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Research on Microclimate Design and Application of Roof Gardens in High-Density Cities

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Abstract:

Roof gardens can alleviate the urban heat island effect, regulate urban rainwater, improve air quality, and increase green coverage. In particular, it has a relatively prominent benefit in improving the urban microclimate. Through the research on the Taikoo Hui roof garden built in Guangzhou Tianhe Commercial Center, using the structured observation method and field survey method, from the perspectives of space layout, plant design, and paving materials, the design and application of microclimate are studied, and it is concluded that Three design conclusions that affect the microclimate of urban roof gardens are presented. First, the space layout should be designed according to the climatic conditions, which can effectively block solar radiation, heat, cold, humidity, and airflow; second, the plant design should be based on on-site needs, plant characteristics, and plant community structure. Comprehensive design, effectively controlling solar radiation, protecting soil, providing shading, shading, restraining wind speed, etc., and reducing the air temperature of the regional environment; The collection system is combined to increase the heat exchange between the underlying surface and the air and to better adjust the microclimate. The research provides design ideas and suggestions for the design and application of microclimates in high-density urban roof gardens.

Keywords:

Roof Garden, Microclimate Design, Landscape Spaces

1. Introduction

1.1. Roof Garden

In high-density cities, the limited space for green space on the ground has led to the extension of greening to three-dimensional space, and rooftop gardens have become one of the effective ways to increase the green coverage of cities and *enhance* ecological environment issues. [1] Rooftop gardens are a form of greening and landscape that uses the roof of a building as a backdrop to store water, cover soil and create a landscape. [2] It has the *climatic* effectiveness of *decreasing* urban heat island effect [3], alleviating urban rainwater flooding problem, increasing urban rainwater

collection [4], protecting urban biodiversity, [5] improving urban air quality [6] and beautifying urban environment [7]. Studies have proven that rooftop gardens have a more *visible* role in improving urban microclimates.

1.2. Microclimate

The microclimate is mainly the climate within the space from the ground to a height of a dozen to a hundred metres. [8] Some experts also consider microclimates to be climatic features that are different from the larger climate on a small scale due to the influence of various local factors. [9] It is the climate of a small, local area with consistent and amenable climatic characteristics. [10] Among the components of microclimate are temperature, humidity, air convection, heat absorption and dissipation in a local area. [11] In this paper, the microclimate of a rooftop garden is defined as a unique climatic condition that develops in a local environment within a range with the same broad climatic characteristics due to various factors such as substrate conditions and topographic orientation.

1.3. Roof Gardens and Microclimate

The density of urban buildings accounts for a large proportion of the total urban area. Under solar radiation, building surfaces dissipate heat into the air, especially roof surfaces, which are largely exposed to the sun during the day, and especially in hot summer weather, roofs absorb and release a large amount of solar radiation, exacerbating the heat island effect. Rooftop gardens are an effective measure to promote the ecological balance of the urban environment and are one of the most effective ways to improve the urban microclimate. [12] Rooftop garden microclimate design is an ecological design meant to create a microclimate that meets human comfort, mainly through the layout of space, plant configuration, and the creation of structures. [13] This paper studies the influence of the roof garden microclimate on the spatial layout, plant design, and paving material design and application of the Guangzhou Taikoo Hui roof garden.

2. Materials and Methods

2.1. Case Overview

The sample site is located on the third floor of the TaiKoo Hui Shopping Centre in Tianhe District, Guangzhou, at coordinates 113.334638N, 23.141848E. It is a large mixed-use commercial building consisting of shopping malls, office buildings, hotels, and residential buildings with a total gross floor area of approximately 358,000 square metres (excluding the cultural center). It is surrounded by several commercial complexes and is a typical high-density urban space. (Figure 1) The transport hub at the junction of Tianhe Road and Tianhe East Road is served by dozens of bus routes, and the platforms of the BRT and Metro Line 3 are connected to the M level of the mall. (Figure 2)

Located in Guangzhou, Swireway has a subtropical monsoon climate, characterized by humidity, high temperatures, and rain; the average temperature over the last three years is 23.5 °C - 24 °C, with a maximum temperature of 37.5 °C - 38.4 °C, ample light, and long summers; the average rainfall is 1503.3 mm–2214.8 mm. (Table 1 [14], Figure 3) The roof garden covers an area of about 8,000m2 in a modern and minimalist style with a beautiful green environment, mainly as a space for dining, resting, performing, and entertainment, but also as a platform for fire evacuation in

case of emergency, with a certain nature and function of a city square. Both the east and west sides of the roof garden have direct entrances to the roof garden from the street level, which makes it a semi-open commercial roof garden. The vegetation is diverse, mainly consisting of trees and shrubs, and ground cover plants. The plant species are all adapted to Guangzhou's hot, rainy, and humid climate and are mostly evergreen plants that are highly adaptable, resistant to high roof winds, air pollution, absorption of toxic substances, pruning resistance, easy maintenance, and low maintenance costs. The performance and community structure of the plants are designed according to the needs of the functional space, creating a different atmosphere and feeling for each space.

