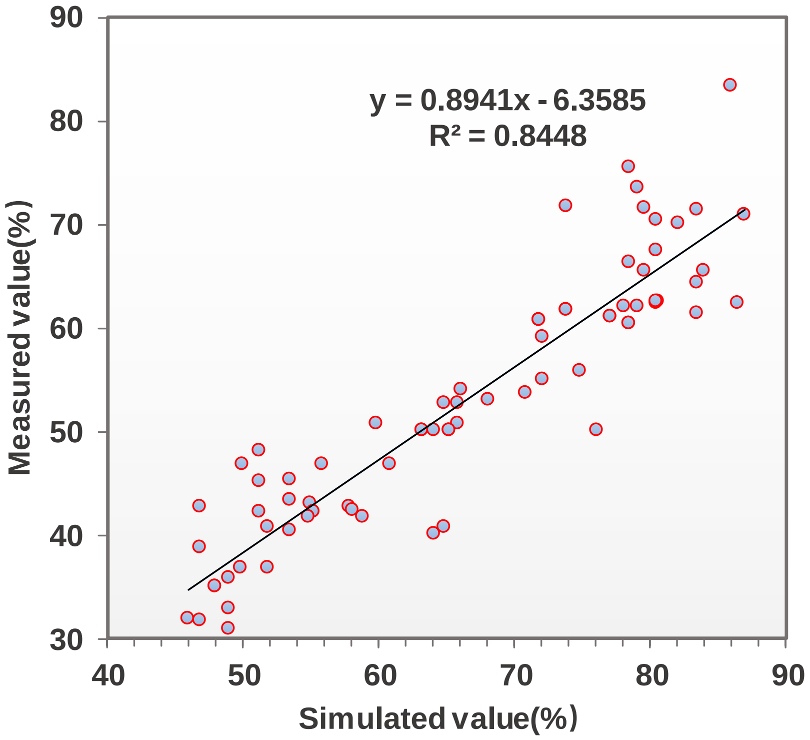


**Figure 5-3 (d)**

**Figure 5-3 (a)** Accuracy validation of simulation of air temperature using field measurements; **(b)** Accuracy validation of simulation of relative humidity using field measurements; **(c)** Comparison between measured and ENVI-met simulation's air temperature at 1.4 m height; **(d)** Comparison between measured and ENVI-met simulation's relative humidity at 1.4 m height.

### 5.2.4 the Establishment of Simulation Prototype

The ENVI-met model simplifies the processing of the boundary conditions based on the hottest day, July 22, 2017 in history, which is analyzed as shown in figure 5-4. The climatic conditions are posted by the website, Weather Underground. Model boundary conditions are set, as shown in table 5-1; the wind speed value of 1.5 m/s is applied. There is a 24-hour simulation, starting from 0:00 in the morning to 24: 00 the next day. The study was focused that the simulation results of air temperature and relative humidity were the average value of all grids in street canyon at the hottest time of the day (at 14:00) in the canyon. Through simulation of the various morphologies of bilateral buildings and the singular morphology of street canyon, the microclimatic variations are explored by different building depths, heights, widths respectively. Initial morphology of bilateral building is emulated by aspect ratio of real community. The simulation result included an average value at a pedestrian level of 1.4 meters, at the same time, the model without green roofs (equal to bare roofs) was used as a contrast, as shown in figure 5-5.

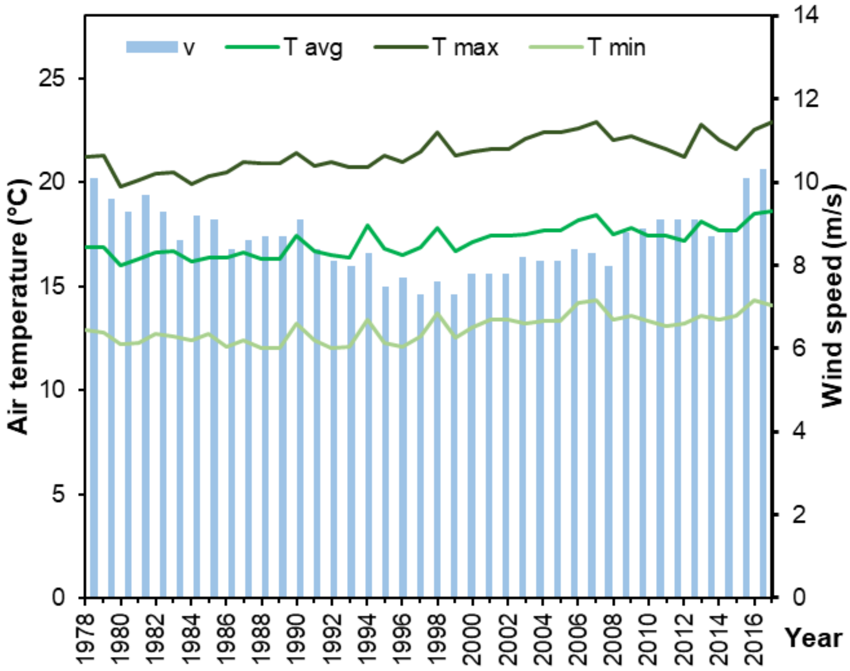


**Figure 5-4 (a)**

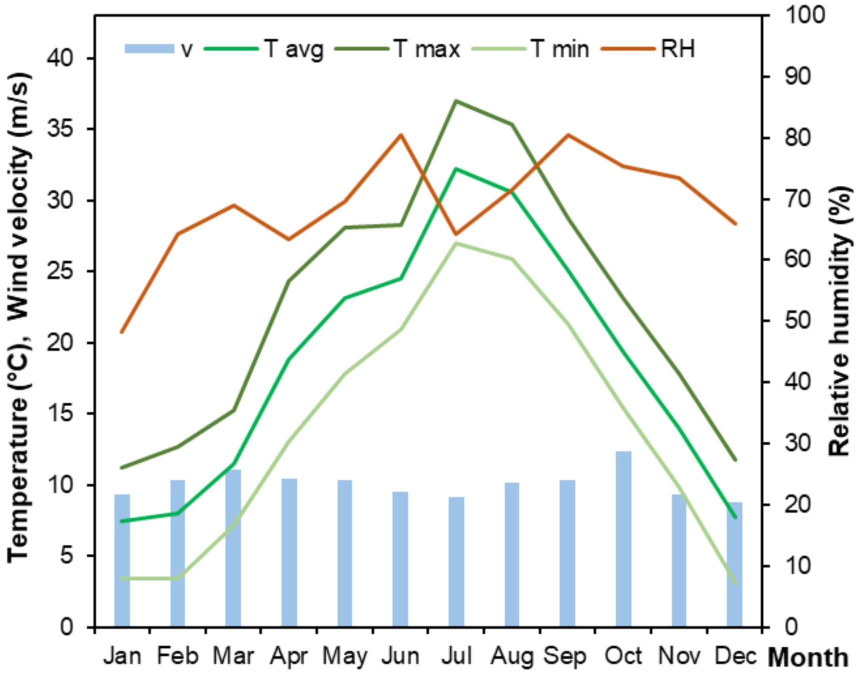


**Figure 5-4 (b)**

**Figure 5-4 (a)** Meteorological condition of Hangzhou City (1978-2017) **(b)** Weather condition of Hangzhou in the 2017 year (Note: v: wind speed, T avg: average air temperature, T max; average maximum air temperature, T min: average minimum air temperature, RH: relative humidity)

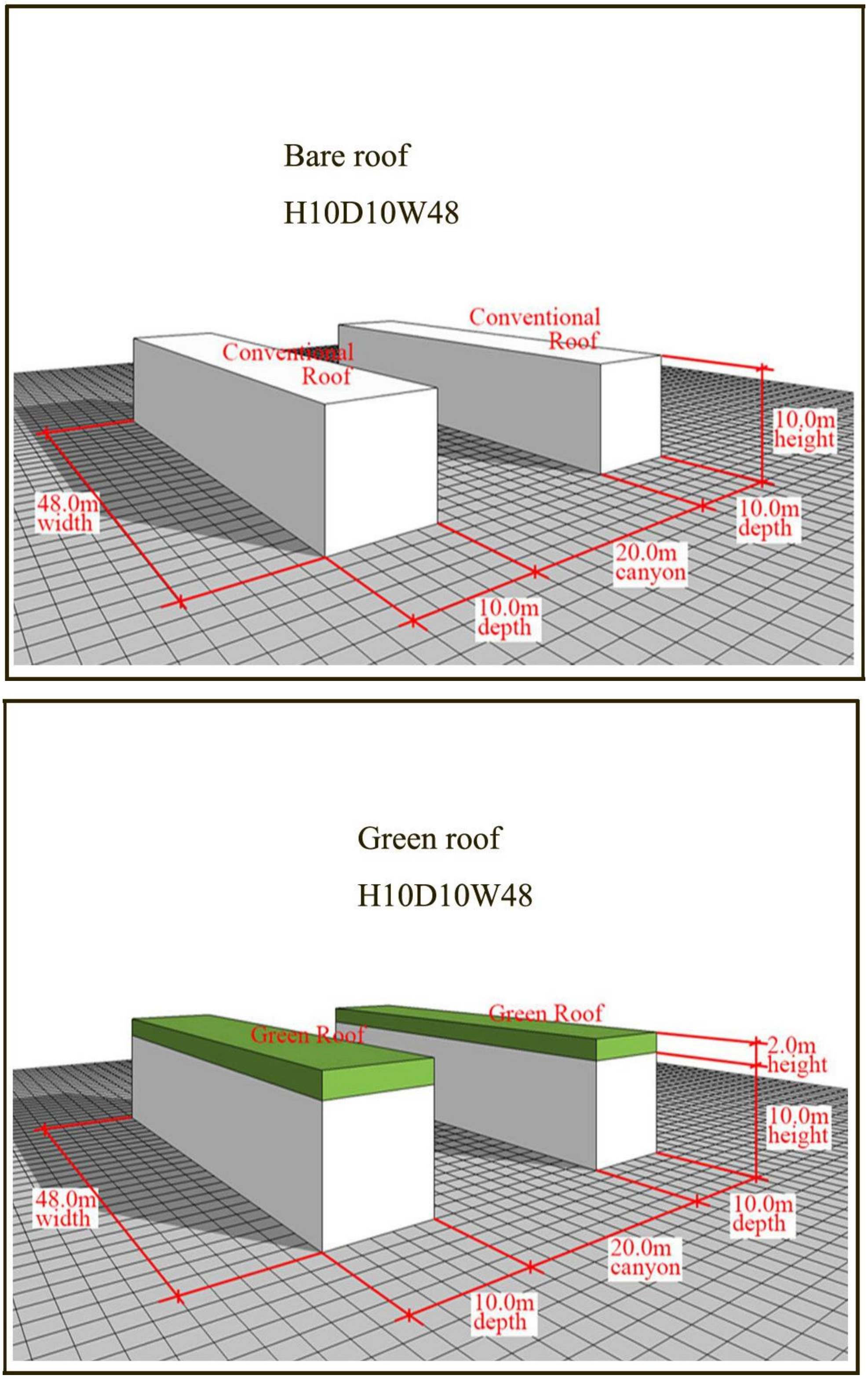


**Figure 5-5** The simulation parameters of bare roof and green roof

## 5.3 Results and Discussion

### 5.3.1 Thermal Analysis of Prototype at Peak Time

According to the figure 5-6, the thermal scenario distributions of bare roof（BR）and green roof （GR）illustrates the air temperature is from 40.67 to 42.74℃ and 40.43 to 42.68℃ respectively which is far away to Chinese requirements of thermal safety of 35℃ [9]. meanwhile, the relative humidity of BR and GR is from 33.42 to 37.06% and 33.51 to 37.46% respectively. In comparison, it means green roof has cooling effect to decrease the maximum value of 0.24℃( 40.67 - 40.43℃) and the minimum value of 0.06 ℃( 40.74 - 40.68℃) at peak value, at the same time, humidifying effect of green roof could increase the minimum value of 0.09% ( 33.51 - 33.42%) and maximum value of 0.4%(37.46 - 37.06%). This result is agreement with that green roof of cooling and humidifying effect on street canyon is not significant in summer [10, 11]. At the air inlet of street canyon, figure 5-6 demonstrates a worse thermal environment but the air outlet is different feature which is consistence with the green roof will provide a better cooling effect in downwind direction[12, 13]. Besides, its humidifying effect in downwind direction could not be neglected.

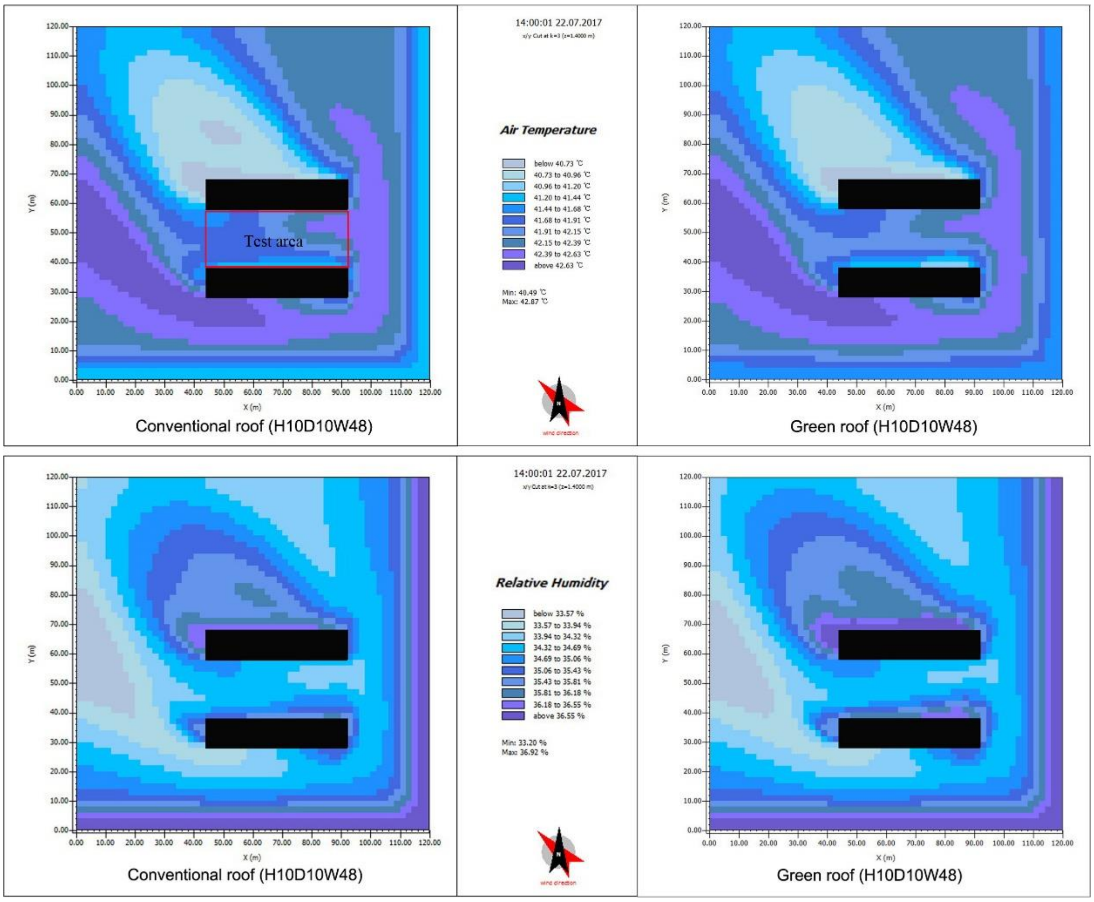


**Figure 5-6** Pedestrian thermal environment at 14:00 h

(Note: Test area is calculated by average value.)

### 5.3.2 Building Depths Impact on the Microclimate of Street Canyon

Based on the prototype model, there are eleven building models and eleven building models covered green roof as a comparison to be built where only during the process could change building depths. According to the thermal distribution of air temperature and relative humidity in street canyon, each grid was extracted and analyzed by average value. For example, the figure 5-7 illustrates the microclimatic distribution of air temperature and relative humidity in street canyon.

To further explore the microclimatic effect of the building depth covered or not covered green roofs at the pedestrian level of street canyons, the establishment of the objective model coincides with the fixed value by 10-meters height and 48-meters width for basic prototype. Meanwhile, eleven groups of greening models with a depth of 4 m, 8 m, 10 m, 12 m, 16 m, 20 m, 24 m, 28 m, 32 m, 36 m, and 40 m, were set up to be simulated and simultaneously compared with bare roofs. Generally, the study could find the regulation between building depth and thermal performance in the street canyon as shown in table 5-2, demonstrating that building covered green roof on both sides in street canyon have a slightly cooling and humidifying effect at the pedestrian level. When building depth increases from 4 to 40 meters, the average value of air temperature is gradual to be hot including green roof and bare roof. While, green roof improves the relative humidity in street canyon. The deeper building without green roof has a much hotter and drier performance in the street. With depth increasing, the cooling and humidifying effect for green roof do not increase simultaneously. However, the green roof has the opposite trend about relative humidity in street canyon. The cooling and humidifying effect of the green roof always exists, companying with depth increasing. The width of the building will also affect the temperature of the street canyon, based on the expansion of the green area of the roof by building depth increasing. While, it could be divided into two stages.

On the one hand, when the building deepens from 4 to 24 meters, the cooling and humidifying effect for green roof to street canyon are relative stable which is less than 0.15 ℃and 0.35 % respectively, and it does not improve companying with the green-roof area increasing. In the stage, the thermal performance of the street canyon is trend to balance. It could be deduced that due to the building deepens and its surface area increases, building absorbs and releases more solar heat radiation [14].On the other hand, after the building depth beyond 24 meters, the cooling and humidifying of the building covered green roof would have influenced on the microclimate more and more remarkable in street canyon. For this reason, the regulation indicates that the building covered green roof have a depth limitation to impact on microclimate at pedestrian level. It is to say that the increment of green-roof area is efficient to alleviate the UHI[15], the cooling and humidifying effect of green roof could not be effective.

