

## Article

# Sky Gardens, Public Spaces and Urban Sustainability in Dense Cities: Shenzhen, Hong Kong and Singapore

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**Abstract:** This paper studies the spatial characteristics of sky gardens as public spaces to explore their potential to support urban sustainability in dense cities. This research understands public spaces as spaces that are open and available in different levels of access and use. The research focuses on 982 sky gardens in Shenzhen, Hong Kong, and Singapore. It adopts a mixed methodology, including site visits and observations, statistic measurements (based on SPSS software), and Grey Relation Analysis (GRA) methods. The research follows three steps: first, it studies the urban context, including urban density, land uses, and policy regulations regarding sky gardens and sustainability. Second, it examines sky gardens' spatial characteristics in terms of form (morphology, typology, size, affordances, configuration), openness quality (accessibility, ownership, permeability), and geometry (open space ratio, height of space-to-building, void-to-solid ratio, shape index). Third, the research compares the findings in three case cities and discusses their potential to support urban sustainability. The results suggest that despite the limitations of sky gardens, they may play, to different degrees, fundamental roles as open public spaces in high-density urban environments supporting cities' sustainability. High-density environments offer more opportunities for the sustainable development of sky gardens, which creates a new spatial paradigm for compact vertical greenery in high-density cities.

**Keywords:** sky gardens; public spaces; sustainability; high-dense cities; spatial characteristics



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## 1. Introduction

With the rapid urbanization process, the investigation of environmental sustainability is a critical issue in fostering sustainable social development [1]. The availability and accessibility of public spaces in dense urban settings are fundamental to promoting sustainability in dense urban environments, such as Asian cities, where public spaces have been drastically shrinking in the last decades [2]. Urban sustainability contains various aspects. According to existing studies, people widely consider urban sustainability as a coordinated development among three main systems: economic, social, and environmental [3]. This research understands sustainability as the ability to maintain or support the livability and well-being of cities over time through three perspectives. It is undeniable that urban sustainability is not limited to the three aspects described in this paper.

Fueled by the importance to adapt the public spaces to the impacts of urbanization and population expansion, there is presently a concern in increasing the know-how on the adaptation of the alternative public spaces to the substantial increase in socio-environmental implications brought by high-density urban environments. The chances created for people to be engaged in daily activities in public spaces should deal with the extent to which occupants can fit their personal requirements with the densification of urban environments.

Built environment designers and city governments put particular emphasis on integrating open spaces into the cities through various strategies such as by adding sky gardens,

sky terraces, vertical parks, and green facades in high-rise buildings. Among them, sky gardens emerged as a new spatial paradigm for developing compact vertical greenery in dense cities. Sky gardens are potentially alternative open and green spaces located above ground level, on intermediate floors, and rooftops [4–6].

Sky gardens may potentially support urban sustainability from the environmental, social, and economic aspects. They contribute not only to climate change but can also offer new (semi-)public spaces for communities with limited public spaces due to high population density, high land values, or similar factors [7]. They integrate the vertical public realm, landscaping, and community facilities [8], and are scattered in high-rise buildings to bring recreational activities closer to the occupants [9]. In addition, sky gardens establish a branding effect for buildings and whole districts within growing location competition, increasing the rental prices and saleable areas of adjacent buildings [10].

The benefits of sky gardens are manifold, and people do perceive to obtain certain benefits from sky gardens in urban areas. However, not enough studies address the spatial characteristics of sky gardens, which would help to analyze their potential to maintain or support the livability and well-being of cities, and there are no adequate guidelines that promote sustainable development of sky gardens. As alternative public spaces, sky gardens can increase community cohesiveness in high dense cities. Sky gardens can offer valuable green open spaces in dense cities to provide a precious alternative to supplement the shortage of public space at the ground level [11,12].

This study studies sky gardens as potential public spaces to promote urban sustainability. It focuses on the spatial characteristics of sky gardens to explore the threshold range (based on the quantitative spatial analysis) of their sustainability as alternative public spaces at the effects of urban densification. The study focuses on three Asian cities: Hong Kong, Shenzhen, and Singapore. Forty-four high-rise buildings with sky gardens (totaling 982) have won worldwide and widespread attention for their achievement in introducing open green spaces into dense urban environments. Then, based on the conceptual framework, intensity context, spatial form, public attributes, and geometric characteristics of sky gardens are evaluated, and their significant factors in sustainable development are identified.

The paper is organized as follows. Following the introduction, it presents a literature review on sky gardens and their potential role in supporting urban sustainability. After the section on methodology, the paper presents the fieldwork and research findings. It concludes by discussing the potential of sky gardens to promote sustainable cities.

## 2. Sky Gardens as Public Spaces for Sustainable Dense Cities

In dense urban environments, such as Asian cities, achieving sustainable urban development is a challenge. Although dense urban planning and development has been the preferred response to development challenges [13], it also exacerbates problems in terms of economic, environmental, and social sustainability: (1) The environmental dimension, including the related loss of open green spaces [14], pollution, increased energy consumption, resource depletion, and toxic waste disposal [15]; (2) The social dimension challenges are mostly related to public physical and mental health, such as poor housing and working conditions, saturated transport networks, endemic congestion, social density, social isolation, and social inequality [16,17]; and (3) Economic goals remain intrinsically central to urban sustainability [13], while environmental and social sustainability face challenges that require economic benefits to feed into environmental and social matters to some extent.

Sky gardens appeared as a crucial element of urban fabric in sustainable urban development debates [12,18,19]. Sky gardens are a form of open public space located above ground level and integrate the vertical public realm, landscaping, and community facilities into architecture to enhance livability [6,8,20]. The dense urban form has inherent physical, social, and institutional constraints to the achievement of sustainability in urban green spaces [21,22]. Sky gardens are an effective strategy to counteract the negative effects of urban sprawl and expansion [23] from environmental, economic, and social aspects.

Regarding the environmental perspective, sky gardens present the advantage of alternative green spaces [23,24]. Sky gardens can reduce rooftop temperatures and pedestrian-level air temperatures through vegetation shading and evaporation, provide feasible strategies for mitigating urban heat islands, improve neighborhood microclimates, and enhance human thermal comfort [25–28]. Vertical greenery systems are a key element in addressing noise pollution [29] and can improve air quality and reduce respiratory diseases [30]. Sky gardens enhance the natural ventilation performance of adjacent spaces [31], reduce urban rainfall runoff [32] and carbon dioxide emissions [33], and improve the quality of roof runoff water [34] and the overall biodiversity of the urban environment [35].

From the social perspective of sustainability, sky gardens provide transitional, social, and environmental greenery spaces to their occupants [36], improve the overall performance of buildings [37,38], and ultimately benefit urban habitats [4,5]. Sky gardens integrate the vertical public realm, vertical landscaping, and vertical community facilities [8] and scattered in high-rise buildings bring recreational activities closer to the occupants and provide convenient access [9], which has considerable potential as an alternative strategy for recreational effects on occupants' health, attitudes, and perceived stress levels [39,40].

Sky gardens' economic benefits are reflected mainly in the benefits of energy savings, emissions reduction, and indirect income generation [41,42]. Green roofs offer an extension of roof life, reduce maintenance costs [43], strengthen thermal insulation performance, and consequently reduce cold production energy consumption and operating costs [44]. They even increase rental prices and saleable areas of adjacent buildings because a sky courtyard improves the living environment, thus endowing a building with enhanced economic significance.