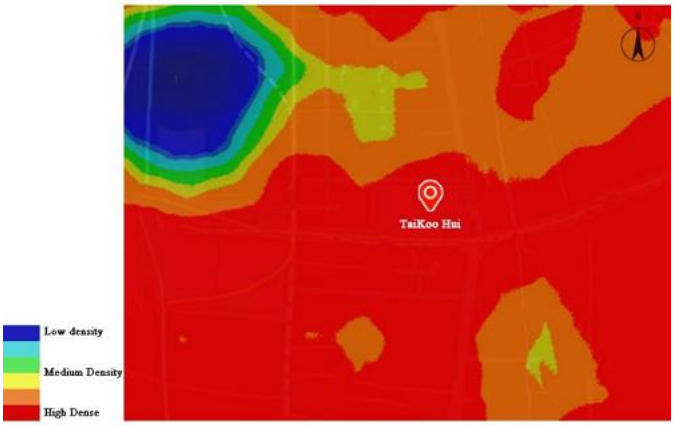


Figure 1. *Thermal map of the sample site perimeter.*

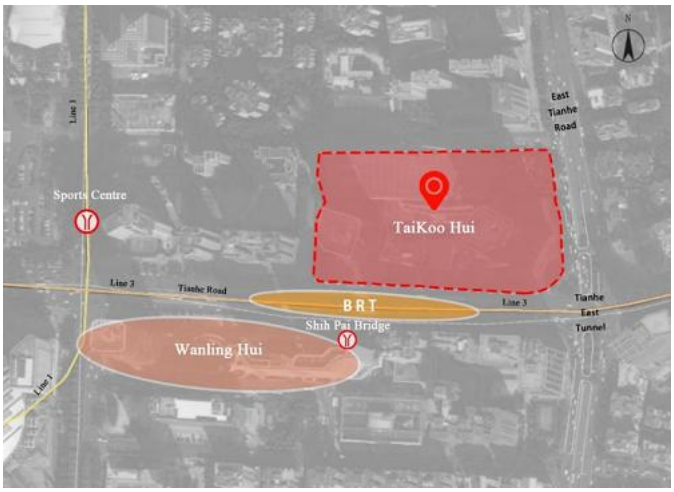


Figure 2. *Analysis of the sample site surroundings.*

Table 1. *List of meteorological elements in Tianhe District 2019-2021.*

Year	Average temperature (°C)	More recent decade from flat (°C)	Maximum temperature (°C)	Maximum temperature (°C)	Precipitation (mm)	Percentage of distance from flat over the last ten years (%)	Sunshine hours (hours)	Percentage of sunlight spacing (%)
2019	23.5	0.7	37.5	7.4	2214.8	-22.5	-	-
2020	23.5	0.7	37.7	5.3	1782.8	-22.5	-	-
2021	24.0	0.7	38.4	2.2	1503.3	-22.5	-	-

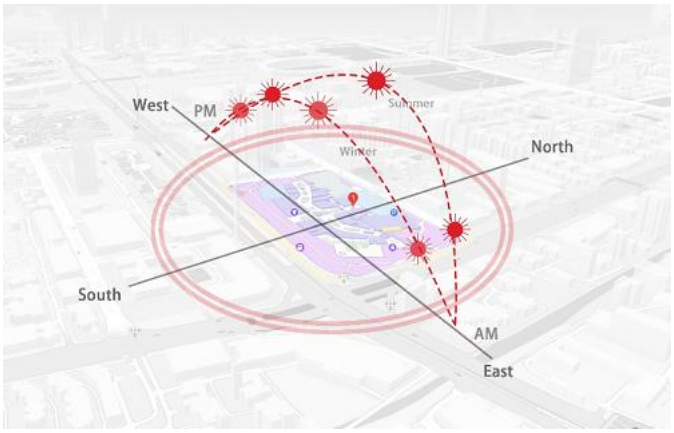


Figure 3. *Light analysis of sample plots.*

2.2. Research Methodology

The methods used in this paper are literature induction, structured observation, and fieldwork. The site was observed and analyzed to study the impact of the spatial layout, planting design, and paving materials on the microclimate of the roof garden of TaiKoo Hui, Guangzhou. The structured observation method is a research method proposed by Dr. Visas Mehta of the School of Architecture and Community Design at the University of South Florida. [15] is an observation from the user's perspective, focusing on micro-environmental characteristics, spatial information, etc., to distill valid information for further research and analysis, and to collect accurate and valuable material. Based on this, the site is visited, researched, photographed, and actual information is collected for statistical and analytical purposes. [16]

