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Natural ventilation as a passive cooling strategy for multi-story buildings: analytic vertical skycourt formations

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Abstract

Natural ventilation has been one of the most important passive cooling strategies for conditioning the built environment. However, several challenges influence natural ventilation in multi-story buildings. Consequently, skycourt presents a passive cooling strategy to provide a direct airflow into the space to cool the surroundings, increase thermal comfort, and reduce the need for mechanical ventilation. Therefore, this study proposes utilizing the skycourt as a passive cooling strategy that helps to enhance natural ventilation in multi-story buildings. The aim of the research is achieved by analyzing various global examples of buildings, based on the skycourt, in different climatic zones; dry, tropical, temperate, and cold. These examples covered all classifications of multi-story buildings (e.g., mid-rise, high-rise, and skyscrapers). Through this analysis, the influence of skycourt in providing natural ventilation is determined, which contributes to reduce energy consumption. Finally, a reference matrix for designers and decision-makers in the four studied climatic zones can be conducted to promote natural ventilation using the skycourt strategy.

Highlights

- Improving natural ventilation contributes to the reduction of energy consumption in multi-story buildings.
- Skycourts have a significant impact on enhancing natural ventilation in buildings.
- The role of the skycourt in natural ventilation was verified by comparing international examples.

Keywords Passive cooling strategy, Multi-story buildings, Skycourt, Natural ventilation, Energy consumption

Introduction

Buildings contribute in a significant proportion to total energy consumption and emit a large proportion of carbon dioxide emissions worldwide (Abo EL Einen et al. 2019; Nejat et al. 2015; Zhang et al. 2022; Hassan et al. 2022; Shehata et al. 2022). Even if the proportions vary by country, the construction sector is responsible for approximately 30–40% of the total energy demand (Noaman et al. 2022; Abd Elraouf et al. 2022). About 40% of total building energy worldwide is consumed for heating, Ventilation, and Air Conditioning (HVAC) systems in the residential and commercial sectors (Elmokadem et al. 2016; Shahda and Megahed 2022; Hassan and Megahed 2022), which caused serious environmental problems. Thus, developing passive cooling strategies that reduce energy consumption, support the environment and the ecosystem, and provide a satisfactory degree of comfort presents an essential and critical need at this time (Shahda 2018; Elmokadem et al. 2019).

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Passive cooling is based on the transfer of energy from one space to another to reach a temperature lower than the surrounding environment (Geetha and Velraj 2012; Parys et al. 2012). Preventing heat from entering the building is the basic cooling principle of the passive cooling concept (Song et al. 2021; Elzeni et al. 2021). As shown in Fig. 1, passive cooling emphasizes three main strategies: heat prevention (reducing heat absorption), heat modulation (modifying heat gain), and heat dissipation (removing endogenous heat) (Song et al. 2021; Shahda et al. 2018; Mohammad Alinezhad 2019).

As shown in Fig. 1, natural ventilation is a passive cooling strategy that disperses heat and facilitates thermal comfort and a comfortable indoor environment, contributing to energy consumption saving (Seidabadi et al. 2019; Yao et al. 2018; Chen et al. 2019; Pan et al. 2019). The building form is a passive design strategy that prevents heat transfer. One of the most important forms of building in architecture in all climatic regions is the courtyard (Aldawoud and Clark 2008; Safarzadeh and Bahadori 2005). In this paper, "courtyard" refers to any open space surrounded by walls or buildings (Abo EL Einen et al. 2019). Courtyards present thermal barriers against the external climate because they reduce energy losses from surfaces in contact with the outside air and contribute to providing natural ventilation for internal spaces, which reduces energy consumption (Abo EL Einen et al. 2019; Taleghani et al. 2012, 2014).

Driven by the spread of multi-story buildings promoted by economic development, designers developed the traditional courtyard into an atrium (Muhaisen 2006; Meir et al. 1995). Atriums are spaces surrounded by walls but differ from courtyards in that atriums are covered with glass. Similar to courtyards, atriums provide significant benefits from natural ventilation (Zhao et al. 2022; Acred and Hunt 2014). The courtyard and the atrium were then designed to extend into the vertical plane of the multi-story buildings' facades creating the skycourt (Priyadarsini et al. 2004; Moosavi et al. 2015).