Urban design and architecture literature has explored spatial characteristics related to sky gardens' various aspects. Previous studies have studied the spatial characteristics of sky gardens in terms of type, design typology, open spaces' attributes, urban form, and the high-rise buildings in which sky gardens are located. Depending on the location, the types of sky gardens are classified as roof gardens, podium gardens, and gardens at the intermediate level of the building [18,45]. To be combined with the refuge floor to form the layout of the space is typical of sky gardens' design typology [45,46]. The land use, building area, and building story types have great effects on the development of sky gardens. The age of urban development has little impact on sky garden areas [21], but the land uses have higher potential for sky gardens in commercial, residential, and comprehensive development areas [12,18]. Sky garden areas are influenced by the dense urban development mode and the location of the sky gardens [12,21]. The building area has the most significant effect, building height has the least effect on a roof garden, and the effects of building story types is not currently apparent. As the open space properties of sky gardens have been demonstrated, affordance and functional attributes play an important role, among which spatial behaviors such as relaxation, leisure, play, and exercise are predominant [4,20,45]. Spatial function is the main attraction, and connectivity to sky gardens is crucial [12,18]. In addition, the visual access to the sky garden also has a positive impact in promoting healthy lifestyles and emotional experiences for the users [18].

However, there is a lack of systematic and comprehensive assessment of the sustainable performance of sky gardens implemented in dense urban environment [12], and studies proposing strategies to overcome the development constraints of sky gardens are also scant [21]. The literature review indicates that current research on high-rise sky gardens primarily focuses on individual evaluation of design, environment, behavior, and social factors.

### 3. Methodological Approach

The research investigates the relations between urban form, building factors in which sky gardens are located, and different spatial characteristics. For this, the research studies the high-rise buildings intensity characteristics, spatial qualities of sky gardens (form characteristics, public attributes, geometric characteristics), and evaluates the crucial factors

affecting the sky gardens' sustainable performance and effectiveness. It then provides information that can inspire decisions about planning developments continuation, expansion, reduction, or termination.

### 3.1. Data Collection and Processing

Using integrated methods (descriptive analysis and relation analysis) to demonstrate the sky gardens' spatial characteristics, utilization, sustainability, and performance in high-rise buildings through a comparative study of sky garden cases in Hong Kong, Shenzhen, and Singapore, (1) SPSS is used in descriptive analysis to characterize several aspects of sky gardens, including high-rise buildings' density characteristics (intensity of construction, height, functionality, and energy efficiency), sky gardens' form characteristics (type, configuration, and affordance), openness attributes (accessibility, privateness and permeability), and geometric characteristics. (2) Grey Relation Analysis is used to find the correlations between the aspects of sky gardens, in order to understand the primary variables influencing the sustainable growth of sky gardens.

The study focuses on sky gardens in Shenzhen, Hong Kong, and Singapore. The selection criteria for the sky gardens are: (1) the buildings in which the sky gardens were located are high rise; (2) the high-rise buildings are located in dense urban environments; (3) the architectural projects received international and public recognition in terms of their success to introduce green public spaces into the dense urban fabric and their positive image and attractiveness among city inhabitants.

To answer the research questions, we followed the steps presented below.

#### 3.1.1. Formulate an Analysis Model

Formulate an analysis model that integrates elements across the previous research regarding green spaces and open/public spaces (Extend this in reference to Table 1).

#### 3.1.2. Data Collection

The sky gardens' spatial characteristics data based on the model from Shenzhen, Hong Kong, and Singapore. The high-rise building data were obtained from the Skyscraper Center database in the Council on Tall Buildings and Urban Habitat (CTBUH), ArchDaily, Dezeen, and other architectural design websites. The sky gardens' form characteristics data and public characteristics data were obtained based on virtual built environment audits (Google Street View) and field researches. The sky gardens' geometric characteristics data were calculated and collected using CAD software based on architectural drawings, and some drawings with missing scales were verified by comparing with Google Earth.

**Table 1.** The spatial characteristic indicators of sky gardens.

Aspects	Indicators	Description
High-rise building characteristics	City	Hong Kong, Shenzhen, and Singapore.
	Year	Completion year of high-rise buildings with sky garden.
	Height	Buildings' height.
	Floor	Building story number.
	Function	Buildings' use function for occupants.
	Building Area	Total Gross Floor Area of building.
	Site Area	Site Area of building.
	PR	Plot Ratio (PR) determines the intensity of land usage and is the determinant in calculating the maximum Gross Floor Area (GFA).
	Energy Labels	Received awards of energy efficiency for understanding the development potential of sky gardens.

Table 1. Cont.

		Aspects	Indicators	Description
Qualities of Sky Gardens	Form characteristics	Type		Classification of sky gardens in high-rise buildings according to their height.
		Size Scale		Sky garden area.
		Configuration		The figure ground diagrams of sky garden on floor plan [36,45,47].
		Affordance		Space or place can afford the function for human activities [48,49].
	Openness attributes	Accessibility		Space supports the ability of different people to come and do many different things, and is an accessible node and place [50,51].
		Privateness		POPS are accessible to the public and available for individual or community activities. The private sector has played a role in shaping public space in the past [52,53].
		Permeability		The quality indicator that increases the value of space in terms of physical, functional, and perceptual characteristics [54,55].
	Geometric characteristics	OSR		Open Space Ratio (OSR) is the amount of non-built space at ground level per square meter of floor area [56,57].
		HSB		Height of Space-to-Building (HSB) measures the sky garden's relative height in high-rise buildings, with smaller values closer to the ground level.
		VSR		Void-to-Solid Ratio (VSR) is defined as the area of openings on the façade divided by the solid area of the façade [58] and has been described as the ratio of transparency to opacity, lightness to heaviness, or openness to enclosure (void/solid).
SI			Shape Index (SI) is the corrected Perimeter-Area Ratio (PAR) [59,60] that overcomes size-dependence by comparing the PAR to a standard shape [61].	

### 3.1.3. Analysis

The analysis adapts statistics analysis with SPSS to understand the existing situation from urban form, the building factors in which sky gardens are located, and different spatial characteristics, and using Grey Relational Analysis (GRA) to perform a quantitative analysis of the association between the variables of sky gardens. GRA is a quantitative analysis tool of grey system theory for analyzing the similarity and dissimilarity between a reference series and other series of the parameters [62]. It was employed to analyze the main factors such as building height, Gross Floor Area, Plot Ratio, garden area, and public attributes on the sky gardens. The process of the analysis includes: (1) normalizing the original data; (2) computing the absolute different values of the standard data from the mean; (3) calculating the grey relational coefficient; and (4) calculating the grey relational grade.

### 3.1.4. Synthesis

Explore the crucial characteristics affecting the sustainability and performance for providing useful strategies, approaches, and recommendations for sky gardens' planning based on the comparison and integration of the results of grey correlation analysis.