3. Results and Discussion

3.1. Structured Observation Results

3.1.1. The Impact of Spatial Layout on Microclimate

In the design of roof garden microclimates, buildings play a role in shading solar radiation and blocking and directing air currents, and their influence on the microclimate is reflected in the form of the building, its spatial layout and material characteristics. [17] The influence of the spatial layout, floor plan and shaded area of a building on the microclimate of its external space. [18]

The roof garden is designed in a zigzag flow (Figure 4), with the atrium connected by three entrances, both on the east and west sides, with direct access to the roof garden from the street level. The roof garden is divided by two stepped glass roofs that divide the space into two zones, North and South, creating a clear division of movement and tranquillity. The restaurants in the north zone both have floor-to-ceiling glass and outside dining areas, blurring the line between them and the roof garden; the towering office blocks to the east and west define the absolute boundary of the roof garden. The roof garden is enclosed on all sides by the building, which provides a ventilation corridor within the roof garden by directing air through the perimeter of the space. Access openings to the east and south-east introduce airflow into the garden in summer, while the west side forms an air outlet to enhance natural ventilation and cooling in summer; in winter, the buildings in the north block the

north-west wind (Figure 5). The buildings and the tall trees planted around them block out direct sunlight and create a certain amount of shaded area. (Figure 6)