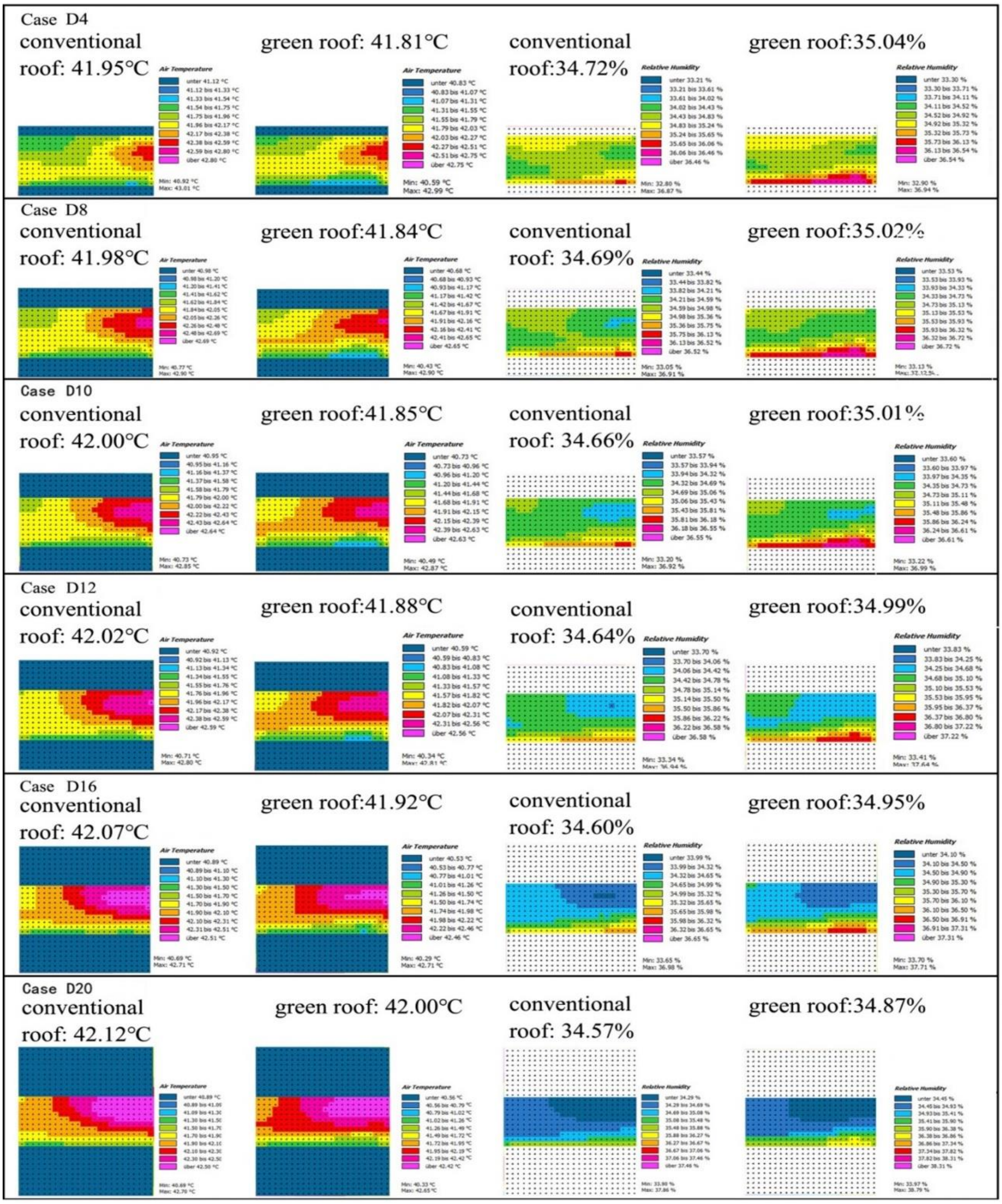


**Figure 5-7** The temperature and humidity in the canyon by various building depths

**Table 5-2** The average air temperature and relative humidity of the building within 40 m in depth

| Depth (m) | CR (℃) | GR (℃) | Difference in (℃) | CR (%) | GR (%) | Difference in (%) |
|---|---|---|---|---|---|---|
| 4 | 41.95 | 41.81 | 0.14 | 34.72 | 35.04 | 0.32 |
| 8 | 41.98 | 41.84 | 0.14 | 34.69 | 35.02 | 0.33 |
| 10 | 42.00 | 41.85 | 0.15 | 34.66 | 35.01 | 0.35 |
| 12 | 42.02 | 41.88 | 0.14 | 34.64 | 34.99 | 0.35 |
| 16 | 42.07 | 41.92 | 0.15 | 34.60 | 34.95 | 0.35 |
| 20 | 42.12 | 42.00 | 0.12 | 34.57 | 34.87 | 0.30 |
| 24 | 42.16 | 42.02 | 0.14 | 34.55 | 34.90 | 0.35 |
| 28 | 42.21 | 42.05 | 0.16 | 34.54 | 34.94 | 0.40 |
| 32 | 42.27 | 42.1 | 0.17 | 34.51 | 34.99 | 0.48 |
| 36 | 42.31 | 42.11 | 0.20 | 34.42 | 35.02 | 0.60 |
| 40 | 42.37 | 42.12 | 0.25 | 34.37 | 35.03 | 0.66 |

Note: CR is Conventional roof (bare roof), GR is Green roof, (℃) is air temperature, (%) is relative humidity. Green color is basic model.

### 5.3.3 Building Heights Impact on the Microclimate of Street Canyon

According to simulation prototype, only does building heights change. The regulation between building height and thermal performance at the pedestrian level is shown in table 5-3. The maximum value of cooling performance is up to 0.3 ℃ for green roof at building height of 2 meters. With height increasing, the average air temperature of street canyons decreased including green roofs and bare roofs, simultaneously, the average relative humidity increases. The results demonstrated that the closer the green roof was to the ground, the better the cooling and humidifying effect on microclimate of street canyon. Companying with the height increment, the cooling performance of green roof represents to be gradually weak while humidifying effect displays in a similar way at pedestrian level. It is agreement that plants took away much of the heat nearby through transpiration and the increment of building height provide extra shade for street canyon to create microclimate [5, 16].

Green roof has a stable trend to cooling and humidify street canyon when the building height is above 42 meters which is fixed in cooling value of 0.1 ℃ and humidifying value of 0.16 %.

**Table 5-3** The average air temperature and relative humidity of the building within 50 m in height

| Height (m) | CR (℃) | GR (℃) | Difference in (℃) | CR (%) | GR (%) | Difference in (%) |
|---|---|---|---|---|---|---|
| 2 | 42.09 | 41.79 | 0.3 | 34.51 | 35.39 | 0.88 |
| 4 | 42.07 | 41.81 | 0.26 | 34.55 | 35.22 | 0.67 |
| 6 | 42.04 | 41.87 | 0.17 | 34.57 | 35.07 | 0.5 |
| 8 | 42.01 | 41.89 | 0.12 | 34.63 | 34.99 | 0.36 |
| 10 | 42.00 | 41.85 | 0.15 | 34.66 | 35.01 | 0.35 |
| 12 | 41.99 | 41.82 | 0.17 | 34.70 | 35.07 | 0.37 |
| 14 | 41.95 | 41.78 | 0.17 | 34.76 | 35.15 | 0.39 |
| 16 | 41.89 | 41.71 | 0.18 | 34.98 | 35.25 | 0.27 |
| 18 | 41.76 | 41.61 | 0.15 | 35.19 | 35.39 | 0.2 |
| 20 | 41.70 | 41.54 | 0.16 | 35.29 | 35.59 | 0.30 |
| 22 | 41.54 | 41.40 | 0.14 | 35.52 | 35.80 | 0.28 |
| 24 | 41.48 | 41.34 | 0.14 | 35.61 | 35.89 | 0.28 |
| 26 | 41.41 | 41.28 | 0.13 | 35.71 | 35.97 | 0.26 |
| 28 | 41.36 | 41.24 | 0.12 | 35.8 | 36.06 | 0.26 |
| 30 | 41.27 | 41.14 | 0.13 | 35.96 | 36.19 | 0.23 |
| 32 | 41.19 | 41.04 | 0.15 | 36.10 | 36.33 | 0.23 |
| 34 | 41.12 | 41.00 | 0.12 | 36.23 | 36.43 | 0.20 |
| 36 | 41.05 | 40.89 | 0.16 | 36.38 | 36.59 | 0.21 |
| 38 | 40.89 | 40.78 | 0.11 | 36.56 | 36.74 | 0.18 |
| 40 | 40.83 | 40.72 | 0.11 | 36.64 | 36.87 | 0.23 |
| 42 | 40.76 | 40.65 | 0.11 | 36.74 | 36.92 | 0.18 |
| 44 | 40.68 | 40.58 | 0.10 | 36.84 | 37.00 | 0.16 |
| 46 | 40.61 | 40.51 | 0.10 | 36.95 | 37.11 | 0.16 |
| 48 | 40.53 | 40.43 | 0.10 | 37.05 | 37.21 | 0.16 |
| 50 | 40.42 | 40.32 | 0.10 | 37.15 | 37.35 | 0.16 |

**Table 5-4** The average air temperature and relative humidity of the building within 160 m in width

| Width (m) | CR（℃） | GR（℃） | Difference in（℃） | CR（%） | GR（%） | Difference in（%） |
|---|---|---|---|---|---|---|
| 12 | 42.12 | 41.96 | 0.16 | 34.38 | 34.72 | 0.34 |
| 24 | 42.10 | 41.95 | 0.15 | 34.38 | 34.74 | 0.36 |
| 36 | 42.05 | 41.90 | 0.15 | 34.49 | 34.82 | 0.33 |
| 48 | 42.00 | 41.85 | 0.15 | 34.66 | 35.01 | 0.35 |
| 60 | 41.93 | 41.77 | 0.16 | 34.72 | 35.10 | 0.38 |
| 72 | 41.92 | 41.77 | 0.15 | 34.83 | 35.17 | 0.34 |
| 84 | 41.90 | 41.75 | 0.15 | 34.91 | 35.26 | 0.35 |
| 96 | 41.88 | 41.74 | 0.14 | 34.98 | 35.50 | 0.52 |
| 108 | 41.88 | 41.73 | 0.15 | 35.05 | 35.70 | 0.65 |
| 120 | 41.87 | 41.73 | 0.14 | 35.12 | 36.01 | 0.89 |
| 132 | 41.86 | 41.72 | 0.14 | 35.18 | 36.11 | 0.90 |
| 144 | 41.86 | 41.72 | 0.14 | 35.24 | 36.21 | 0.93 |
| 156 | 41.86 | 41.72 | 0.14 | 35.29 | 36.23 | 0.94 |

Therefore, it can be concluded that when the building height exceeds 42 meters, green roof has a limitation effect on microclimate for street canyon at the pedestrian level. Under the limitative height, green roof has a fluctuant variation regarding the cooling and humidifying effect on the canyon at the pedestrian level. It is to say, the microclimate of street canyon could be affected by aspect ratio [17, 18]. In other words, it is agreement that the lower height is easier to obtain the comfortable thermal environment by improving green coverage [11, 19]. For these reasons, building height have a limitative cooling effect on green roof, the lower part of severe UHI which should be initially taken into consideration to implement green roof than higher areas.

### 5.3.4 Building Widths Impact on the Microclimate of Street Canyon

Similarly, according to simulation prototype, only does the building widths change. There are twenty- six models divided thirteen green roofs and thirteen bare roofs to be built. In fact, there would not be a continuous and uninterrupted 156-meter-wide street canyon in China due to fire protection demand. The regulation between building widths and thermal performance was shown in table 5-4. The simulation results displayed that when the building width increases, street canyon is more and more cool and humid including green roof and bare roof. When the building width is beyond 108 meters, the cooling effect of green roof is limited in 0.14℃. In other words, it is agreement with that the cooling effect in street canyon is much more affected by aspect ratio rather than building width [18, 20]. However, the humidifying effect of green roof is not limitative by building width, the wider the street canyon the better humidifying effect for green roof. Especially, when building width is in 108 meters, the humidifying value increases up to 0.24% (0.89% - 0.65%). As a whole, the cooling effect between green roofs and bare roofs is basically constant and has a certain cooling effect in street canyon, which means the increment of building width is relevant to humidifying effect of green roof and irrelevant to the cooling effect of green roof in street canyon.

### 5.4 Limitations of the software ENVI-met

In recent version of 4.3.1 winter, the software of ENVI-met could not freely choose plant type which is limited in plant database, so the research of plant collocation to influence the thermal performance is limited. In addition, ENVI-met lacks of the function of spray and water that could layout in roof, which is important part to influence microclimate and organize green roof. In terms of database plant stated in ENVI-met software, there was only one type of vegetation to green roof employed in this study. Owing to the inability of the ENVI-met software to simulate the heat dissipation of the human body, inability to precisely choose façade material for blocks to simulate the scene environment and boundary conditions, and the influence of air flow owing to human movement on the microclimate of the pedestrian level, the software parameters need to be further explored. In addition, it needs further verified in ENVI-met that which meteorological regions is more comfortable to implement green roof by different thermal performance. At last, it was assumed that when the wind speed remained unchanged all day, the wind was more uniform in the ENVI-met model. Nevertheless, wind speed can be influenced by factors such as weather with changed shade and clouds, leading to deviation of the expected temperature and humidity from measured values.

### 5.5 Summary

Generally, the ideas of building morphology showing in this chapter demonstrate that offering green roof is an effective method to be adopted to tackle the problem of dry and hot street canyons in summer. The green roofs could be represented as many green islands or suspending parks in a city and change the aspect ratio for street canyon providing more shade spaces. The study highlights the optimal scope by green roof implementation in mitigating the UHI effect and improve thermal environment in street canyon at pedestrian level through a way of numerical simulation to calculate the air temperature and relative humidity. Generally speaking, this study enhances the perspectives of previous studies focus on the cooling and humidifying effect for building variations covered green roof by depth, height, and width which can play a key role in improving the comfort in street canyon at the pedestrian level. However, green roof's cooling and humidifying effect is slightly neglected in building scale. By numerical simulation, the paper mainly found as follows:

(1) The basic model in both sides of street canyon only changed the depth, the simulation results find that when the depth of green roof was more than 24 meters, the cooling and humidity effect on the street canyon arise. The deeper the bare roof, the hotter and drier the street, but the green roof has the opposite trend about humidity in street canyon

(2) the lower green roof, in which the maximum value to decrease air temperature appeared, was 2 meters. When the building height exceeded 42 meters, there is a stable and fixed effect on air temperature reduction and relative humidity increment which are only 0.1 ℃ and 0.16% respectively in street canyon at the pedestrian level.

(3) The cooling effect of green roof which is limited in 108 meters of building width could not change obviously in street canyon at the pedestrian level. However, the humidifying effect does which is the wider the more humid.

(4) The inabilities of the ENVI-met software have been pointed out.

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*Chapter 6*

# *Field Measurement of Near-surface Thermal Performance of Green Roofs in Subtropical Area*

**Chapter 6: Field Measurement of Near-surface Thermal Performance of Green Roofs in Subtropical Area**

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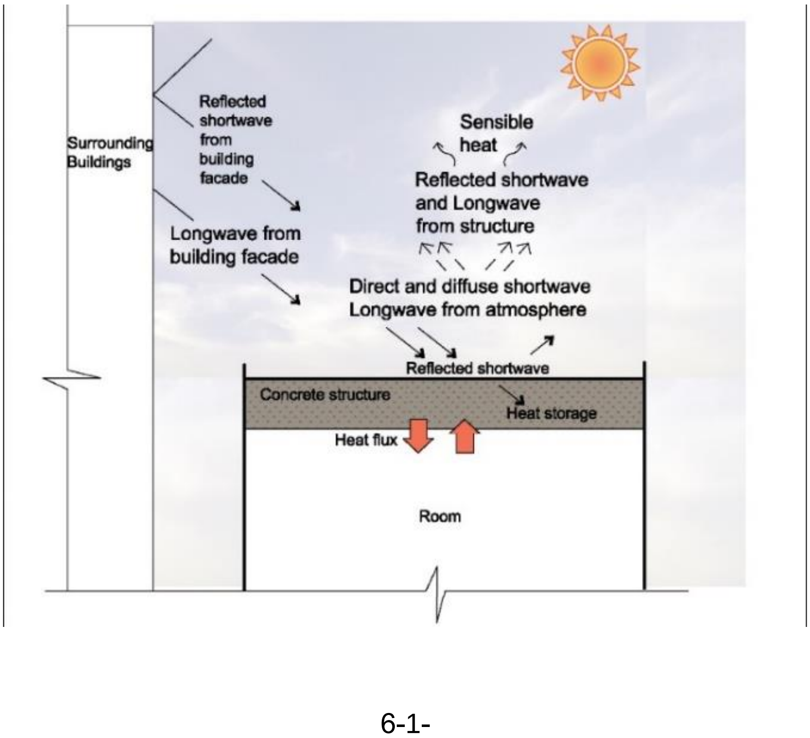
### 6.1 Introduction

The remainder of this chapter is structured as follows. Section 6.2 introduces the basic information of the cooling effects of green roof and Section 6.3 describes the field measurement, main research vegetation and experimental design. Section 6.4 analyzes and discusses the thermal performance of green roof in different meteorological and artificial (watering) condition, and Section 6.5 summaries this chapter. Overall, this chapter adds the knowledge of explain and analysis the thermal performance of common plant of green roof in Hangzhou City, China. The comparative and scientific assessments of green roof cooling performance in near-surface space can practically instruct urban planners and biologists to understand the ecological characteristics of common green roof. This chapter is also an important way to reveal the cooling and humidifying mechanisms of green roofs and significant to build green roofs (or rooftop gardens) for urban cooling in practice.

### 6.2 Cooling effects of green roof

Green roof is an alternative thought to enhance urban greenery, and the extensively built green rooftops can bring the urban areas with ecological, social and economic benefits. Regarding the urban climate, green roof is an important and feasible natural intervention architects and designers can rely on to mitigate the adverse impacts of urban overheating resulted from the combining effects of global warming and urban heat island phenomenon [1]. In general, cooling effect of green roof depends on a set of physical phenomena such as evapotranspiration, photosynthesis, shade and reflection, as shown in figure 6-1. Moreover, the process of heat insulation, absorption and conversion is also influenced by green roof typology (i.e. vegetation species and size, building height), local climate (i.e. solar radiation, temperature, wind speed and relative humidity) and water supply and availability [2-4].