## 3.2. The Sites: Shenzhen, Hong Kong and Singapore

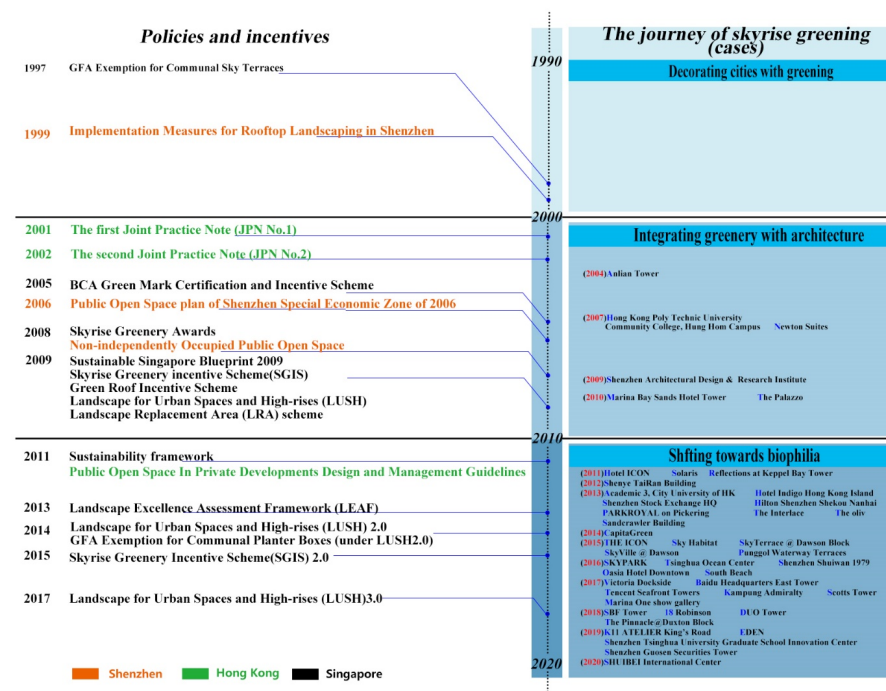
Shenzhen, Hong Kong, and Singapore, as highly urbanized and densely populated cities with many high-rise buildings, have relatively good contexts, opportunities, and incentives for the development of sky gardens. The central district of Shenzhen has the highest population density (19,872 per km<sup>2</sup>), followed by Hong Kong (14,957 per km<sup>2</sup>) and Singapore (8076 per km<sup>2</sup>). Meanwhile, living area per person of Hong Kong and Shenzhen are less than 20 m<sup>2</sup>, and Singapore's park/green area per person is the highest with 7.9 m<sup>2</sup> (Table 2).



**Table 2.** Area, population, population density, urbanization, and related area per person of the center area in Shenzhen, Hong Kong, and Singapore.

City		Shenzhen	Hong Kong	Singapore
Center area		Futian district	Hongkong island	Central area
Area (km <sup>2</sup> )		78.66	80.72	132.7
Population density (per km <sup>2</sup> )		19,872	14,957	8076
Urbanization		100%	100%	100%
Area per person (m <sup>2</sup> /per)	Park/Green	5.6	2.7	7.9
	Living	19.7	15	30
Source		[63,64]	[65,66]	[67,68]

Over the last 20–30 years, these three cities have developed sky gardens in varying degrees to mitigate the conflict between open space and high-density urban environments (Figure 1). The sustainable development of sky gardens can be divided into three stages, from decorating cities with greening, integrating greenery with architecture, and shifting towards biophilia [69]. There are many examples of sky gardens in Shenzhen, driven by the concept of sustainable urban development. Indeed, Shenzhen’s sky gardens display vertical forms morphologically, but their spatial organization, utilization, and eco-effectiveness remain limited, which is in the preliminary stage of “integrating greenery with architecture” in the journey of the sky gardens. Hong Kong launched the Joint Practice Note No. 1 and No. 2 [70,71]; sky gardens become one of the design features of high-rise buildings by providing the basic requirements and fundamental principles. Singapore has developed into a high-density, vertical “city in a garden” with the widely adopted “vertical green space” model with public, quasi-public, and communal spaces in various high-rise buildings [72]. Singapore’s sky gardens have evolved to the stage of “shifting towards biophilia”, through the BCA Green Mark Scheme, Skyrise Greenery Incentive Scheme (SGIS) [73,74], Green Plot Ratio (GnPR), and Landscaping for Urban Spaces and High-Rises (LUSH) [75–77]. Singapore’s sky gardens offer opportunities to improve occupants’ health and well-being, and provide respite from the density of the urban environment.



**Figure 1.** Timeline showing the correlation between sky garden development and planning ordinances in Hong Kong, Shenzhen, and Singapore.

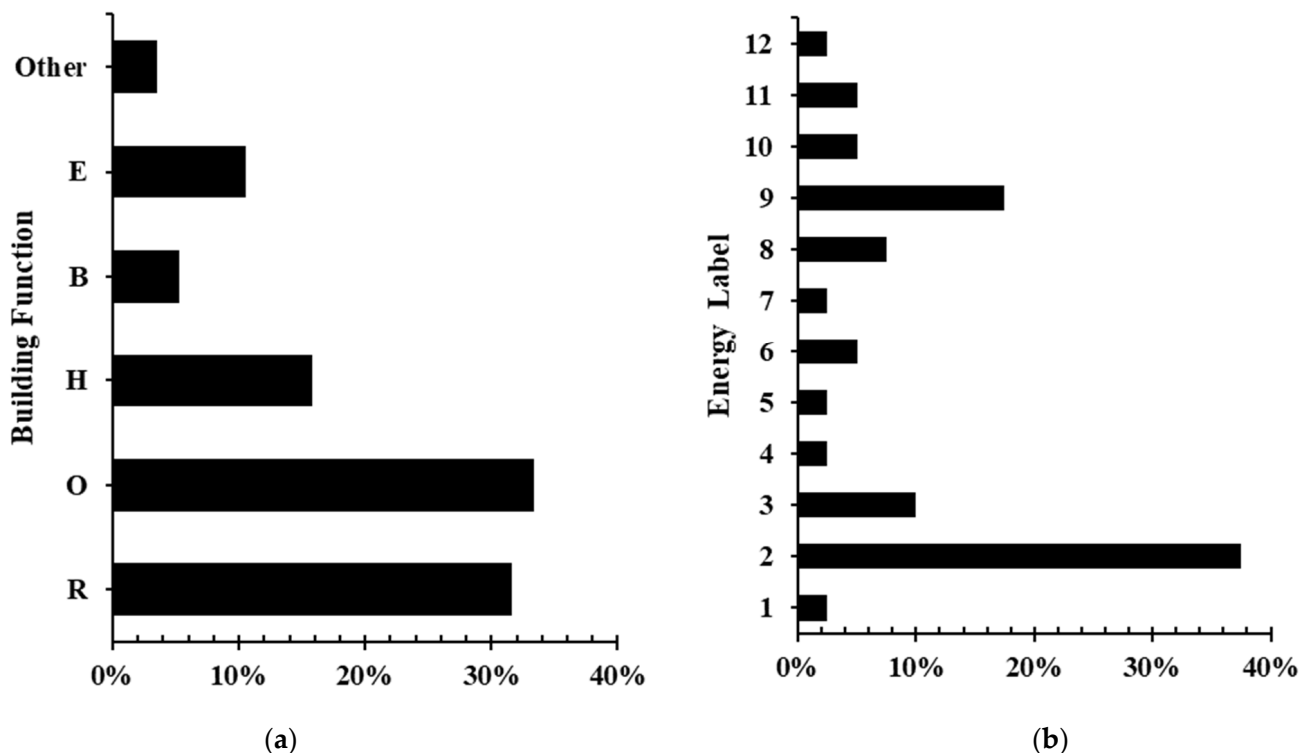
In the three cities, namely Hong Kong, Shenzhen, and Singapore, 982 sky gardens in 8, 14, and 22 high-rise buildings and 37, 247, and 698 sky gardens located mainly in the city center were selected as the study site, and the selection of cases focuses on the period since the beginning of the 21st century, particularly since 2010. It is an important period for sustainable urban development and the integration of sky gardens into high-rise buildings.