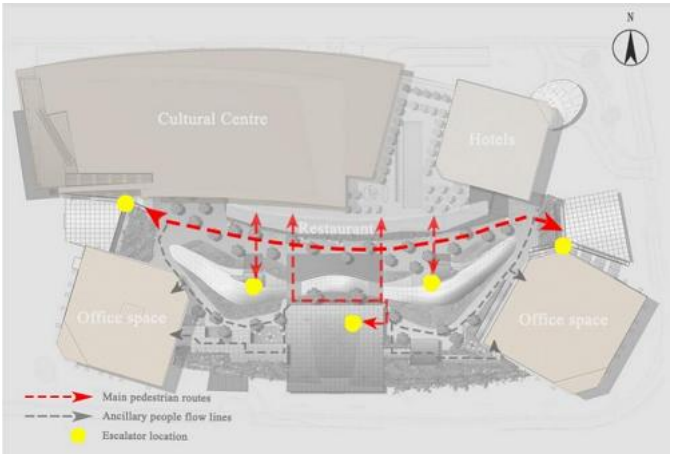


Figure 4. *Roof garden pedestrian flow diagram.*

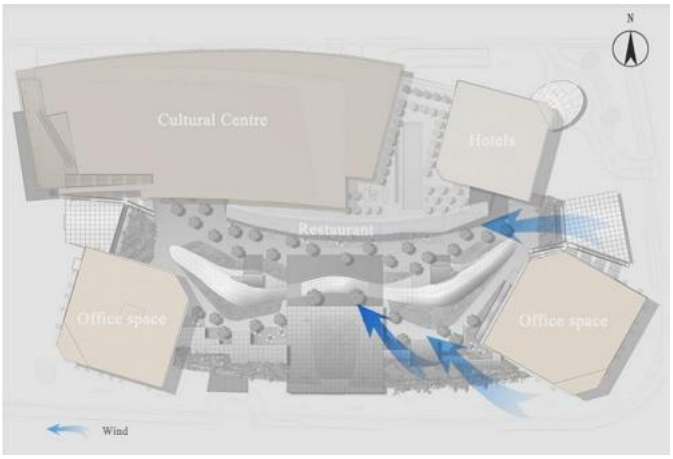


Figure 5. *Summer wind analysis of the roof garden.*

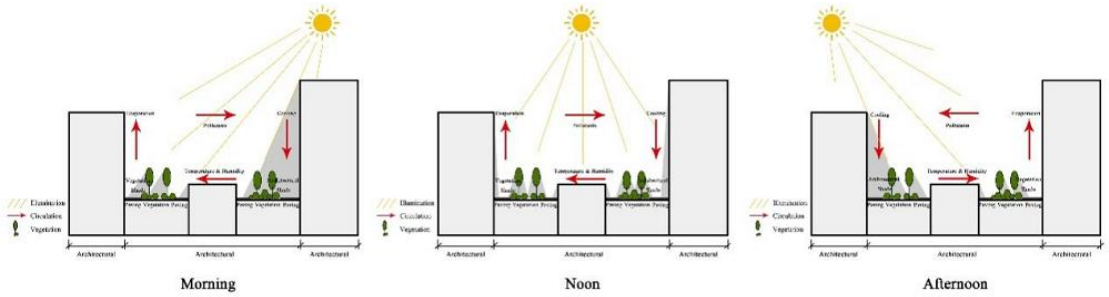


Figure 6. *Light and shadow analysis of the roof garden in the morning, midday and afternoon.*

3.1.2. The impact of Plant Design on Microclimate

Vegetation plays a vital role in urban landscape elements. In addition to aesthetics, the transpiration, shade formation, and cooling and ventilation functions of plants themselves are of significant importance for the improvement of the microclimate in urban spaces. [19] Different vegetation planting methods have an improved effect on the thermal comfort of the environment. [20] The microclimate of urban spaces is often affected by a combination of plant community features, and community plants are more effective in improving the microclimate of a region. The multi-layered structure of a community can usually be divided into three basic layers: the tree layer,

shrub layer, and ground cover layer. A compound community structure provides a better cooling effect than other types of plant configurations for microclimate regulation purposes. [21] Plants are classified according to the type of plant growth: trees, shrubs, and groundcovers. (Figure 7, Table 2) The classification criteria are as follows: [22]