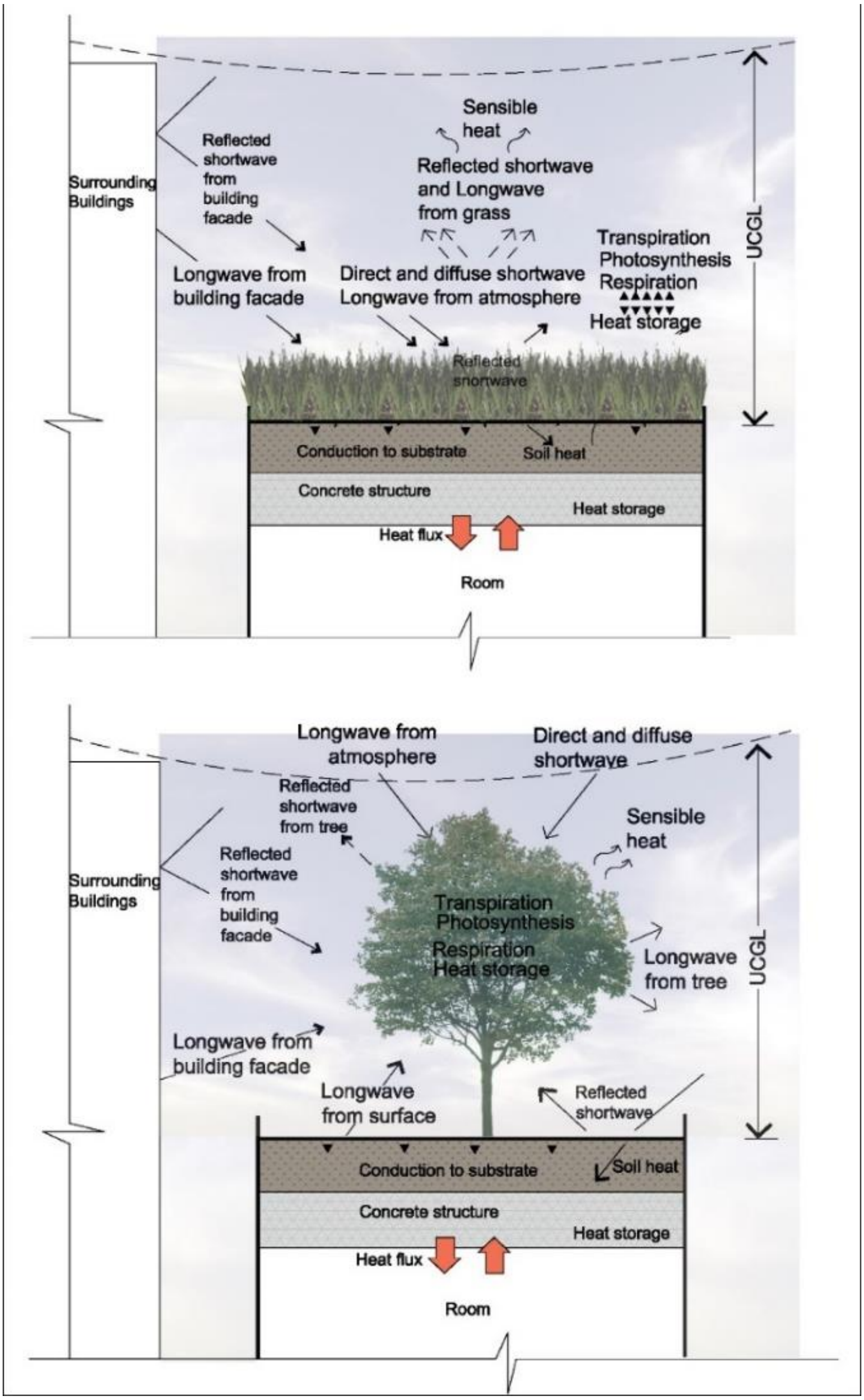



**Figure 6-1** A comparison of diurnal energy exchange pattern between rooftop vegetation and urban built form

## 6.3 Field measurement and design

### 6.3.1 Experiment site

The current study was conducted in the context of Hangzhou (30°15’39” N, 120°15’26” E), the capital city of Zhejiang Province, China, as shown in figure 6-2. Hangzhou is located in a humid subtropical climate (Cfa) zone, according to the World Map of Köppen-Geiger climate classification. Its hottest months are June, July and August. In July, the average daily temperature is more than 32 °C, and the daily minimum and maximum temperatures are 27 °C and 36 °C, respectively. Hangzhou is enduring the problem of urban overheating. For instance, the year of 2017 has been the hottest year in the past 40 years, and the recorded highest temperature is 41°C on 24 July, 2017 [5, 6].

Hangzhou has undergone rapid urbanization in the past decades, with the urbanization ratio of 75.3% in 2016 [6]. Nevertheless, the urbanization ratio will continue to increase. The urban

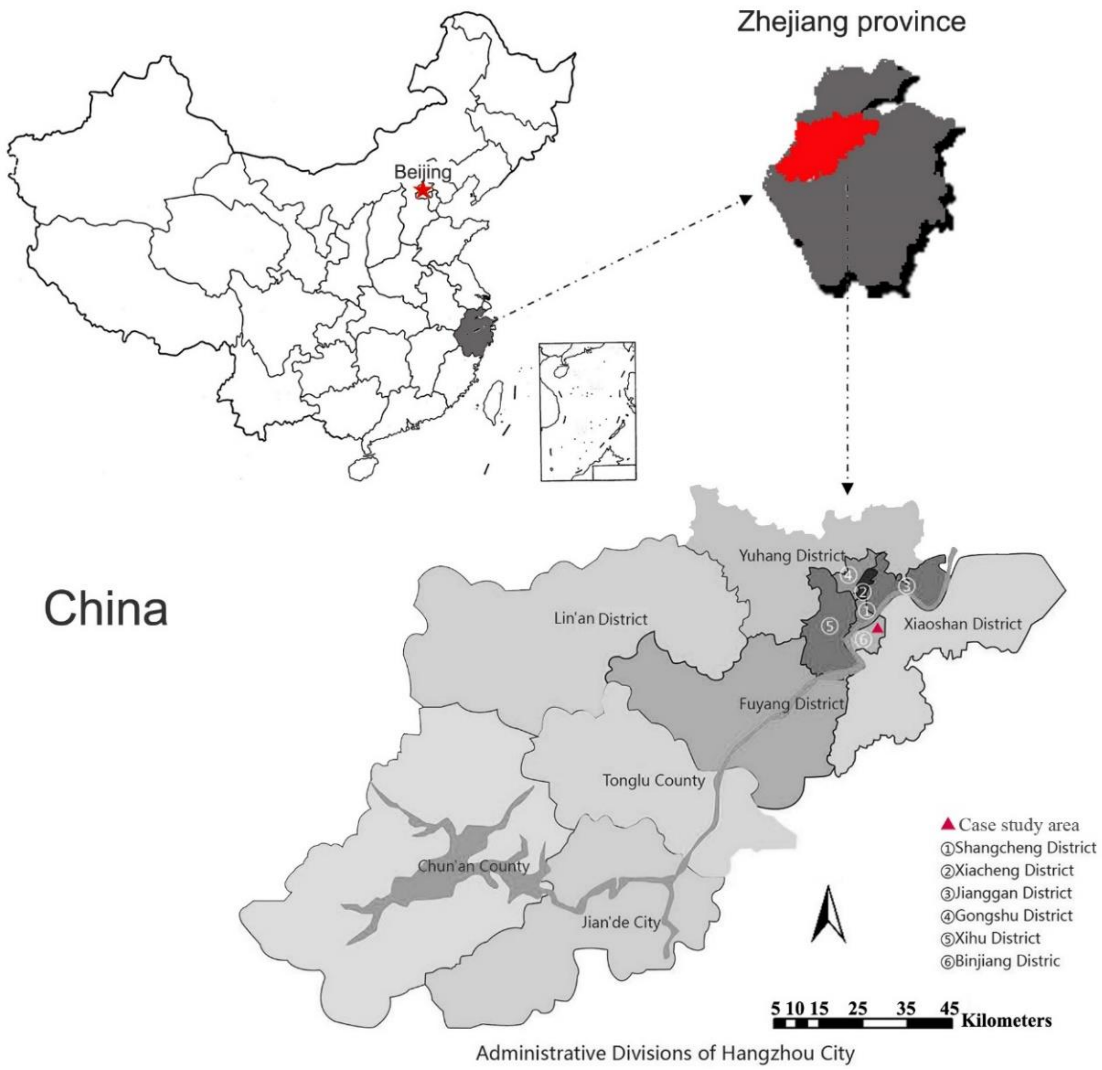



**Figure 6-2** Location of Hangzhou City and the fixed weather station

overheating problem will be further aggravated in the near future. However, the limited land space for urban greenery makes it difficult to seek help from the parks and other forms of green land. Alternatively, green roofing may be a good solution to the increasing temperature. In specific, the field measurement was carried out on the rooftop of a high-rise residential building with cement surface. The high-rise residential buildings are very common in Hangzhou, as Hangzhou is overpopulated with the density of 993.81 person/km$^2$ [6].

### 6.3.2 Description of plant materials

In this study, there were three kinds of green roof, with the plant types of groundcover, perennial herb and shrub. The growth medium layer was 180 mm in thickness. Trees were excluded because of their higher requirements on the growth medium layer, at least 300 mm in thickness [7]. Thermal performance of bare roof was also considered, being the base reference to the thermal performance of these three types of green roof. The representative species of the groundcover, perennial herb and shrub plant types were *Bermuda grass* (also known as *Cynodon dactylon*), *Sedum lineare* (also know as *carpet sedum*), and *Pomegranate* (also known as *Punica granatum*), respectively. They were selected because of their practical implications of the future use on rooftops. *Bermuda grass* is fast growing, cost-efficient, trampling resistant, drought and heat tolerant, and easy to achieve 100% coverage. The *Sedum lineare* is evergreen, so that it is able to provide a year-round visually pleasing environment to citizens and a favorable setting for insects living. Moreover, it is the most popular and accommodative plant for the rooftops in many different climatic zones [8-11]. Both *Bermuda grass* and *Sedum lineare* are rather invasive but easy to manage since the roots are never very deep [12]. *Pomegranate* is deciduous, slow growing, easy to manage, air pollution resistant, suitable for various soils, and widely distributed in the tropical and subtropical regions of the world [13, 14]. It has very dense and multilayered leaves that can exert shading effects and produces a distinctive fragrance and bloom in summer. Meanwhile, its long lifespan makes the *Pomegranate* attractive for birds and insects. *Pomegranate* is capable of providing a visually colourful and fruitful environment in the agricultural roof.

### 6.3.3 Experimental design

The planting bed used in this study had the dimension of 50cm × 50cm × 20 cm. The planting box consisted of several layers following the order from the top to down: vegetation layer, soil substrate layer, water storage layer, filter layer, drainage layer, and plastic supporting (root barrier), as shown in figure 6-3. It should be noted that to prevent the penetration of plant roots into the structural layer of building, the root barrier layer was much thicker, and this study added the air layer beneath it (figure 6-3). To avoid rotting roots, drainage holes were set to allow overflowing water to be discharged. Three planting boxes for *Bermuda grass*, *Sedum lineare* and *Pomegranate* were filled with the same type of fertile soil, forming the 18cm-thick substrate. Finally, three kinds of vegetation for investigation and a bare roof as a reference were individually planted in the same period. In addition, in order to ensure the survival and alive cultivation, these three types of green models were maintained for one week in the culture room before field experiment.

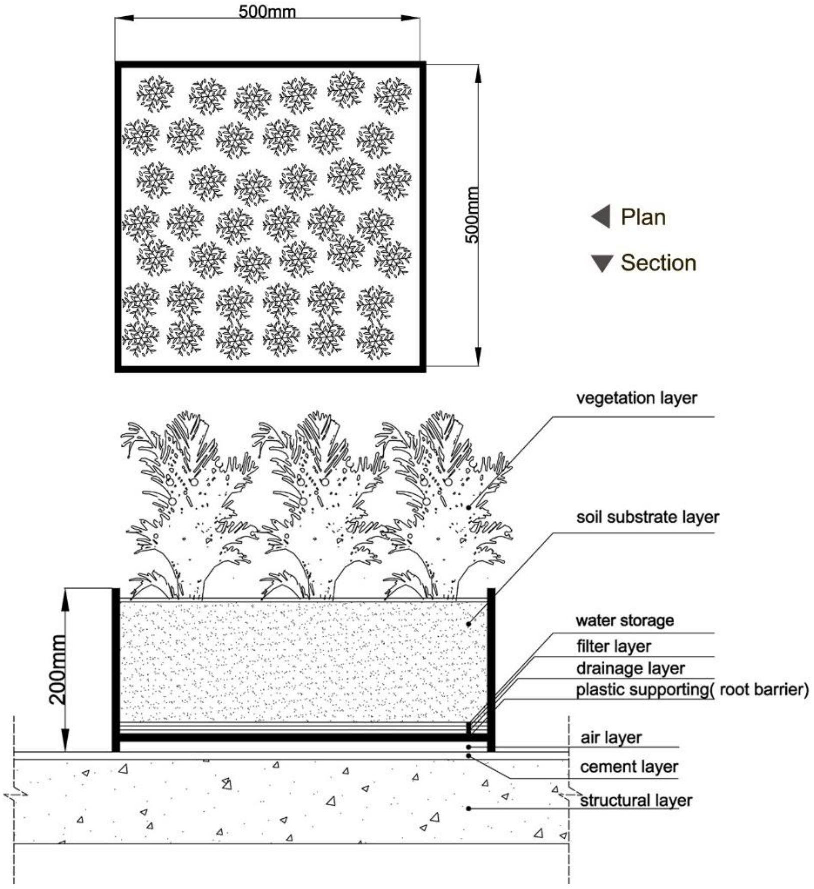



**Figure 6-3** The construction of planting beds: plan (top) and cross section (bottom)

### 6.3.4 Instrument settings and field measurement

The planting boxes were placed on the rooftop of a high-rise residential building (48m in height). There is no other urban heat intervention such as vegetation and water bodies that may affect the quantification and comparison of the thermal performances of green roof in current study. Meanwhile, this building was higher than surrounding buildings to avoid the reflected heat from them. The rooftop is surrounded by the parapet, protecting the cooling effects of vegetation from the rooftop wind influence. The measurement points were positioned above the soil layer and bare roof, respectively (as shown in figure 6-4). Because of the differences of green roof typology, the sensors were also installed at different positions.

For the Model-1, the sensor was placed under *Pomegranate* and above the substrate, and two others were above *Bermuda grass* and *Sedum lineare*, respectively.

The instrument (type: cos-03) used in this study could record the air temperature (accuracy: ± 0.1 °C, range: - 20°C – 60 °C) and relative humidity (RH, accuracy: ± 1.5%, range: 0-100%) automatically. To exclude the influence of solar radiation, sensors were shielded in aluminium alloy sleeves, while both sides of the aluminium alloy sleeve was open to make sure the air can flow smoothly. The data was recorded every five minutes, and the field measurement was conducted between June 11 and June 19, 2018. The hourly climatic data reported by the local meteorological station is presented in figure 6-5. Before 6:00 of June 11, there was a slight rain, so that the relative humidity(RH) was much higher. The weather was cloudy between 7:00 and 14:00 June 16, so that the ambient temperature was lower. For other days, the weather was sunny. To make sure vegetation could be survived in extremely dry and hot roof environment without rain, four models (including three types of green roofs, and the bare roof for comparison) were watered by 0.5L at 10:30 and 18:30 on June 12, at 17:00 on June 13, at 12:00 and 21:30 in June 14, at 9:40 on June 15, at 10:00 and 21:00 on June 16, at 12:00 on June 17. The variation of watering time allows us to compare if the watering time affects the thermal performance of green roofs.