#### 4. Results

The following sections presents the fieldwork findings for (1) the high-rise building characteristics of where sky gardens are located, (2) the spatial quality of sky gardens according to form characteristics, openness attributes, and geometric characteristics (See Appendix A for the detailed indicator results), and (3) the association among the parameters to distill general hints, approaches, and recommendations for future sustainable planning of sky gardens in similar urban forms.

##### 4.1. High-Rise Building Characteristic of Sky Gardens

High-rise buildings, high density urban environments, provide the opportunity for the sustainable development of sky gardens. Sky gardens have been introduced into high-rise buildings since it was realized that the vertical green/open spaces are important complements for high density urban living. The intensity, height, and story of high-rise buildings that sky gardens are located in are generally high; PR of 5–12 accounts for 79.54%, with an average height of 149.43 m and 35.44 stories. Affected by the implementation time of the incentive, policy, and approaches, the main construction period is between 2014 and 2018. Furthermore, sky gardens mainly located in residential and office high-rises account for 64.90%, and the energy award is one of the most important features in high-rise buildings, especially the awards of BCA Green Mark (37.5%) and LEED (17.5%) (Figure 2).

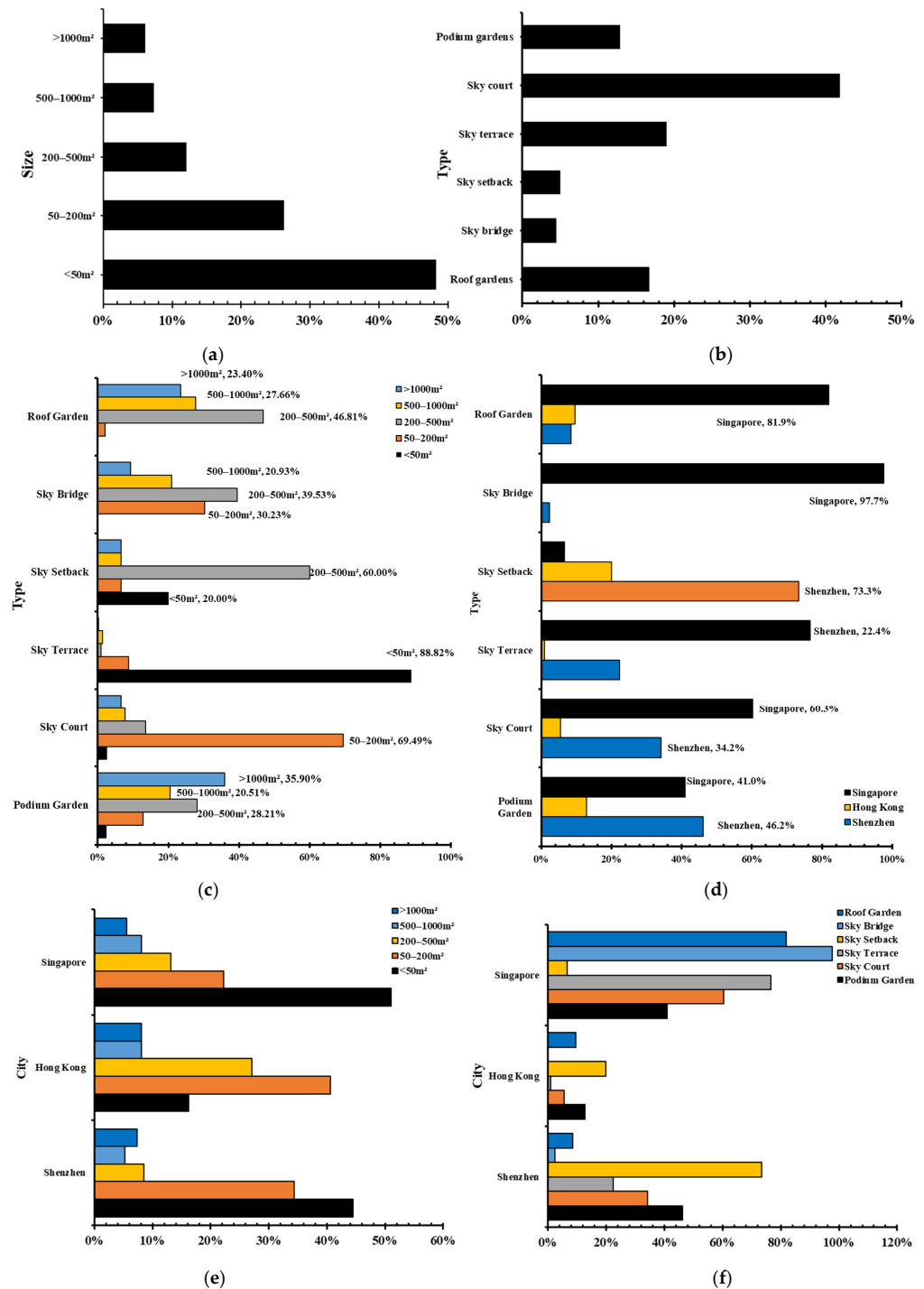


**Figure 2.** The diagram of high-rise building functions and energy label. (a) R, resident; O, office; H, hotel; B, business; E, education; other. (b) 1, Asia Pacific Green Building; 2, BCA Green Mark; 3, BEAM Plus Platinum; 4, EIC Sustainable Event Standards (Gold Level); 5, Excellence Skyrise Greenery; 6, Green Building; 7, Green Good Design; 8, Green Star; 9, LEED; 10, SGBC-BCA Sustainability; 11, SIA-NParks Skywise Greenery Award; 12, WELL Platinum.

## 4.2. Form Characteristic of Sky Gardens

### 4.2.1. Size Scale and Type

Figure 3 shows the type, size, and the difference of the sustainable development of sky gardens in Shenzhen, Hong Kong, and Singapore. As the usage areas are contested by high-rise building functional services and room for profit, sky garden areas are limited. The result showed that sky court typology accounted for the higher proportion (41.90%) and the mini scale (<50 m<sup>2</sup>, 48.27%) and small scale (50–200 m<sup>2</sup>, 26.27%) of sky gardens accounting for 74.54% in total.



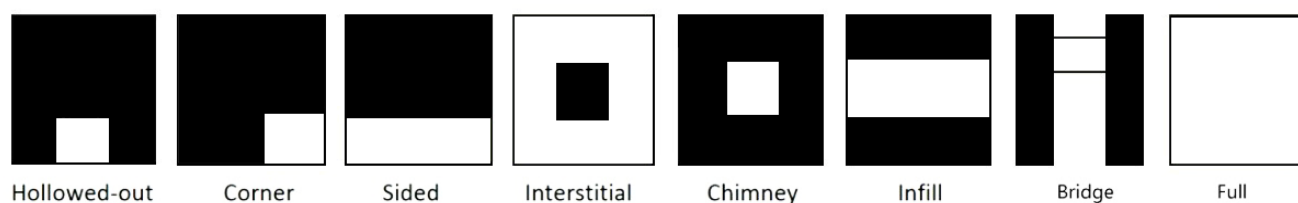
**Figure 3.** Percentage of sky garden areas and types (a,b), sky garden types for the size scale and cities (c,d), and the percentage of sky garden size scales and types by cities (e,f).