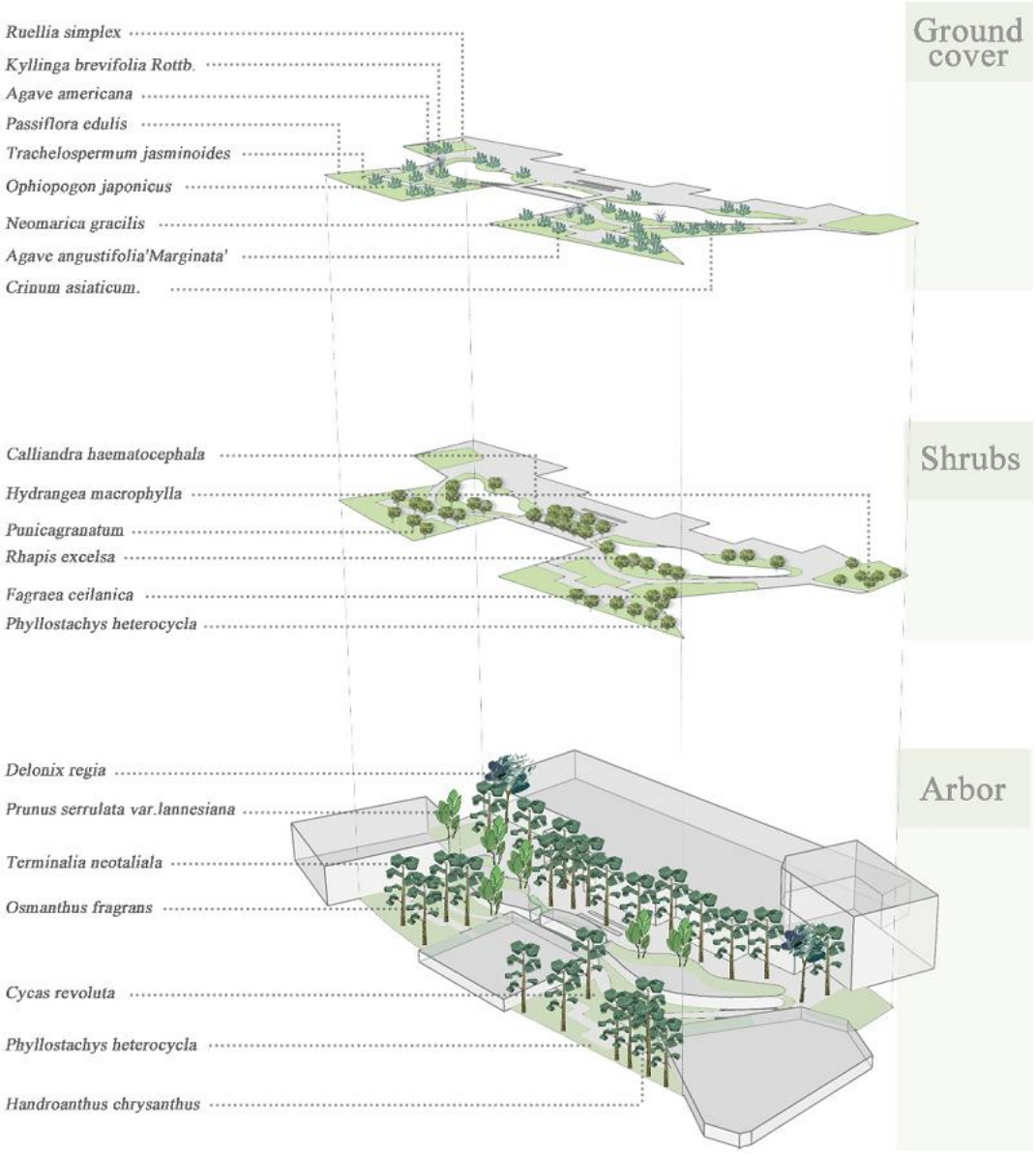


Figure 7. *Roof garden plant layered diagram.*

a. Arbor

The trees are tall (usually 6-10 m) and have a distinctly tall trunks. Depending on their height, they can be classified as great trees (over 30m), large trees (20-30m), medium trees (10-20m), and small trees (6-10m). They are also classified according to their growth rate as fast-growing, medium-growing, or slow-growing trees. Roof garden trees include Terminalia Natalia, Delonix regia, Prunus serrulata var., etc. The trees planted in the roof garden are mainly small-leaved olive trees, which are graceful, deep-rooted, and resistant to strong winds and pollution.

b. Shrubs

The trees are dwarf (usually under 6 m) with low main trunks. There are six species of shrubs in the roof garden, including Nandina Domestica, Calliandra haematocephala, Hydrangea macrophylla, etc. The flowers are solitary, spherical, with dense filaments and warm red colors.

c. Ground cover

Groundcovers are generally low-growing, perennial, low herbaceous plants, more adaptable low creeping shrubs, vines, and lawn plants that fall under the category of groundcovers. Rooftop garden groundcovers include Crinum asiaticum, Ophiopogon japonicus, Neomarica gracilis, etc. Rooftop gardens grow a greater proportion of Manjus orchids, which are highly adaptable and protect the soil; they flower from June to August and have white linear flowers with light red stamens, etc.

Table 2. *Swireway Roof Garden Plant Configuration.*

Plant Type	Scientific Name	Growth Habits
Arbor	*Terminalia neotaliala*	Large deciduous tree, likes light, tolerates half shade, likes high temperature and humid climate, deep rooting, wind resistance, pollution resistance, long lifespan
	Delonix regia	Tall deciduous tree, likes light, likes sunny, high temperature and humid environment, fast growth, developed root system, dense branches and leaves, resistance to wind, disease and insect pests, and resistance to air pollution
	Handroanthus chrysanthus	Deciduous tree, likes high temperature, likes light, slightly tolerant to shade
	Prunus serrulata var. lannesiana	Deciduous tree, likes light and shade, strong cold resistance, likes moist soil
	Osmanthus fragrans	Evergreen shrubs or small trees, liking sunshine, warmth, humidity, and intolerance to drought and barrenness
	Cycas revoluta	Evergreen tree, likes warm and humid environment, not cold-resistant in winter, grows slowly, likes light, likes iron elements, and tolerates half shade
	Phyllostachys heterocycla	Evergreen tree-like bamboo plants, like warm and humid, perennial evergreen species
Shrubs	*Common Nandina*	Small evergreen shrub, likes warm and humid environment, shade-tolerant and cold-tolerant
	Punicagranatum	Likes sunny and dry environment, cold-resistant, drought-resistant, intolerant of waterlogging, intolerant of shade, not strict with soil requirements, fertile, loose and nutritious sandy loam is best
	Rhapis excelsa	Bushy shrub, likes warm, humid and well-ventilated semi-shade environment, intolerant of standing water, extremely shade-tolerant
	Calliandra haematocephala	Deciduous shrub or small tree, likes light, likes warm and humid climate, not cold-resistant, suitable for deep fertile and well-drained acidic soil
	Fagraea ceilanica	Evergreen trees or shrubs, like sunshine, drought tolerance, shade tolerance, strong cold tolerance, not strict on soil requirements, strong adaptability, rough and easy to cultivate
	Hydrangea macrophylla	Shrub, prefers warm, humid and semi-shady conditions
Ground	*Crinum asiaticum.*	Perennial rough herb, prefers warm, humid, sunny,