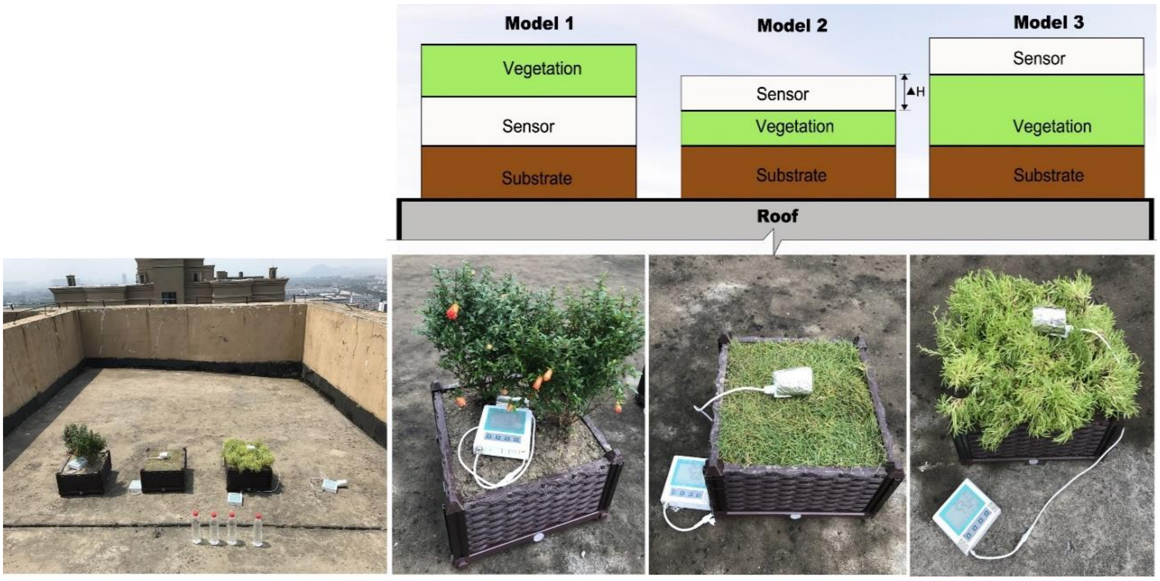



**Figure 6-4** Three plant types including *Pomegranate* (left), *Bermuda grass* (middle) and *Sedum lineare* (right), and bare roof for reference

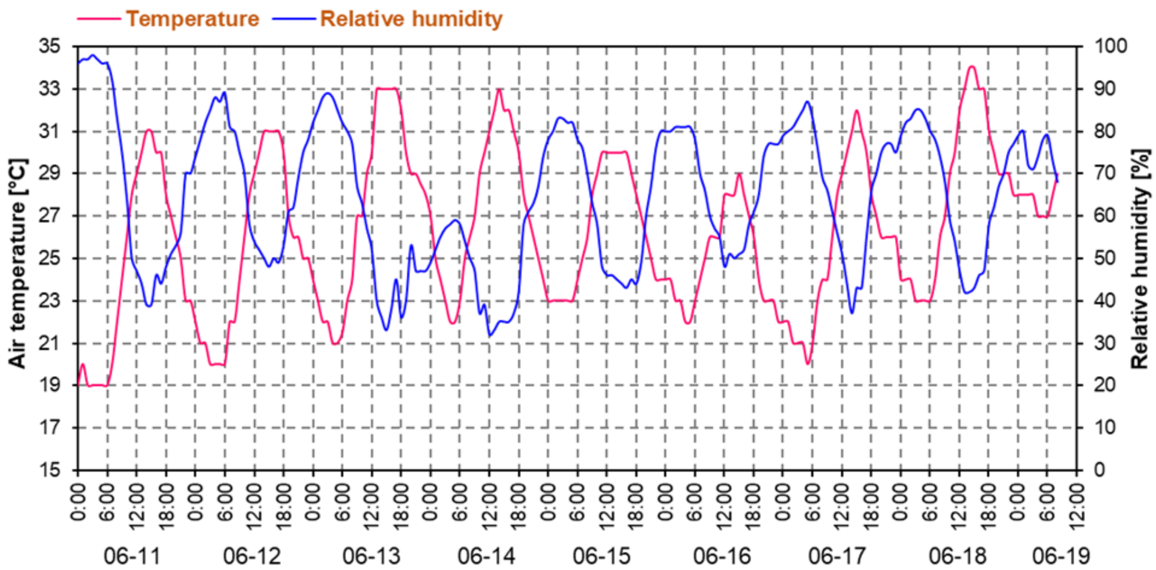



**Figure 6-5** The climatic conditions reported by the local meteorological station

### 6.4 Results and discussion

This section compares the near-surface thermal performance of *Pomegranate* roof, *Bermuda grass* roof and *Sedum lineare* roof under different situations. First, this section analyzed the overall performance of both near-surface temperature and relative humidity during the test period. Afterwards, one full day of June 13, 2018, a sunny day without cloud interference, was selected to investigate the green roofing performance on the sunny days. The local sunrise and sunset time on that day were 4:57 and 19:02, respectively. In addition, the impacts of watering and cloud on the green roofing performance were further investigated.

#### 6.4.1 Green roofing performance during whole test period

Figure 6-6 presents the near-surface air temperature and relative humidity over different roofing types. Overall, the amplitudes of temperature and relative humidity varied with the weather conditions (figure 6-5), while their curves in each day were generally consistent. During the daytime, the temperature of *Sedum lineare* roof was always the highest among four types of roofs, while the *Pomegranate* roof generated the lowest diurnal temperature. The air temperature over bare roof and Bermuda grass roof ranked the second and third places, with most situation that *Bermuda grass* roof had a lower diurnal temperature. Meanwhile, the diurnal temperature of *Pomegranate* roof was the most stable with the least fluctuations, while the temperature over *Sedum lineare* indicated a continuous increase to the peak and then a continuous decrease. In comparison, the nocturnal temperature difference among different roofing types was small. Nevertheless, the temperature over bare roof was the highest, followed by that over *Pomegranate* roof, *Bermuda grass* roof and *Sedum lineare*. Compared with diurnal temperature, the nocturnal one was more stable without substantial changes. Therefore, it is concluded that *Pomegranate* roof has the best and the most stable cooling performance, while the *Sedum lineare* cannot play a role in cooling while aggravate the roof thermal environment.

For the relative humidity, the diurnal one was much lower than the nocturnal one. *Pomegranate* roof had the highest diurnal relative humidity, followed by the *Bermuda grass* roof, while the *Sedum lineare* roof and bare roof had the lowest. What's worse, the *Sedum lineare* roof sometimes witnessed a lower diurnal relative humidity than the bare roof. The nocturnal relative humidity followed the reversed order: *Sedum lineare*> *Bermuda grass*> *Pomegranate*, while the relative humidity over the bare roof was the lowest. The results indicate the *Pomegranate* roof and *Bermuda grass* roof can humidify surrounding environment in the daytime, while *Sedum lineare* cannot. All green roofs can play their roles in humidifying the surrounding environment in the night time.

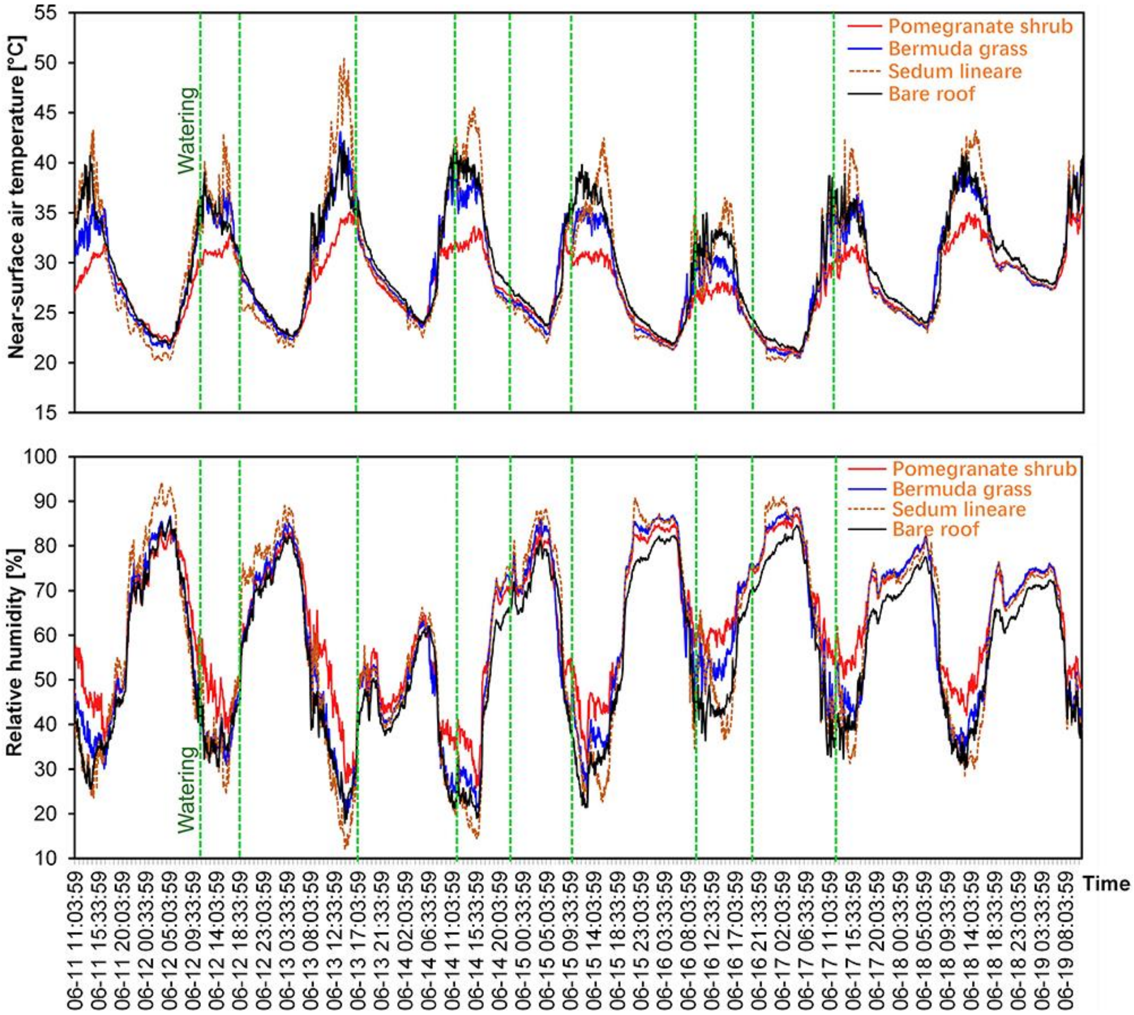



**Figure 6-6** Near-surface air temperature and relative humidity over four kinds of roofs during the whole test period (2018/06/11-2018/06/19)

Table 6-1 further shows the corresponding amplitude variations in detail. Overall, during the test period, the average near-surface air temperatures for *Pomegranate* roof, *Bermuda grass* roof, *Sedum lineare* roof and bare roof were 27.6 °C, 28.9 °C, 29.5 °C and 29.7 °C, respectively. The corresponding relative humidity were 62.2%, 59.1%, 58.8% and 55.5%, respectively. The average values indicate three kinds of green roofs have positive effects to cool and humidify the air near the roof surfaces. In particular, the *Pomegranate* had the best cooling and humidifying performance up to 2.1 °C and 6.7% compared with bare roof, followed by *Bermuda grass* and the *Sedum lineare* the worst.

For the range of near-surface temperature, the *Pomegranate* provided the most comfortable and stable environment with temperature range of 20.9-36.1 °C and relative humidity range of 25.8-87.1%. Sedum lineare witnessed the highest fluctuation range of air temperature (20.1-50.4 °C) and relative humidity (11.8~94.2%) than all other three kinds of roofs. The Bermuda grass also witnessed the larger ranges, compared with *Pomegranate* roof and bare roof. This further indicates the cooling and humidifying performances of Bermuda grass and *Sedum lineare* were unreliable during specific time periods. Therefore, to examine in what time period can green roofs played their roles in cooling and humidifying, the thermal performances of four kinds of roofs on a typical sunny day (June 13) were further analyzed in the following section.

**Table 6-1** Near-surface temperature and relative humidity amplitude of green roofs and bare roof (2018/06/11-2018/06/19)

| Vegetation category | Pomegranate shrub | Bermuda grass | Sedum lineare | Bare roof |
|---|---|---|---|---|
| Range of air temperature (°C) | 20.9-36.1 | 19.2-43.1 | 20.1-50.4 | 19.2-42.2 |
| Mean air temperature (°C) | 27.6 | 28.9 | 29.5 | 29.7 |
| Range of relative humidity (%) | 25.8-88.7 | 20.3-87.1 | 11.8-94.2 | 17.9-86.1 |
| Mean relative humidity (%) | 62.2 | 59.1 | 58.8 | 55.5 |

### 6.4.2 Thermal performance of green roofs on a typical sunny day

6.4.2.1 Comparison of overall thermal patterns of three kinds of green roofs

figure 6-7 presents advantages of three kinds of green roofs comparable to the bare roof, in aspects of near-surface air temperature and relative humidity. From the one-day average data, the temperature reduction and humidity increase of *Pomegranate* and *Bermuda grass* were significant. In general, *Pomegranate* showed the best cooling and humidifying effects with the average temperature reduction of 1.5 °C and the relative humidity increase of 5% in the whole day. The maximum air temperature reduction of is up to 8 °C, indicating its great benefits to regulating the thermal environment. Bermuda grass exhibited better cooling and humidifying performances, fluctuating from -2 °C to 3 °C and from -2% to 5%, respectively. Nevertheless, in most situation the cooling and humidifying effects were positive, also beneficial to mitigate microclimates. In comparison, the *Sedum lineare* showed erratic and the worst cooling and humidifying effects, in most of which time the thermal environment over the rooftop was worsened.

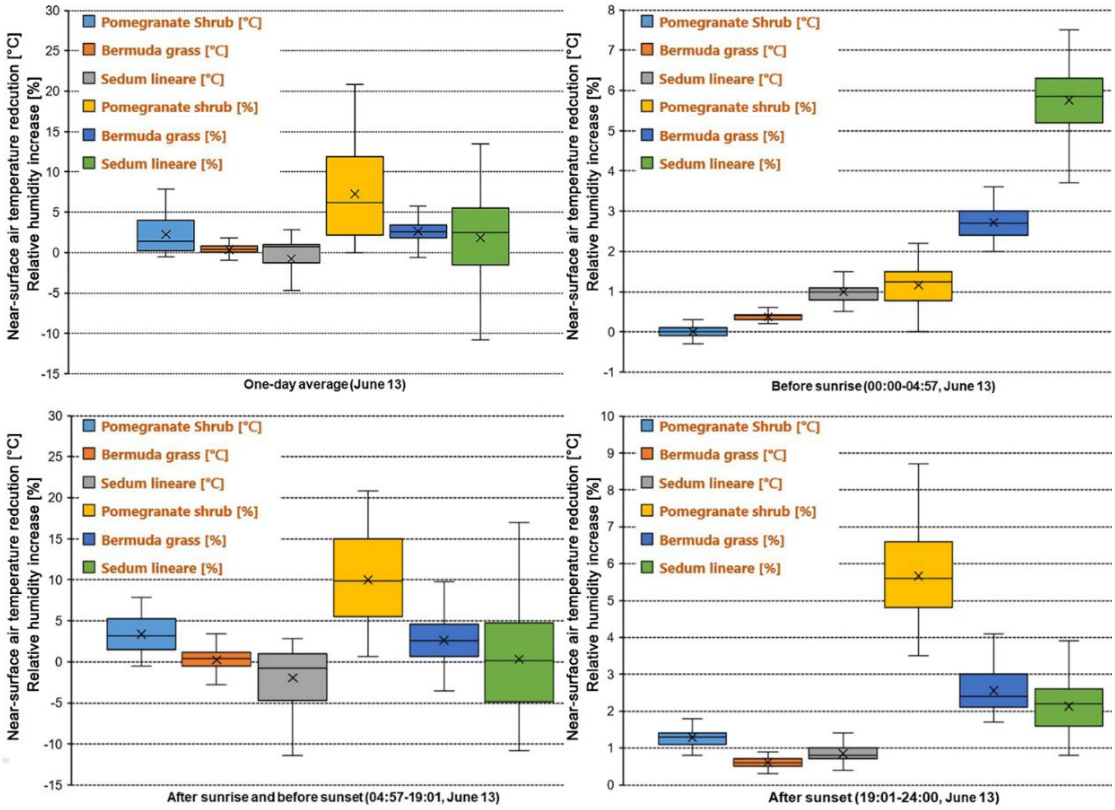



**Figure 6-7** Average reduction of air temperature and average increase of relative humidity in three green roofs (The centre thick black horizontal line in each box of the boxplots is the median value, and the cross is the mean value. The coloured box indicates the 1st quartile (Q1) and 3rd quartile (Q3))

The near-surface performance of green roofs comparable to bare roof was further investigated according to time period. There were three stages in the typical sunny day, including before sunrise (00:00-04:57), from sunrise to sunset (04:57-19:01), after sunset (19:01-24:00), as shown in figure 6-7. Before sunrise, the *Pomegranate* made negligible differences to air temperature (fluctuating around 0 with small deviation) and relative humidity (1% increase in average value). Comparatively, *Bermuda grass* and *Sedum lineare* were helpful to reduce air temperature and increase relative humidity, at which time *Sedum lineare* showed the most significant cooling (1 °C) and humidifying (6%) effects. During the period fom sunrise to sunset, the *Pomegranate* exhibited its excellent cooling effects, with average temperature reduction by up to 3 °C, and its best humidifying effects with average temperature increase by up to 10%. *Bermuda grass* generated slight cooling and humidifying effects, with the average values of 0.5 °C and 2%, respectively. However, the *Sedum lineare* negatively elevated the near-surface temperature by about 2.5 °C and it in 50% situation dried the near-surface environment. After sunset, three kinds of green roof had uniformly cooling and humidifying effects compared with bare roof, while the thermal performances of *Pomegranate* maintained the best.

6.4.2.2 Near-surface thermal performance of *Pomegranate* roof

This section compares the near-surface thermal performance of *Pomegranate* roof and bare roof on a typical sunny day, as shown in table 6-2 and figure 6-8. It is observed from table 6-2 that the *Pomegranate* can lead to average and maximum temperature reduction by up to 3 °C and 6.5 °C, and the increase in average and maximum relative humidity by up to 7.2% and 0.9%, respectively. In addition, the amplitude reduction of air temperature reached up to 33.1% and that of relative humidity increased by 10.9%. On the one hand, the cooling and humidifying effects are resulted from the shading, transpiration, photosynthetic and reflective effects of the vegetation layer. On the other hand, the insulation, absorption, and evapotranspiration effects of the growth medium layer of the shrub roof result in the reduction of temperature magnitude and the increase in relative humidity magnitude [15, 16].

From figure 6-8, it is observed that *Pomegranate* roof significantly reduced the air temperature from sunrise to peak time (5:00-15:00), while the cooling effects of green roof disappeared when the temperature over bare roof exceeded 35 °C (background ambient temperature 33 °C, figure 6-5) after 15:00. This is consistent with the existing conclusion that the transpiration rate reached the highest level when background temperature ranges between 20 and 30 °C, while a higher temperature results in the close of stomata [17, 18]. Moreover, the cooling effects of green roof were even weakened between 16:00 and 17:30, which is consistent with the lagging root response that roots respond to soil drying by producing the hydraulic or non-hydraulic signal in peak period, and these signals are delivered to shoot through transpiration stream and then limit the stomatal conductance for regulating transpiration and photosynthesis of vegetation [19]. During the periods before sunrise at 04:57 and after sunset at 19:01, both near-surface air temperature and relative humidity were stable, indicating that solar radiation is an important factor affecting the transpiration and photosynthesis [2, 20].