The differences in area between the sky garden types is significant. The podium gardens, roof gardens, and sky bridge are of relatively large scale ( $>1000\text{ m}^2$  and  $500\text{--}1000\text{ m}^2$ ), sky setback are mainly medium scale ( $200\text{--}500\text{ m}^2$ ), sky courts are predominantly small scale ( $50\text{--}200\text{ m}^2$ ), and sky terraces are mini scale ( $<50\text{ m}^2$ ). With the launch of some policies and incentives, the private real estate sector has also realized the importance of public space and greening space for image branding of buildings and whole districts within growing location competition. Thus, the flexible spatial types of sky gardens have some applicability in accommodating alternative uses to meet the more environmental, behavioral, and psychological needs of occupants in high-rise buildings.

#### 4.2.2. Configuration and Affordance

Common spatial configurations of sky gardens were extracted (Figure 4) through analyzing their plan prototypes based on the existing cases of sky garden. Figure 5 indicates that the sided prototype of sky gardens has the highest proportion in high-rise buildings, followed by configuration with hollowed-out and corner. Chimney prototypes have the lowest. Hollowed-out prototypes are dominant in Shenzhen, and Singapore has the most diverse configurations.



**Figure 4.** The common spatial configurations of sky gardens in high-rise buildings.

Sky gardens' affordance is distinctly hierarchical: (1) nature; (2) recreation, socializing, sightseeing; and (3) transition, entertainment, and exercising. Besides, the affordance of nature is concentrated in mini-scale sky gardens; small-scale sky gardens are the most flexible and contain varieties of functions to encourage usages and activities; the upper-medium and large-scale sky gardens can be beneficial in terms of entertainment and exercising activities. The differences in affordance among cities are insignificant, except for Shenzhen, in which the gardens are comparatively less endowed.

#### 4.3. Openness Attributes of Sky Gardens by Cities

Figure 6 shows the accessibility, privacy, and permeability for the development of sky gardens. Permeability is the highest public attribute, where interaction is enhanced by great openness through providing some visual guidance of sky gardens into high-rise buildings. The difference in public attributes among sky garden types are insignificant—permeability  $>$  privacy  $>$  accessibility—except for the sky terrace. Sky gardens have been influenced by the originally intended design of Privately Owned Public Space, which does not encourage use by outsiders and seems to cater only to the users who live/work in the complex [78]. Thus, the spatial type has little effects on public attributes in most sky gardens except for the sky terrace.

Singapore's sky gardens present more varied and higher spatial qualities than Shenzhen and Hong Kong, as shown in Figure 7. Among them, Hong Kong PTUCC Hung Hom Campus (9.00), Shenzhen Architectural Design & Research Institute (9.00), Scotts Tower (8.33), and The Oliv (8.03) record the higher overall scores (Figure 8).

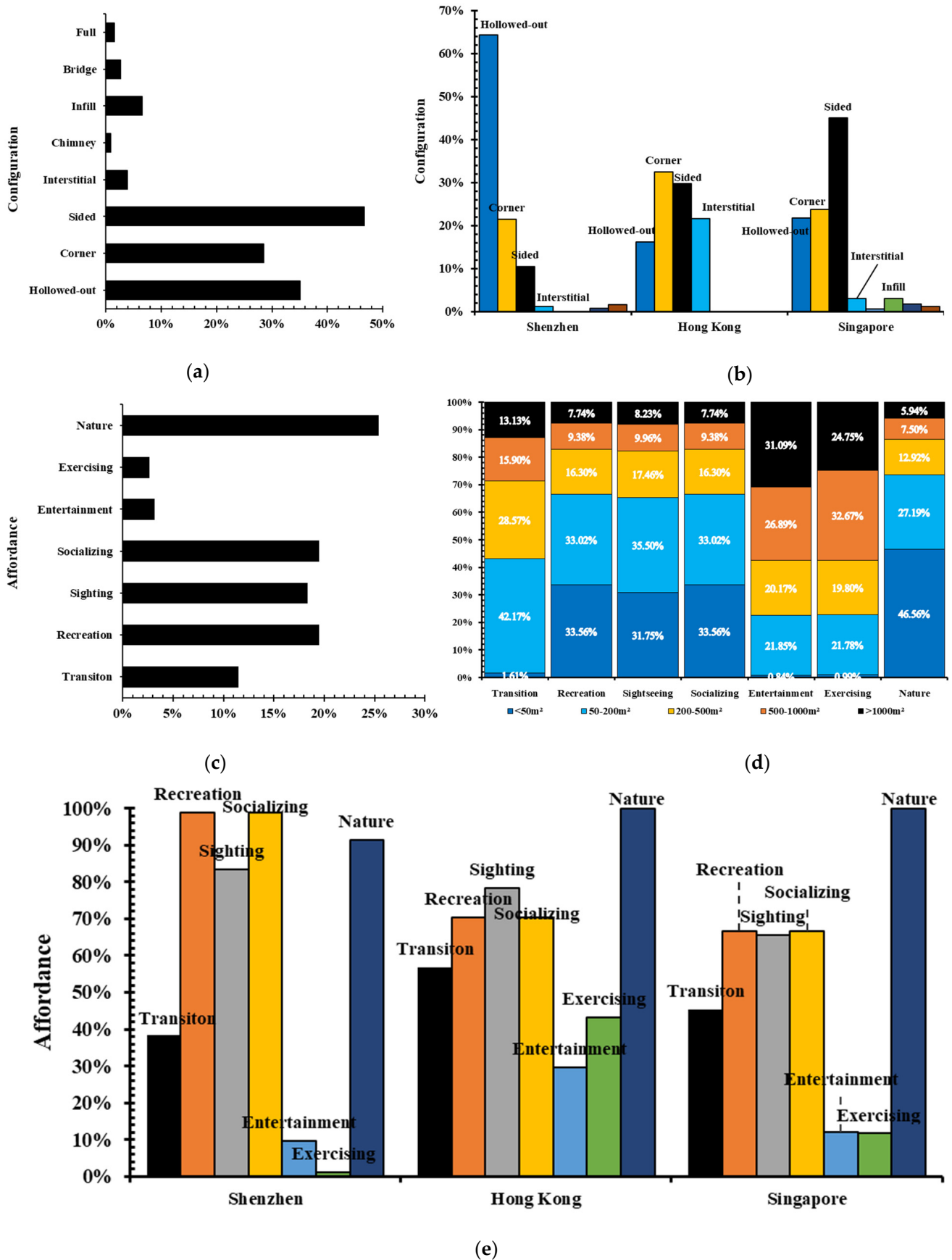


Figure 5. Configuration (a,b), affordance (c,d) characteristic of sky gardens and their correlation (e).

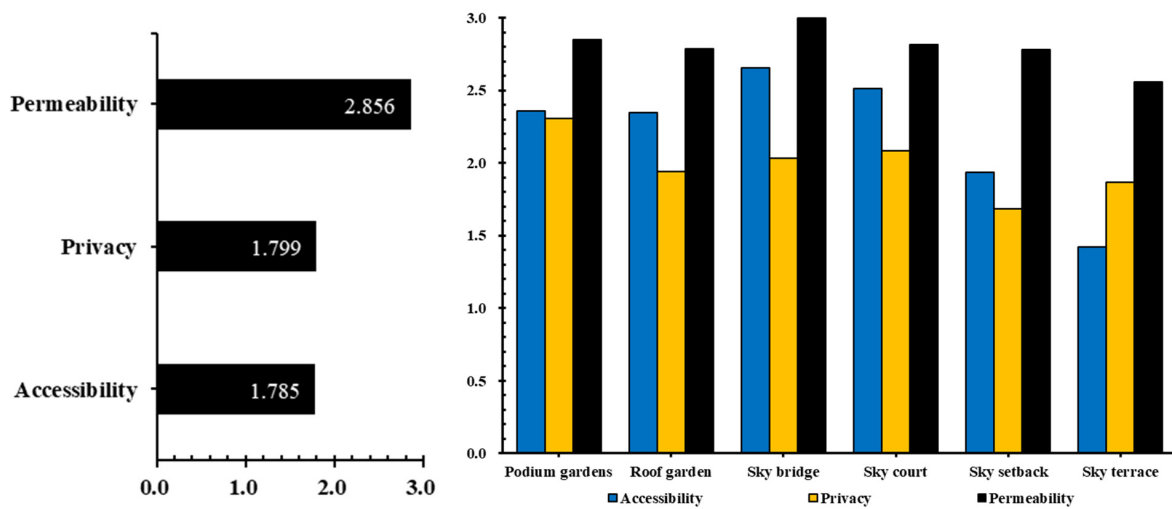


Figure 6. The sky gardens’ openness attribute characteristics.