Cover		fertile sandy soil environment, not cold-resistant
	Ophiopogon japonicus	Perennial evergreen herb, prefers warm, humid, sunny environments
	Agave americana L.	Evergreen large herb, likes full sun, slightly cold-tolerant, shade-intolerant, likes cool and dry environment
	Agave angustifolia'Marginata'	Evergreen herbs for many years, like high temperature and dry resistance, good growth in sunlight
	Ruellia simplex	Herbaceous plants, like warm, humid and sunny environment, resistant to high temperature and drought, not strict on light and soil
	Neomarica gracilis	Perennial herb, likes high temperature and humid climate environment, likes sunshine, tolerates half shade, not cold, and avoids standing water. Prefers loose, well-drained loamy or humus soils
	Trachelospermum jasminoides	Evergreen woody vines, liking low light, resistant to hot sun and high temperature, strong adaptability to climate, able to withstand cold and heat, but avoid severe cold
	Kyllinga brevifolia Rottb.	Cyperus rotundus
	Passiflora edulis	Herbaceous vines, like sunny, warm climate, fertile soil, good drainage environment. Not resistant to cold, avoid water accumulation

The rooftop garden is planted according to the different functions and characteristics of the site, with a community structure of a tree - shrub - grass, tree - grass, shrub - grass, tree, shrub, and grass (Table 3): the central plaza in front of the restaurant in the north area is mainly planted in the form of trees, with the straight trunk of the small-leaved olive tree and its cascading and progressive growth characteristics shading the ground and providing shade in the summer, and bringing in warm sunlight and suppressing wind speed in the winter. The atrium space is planted in the form of shrubs - lawn, shrubs, and lawn, enclosing a stepped glass roof and semi-enclosed stone benches to form a more private resting space; the boundary is enclosed in the form of trees - shrubs - grass, trees, and grass plants, tall trees can directly block solar radiation and help regulate the temperature and air humidity balance; the compound plant community can better introduce wind bodies, sound insulation, and noise reduction, filtering dust and other functions. (Figure 8)

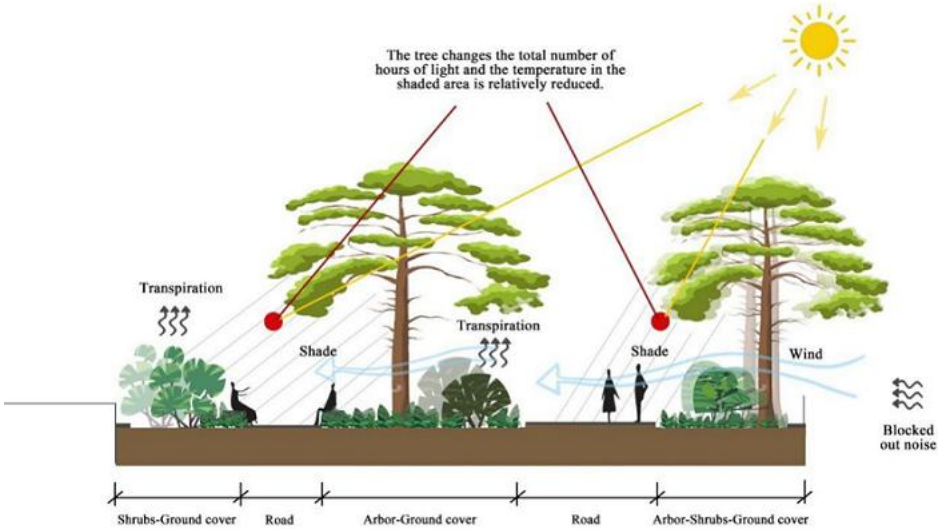
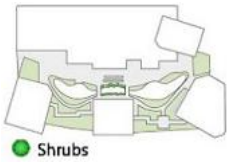