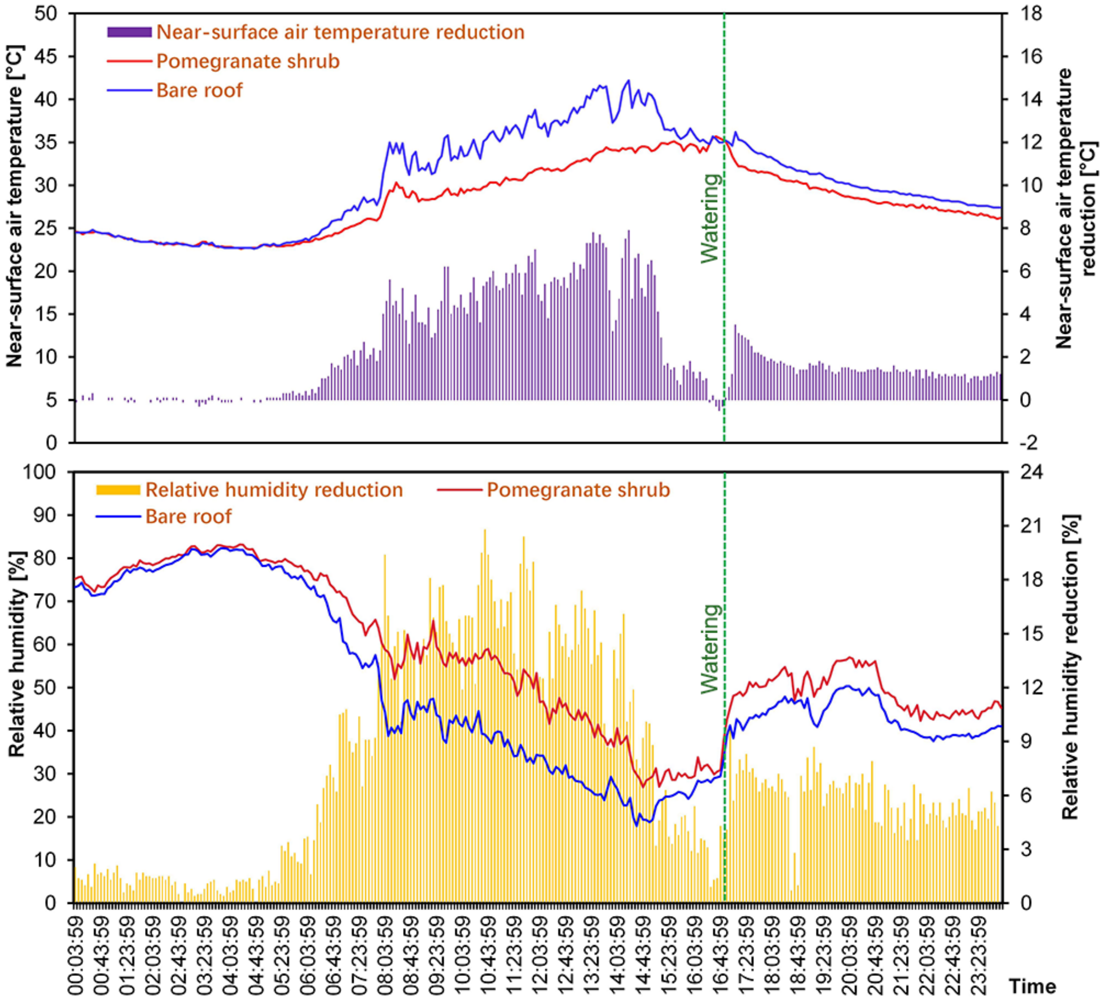



**Figure 6-8** Comparison of the near-surface air temperature and relative humidity over Pomegranate roof and bare roof (On June 13, 2018)

**Table 6-2** Thermal amplitude variation of Pomegranate roof and bare roof (On June 13, 2018)

| | Roof | Average | Gap | Range and range length | | Maximum | Amplitude |
|---|---|---|---|---|---|---|---|
| Temperature (°C) | Pomegranate | 28.3 | -3 | 22.6~35.7 | 13.1 | 6.5°C↓ | 33.1%↓ |
| | Bare roof | 31.3 | | 22.6~42.2 | 19.6 | | |
| Relative humidity (%) | Pomegranate | 56.8 | 7.2 | 11.8~83.2 | 71.4 | 0.9%↑ | 10.9%↑ |
| | Bare roof | 49.6 | | 26.9~82.3 | 64.4 | | |

6.4.2.3 Near-surface thermal performance of *Bermuda grass* roof

This section compares the near-surface thermal performance of *Bermuda grass* roof and bare roof on a typical sunny day, as shown in table 6-3 and figure 6-9. It is observed from table 6-3 that *Bermuda grass* can lead to the average near-surface air temperature reduction of 1.1 °C, and the maximum temperature increase of 0.9 °C, and the increase in average and maximum relative humidity up to 2.6% and 2.8%, respectively. In addition, the increase of air temperature amplitude reached up to 6.1% and that of relative humidity increased by 0.6%. This means *Bermuda grass* can generally generate cooling effects, while it aggravates rather alleviates the peak temperature. In detail, as shown in figure 6-9, the *Bermuda grass* reduced the maximum near-surface air temperature by up to 3.4°C at 08:00 but elevated the near-surface air temperature by up to 3.7 °C at 15:00.

**Table 6-3** Thermal amplitude variation of *Bermuda grass* roof and bare roof (On June 13, 2018).

| | Roof | Average | Gap | Range and range length | | Maximum | Amplitude |
|---|---|---|---|---|---|---|---|
| Temperature (°C) | *Bermuda grass* | 30.2 | -1.1 | 22.3-43.1 | 20.8 | 0.9°C↑ | 6.1%↑ |
| | Bare roof | 31.3 | | 22.6-42.2 | 19.6 | | |
| Relative humidity (%) | *Bermuda grass* | 52.2 | 2.6 | 20.3-85.1 | 64.8 | 2.8%↑ | 0.6%↑ |
| | Bare roof | 49.6 | | 26.9-82.3 | 64.4 | | |

From figure 6-9, it is observed that *Bermuda grass* had better cooling and humidifying effects at 8:00. Afterwards, from 8:00 to 19:00 when air temperature over bare roof beyond 35 °C, there was no obvious difference between the air temperature over bare roof and *Bermuda grass* roof. Until 15:00, this section could observe that the near-surface temperature over *Bermuda grass* roof was much hotter than that over the bare roof at 15:00. This might be because the variation of transpiration rate, and the stomata closes and stops working [17, 18]. In addition, it is found that watering is also an important reason to change the thermal performance of the green roof at 17:00.

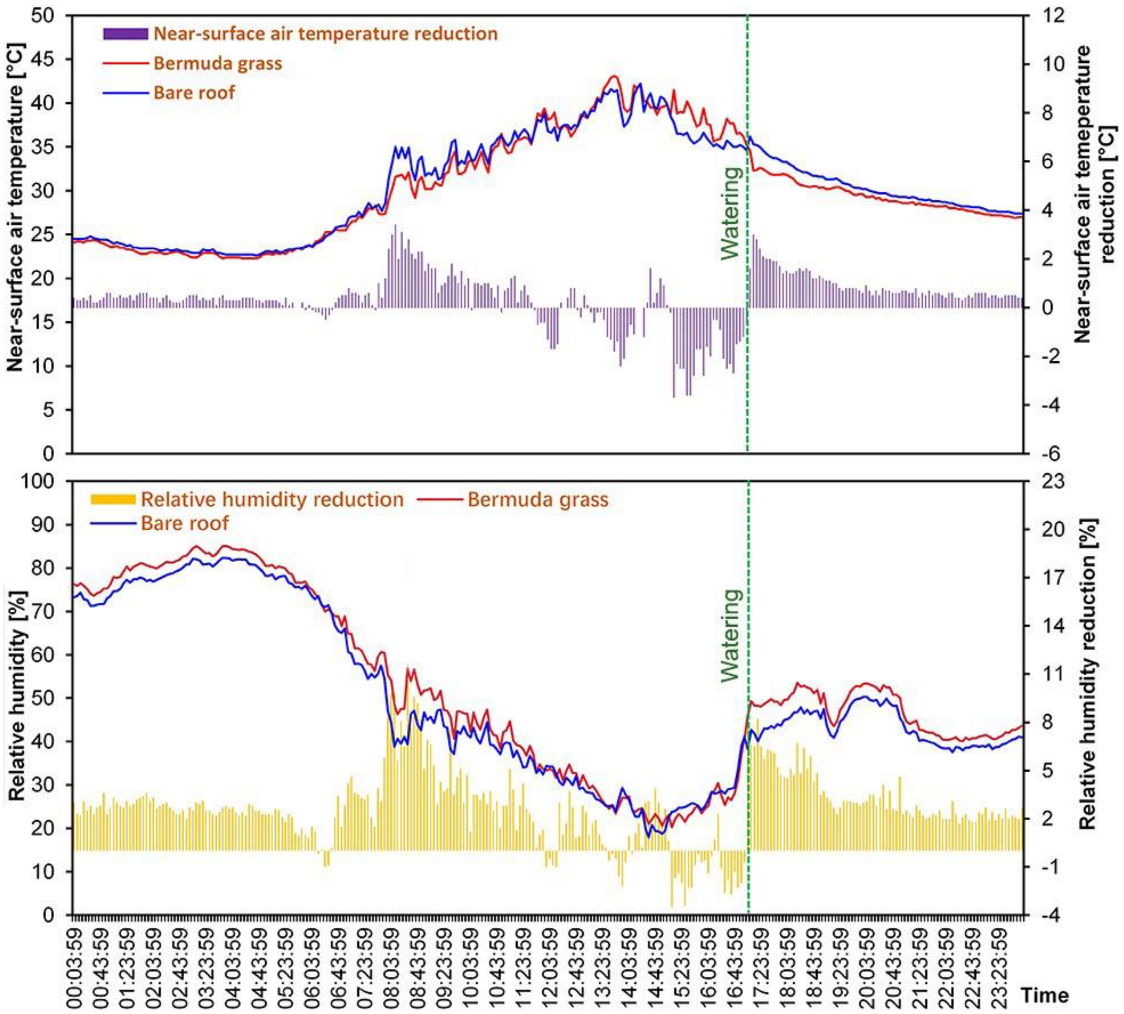



**Figure 6-9** Comparison of the near-surface air temperature and relative humidity over *Bermuda grass* roof and bare roof (On June 13, 2018)

6.4.2.4 Near-surface thermal performance of *Sedum lineare* roof

This section compares the near-surface thermal performance of *Sedum lineare* roof and bare roof on a typical sunny day, as shown in table 6-4 and figure 6-10. It is observed from table 6-4 that *Sedum lineare* could generate an average cooling effect of 0.8 °C, while the maximum near-surface temperature was elevated by 8.2 °C. It also led to an increase in average and maximum relative humidity by 1.8% and 6.8%, respectively. The results were in agreement with previous study that *Sedum lineare* could elevate the air temperature at 15 cm above the ground [8]. In addition, the increase of air temperature amplitude reached up to 47.5%, so that *Sedum lineare* should not be suggested for roof cooling.

**Table 6-4** Thermal amplitude variation of *Sedum lineare* roof and bare roof

(On June 13, 2018)

| | Roof | Average | Gap | Range and range length | | Maximum | Amplitude |
|---|---|---|---|---|---|---|---|
| Temperature (°C) | *Sedum lineare* | 30.5 | -0.8 | 21.5-50.4 | 28.9 | 8.2°C↑ | 47.5%↑ |
| | Bare roof | 31.3 | | 22.6-42.2 | 19.6 | | |
| Relative humidity (%) | *Sedum lineare* | 51.4 | 1.8 | 11.8-89.1 | 77.3 | 6.8%↑ | 20.0%↑ |
| | Bare roof | 49.6 | | 17.9-82.3 | 64.4 | | |

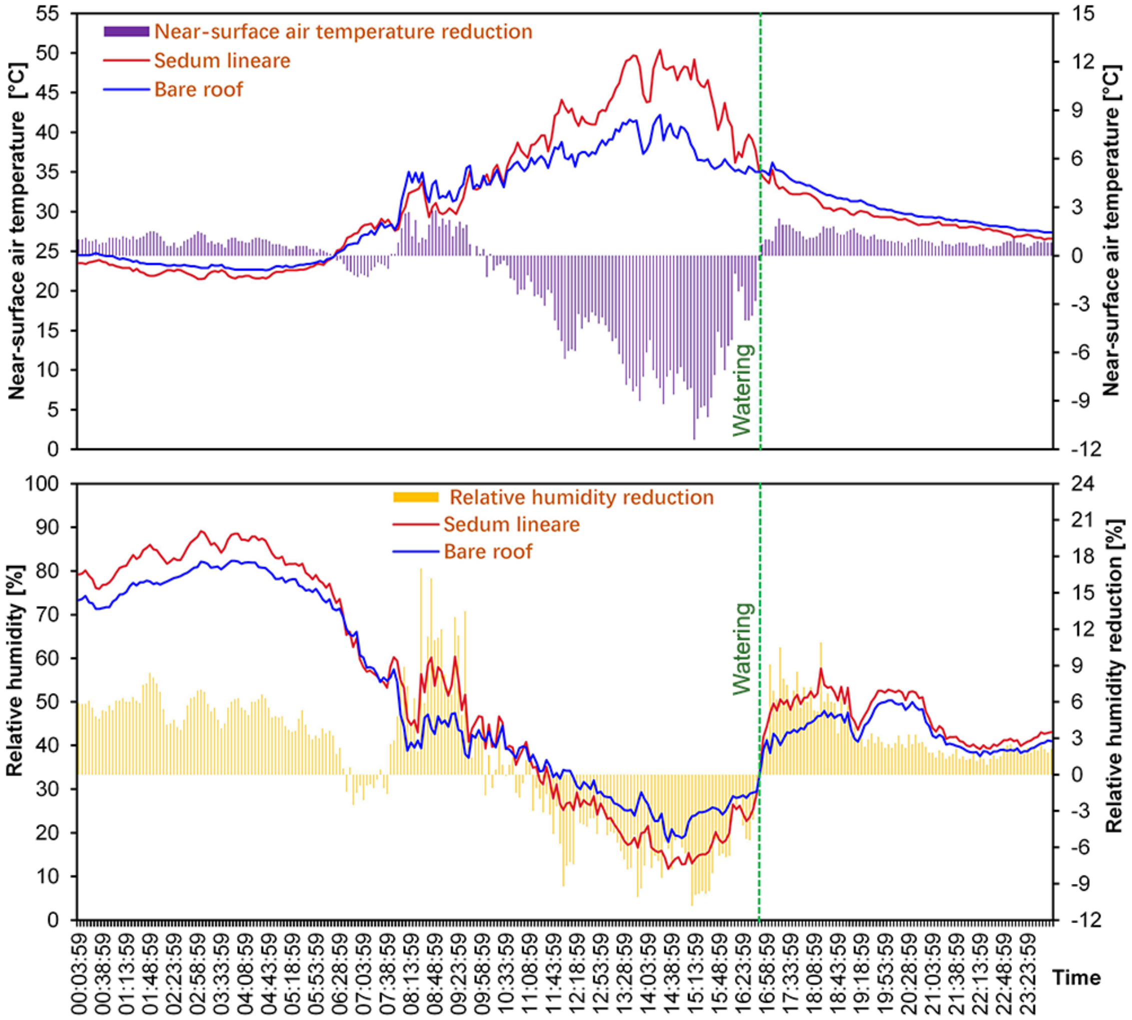



**Figure 6-10** Comparison of the near-surface air temperature and relative humidity over *Sedum lineare* roof and bare roof (On June 13, 2018)

As shown in figure 6-10, during the period from sunrise to sunset, the *Sedum lineare* exhibited higher near-surface temperature and lower relative humidity, compared with bare roof. This further demonstrates that *Sedum lineare* is not useful to alleviate hot and dry microclimate in summer. Moreover, the water vapour in the air could be much less due to the decrease of relative humidity. In detail, when the air temperature of *Sedum lineare* roof was more than 35 °C at 10:30-16:30, the cooling effect disappeared. What's worse, the maximum increment of air temperature reached up to 11.4 °C at 15:00 in peak time. This verifies that during soil moisture deficit, crassulacean acid metabolism plants of sedum keep their stomata closed during the day, so that the transpiration rates are significantly lower than the night scenario when transpiration rates are normally high and open [21]. This phenomenon helps sedum save water. After being watered, both the air temperature and relative humidity showed the opposite trend and turned to be much cooler than before. Nevertheless, *Sedum lineare* resulted in the unstable rooftop thermal environment, which is negative to improve rooftop thermal environment comparing with the other two green roofs.

### 6.4.3 Impact of watering on thermal performance of green roofs

From figure 6-8, figure 6-9 and figure 6-10, it is observed water is an important factor affecting the near-surface thermal performance of green roofs. It is understandable that plants need to constantly absorb water through roots for transpiration, and to avoid dehydration making water loss [22]. To understand the effect of watering on the thermal performance of green roofs, this section investigated thermal performance on a sunny day without watering (On June 18, 2018) and compared the thermal performance variation before and after watering in the following part.

#### 6.4.3.1 Thermal performance of four roofs without watering

To investigate the water impact on thermal performance of green roofs, this section compared the near-surface air temperature and relative humidity of green roofs and the bare roof on June 18, 2018, as shown in figure 6-11. Before sunrise (0:00-4:57), the near-surface temperature and humidity over all four roofs were quite stable, akin to the situation with watering. After sunrise (4:57-19:03), the thermal environment changed obviously that the temperature increased rapidly and the humidity decreased sharply, indicating that the solar intensity was the dominant factor to change the near-surface thermal environment [23, 24]. After 11:00, the air temperature over *Sedum lineare* was above 40 °C, showing that the *Sedum lineare* could protect themselves and adapt to surrounding environment, reducing transpiration and water evaporation, according to the extreme climates [21]. *Bermuda grass* had good thermal adaptability from 15:00 to 17:00 when the temperature was higher than the bare roof. However, without watering, the temperature was slightly higher than the *Sedum lineare* around 17:00. At the same time, Pomegranate had exhibited low temperature and high humidity. However, without watering, at the end of the experiment on June 19, this section observed withered and yellow leaves of Pomegranate trees and grass died to a certain extent, but the *Sedum lineare* was more vigorous, in an agreement with that its growth requires low amount of moisture content in soil [25]. After sunset (19:03-24:00), there was no obvious difference with the watering situation in figure 6-11. Therefore, without watering did not generate significant impact on the cooling performance of green roofs but generated accumulative influences after one day.