Skycourts are a contemporary alternative to courtyards for multi-story buildings. Skycourt allows natural light to penetrate deeper into interior spaces, enhancing ventilation while avoiding unwanted solar energy gain, and significantly reducing energy consumption, besides many benefits from a social and economic perspective (Yeang 1999).

The research aims to highlight the role of the skycourt in providing natural ventilation for multi-story buildings, which presents a significant gap in the literature through the following sections. A theoretical background on the skycourt and its role as a passive design strategy is discussed in the first section. In the second section, natural ventilation and its role as a passive design strategy are highlighted. Then, in the third and fourth sections, various global examples of buildings, based on the skycourts, in different climatic zones are analyzed and explained to identify their role in providing natural ventilation in four climatic regions, namely dry, tropical, temperate, and cold, for all types of multi-story buildings, mid-rise, high-rise, and skyscrapers. Then, the reference matrix is conducted to determine the interrelationship between; a) the skycourt as a passive cooling strategy and the four main types of climates, and b) the multi-story building types.

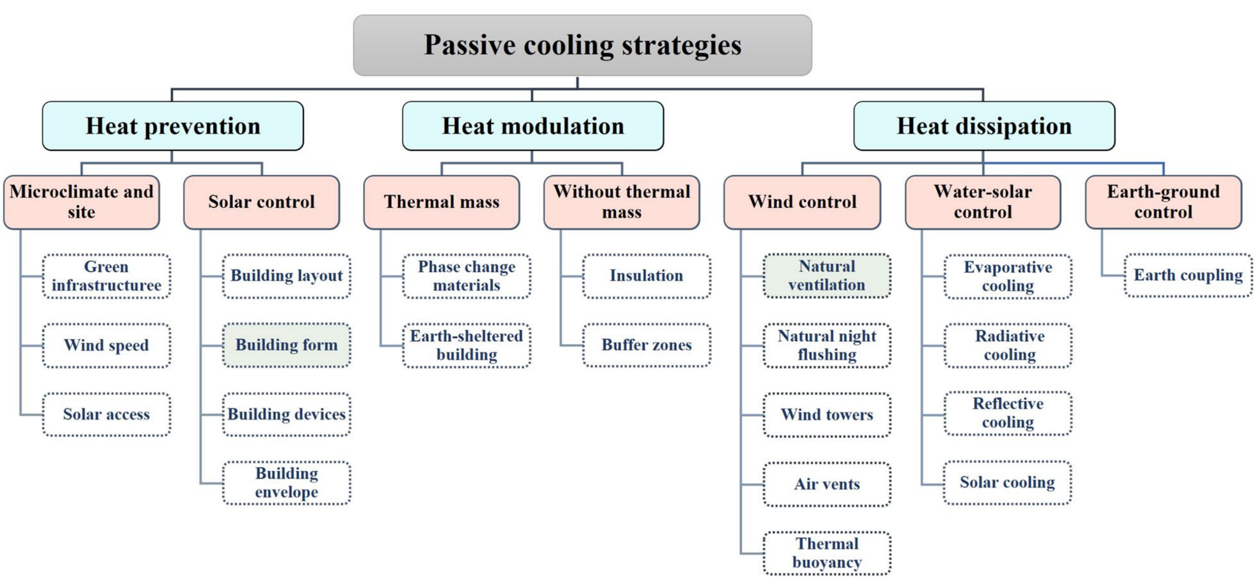


Fig. 1 Classification of passive cooling strategies, based on (Song et al. 2021; Mohammad Alinezhad 2019)

Finally, the final section presents the conclusion of this study.

Skycourts as a passive cooling strategy

Skycourts are increasingly included in multi-story buildings. Skycourts spaces serve as spaces for transition nodes and social gatherings, besides their environmental and economic benefits (Alnusairat 2018). This section aims to discuss the role of skycourt as a passive cooling strategy in multi-story buildings.