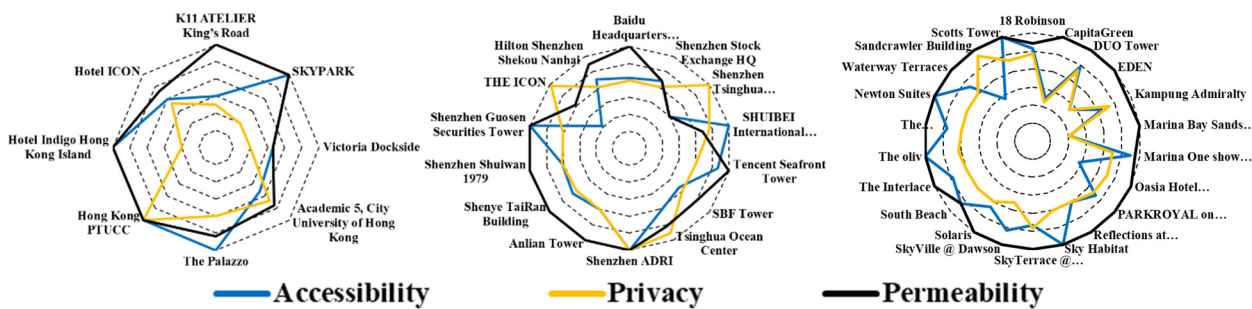


Figure 7. The radar diagram of sky gardens organized by accessibility, privateness, and permeability in Hong Kong, Shenzhen, and Singapore.



Figure 8. The highest score of sky gardens in the assessment (from the left: Hong Kong PTUCC Hung Hom Campus; Shenzhen Architectural Design & Research Institute; Scotts Tower; The Oliv).

#### 4.4. Geometric Characteristic of Sky Gardens

The geometric characteristics reflect that sky gardens are mostly located away from the ground, with low spatial coverage, poor visibility, and linear ribbon shapes. Figure 9 shows: (1) Sky gardens’ OSR is less than 10%, accounting for 74.7%, which restricts the usage of open space in the vertical realm by occupants; (2) The height locations of sky gardens are mainly concentrated in the high-medium zone; (3) A W-shaped distribution of sky gardens’ VSR (peak interval 0–0.2 (44.5%), 0.5–0.6 and 0.9–1.0); (4) Sky gardens have relatively high SI (SI value is 1.0 for a perfect circle, 1.128 for squares, 1.286 for square triangles), indicating the spaces are long, skinny polygons.

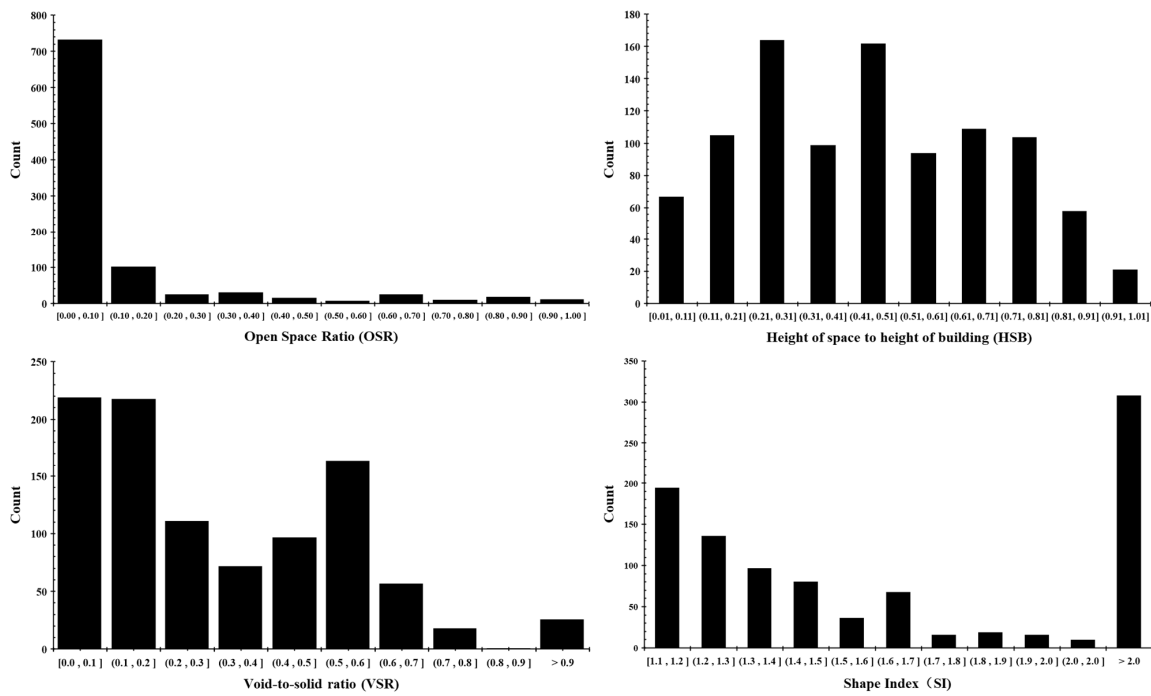


Figure 9. The distribution histogram of the sky gardens’ geometric characteristics: OSR, HSB, VSR, and SI.

#### 4.5. Factors on Development of Sky Gardens

Under the influence of high-density urban form, the development stage and concept of sky gardens, the sustainable development of sky gardens, is affected by different factors. The analyses of grey relation grade (Figure 10) indicate that (1) the factors about high-rise buildings intensity (site areas, GFA) have an important effect on sky gardens’ sustainability and performance, (2) and among the factors influencing the quality of sky gardens, size scale has the most significant effect, followed by VSR, OSR, and configuration. In contrast, located city, constructed year, and permeability relatively have little influence on the sky gardens’ sustainability.

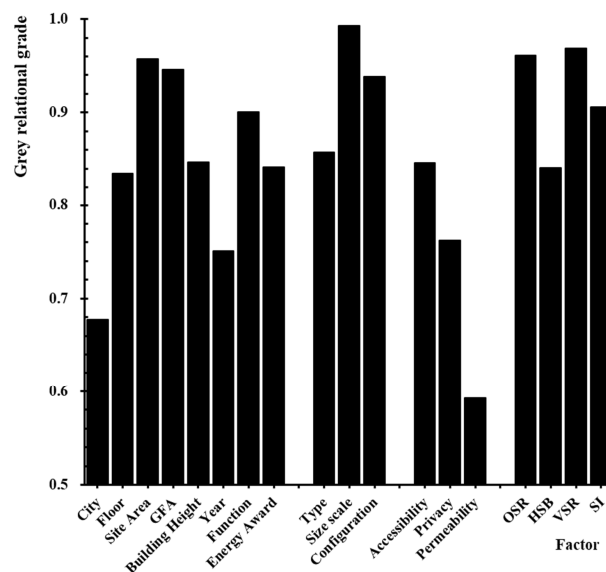


Figure 10. Grey relational grades (calculated from Gray Relational Analysis) between high-rise building intensity characteristic, qualities of sky gardens in terms of form characteristics, openness attributes and geometric characteristics and the factors.