Figure 8. *Roof garden plant microclimate elevation analysis.*

Table 3. *Status of the Swireway Rooftop Garden Plant Communities.*

Green space structure	Plant composition	Plant community composition characteristics	Site distribution
Arbor-Shrubs-Ground cover	*Terminalia neotaliala* *Common Nandina* *Neomarica gracilis* *Terminalia neotaliala* *Handroanthus chrysanthus* *Rhapis excelsa* *Fagraea ceilanica* *Crinum asiaticum.* *Terminalia neotaliala* *Cycas revoluta* *Rhapis excelsa* *Neomarica gracilis* *Terminalia neotaliala* *Cycas revoluta* *Punicagranatum* *Common Nandina* *Neomarica gracilis* *Ophiopogon japonicus*	High:10m; Crown Width:3m; Linear Planting High:1.2m; Crown Width:0.8m; Linear Planting — High:14m; Crown Width:5m; Solitary Planting High:5m; Crown Width:1m; Solitary Planting High:1.0; Crown Width:0.8m; Group Planting High:0.6m; Crown Width:0.6; Group Planting — High:10m; Crown Width:4m; Linear Planting High:0.6m; Crown Width:0.6; Group Planting — — High:14m; Crown Width:4m; Linear Planting High:0.6m; Crown Width:0.6; Linear Planting High:1.8m; Crown Width:0.5; Solitary Planting High:1.2m; Crown Width:0.8m; Linear Planting — —	
Arbor-Ground cover	*Terminalia neotaliala* *Cycas revoluta .* *Agave americana* *Ophiopogon japonicus* *Prunus serrulata var. lannesiana* *Cycas revoluta* *Agave americana* *Ruellia simplex* *Neomarica gracilis* *Ophiopogon*	High:15m; Crown Width:6m; Solitary Planting High:1.6m; Crown Width:1.2m; Group Planting — — High:2.0m; Crown Width:1.0m; Group Planting High:1.6m; Crown Width:1.2m; Linear Planting — —	

	japonicus *Cycas revoluta* *Ophiopogon japonicus*	— — — High:1.6m; Crown Width:1.2m; Group Planting —	
Shrubs-Ground cover	*Rhapis excelsa* *Crinum asiaticum.*	High:1.5m; Crown Width:0.8m; Group Planting —	
Arbor	*Terminalia neotaliala* *Delonix regia*	High:13m; Crown Width:3m; Linear Planting High:13m; Crown Width:4m; Linear Planting	
Shrubs	*Calliandra haematocephala*	High:1.2m; Crown Width:1.5m; Group Planting	
Ground cover	*Agave americana*	—	

3.1.1. The Impact of Spatial Layout on Microclimate

Ground cover is one of the most important elements of a roof garden. [23]The paving material is the only 'hard' component of the ground cover material and has a wide range of roles in the landscape space, with a strong influence on the microclimate. Solar radiation from the ground and atmospheric heat are important influences on the formation of different climates, and different paving materials can affect the thermal environment in a landscape space. [24]

The paving materials for the roof garden are simple and have a strong sense of integrity, with grey granite as the main material, including sesame white burnt granite, sesame grey burnt granite, sesame black burnt granite, sesame grey lychee faced granite, prefabricated concrete, and so on, which are unified with the architectural style. The grey surface of the rough material refracts heat and reduces the surface temperature. (Figure 9)

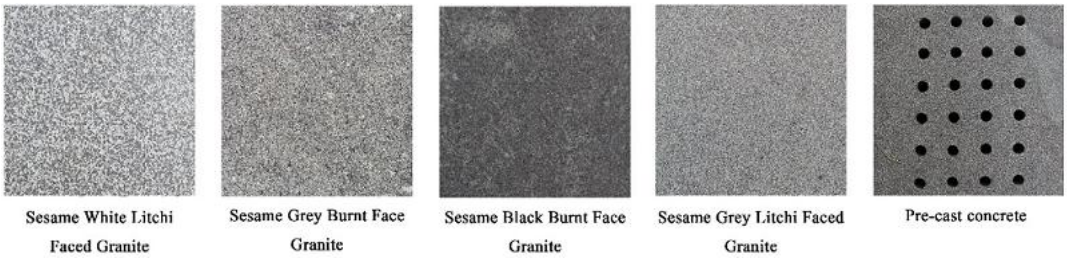


Figure 9. *Paving materials for roof gardens*

The paving material of the roof garden is made of granite with different rough surfaces to prevent slippage when it rains, and the rough material also penetrates rainwater better. There are gaps between the different colored granite blocks to collect rainwater and enhance the effect of the roof garden in storing rainwater. The left A on the west side is about 100mm higher than the right B to disperse rainwater runoff; there is a stainless steel gutter between the road and the planters in A with several drainage holes to avoid rainwater accumulation; the planters in the C planting and irrigation structure have prefabricated concrete drainage holes between them and the stepped glass roof so that some of the rainwater can flow into the planters and any excess will be collected. Black pebbles are placed on the planting surface of tree D in front of the north restaurant to protect the soil from water loss. During the day, the cobbles provide shade when the sun is shining and reduce the evaporation of soil water. (Figure 10, Figure 11)