Development of the skycourt

The skycourt was developed from the principles of courts and atriums to enhance ventilation and capture daylight (Alnusairat 2018). Skycourts were featured in multi-story buildings between 1890 and 1930 as void layouts within U-, H-, E-, and O-shaped building plans. After the invention of air conditioning, the construction of multi-story buildings based on mechanical systems for air conditioning increased. However, after the oil crisis in 1973, new strategies emerged to reduce energy consumption for heating, ventilation, cooling, and lighting (Noaman et al. 2022; Shahda and Megahed 2022; Nashaat et al. 2022; Ismail et al. 2022, 2023; Elgheznawy et al. 2022). Thus, skycourts, as one of these environmental strategies, have been reintroduced to facilitate occupant interaction, provide daylight, and promote natural ventilation (Linden 1999; Al-Kodmany 2015).

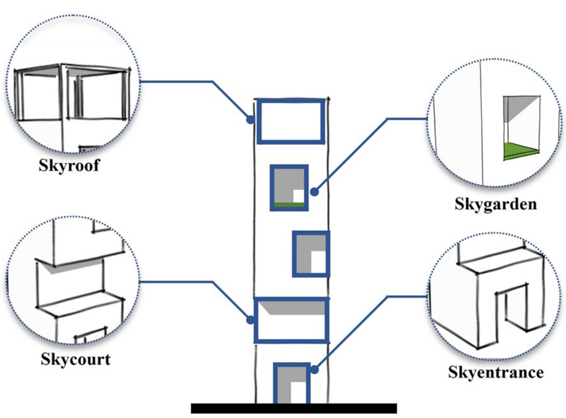


Fig. 2 Configurations of skycourts in multi-story buildings, based on (Alnusairat 2018; Pomeroy 2008)

Configurations of skycourts in multi-story buildings

As shown in Fig. 2, courts can be located in the lower part of the multi-story building as a skyentrance, between the middle floors as a skycourt or skygarden, or at the top of the building as a skyroof (Alnusairat 2018). These empty spaces can be two or more stories high, connected to the interior and exterior surrounding areas by open or closed walls (Pomeroy 2008).

Figure 3 shows an example of the spatial configuration of a skycourt categorized into six archetypes; (a) hollow space, the skycourt is connected to the outside air by only one edge, and the remaining walls are attached to the building edges, (b) corner space, the skycourt is connected to the outside air through two walls and the other two edges connected to the building, (c) lateral space, the skycourt is also connected to the outside air through two walls and the other two walls connected to the building, but the proportion of the skycourt is more elongated than the corner space model, (d) interstitial space, the building is in the middle of the skycourt area, (e) chimney, this case is the opposite of case d because the skycourt is in the middle of the building, known as the courtyard, and (f) filling space, also the skycourt in the middle of the building, but it spans the entire width of the building (Alnusairat 2018; Pomeroy 2008, 2013; Rabbat 2017).

Fundamental benefits of skycourts in multi-story buildings

Skycourt spaces have many benefits that make them one of the most important passive design strategies in this era. Their primary function is to serve as public and social spaces for multi-story buildings (Alnusairat 2018). These spaces are also used as transitional and heat-insulating zones and contribute to providing natural lighting and natural ventilation in the adjacent interior spaces, which helps to reduce the use of mechanical devices for lighting and ventilation, hence saving energy consumption, in addition to the benefits of skycourt

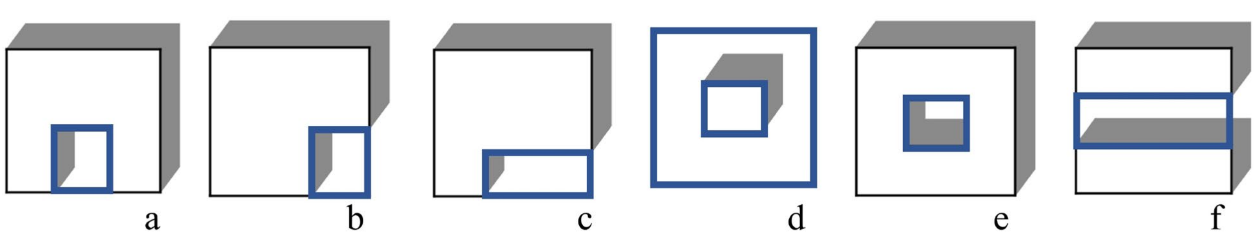


Fig. 3 The spatial configuration of skycourts in multi-story buildings (colored zone represents skycourt space; **a** hollow space, **b** corner space, **c** lateral space, **d** interstitial space, **e** chimney, and **f** filling space, based on (Alnusairat 2018; Pomeroy 2013, 2007; Cantón et al. 2014)