### 5. Discussion and Conclusions

#### 5.1. Government-Led Management and Control Measures Play an Important Role

The costs of sky gardens pose one of the biggest barriers for implementation. Governments can implement various types of instruments in sky garden policies, through direct/indirect financial incentives, regulations, communication, and information provision and leading by example. The government of Hong Kong, Shenzhen, and Singapore have enacted numerous measures to improve the conditions of vertical green spaces in high density cities. Compared with sky garden construction in Shenzhen and Hong Kong, Singapore’s policies are comprehensive and clear. There are both macro planning objectives and micro control indicators [73,79,80], both mandatory regulations and guidance initiatives [73,74,76,77,81]. In terms of management and operation mechanisms, Singapore has multiparty collaborations and orderly construction management. The joint participation of many departments, clear construction management procedures, power and responsibility, and supervision involve good operability and are highly effective (Figure 11). Government-led management and control measures play an important role in the conduct and intervention of sky gardens.

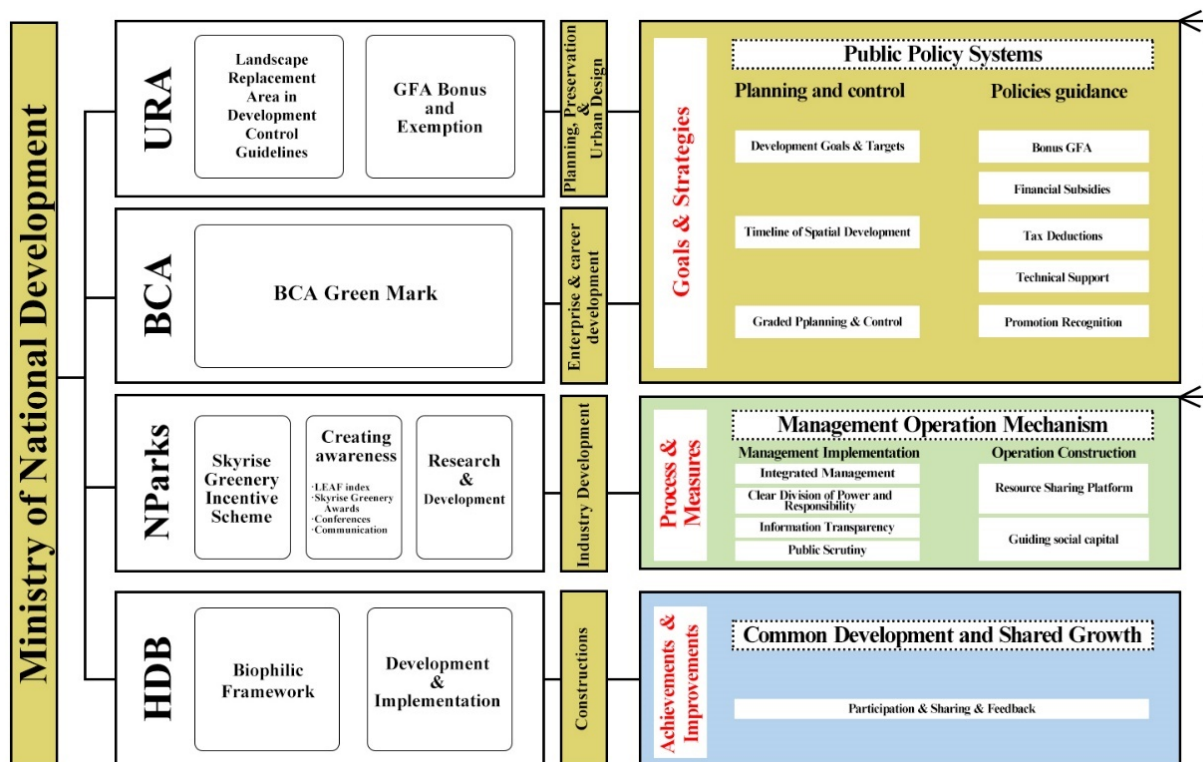


Figure 11. An overview of the Singaporean government agencies and management mechanisms for skyscraper greening.

#### 5.2. High-Density Urban Environment Provides More Opportunities to Create Compact Vertical Greenery

This research studied the context of SGs in high-density urban environments, general information on high rises with SGs and SGs’ qualities regarding spatial, openness, and geometric characteristics. The peak construction period for SGs in high-rise buildings was between 2014 and 2018; PR > 8 accounts for 72.73%, and several buildings received more than one energy label, reflecting the importance of SGs as open spaces and green areas for the public in a high-rise, high-density environment. These research results corroborated previous studies showing that higher building density provides more opportunities for development [82] and creates a new spatial paradigm for compact vertical greenery in high-density cities [10].



### *5.3. Sky Gardens Are Complementary to the Green Space on the Ground for Foundational Activities*

The spatial characteristic results show that sky gardens are complementary to the green space on the ground for foundational activities rather than precisely replicating and replacing them [12]. Sky gardens, as open green spaces in the vertical realm, have small scale, high permeability, and natural functions and provide fundamental recreational activities for occupants in high-rise buildings. Sky gardens are mainly sized on a mini scale (<50 m<sup>2</sup>) and small scale (50–200 m<sup>2</sup>) and can be considered similar to miniparks or pocket parks [83], which are more suitable for daily and stop-over recreational activities for occupants. The configuration and permeability of sky gardens both indicate high openness, which is more conducive to green spaces integrated with the building interior and urban environment to provide livable urban habitats for citizens. Nature (97.76%) is the most typical affordance of sky gardens, indicating that it is an important functional representation of urban green space systems in high-rise buildings. Leisure is the most dominant spatial activity in sky gardens, including recreation (74.95%), socializing (74.95%), and sightseeing (70.57%), indicating that sky gardens' spatial identity is green spaces used for routine relaxation.

In terms of sky gardens' openness, the order is permeability > accessibility > privateness. Sky gardens' privateness is relatively high and may have been influenced by the originally intended design of POPS; they do not encourage use by outsiders and seem to cater only to users who live/work in the complex [78]. However, sky gardens still provide alternative open spaces and, to some extent, mitigate the lack of public spaces caused by dense cities.

Moreover, the geometric characteristics reflect that sky gardens are mostly located away from the ground, with low spatial coverage, poor visibility, and linear ribbon shapes. Although the open space ratio in the sky is not clearly defined, sky gardens' OSR is less than 10%, accounting for 74.7%, which restricts the usage of open space in the vertical realm by occupants. Previous research has shown that tall buildings' lower public spaces impact the health and behavior of the public in the street [84,85], but the association between the vertical position of sky gardens and occupants' spatial perception and preferences in tall buildings is not yet clear.