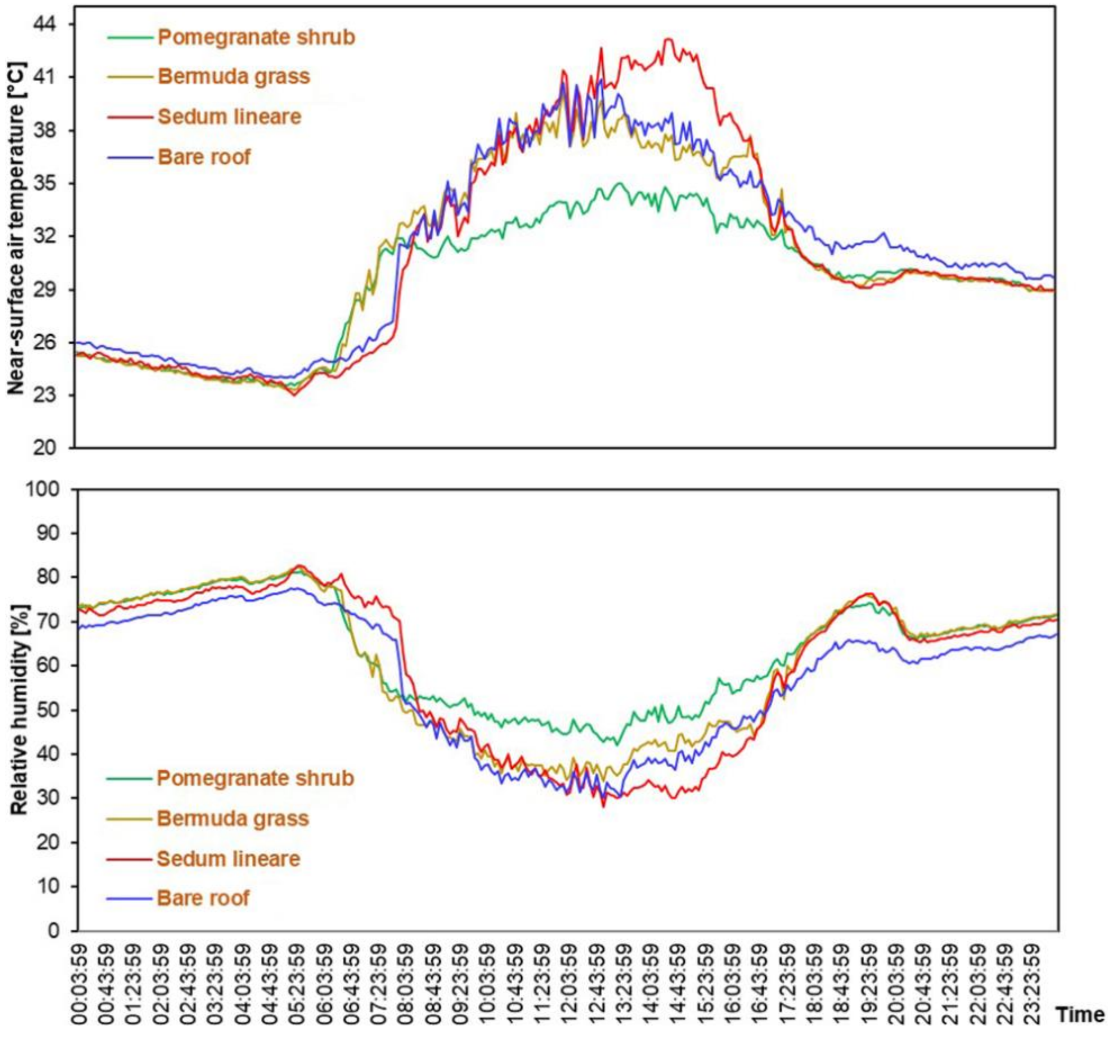



**Figure 6-11** Thermal variations of four roofs without watering in 24 hours

6.4.3.2 Thermal performance of green roofs before and after watering

Because of transpiration and photosynthesis, plants lose an average of 400 water molecules when they get one carbon dioxide molecule, meaning 95% of the water absorbed by roots is lost [26]. Daytime watering on June 12, 13, 14, 15, 16 and 17 showed that the thermal environment changed significantly before and after watering, resulting in instantaneous cooling and humidifying effects as shown in figure 6-12. This is because soil moisture content directly affects the transpiration rate of plants, and a higher soil moisture content results in better transpiration effects [27]. The Pomegranate green roof had the best cooling and humidifying effects, as the leaf photosynthesis rates and stomatal conductance have a greater potential for irrigation scheduling of Pomegranate than stem at noon [14]. The results of night watering on June 14 and 16 show that night watering had less impacts on the change of air temperature and relative humidity than daily watering, as there is no solar radiation in night and night transpiration rate is usually 5-15% of that in the day time [23, 24]. Based on the analysis of air temperature and relative humidity during the daytime on June 14 at 11:52 and June 17 at 12:02, it is found that the effect of watering on the cooling effect was not remarkable when bare roof's temperature was above 40 °C, while it became useful when bare roof was under 40 °C. That is to say, in summer, the leaf temperature is higher (about 36 °C) and leaves lose a lot of water, resulting in water deficit and stomatal closure, and then the transpiration rate decreases. However, the cooling effect of watering was not sustainable for more than 10 minutes.


**Figure 6-12** Thermal variations of four roofs by watering before and after one hour

### 6.4.4 Impact of clouds on the thermal performance of green roofs

In addition, this section analyzed the impact of clouds on the near-surface thermal performance of green roofs. The air temperature reduction and relative humidity increase on the morning of June 16, 2018 were compared with that on June 13, 2018, as shown in table 6-5 and figure 6-13. Overall, it is observed from table 6-5 that the cooling performances of *Bermuda grass* and *Sedum lineare* on the cloudy day were much better than that on sunny day. The cooling performance of *Sedum lineare* was enhanced by 2.7 °C in the average air temperature reduction from -1.8 °C on the sunny day to the 0.9 °C on the cloudy day. Meanwhile, the *Bermuda grass* saw the 1.1 °C increase in the cooling performance from 0.5 °C to 1.6 °C. Comparatively, cooling performance of *Pomegranate* was weakened on the cloudy day. For the relative humidity, the *Bermuda grass* and *Sedum lineare* saw the enhanced humidifying effects, about 3% and 6% in value, respectively. A slight reduction in the humidifying effect was found in Pomegranate, from the 14.3% on the sunny day to the 12.5% on the cloudy day in average value.

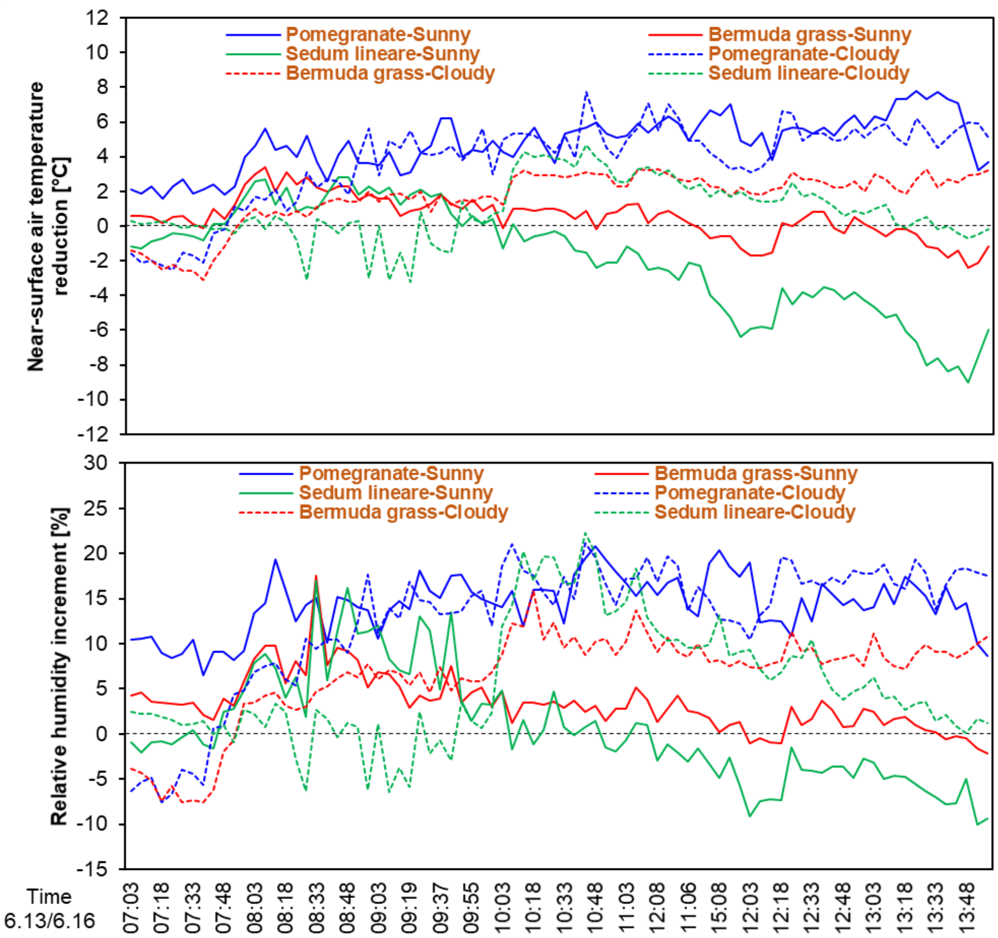



**Figure 6-13** The variation of near-surface air temperature and relative humidity over green roofs under different weather conditions

Figure 6-13 further presents the variation of near-surface air temperature and relative humidity over different green roofs along time. It was found that *Pomegranate* 's cooling and humidifying effects were less affected by the cloudiness between 7:00 and 14:00 in the same period on June 13 and June 16, meaning the *Pomegranate* can provide a stable near-surface thermal performance. *Bermuda grass* and *Sedum lineare* had better cooling and humidifying effects when the weather was cloudy rather than sunny. In particular, different from sunny condition, the *Sedum lineare* exhibited absolute cooling and humidifying effects from 10:00 to 12:00. This further indicates sunshine is an important factor controlling the thermal performance of *Bermuda grass* and *Sedum lineare*. *Sedum lineare* can adaptively respond to the sunny time when solar radiation enhances moisture (in air and soil) evaporation and makes surrounding environment drier and hotter.

**Table 6-5** A comparison of cooling and humidifying performance of green roofs on sunny and cloudy days

| Roof category | Temperature reduction range (°C) | Average temperature reduction (°C) | Relative humidity increase range (%) | Average Relative humidity increase (%) |
|---|---|---|---|---|
| Pomegranate-Sunny | 1.6-7.8 | 4.8 | 6.5-20.8 | 14.3 |
| Pomegranate-Cloudy | -2.5-7.7 | 3.7 | -7.6-21.2 | 12.5 |
| Bermuda grass-Sunny | -2.4-3.4 | 0.5 | -2.2-9.8 | 3.4 |
| Bermuda grass-Cloudy | -3.1-3.3 | 1.6 | -7.6-15.9 | 6.4 |
| Sedum lineare-Sunny | -9-2.8 | -1.8 | -10.1-17 | 0.5 |
| Sedum lineare- Cloudy | -3.2-4.7 | 0.9 | -6.5-22.3 | 6.5 |

### 6.4.5 Impact of the environment on air temperature reduction of the green roof with and without plant

During the test period, there are six linear regression models for green roofs, while a differentiated correlation between air temperature (AT) and AT reduction; relative humidity(RH) and RH reduction followed by *pomegranate-tree* green roof (PGR, R2=0.7486 for AT, R2=0.6883 for RH), *Bermuda-grass* green roof (BGR,R2=0.0447 for AT, R2=0.0367 for RH) and *Sedum lineare* green roof (SGR, R2=0.2209 for AT, R2=0.2521 for RH) as shown in figure 6-14. To PGR, it has a strong correlation but both BGF and SGF are randomly distributed. Especially, PGF displays the maximum cooling effect on air temperature which is about 10°C is appeared in 43°C and 24% of bare roof of peak value. In general, the air temperature increment is positive to reduce air temperature for *PGR* and is slight helpful to reduce air temperature for *BGR*, but is negative to *SGR*. While relative humidity increment is negative to reduce air temperature for PGR as well as *BGR* is not significant. However, it is a little helpful to reduce air temperature for *SGR*. In addition, the higher air temperature and lower relative humidity of bare roof, the cooling and humidifying curve line of *PGR* is much sharper which means it has better cooling effect. While *BGR* is weakly similar trend to *PGR*, but *SGR* is opposite to the trend of *PGR*.

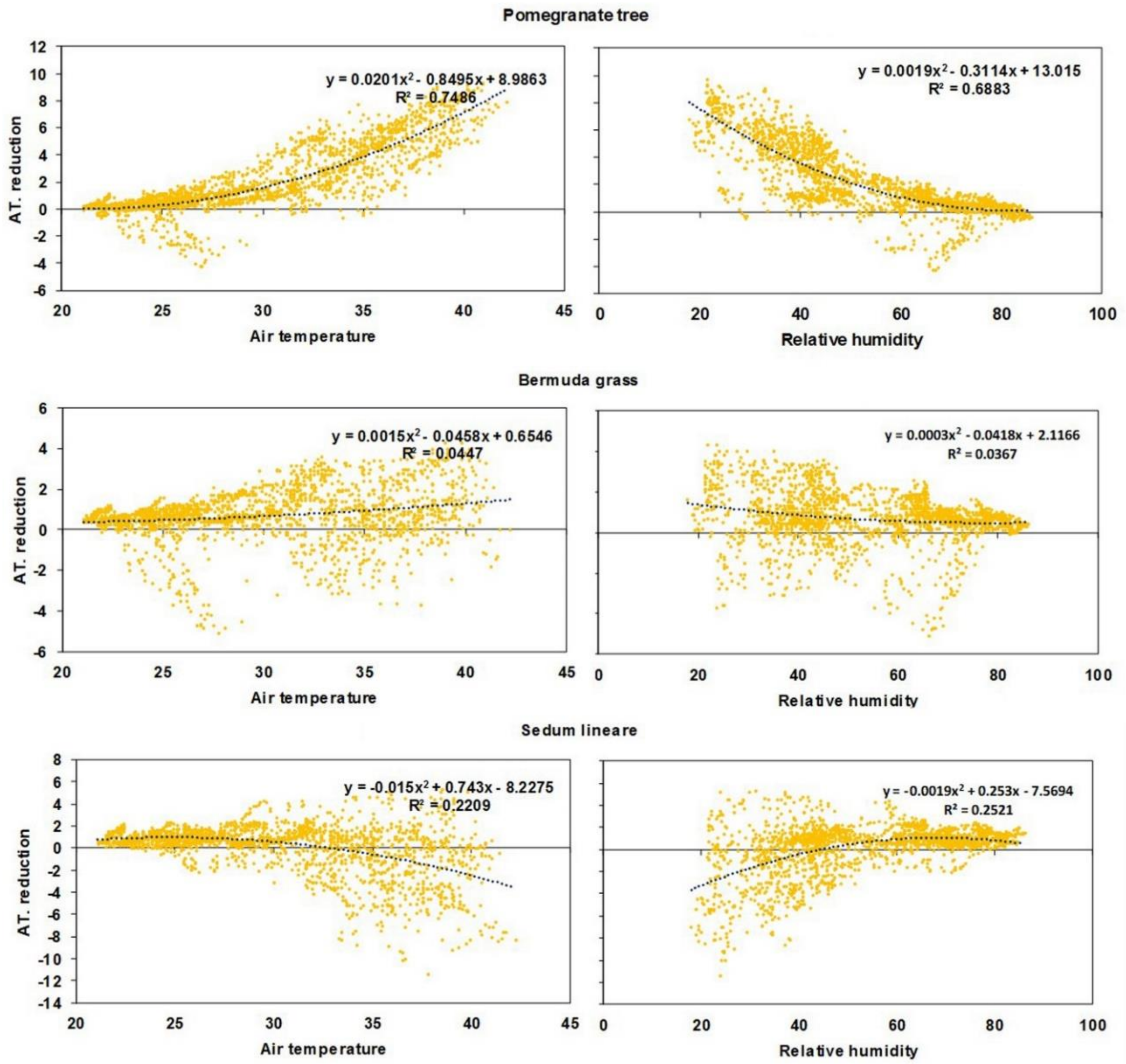



**Figure 6-14** The relationship between air temperature reduction of green roof and thermal environment of bare roof (Note: Y axis is AT and RH of bare roof)

### 6.4.6 Impact of the environment on relative humidity increment of the green roof with and without plant

During the test period, there are six linear regression models for green roofs, while a differentiated correlation between air temperature (AT) and relative humidity(RH) increment; RH and RH increment followed by PGR (R2=0.5247 for AT, R2=0.4826 for RH), BGR (R2=0.0016 for AT, R2=0.0006 for RH) and SGR (R2=0.2181 for AT, R2=0.2475 for RH) as shown in figure 6-15. To pomegranate-tree roof, the higher air temperature of bare roof, the higher RH increment. While the higher RH, the lower RH increment. The maximum value of RH increment is 25% when bare roof is at the 38°C and 35%. The minimum range of RH increment is when bare roof is between the 20°C and 25°C. Bermuda-grass roof and *Sedum lineare* roof have low correlation, while *Sedum lineare* roof which is the higher air temperature or RH and the lower RH Increment demonstrates an opposite trend comparing with other two green roofs.