from an environmental, social and economic perspective (Alnusairat 2018; Pomeroy 2008). Table 1 illustrates the benefits of skycourt spaces in multi-story buildings from an environmental, social, and economic perspective (Pomeroy 2013; Jahnkassim and Ip 1988; Kuo et al. 1998; Bay 2004; Clements-Croome and Baizhan 2000).

Based on Table 1, this study emphasizes the analysis of global examples of skycourts in the context of the passive cooling design strategy, whereas skycourts act as a transitional space between the building spaces, in addition to an environmental filter that contributes to enhancing the natural ventilation and natural lighting of the building spaces. Moreover, it acts as an acoustic and thermal insulator, besides its role in enhancing social interactions and well-being, and this helps in improving productivity.

Natural ventilation of skycourt as a passive cooling strategy

Natural ventilation is one of the most effective passive cooling strategies and can provide building occupants with comfortable thermal conditions and a healthy indoor environment (Liping and Hien 2007; Awada et al. 2021; Hassan et al. 2020a). However, multi-story buildings are based on mechanical ventilation systems (Núñez and García 2022) instead of natural ventilation due to several challenges (Zhong et al. 2022), which influence energy consumption. Therefore, buildings, especially multi-story buildings, can become self-sufficient by returning to nature, avoiding negative impacts on the environment, and promoting natural ventilation in those buildings (Etheridge 2011; Hassan et al. 2020b).

Natural ventilation in buildings has three basic principles; single-sided ventilation, cross-ventilation, and stack-ventilation, which are applied in courtyards and skycourts (Aflaki et al. 2015; Walker 2010). In single-sided ventilation, fresh air enters the room, and used air is exhausted from the same side. In cross-ventilation, fresh air enters the room from one side and exits on the other through windows or openings built into the facades. In stack ventilation, fresh air enters through the lower-level openings and used and polluted air is discharged through the higher-level openings (Shirzadi et al. 2018; Ohba and Lun 2010; Wang et al. 2018). The strategy for natural ventilation in skycourts is based on cross and stack ventilation (Shirzadi et al. 2018; Ohba and Lun 2010; Wang et al. 2018).

Mixed ventilation refers to a hybrid approach to space conditioning that uses a combination of natural ventilation and mechanical systems that include air distribution equipment and refrigeration equipment for cooling. A well-designed mixed building begins with enhancing the role of natural ventilation by using passive design strategies to reduce cooling loads. It then incorporates the use of air conditioning when and where necessary, with the use of natural ventilation whenever possible or desirable, to maximize comfort while avoiding the significant energy use and operating costs of year-round air conditioning (Kim and Dear 2021; Ezzeldin and Rees 2013; Salcido et al. 2016).

Methodology

This research aims to analyze the role of skycourt as a passive cooling design strategy that affects the

Table 1 Skycourts benefits from multiple perspectives

Benefits of skycourts		Refs.
Environmental perspective	Allows light and air to infiltrate the interior spaces	Pomeroy (2013)
	Contributes to acoustic insulation	Kim et al. (2014)
	Acts as a thermal barrier that reduces the effect of solar radiation and glare	Jahnkassim and Ip (1988)
	Provides a comfortable indoor environment in terms of air temperature, relative humidity, and air velocity, and increases occupant satisfaction	Ismail et al. (2011)
	Reduces heat gain in summer and reduces surface heat loss in winter	Castleton et al. (2010)
Social perspective	Promotes different levels of social interaction	Pomeroy (2013)
	Strengthening communication with the city	Yeang (1999)
	Enhances daylight benefits the occupants' health	Altomonte and Daylight and the Occupant, in: Vis. (2009)
	Promotes helpful psychological changes, e.g., reducing stress and increasing pain tolerance	Burghardt et al. (2009)
	Enhances residents' satisfaction with their neighborhood and increases their sense of well-being	Kaplan (2001)
Economic perspective	Provides a space for communication between workers	Pomeroy (2007)
	Saves energy by reducing heating and cooling loads	Clements-Croome and Baizhan (2000)
	Increases productivity by improving worker happiness and health	Miller et al. (2009)