### *5.4. Size Scale, Configuration and Accessibility Are the Crucial Factors for the Sky Gardens Sustainable Development*

Based on the result of Grey Relation Analysis, it was found that there are differences in the association of factors affecting the sustainability of the sky gardens. Specifically, a sky garden is an alternative strategy to increase the outdoor living environment and a solution for inadequate ground-level land. High-rise buildings and dense urban environments can provide more opportunities for sky garden development through creating a new spatial paradigm for compact vertical greenery in high-density cities [10]. Size scale, configuration, and accessibility are the crucial factors for the sky gardens' sustainable development. The location of sky gardens and their familiarity to occupants can also be attributable to this behavior [12]. Accessibility is one of the key factors in sustainable development, enhancing the interactive behavior of occupants as a complementary to green spaces on the ground for foundational activities. When openness and accessibility are not given enough attention, people do not have the freedom to experience and practice sky gardens, even though social infrastructure is provided [18].

### *5.5. Limitations and Future Research*

In high-density urban environments, sky gardens have become prevalent, and their spatial forms are considerable. The COVID-19 pandemic highlights the importance of contact with green spaces for the ability of communities to cope with the stress of the threat, and the role of these spaces as alternative places for physical activity and social interaction [86]. High-density urban environment has spawned more privately owned



public spaces (POPS) that become an important part of the urban open/green space system in compact cities [20,21,87]. Meanwhile, a sky garden is an architectural solution for buildings and part of the urban green infrastructure network and an integrative Nature-based Solutions (NBS) strategy to adapt to urban sustainable development [88]. Although it has been proven that the presence of vegetation and facilities [45], visibility and accessibility [12], stringent rules and stewardship [12,18], and restoratives [85] can impact people's perceptions of and preferences for sky gardens, research on the impact of sky gardens' spatial forms is scarce. This paper has further clarified that a high-density urban environment provides more opportunities for sky garden development, which in turn creates a new space paradigm for compact vertical greenery in high-density cities. In addition, sky gardens provide fundamental recreational activities for occupants. Sky gardens are complementary to green spaces on the ground with foundational activities, rather than precisely replicating and replacing them.

The approach does have certain drawbacks. Cases were chosen based on their influence (widely known, awards, etc.) rather than equal samples in cities to effectively extract the relevant information regarding typical sky gardens, which may undermine the comparative results of sky gardens at the city level. It was inevitable that more sky gardens from Singapore would be chosen because they have shown to be more successful than Shenzhen and Hong Kong. Furthermore, the difference in major functions of high-rise buildings have some influence on the outcomes that require detailed further examination of their features. Sky terraces, for example, are more widespread in residential typologies than in offices, while roof gardens are popular in hotel buildings. This information is helpful for further understanding the spatial attributes and performance of sky gardens in various high-rise building functions.

Our research will continue further on the basis of this paper. First, more in-depth fieldwork should be carried out to confirm the sustainability findings of sky gardens. Furthermore, detailed environment–behavior studies should be conducted to understand the perceptions, requirements, and expectations of sky gardens by occupants. It is important to explore which aspects of open space at ground level could be substituted by sky gardens. To establish connections with ground-level green/open spaces, we should enhance their openness, permeability, accessibility, and availability through spatial interventions and investigate the effects. In order to further determine the spatial value, spatial perception, and user satisfaction of sky gardens in high-density urban habitats, new technologies and data [89] can be used to explore the multiple properties of sky gardens and the correlation with occupant perceptions, such as smart devices, wireless sensors, systems, social network, etc. Third, the mutual effect of open spaces and public perception of sky gardens should be clarified, an environment–behavior bidirectional relationship for vertical open green spaces should be built, and the optimal mechanism for sky gardens should be defined depending on people's preferences.

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## Appendix A. Results of the Indicators Related to the Sky Garden

**Table A1.** Results of descriptive analysis of indicators related to sky gardens.

Indicator	Description of Indicator	N	Mean	S.D.	Variance
City	1 = Shenzhen; 2 = Hong Kong; 3 = Singapore	982	2.46	0.87	0.75
Floor	Floor of the high-rise building	982	35.44	14.55	211.72
Site Area	Site Area of the high-rise building	982	20,150.88	27,061.56	78,129.98
GFA	Gross Floor Area of the high-rise building	982	13,628.49	49,333.52	501,529.03
Building Height	Height of the high-rise building	982	149.43	57.38	3292.32
Year	Contributed year of the high-rise building	982	2014.34	3.84	14.74
Type	1 = podium gardens, 2 = sky courts, 3 = sky terraces, 4 = sky setbacks, 5 = sky bridges, 6 = roof gardens	982	3.03	1.22	1.49
Size	Sky garden area	982	277.17	773.34	98,059.70
Configuration	1 = hollowed-out space, 2 = corner space, 3 = sided space, 4 = interstitial space, 5 = chimney, 6 = infill space, 7 = bridge space, 8 = full space	982	2.34	1.37	1.87
Accessibility	1 = low, access from inside the space; 2 = medium, access via public spaces; 3 = high, direct access via stairs and lifts	982	1.79	0.76	0.58
Privacy	1 = low, used by the public; 2 = medium, used by residents or staff (communal); 3 = high, privately owned	982	2.20	0.66	0.43
Permeability	1 = low, not openness to cities and buildings; 2 = medium, openness to cities or buildings; 3 = high, openness to cities and buildings	982	2.86	0.41	0.17
Floor Area	Floor area where the sky garden is located	982	2645.15	2407.80	97,488.88
OSR	$OSR = \frac{\text{Sky garden area}}{\text{Total floor area}}$	982	0.12	0.21	0.04
Located Height	The sky garden's Located Height	982	67.13	44.94	2019.20
HSB	$HSB = \frac{\text{Sky garden located height}}{\text{Building height}}$	982	0.46	0.24	0.06
Façade Area	Sky garden Façade Area	982	157.53	262.41	68,859.55
Floor Façade Area	Floor Façade Area where the sky garden is located	982	546.75	706.85	499,636.59
VSR	$VSR = \frac{\text{sky garden Façade Area}}{\text{Floor Façade Area}}$	982	0.33	0.27	0.07
Perimeter	Sky garden perimeter	982	83.71	79.07	6251.77
SI	$SI = \frac{\text{perimeter}}{\sqrt{4\pi A}}$	982	1.20	1.11	1.23

**Table A2.** Multiple Response Output of building function, energy label and sky garden affordance.

	Indicator	N	Response Rate	Percent of Cases
Building Function a	Resident	18	31.6%	40.9%
	Office	19	33.3%	43.2%
	Hotel	9	15.8%	20.5%
	Business	3	5.3%	6.8%
	Education	6	10.5%	13.6%
	Other	2	3.5%	4.5%
	Total	57	100.0%	129.5%
Energy Label	Asia Pacific Green Building	1	2.5%	3.6%
	BCA Green Mark	15	37.5%	53.6%
	BEAM Plus Platinum	4	10.0%	14.3%
	EIC Sustainable Event Standards	1	2.5%	3.6%
	Excellence Skyrise Greenery	1	2.5%	3.6%
	Green Building	2	5.0%	7.1%
	Green Good Design	1	2.5%	3.6%
	Green Star	3	7.5%	10.7%
	LEED	7	17.5%	25.0%
	SGBC-BCA Sustainability	2	5.0%	7.1%
	SIA-NParks Skywise Greenery Award	2	5.0%	7.1%
	WELL Platinum	1	2.5%	3.6%
	Total	40	100.0%	142.9%
Sky Garden Affordance	Transition	433	11.5%	44.1%
	Recreation	736	19.5%	74.9%
	Sighting	693	18.3%	70.6%
	Socializing	736	19.5%	74.9%
	Entertainment	119	3.1%	12.1%
	Exercising	101	2.7%	10.3%
	Nature	960	25.4%	97.8%
	Total	3778	100.0%	384.7%

a. Dichotomy group tabulated at value 1.

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