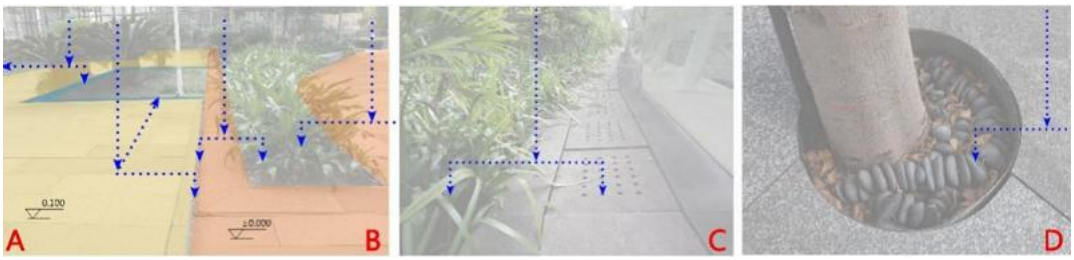


Figure 10. *Roof garden rainwater harvesting analysis diagram.*

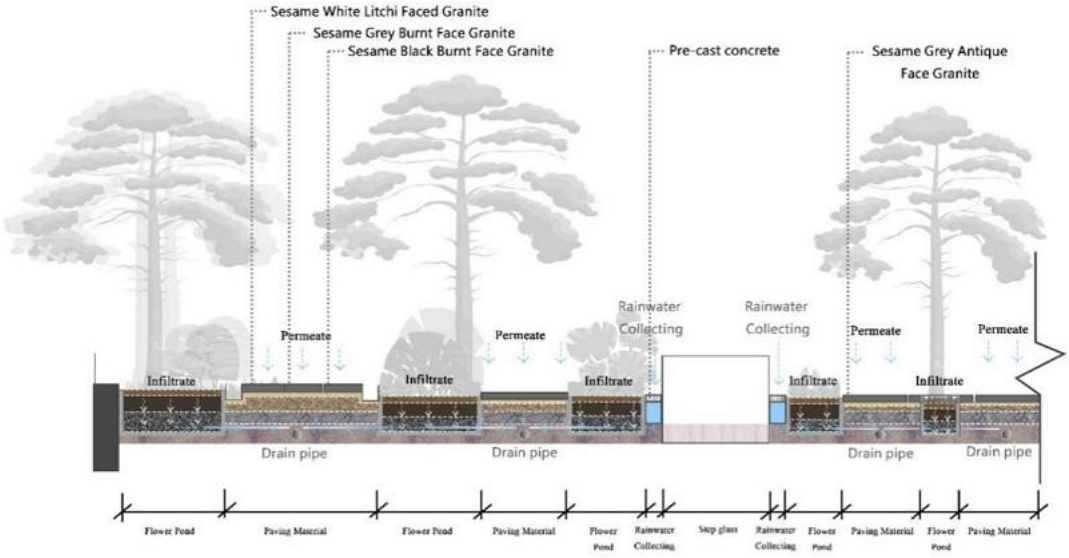


Figure 11. *Microclimate elevation analysis of roof garden paving materials.*

4. Conclusions

Analysis of the design of the Pacific Place Roof Garden has led to the adoption of several guiding principles for the adoption of a beneficial microclimate in a high-density urban environment, particularly in commercial areas:

In terms of spatial layout, combined with the local climatic conditions, the building enclosure form and plan layout are designed to shield solar radiation and block and guide airflow; the shading effect of the building and plants makes the space form an effective shade, reducing the radiation from the sun and lowering the temperature of the regional environment, which can improve the microclimate in the urban landscape space more effectively.

In terms of plant design, plants that are adapted to the local climatic conditions and can adapt to the extreme environment of the roof garden should be planted. The growth characteristics, functional requirements, and landscape characteristics of the plants should be fully considered to build a stable species and functionally sound plant community structure, focusing on creating a good visual effect of the roof garden and improving the ecological benefits of the environment. The design of different plant communities according to different spaces can effectively reduce the air temperature of the regional environment.

In paving materials, different paving materials absorb and release solar radiation differently, which in turn causes different degrees of warming and cooling of the surface temperature. In the choice of paving materials, attention should be paid to materials, colours, surface roughness, pore gaps, water permeability, etc., in harmony with the overall style of the roof garden. Consider different functional spaces and organisation in combination with other landscape facilities such as guided flow. The combination of paving with good permeability and rainwater collection systems can speed up the natural infiltration of rainwater, increase the heat exchange between the lower cushion surface and the air, and better regulate the air temperature in the microclimate of the landscape space.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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