performance of natural ventilation in multi-story buildings. We achieve this objective by analyzing global examples of skycourts. First, we collected many examples of skycourts from different climatic regions and then applied the criteria described in this section to limit the number for analysis. Next, basic information about the skycourts and the providing natural ventilation in such buildings, their role in reducing energy consumption, and the standards of the design of the skycourt were identified. Finally, we summarized the results to develop guidance design criteria for architects and designers in the implementation of skycourts in four climatic regions: dry, tropical, temperate, and cold. Therefore, this paper emphasizes the effective aspects and their approximate weight to highlight the essential aspects of designing skycourts to provide natural ventilation and contribute to reducing energy consumption (Fig. 4).

Global examples of skycourts

Based on this section, an analytical study of our samples, namely, skycourt in buildings located in different climates is conducted. This analysis helped us to determine the existing patterns and spatial configurations of skycourt spaces that serve as transitional buffer spaces in multi-story buildings and contribute to providing natural ventilation of spaces for skycourts and their surrounding spaces.

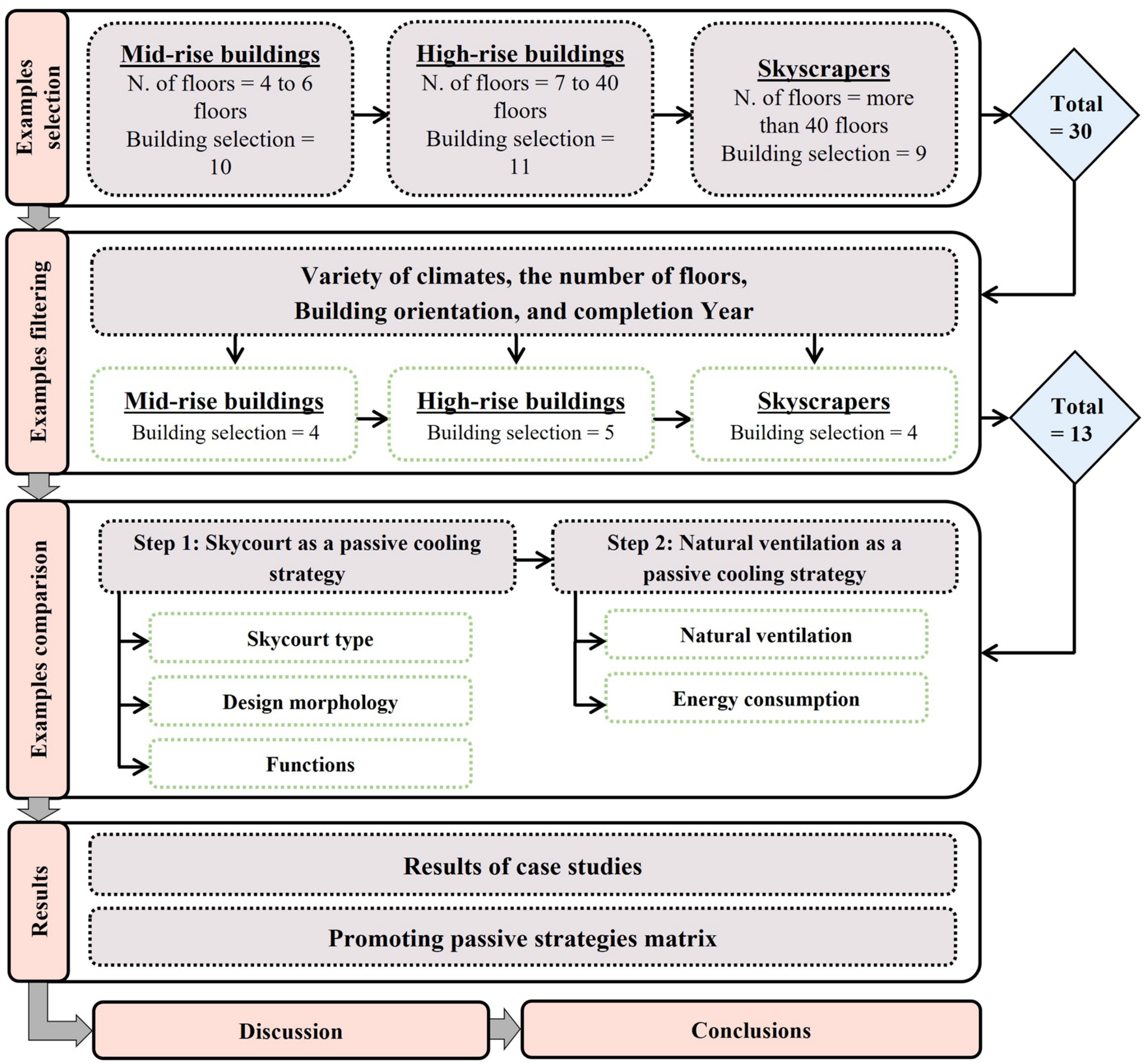


Fig. 4 Block diagram of the research

In the first stage of the analytical approach, we collected general information on our sample of buildings with skycourts. The buildings were designed in different years and located in different climate zones; dry, tropical, temperate, and cold. We selected buildings with diverse functions that were not limited to a specific function. The two criteria for buildings were a skycourt that serves neighborhood residents and classification as a multi-story building.

First, we performed a comprehensive qualitative analysis of many (> 30) buildings in different climatic zones. To achieve this objective, we classified each building by function, building orientation, year of construction, climatic region, height, and skycourt type. Based on the comprehensive qualitative analysis, 13 buildings were selected for a detailed quantitative study to collect accurate information on skycourts and this architectural feature's environmental role in providing natural ventilation within those spaces and the surrounding architectural spaces. Building selection was such that there was diversity in the climatic zones and height of the buildings. The objective of this step was to understand the building standards for each climate and each building classification: mid-rise, high-rise, and skyscraper.