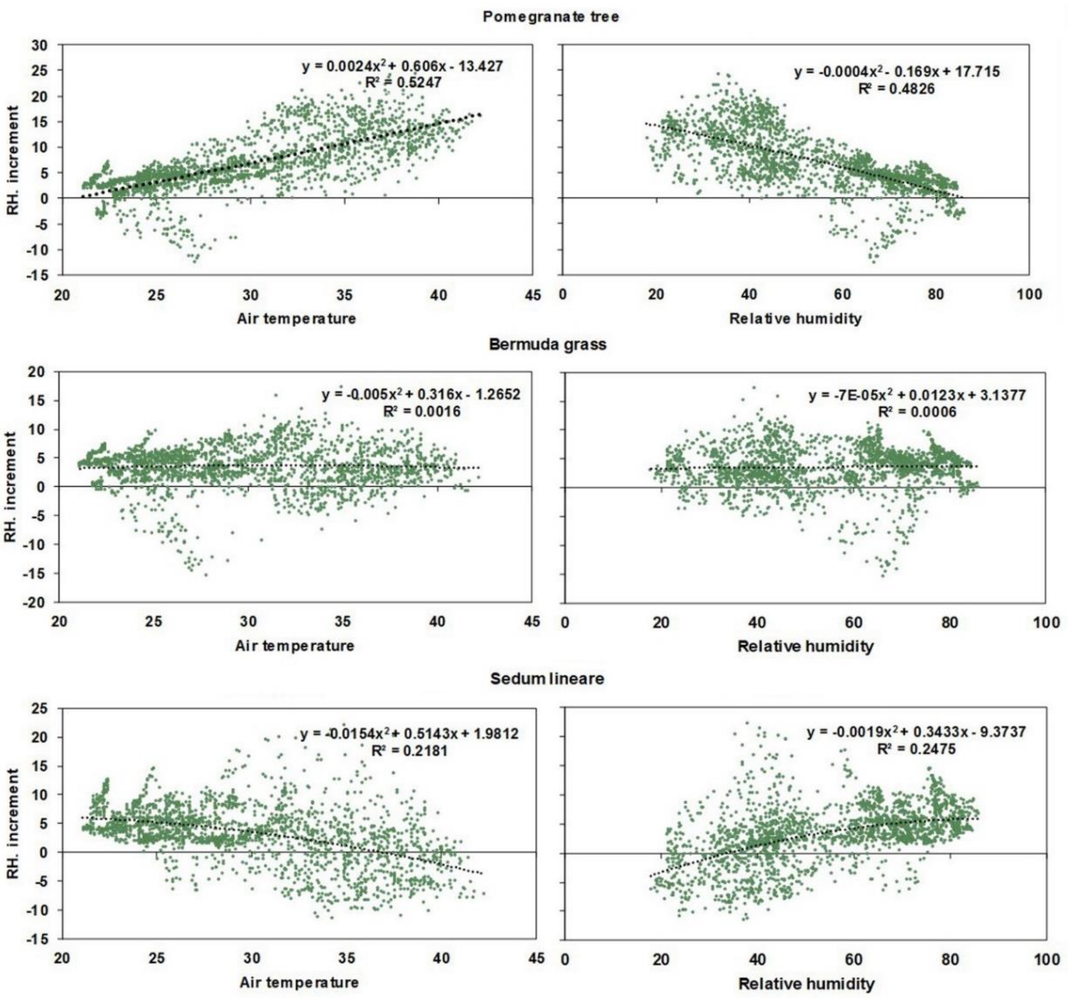



**Figure 6-15** The relationship between relative humidity reduction of green roof and thermal environment of bare roof (Note: Y axis is AT and RH of bare roof)

### 6.4.7 Comparison of four roofs on the relationship between air temperature with relative humidity

During the test period, there are four linear regression models for four types of roofs, while a strong correlation between the temperature and humidity of green roof after sunrise and before sunset, followed by SGR(R2=0.8842), BR (R2=0.8778), BGR (R2=0.8572) and PGR (R2=0.7189) as shown in figure 6-16. An increase of 5°C of near-surface air temperature corresponds to a decline of 17.65%, 15.27%, 13.69%, 15.09% for PGR, BGR, SGR, BR, respectively. Undoubtedly, PGR shows its largest capability to increase relative humidity with every 5°C increase. Contrast with BR, the SGR is not significant to humidify the air circumstance, instead, it still has slight capabilities to increase the humidity load. Therefore, it is advisable for urban planners or policy-makers to utilize PGR or other shrubs in the arid and hot areas if there is a good irrigation condition, while plant SGR in hot and wet areas if it is difficult to sprinkler water.

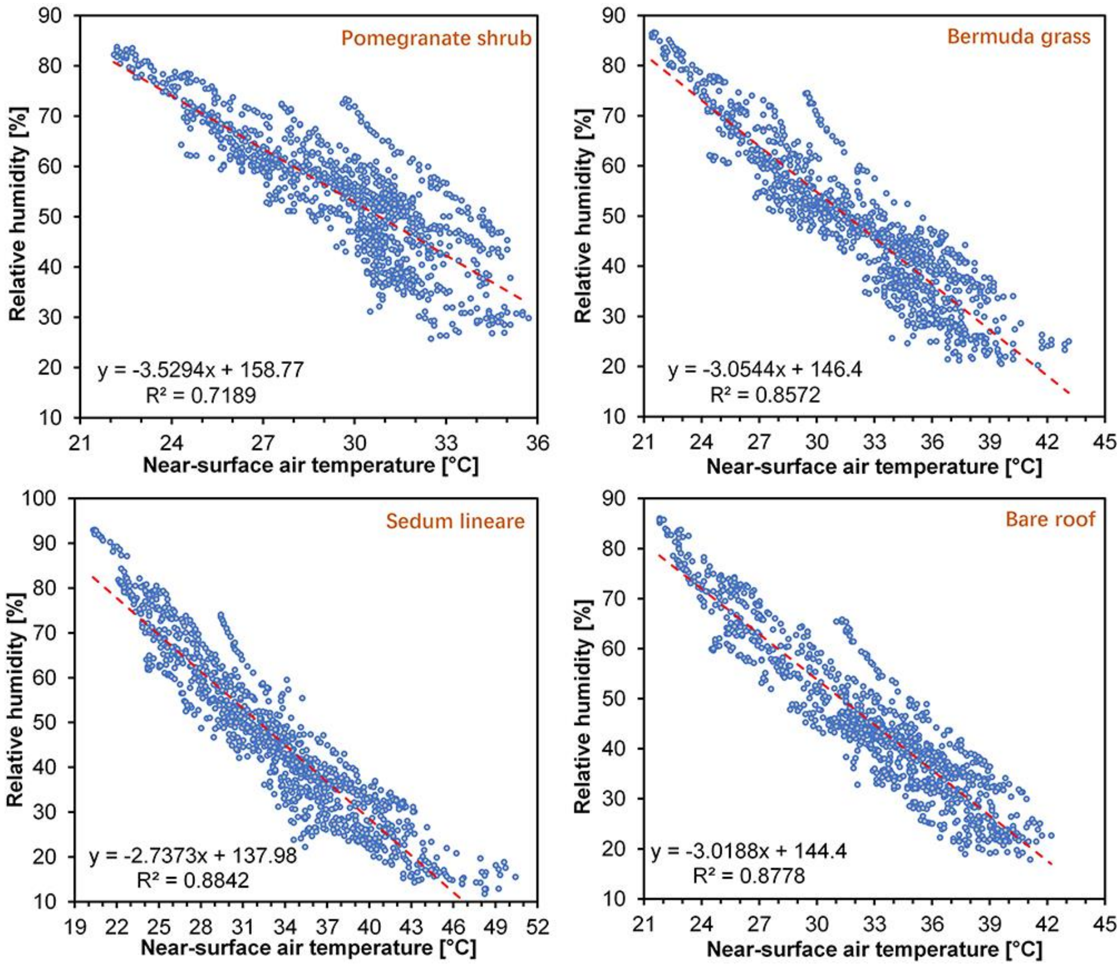



**Figure 6-16** The relationship between RH and AT in Diurnal time (after sunrise and before sunset)

### 6.5 Summary

This chapter mainly presents a dedicated experimental study into the summertime near-surface thermal performance of three typical vegetation for green roofing including *Pomegranate*, *Bermuda grass* and *Sedum lineare* in Hangzhou, China, a city with subtropical climate. Based on the analysis in this study, the following conclusions can be drawn. In general, three kinds of green roofs had positive cooling and humidifying effects. In peak period, *Pomegranate* was positive to improve ambient thermal environment, while both *Bermuda grass* and *Sedum lineare* were not useful even worsened heat loads. *Pomegranate* had the best cooling and humidifying effects by up to 3 °C and 7.2% on a typical sunny day, followed by *Bermuda grass* and *Sedum lineare*. The *Pomegranate* reduced the temperature amplitude by 33.2% and increased the humidity amplitude by 10.9%. When air temperature of bare roof was more than 35 °C, *Bermuda grass* presented insignificant cooling performance. *Sedum lineare* was the worst in providing cooling and humidifying effects, and even it severely intensified the thermal pressure in the peak period. *Sedum lineare* increased the temperature amplitude 47.5%, although it increased the humidity amplitude by 20.0%. In specific, in a sunny day, thermal performance of green roofs could be investigated through three stages: Before sunrise, *Sedum lineare* had the best cooling and humidifying effects, followed by *Bermuda grass* and *Pomegranate*. From sunrise to sunset, *Pomegranate* had the best cooling and humidifying effects, followed by *Bermuda grass* and *Sedum lineare*. After sunrise, *Pomegranate* had the best cooling and humidifying effect, followed by *Sedum lineare* and *Bermuda grass*. Watering played a vital role in changing the diurnal near-surface thermal performance of green roofs, while the influence could not sustain for more than 10 minutes. However, daytime watering was much better than nighttime watering to improve the thermal environment significantly. Weather condition is also a critical factor affecting the near-surface thermal performance of green roofs. No obvious variation could be observed for *Pomegranate*, while the cooling performance of *Bermuda grass* and *Sedum lineare* could be significantly enhanced under cloudy conditions. Overall, this study can help understand the thermal environment at the urban green canopy layer, and the cooling and humidifying mechanism can inform urban designers and landscape architects to reasonably screen rooftop plants in subtropical climate context.

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*Chapter 7*

# *Conclusion and Outlook*

## Chapter 7: Conclusion and Outlook

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### 7.1 Conclusion

Green roof is an effective measure to save limited land and solve UHI problem. However, the thermal performance of green roof is a complex engineering which would be influenced by the plant shape, vegetation type, green scale, green coverage ratio, building morphologies, layout style, geographical position, weather condition and so on. Meanwhile, green roof implementation (GRI) provides multifaceted of environment benefit such as extending roof longevity, air purification, water runoff control, water purification, urban infrastructure improvement, but it is limited by several barriers, such as technological support and policy guide. Therefore, green roof implementation should consider both science fundamental feasibly and market principle cost-benefit.

This dissertation would be conducted in Hangzhou City of subtropical zoon, analysis the green roof market by divers, motivations, barriers is to complement and promote green roof research, furthermore, analysis the green roof market by different area, age group and gender in China. Then, through two studies of numerical simulation, outdoor thermal environment of green roof is improved by building morphologies and green-roof configurations in different scenarios. Lastly, near-surface thermal performance of green roof and virginally reveal its characteristics in different weather and period. The main works and results can be summarized as follows:

***Chapter 1**, **Research background of the study***, firstly presents the current UHI problem in worldwide situations, then puts forward to several countermeasures, furthermore, gradually leads to the topic of this dissertation regarding on green roof strategy as one of the important countermeasures, then, provides the relatively previous researches in green roof implementation of thermal mechanism, buildings morphology, green-roofs layout, promotion explore to find the gaps in all literatures. Lastly, the purpose of this dissertation to complement the gaps is explained.

***Chapter 2**, **A review of drivers, motivations, barriers on green roof implementation***, aims at conducting a systematic review for identifying the influencing factors- drivers, motivations, and barriers to GRI. Specifically, 217 published works, in which 164 entirely for GRI and 53 partially for GRI, from 2000 to 2019 were reviewed. Based on the review, it was found that the there are three types of drivers to GRI, namely policy pressure, market pressure (e.g., customers demand, award or certification, cost-benefit demand), and innovation and technology advancement. Extensive factors such as energy efficiency, urban heat island mitigation, extending roof longevity, air purification, water runoff control, water purification, urban infrastructure improvement, noise reduction, biodiversity improvement, recreation, and aesthetics, property value increase, and employment improvement may motivate people to implement green roof techniques. The barriers that may hinder GRI include lack of government policy, unsound technological development, high initial cost and long payback period, and individual unwillingness. Suggestions on how to overcome GRI barriers were proposed, namely: increasing governmental policies and support, improving technical innovation, encouraging long-term view, and increasing education and dissemination. Moreover, this section presents some recommendations for sustainable GRI cases. Overall, this chapter is significant in the development and implementation of green roof in both academic and practical perspectives.

***Chapter 3, Methodology selection and feasibility analysis in China***, firstly, specifically selected in Hangzhou city of Southern China as the research site, which is belongs to hot summer and cold winter area. Later, approach for this dissertation is screened and introduced, in detail, comparing with other software or test principles. Lastly, it analyzes the index frequency of green roof by Baidu Index in China, and the main findings are below：(1) in the three levels of spatial scale of large district-province-city, the index volume corresponding to the three levels are East China, Zhejiang province and Hangzhou city respectively which is the highest in hot rank. (2) The age group who are more curious about green roof is between 20 and 29 years old, among which males are slightly higher than females by 12%. (3) through the analysis of the hot rank of related words, users who are interested in green roof concentrates on the construction mode and related technologies, such as stainless-steel tank and reclaimed water.

***Chapter 4, Impact of morphological characteristics of green roofs on pedestrian cooling in subtropical area.*** For better cooling performances, this section is essential to reasonably configure green roofs, especially in real and complex neighborhoods. Therefore, the aim of this section is to investigate the impact of morphological characteristics of green roofs on pedestrian cooling in real and complex neighborhoods. In specific, based on an ENVI-met model, this study studied the effect of greening layout, coverage ratio, vegetation height, and building height on pedestrian air temperature reduction in the tropical city of Hangzhou, China. Results indicate green roofs could generate moderate effects on pedestrian air temperature reduction (around 0.10–0.30 °C), while achieving a cooling performance of 0.82 °C. Green roofs in upwind zones were able to generate the most favorable cooling performance, while green roofs in downwind zones made slight differences to pedestrian thermal environments. Green roofs with a low coverage ratio were not useful for lowering pedestrian temperature, and a greening coverage ratio of 25–75% in upwind zones was effective cooling scope in real neighborhoods. Locations that were horizontally close to green roofs enjoyed better cooling performances. Increasing vegetation height could strengthen cooling effects of green roofs, while an increase in building height weakened the cooling performance. Nevertheless, higher building height could enhance pedestrian cooling performances because of building shading effects. In addition, because of wind effects and building shading, building height limits for the cooling performance of green roofs could be higher than 60 m. And the layout of orientation array of green roof along the wind direction is more comfortable to expand the cool resource at the same ratio of green roof.

***Chapter 5**, **Impact of green roofs' pedestrian cooling and humidity by changing bilateral buildings of street canyon in subtropical area,*** is to explore the optimal and effective GRI strategy to mitigate the UHI effect. This chapter focused on the thermal performance of morphological characteristics of buildings with and without green roofs at pedestrian level in street canyon. There are four experimental tests in the Wangma community, Changqing Street, Shangcheng District Hangzhou city, China. Then the simulation software of ENVI-met is employed to simulate and verify the appropriate parameter which wind speed is 1.5 m/s. Afterwards, this section analyzed the microclimate in street canyon by aspect ratio of real environment at the pedestrian level (1.4m). Lastly, by changing building heights, depths, and widths on the both sides of street canyon, the simulation results find (1) the building depth covered green roof has a limited value at 24 meters; (2) The lower the height, the better the cooling effect, and the height is more than 42 meters which will be the limit value; (3) The cooling effect of green roof which is limited in 108 meters of building width could not change obviously in street canyon at the pedestrian level. However, the humidifying effect does which is the wider the more humid. (4) the limitations of software have discussed.

***Chapter 6**, **Field measurement of near-surface thermal performance of green roofs in subtropical area***, investigates the near-surface thermal performance of green roofs. In specific, based on the field measurement in a city with subtropical climate, chapter six compared the cooling and humidifying effects of three types of green roofs, including *Pomegranate*, *Bermuda grass* and *Sedum lineare*, on a typical sunny day. Afterwards, the test investigated the influence of watering activity and weather condition on the thermal performance of green roofs. Results indicate that the *Pomegranate* generally had the best cooling and humidifying effects by up to 3°C and 7.2%, followed by *Bermuda grass* and *Sedum lineare*. When air temperature of bare roof was more than 35°C, *Bermuda grass* presented insignificant cooling performance. *Sedum lineare* was the worst in providing cooling and humidifying effects, and even it severely intensified the thermal pressure in the peak period. However, the thermal performance of green roofs depended on the time in a day. *Sedum lineare* and *Bermuda grass* could also generate better cooling and humidifying effects, compared with *Pomegranate* before sunrise. Watering played a vital role in changing the diurnal near-surface thermal performance of green roofs, while the influence could not sustain for more than 10 minutes. Cooling performance of *Pomegranate* did not vary with cloudiness condition, while the cooling performance of *Bermuda grass* and *Sedum lineare* could be significantly enhanced under cloudy conditions. Overall, this section can help understand the thermal environment at the urban green canopy layer and inform designers and architects to reasonably select rooftop plants for cooling.

***Chapter 7, Conclusion and outlook*** have been presented.

## 7.2 Outlook

There are a number of configurations and collocation of different plants are worth to studying. And, green roof implements in the different regions with changing floor area ratio (FAR), building density (BD), greening rate (GR), built-up area (BA), wind direction (WD), climatic zone (CZ)which is need to think twice. The figure 7-1 preliminarily shows a test of green-roof community in Japan, and would be further explored by different FAR, BD, GR, BA, WD, CZ. Besides, the limitation of software ENVI-met lead to deviation in the results of related simulation performance, underestimate the thermal variability and green roof adjustment which could be focused in future direction of research, with changing vegetation types, scales and percentage would be thought twice to make sure the cost-beneficial value and the most comfortable condition. If the logical layout of green roof based on the future research was explored in the most effective way, cities and building sections should be planned to popularize these measures, as well as this study. Another future field of study linking to this is to conduct a similar profound analysis by utilizing a greater number of settings and configurations for native plant than that used in this study.

**Figure 7-1** The test of green-roof community in Kitakyushu city

In addition, due to cultural and climatic difference, other parameters such as solar radiation, substrate type, roof material comparing with the near-surface thermal performance of green roof to explore better morphology and layout profiles, as shown in Figure 7-2, which will be conducted to near-surface investigation in future in China.


**Figure 7-2** The near-surface thermal performance of different roof materials

# *APPENDIX*

# The Suggestion of Plant Species for Roof Greening

## 1.Dwarf Coniferous Plants Suitable for Roof Greening

| No | Scientific Name | Plant Family | Ornamental Character | Adaptation Star | Star Statement | Other Habits |
|---|---|---|---|---|---|---|
| 1 | Cephalotaxus sinensis | Cephalotaxaceae | evergreen,leaf comb | ★☆☆★★★★ | light-loving/more drought-tolerant/more cold-resistant/low maintenance/low requirements for medium/small trees or shrubs/higher ornamentality | pruning resistance,slow growth |
| 2 | Chamaecyparis lawsoniana ‘Golden Wander' | Cupressaceae | tree columnar,golden shiny leaves | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | pH acid neutrality,pruning resistance |
| 3 | Chamaecyparis lawsoniana ‘Van Pelt's Blue' | Cupressaceae | tree columnar,from blue-grey to dark blue-green leaves | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | ,pruning resistance |
| 4 | Chamaecyparis obtusa ‘Breviramea' | Cupressaceae | tree columnar branch,thin and cloud-like leaves | ★★★★★☆★ | all-day illumination/cold-resistant/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | pruning resistance,rapid growth,shallow root |
| 5 | Chamaecyparis pisifera ‘Filifera Aurea' | Cupressaceae | golden linear leaves | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/semi-dwarf shrub/higher ornamentality | pH acid neutrality,slow growth |

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| 6 | Chamaecyparis pisifera 'Filifera Nana' | Cupressaceae | plant type globose,golden linear leaves | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality | pH acid neutrality,slow growth |
| 7 | Chamaecyparis pisifera 'Plumosa' | Cupressaceae | plant type oval or columnar,pinnate leaves,buttery yellow leaf tip | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality | slow growth |
| 8 | Chamaecyparis pisifera 'Pygmaea' | Cupressaceae | plant type globose,emerald leaves | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality | slow growth |
| 9 | Chamaecyparis pisifera 'Squarrosa' | Cupressaceae | plant type narrow egg or columnar,young leaves are soft needles,summer is light yellow,winter is grey | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | pH acid neutrality,slow growth |
| 10 | Cryptomeria japonica 'compacta globosa' | Taxodiaceae | clustered spheres,Drill-shaped leaves | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality | slow growth |
| 11 | Cryptomeria japonica 'Vilmoriniana' | Taxodiaceae | dense globular shrubs of plant type,tip of leaf cone,spiral arrangement,winter is red and purple | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality | slow growth |
| 12 | Cupressus arizonica var. glabra 'Blue Ice' | Cupressaceae | narrow flaming plant type,light blue bright leaves | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | |

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| 13 | Cupressus lusitanica ‘Pendula' | Cupressaceae | branches droop,silver-blue leaves | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | |
| 14 | Cupressus macrocarpa ‘Goldcrest' | Cupressaceae | plant type narrow egg or columnar,golden shiny leaves | ★★★★☆★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/small trees/higher ornamentality | |
| 15 | Cycas revoluta | Cycadaceae | Palmate plant type,feather-shaped long leaves,flower eggs are golden and globular | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality | pH acid neutrality,slow growth |

## 2.Shrubs Suitable for Roof Greening

| No | Scientific Name | Plant Family | Ornamental Character | Adaptation Star | Star Statement |
|---|---|---|---|---|---|
| 1 | Abelia x grandiflora | Caprifoliaceae | semi-evergreen,dwarf,golden leaves,white pollen,long flowering period | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/dwarf shrub/higher ornamentality |
| 2 | Abelia biflora | Caprifoliaceae | fallen leaves,stem branches have 6 longitudinal grooves,pale yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/shrub/higher ornamentality |
| 3 | Amorpha fruticosa | Leguminosae | fallen leaves,purple spikes | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/shrub/higher ornamentality |

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| 4 | Berberis thunbergii ‘Aurea' | Berberidaceae | fallen leaves,golden leaves,yellow flowers,red fruit | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality |
| 5 | Berberis thunbergii ‘atropurpurea' | Berberidaceae | fallen leaves,purple-red leaves,yellow flowers,red fruit | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality |
| 6 | Berberis thunbergii ‘atropurpurea nana' | Berberidaceae | fallen leaves,dwarf plant,purple leaves,yellow flowers,red fruit | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality |
| 7 | Berberis thunbergii ‘Golden Ring' | Berberidaceae | fallen leaves,dwarf plant,purple leaves with golden edges,yellow flowers,red fruit | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality |
| 8 | Buddleja lindleyana | Buddleia division | semi-evergreen,spike flower、purple、fragrant | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/shrub/higher ornamentality |
| 9 | Buxus bodinieri | Buxaceae | evergreen,bright green leaves,spoon shape | ★☆★★★★★ | all-day illumination/more cold-resistant/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/higher ornamentality |
| 10 | Buxus sinica | Buxaceae | evergreen,bright green leaves,leaves are red in autumn and winter | ★★★★★★☆ | all-day illumination/heat-resistant hardy/drought-tolerant/low maintenance/low requirements for medium/dwarf shrub/general ornamentality |
| 11 | Callicarpa dichotoma | Verbenaceae | fallen leaves,lilac-red flowers,globular bright purple fruit | ★★★★★★★ | all-day illumination/cold and heat resistance/drought-tolerant/poor soil tolerance/low requirements for medium/shrub//higher ornamentality |
| 12 | Caragana sinica | Leguminosae | fallen leaves,yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/dwarf shrub/higher ornamentality |

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| 13 | Cassia tora | Leguminosae | evergreen,yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/dwarf shrub/higher ornamentality |
| 14 | Cerasus glandulosa | Rosaceae | fallen leaves,white or pink flowers,red fruit | ★☆★★★★★ | all-day illumination/more cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/shrub/higher ornamentality |
| 15 | Cerasus japonica | Rosaceae | fallen leaves,white or pink flowers,red fruit | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/shrub/higher ornamentality |

## 3.Ornamental grass species suitable for roof greening

| No | Scientific Name | Plant Family | Ornamental Character | Growth Characteristic | Adaptation Star(7) | Star Statement |
|---|---|---|---|---|---|---|
| 1 | Andropogon yunnanensis | Gramineae | linear stems and leaves, persistent spikes | H20-70/ warm-season | ★★★★★★★ | light-loving/heat-resisting/drought-tolerant/poor soil tolerance/low requirements formedium/perennation/higher ornamentality |
| 2 | Andropogon gerardii | Gramineae | blue-purple stalks, purple-red spikes | H120-180/ warm-season | ★★★★★★ | all-day illumination/drought-tolerant/low maintenance/low requirements for medium/low requirements for medium/higher ornamentality |
| 3 | Andropogon scoparius | Gramineae | autumn is red, white spikes | H50-100/ warm-season | ★★★★★★ | light-loving/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 4 | Andropogon munroi | Gramineae | slender,persistent spikes | H60-100/ warm-season | ★★★★ | cold resistance/drought-tolerant/perennation/ higher ornamentalitys |

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| 5 | Arrhenatherum elatius | Gramineae | there are white stripes on the leaves | H30/ cool-season | ★★★★★ | cold-resistant/drought-tolerant/low requirements for medium/perennation/higher ornamentality |
| 6 | Arrhenatherum elatius var.bulbosum 'Variegatum' | Gramineae | green leaves with silver edges, inflorescence gray green | H30-40/ cool-season | ★★★★★ | cold-resistant/drought-tolerant/low requirements for medium/perennation/higher ornamentality |
| 7 | Briza minor | Gramineae | triangular fruits | annual/ H20-30 | ★★★★ | light-loving/cold-resistant/drought-tolerant/higher ornamentality |
| 8 | Calamagrostis x acutiflora 'Avalanche' | Gramineae | the leaves of autumn change from orange to yellow,spikes from golden to yellow-white | H50-100/ warm-season | ★★★★★ | light-loving/cold-resistant/poor soil tolerance /perennation/higher ornamentality |
| 9 | Calamagrostis x acutiflora 'Karl Foerster' | Gramineae | pink-purple spikes | H50-100/ warm-season | ★★★★★★ | light-loving/cold-resistant/poor soil tolerance/ low requirements for medium/perennation/higher ornamentality |
| 10 | Calamagrostis epigeios | Gramineae | inflorescence from pink to purple | H80-150/ warm-season | ★★★★ | heat-resisting/low requirements for medium/ perennation/higher ornamentality |
| 11 | Calamagrostis x acutiflora 'Overdam' | Gramineae | white alternate with green leaves, lilac inflorescence | H50-75/ cool-season | ★★★★ | light-loving/low requirements for medium/ perennation/higher ornamentality |
| 12 | Carex comans 'Frosted Curls' | Cyperaceae | silver green leaves,leaf end curl | H40-60/ cool-season | ★★★★ | light-loving/drought-tolerant/perennation/ higher ornamentality |
| 13 | Carex giraldiana | Cyperaceae | narrow and flexible leaves | H35/ cool-season | ★★★★ | light-loving/drought-tolerant/perennation/ higher ornamentality |

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| 14 | Carex kobomugi | Cyperaceae | | H10-20/ cool-season | ★★★☆ | drought-tolerant/poor soil tolerance/ perennation/general ornamentality |
| 15 | Carex lanceolata | Cyperaceae | narrow and flexible leaves | H30/ cool-season | ★★★★ | heat-resistant hardy/poor soil tolerance/ perennation/higher ornamentality |

## 4. Sedum and Meat Plants Suitable for Roof Greening

| No | Scientific Name | Plant Family | Ornamental Character | Adaptation Star | Star Statement |
|---|---|---|---|---|---|
| 1 | Ariocarpus retusus | Cactaceae | the shape of lotus pedestal,gray-green leaves,white or yellow flowers | ★☆★★★★★ | all-day illumination/more cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 2 | Bryophyllum pinnatum | Crassulaceae | a saucer-shaped drooping flower with pointed red feet | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 3 | Cumulopuntia mistiensis | Cactaceae | yellow flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 4 | Ferocactus acanthodes | Cactaceae | yellow flowers | ★★★★★★★ | all-day illumination/heat and cold resistance/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 5 | Gymnocalycium mihanovichii ‘Hibotan’ | Cactaceae | red oblate stem | ★★★★★★★ | all-day illumination/heat and cold resistance/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 6 | Opuntia cv. | Cactaceae | yellow flowers | ★★★★★★★ | all-day illumination/heat and cold resistance/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |

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| 7 | Opuntia ficus-indica | Cactaceae | yellow flowers | ★★★★★★★ | all-day illumination/heat-resisting/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 8 | Oreocereus celsianus | Cactaceae | thorn base densely covered with white hair,white funnel-shaped flowers | ★★★★★★★ | all-day illumination/heat and cold resistance/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 9 | Orostachys malacophylla | Crassulaceae | the shape of lotus pedestal | ★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/higher ornamentality |
| 10 | Phedimus aizoon | Crassulaceae | bright green leaves, yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 11 | Phedimus floriferus | Crassulaceae | bright green leaves, yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 12 | Phedimus hybridus | Crassulaceae | bright green leaves, yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 13 | Phedimus odontophyllus | Crassulaceae | bright green leaves, yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 14 | Rhodiola sacra | Crassulaceae | purple-red medicinal ovoid flowers,white petals | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |
| 15 | Sedum x rubrotinctum | Crassulaceae | bright green leaves,pale yellow-red flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennation/higher ornamentality |

## 5. Groundcover plants suitable for roof greening

| No | Scientific Name | Plant Family | Ornamental Character | Adaptation Star | Star Statement |
|---|---|---|---|---|---|
| 1 | Achillea sibirca | Compositae | feather-shaped thin split leaves,from white to light pink flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 2 | Ajana pallasiana | Compositae | the leaves have different colors on both sides,below is white,the edges of the leaves are white | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 3 | Aster novi-belgii | Compositae | blue-purple flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 4 | Aster tataricus | Compositae | blue-purple flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 5 | Bambusa multiplex var.multiplex cv.Fernleaf | Gramineae | cluster dwarf, dense branches and leaves, like Phoenix Tail | ★☆★★★★★ | all-day illumination/more cold-resistant/drought-tolerant/low maintenance/low requirements for medium/perennial ground cover bamboo/higher ornamentality |
| 6 | Brassica olera-cea var.acephala f.tricolor | Cruciferae | biennial herbs,variety,leaves are colorful | ★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/higher ornamentality |
| 7 | Campsis grandiflora | Bignoniaceae | deciduous vine,orange-red flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/woody vines/higher ornamentality |

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| 8 | Canna spp. | Cannaceae | variety,flowers are colorful | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 9 | Caryopteris divaricata | Verbenaceae | purple or red flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 10 | Caryopteris x clandonensis | Verbenaceae | blue flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 11 | Caryopteris x clandonensis ‘Worcester Gold' | Verbenaceae | golden leaves,blue flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 12 | Coreopsis drummondii | Compositae | evergreen,yellow flowers | ★★★★★★★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 13 | Coreopsis grandiflora | Compositae | yellow flowers | ★★★★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/perennial herb/higher ornamentality |
| 14 | Cosmos sulphureus | Compositae | annual,yellow、orange,、red flowers | ★★★★★ | all-day illumination/drought-tolerant/poor soil tolerance/low requirements for medium/higher ornamentality |
| 15 | Dianella ensifolia | liliaceae | blue-purple or green-white flowers,purple-blue fruits | ★★★★★★★ | all-day illumination/heat-resisting/drought-tolerant/low maintenance/low requirements for medium/perennial herb/higher ornamentality |

## 6. Small trees and bamboos suitable for roof greening

| No | Scientific Name | Plant Family | Ornamental Character | Adaptation Star | Star Statement |
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| 1 | Amygdalus persica cv. | Rosaceae | fallen leaves,many varieties,variety of patterns and colors | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 2 | Amygdalus persica ‘Duplex’ | Rosaceae | fallen leaves,pink double petals | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 3 | Pyrus spp. | Rosaceae | fallen leaves,variety,white flowers | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 4 | Armeniaca mume | Rosaceae | fallen leaves,many varieties,White、pink、red flowers,or have fragrance | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 5 | Armeniaca mume ‘Pendula’ | Rosaceae | fallen leaves,vertical branch type， White、pink、red flowers | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 6 | Armeniaca mume ‘Tortuosa’ | Rosaceae | fallen leaves,branches twisted like dragons swimming,white flowers | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 7 | Armeniaca x blireana ‘Meiren’ | Rosaceae | fallen leaves,light purple double petals | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 8 | Amygdalus persica ‘Densa’ | Rosaceae | fallen leaves,small plant type,pink flowers | ★☆★★★★★ | all-day illumination/more cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/dwarf form/higher ornamentality |
| 9 | Amygdalus persica ‘Pendula’ | Rosaceae | fallen leaves,vertical branch type,white or pink flowers | ★★☆★★☆★ | all-day illumination/cold-resistant/more drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality |

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| 10 | Sophora japonica ‘Pendula’ | Leguminosae | fallen leaves,vertical branch type | ★★★★★☆★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality |
| 11 | Ulmus americana ‘Pendula’ | Ulmaceae | fallen leaves,vertical branch type | ★★★★★☆★ | all-day illumination/cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality |
| 12 | Ficus carica | Moraceae | fallen leaves,yellow or purple fruit | ★☆★★★☆☆ | all-day illumination/more cold-resistant/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/general ornamentality |
| 13 | Malus spectabilis | Rosaceae | fallen leaves,many varieties,white or pink flowers | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |
| 14 | Malus Halliana | Rosaceae | fallen leaves,pink flowers, purple pendulous pedicels | ★☆★★☆★ | all-day illumination/more cold-resistant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality |
| 15 | Malus spectabilis ‘Riversii’ | Rosaceae | fallen leaves,pink double petals | ★★★★★☆★ | all-day illumination/heat-resistant hardy/drought-tolerant/poor soil tolerance/low requirements for medium/small trees/higher ornamentality/ |

## 7. Common Vegetable Species Suitable for Roof Greening

| No | Scientific Name | Plant Family | Ornamental Character | Adaptation Star | Star Statement |
|---|---|---|---|---|---|
| 1 | Allium fistulosum | Liliaceae | perennial herb,stem vegetables | ★★★★ | all-day illumination/cold and heat resistance/drought-tolerant/low maintenance |
| 2 | Allium sativum | Liliaceae | semiannual herb,root vegetables | ★★★ | all-day illumination/cold-resistant/low requirements for medium |
| 3 | Allium tuberosum | Liliaceae | perennial herb,stem vegetables | ★★★★ | all-day illumination/heat-resistant hardy/drought-tolerant/low maintenance |

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| 4 | Amaranthus tricolor | Amaranthaceae | annual,leaf vegetables | ★★★★ | all-day illumination/heat-resisting/drought-tolerant/low maintenance |
| 5 | Angelica keiskei | Umbelliferae | perennial herb,leaf vegetables | ★★★ | all-day illumination/heat-resistant hardy/drought-tolerant |
| 6 | Beassica pekinensis | Cruciferae | biennial,leaf vegetables | ★★ | light-loving/heat-resisting |
| 7 | Benincasa hispida | Cucurbitaceae | annual sprawl,fruit vegetables | ★★★ | light-loving/heat-resisting/low requirements for medium |
| 8 | Brassica chinensis | Cruciferae | annual,leaf vegetables | ★★★ | light-loving/heat and cold resistance/low requirements for medium |
| 9 | Brassica juncea 'Multiceps' | Cruciferae | annual,leaf vegetables | ★★★ | all-day illumination/cold and heat resistance/drought-tolerant/ |
| 10 | Brassica oleracea 'Botrytis' | Cruciferae | biennial,cauliflower | ★☆★ | light-loving/more heat-resistant than cold-resistant/low requirements for medium |
| 11 | Brassica oleracea 'Capitata' | Cruciferae | biennial herbs,leaf vegetables | ★☆☆ | all-day illumination/more heat-resistance/more drought-tolerant |
| 12 | Brassica oleracea 'Caulorapa' | Cruciferae | biennial herbs,leaf vegetables | ★★★★ | light-loving/heat and cold resistance/low maintenance/low requirements for medium |
| 13 | Brassica oleracea 'Italic' | Cruciferae | annual and biennial,cauliflower | ★☆★ | light-loving/more heat-resistant than cold-resistant/low requirements for medium |
| 14 | Capsicum annuum | Solanaceae | annual herb,fruit vegetables | ★★★ | all-day illumination/heat-resisting/low requirements for medium |
| 15 | Chrysanthemum coronarium cv. | Compositae | annual and biennial,leaf vegetables,applicable for the south | ☆ | more heat-resistant than cold-resistant |