The examples were classified according to the number of floors of the mid-rise buildings, high-rise buildings, and skyscrapers: mid-rise buildings, 2–6 floors; high-rise buildings, 7–40 floors; and skyscrapers, more than 40 floors (Kovacevic and Dzidic 2018). Table 2 shows the main information collected on the four mid-rise buildings under analysis: the Masdar Institute, the Business Promotion Center, Dongguan's Eco-Park Office Buildings, and The Courtyard House.

Table 3 shows the basic information collected on the five high-rise buildings under analysis: Phinisi Tower, Torre Cube, Century Tower, GSW Headquarters, and 1 Bligh Street.

Table 4 shows the basic information collected on the four skyscrapers under analysis: Al Faisaliah Center, Swiss Re Tower, Commerzbank Headquarters, and The Shard London Bridge Tower.

As shown in Table 2–4, all buildings depend on natural ventilation. The natural ventilation patterns in the buildings varied between stack and cross ventilation. The buildings depended on natural ventilation in different proportions, and the percentage of dependence of some buildings using natural ventilation reached 100%, such as the Masdar Institute, the Business Promotion Center, Dongguan's Eco-Park Office Buildings, Torre Cube, 1 Bligh Street, and Al Faisaliah Center, and the percentages varied in the remaining buildings: The Courtyard House (95%), Phinisi Tower (60%), Century Tower (65%), GSW Headquarters (30–40%), 1 Bligh Street (63%), Swiss Re Tower (40%), Commerzbank Headquarters (85%), and

Table 2 Basic information for examples of mid-rise buildings, based on (Alnusairat 2018; Alsheghri et al. 2015; Bai et al. 2015; Abass et al. 2016)

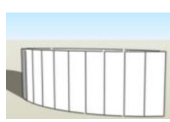
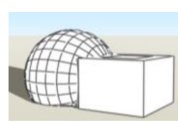
Building name	Masdar institute	Business promotion center	Dongguan's Eco-Park Office Buildings	The Courtyard House
Schematic				
Location	Abu Dhabi, United Arab Emirates	Duisburg, Germany	Dongguan, China	Rajasthan, India
Climate	Hot and dry	Warm and temperate	Humid Subtropical	Hot and dry
Completion Year	2010	2004	2013	2012
Use	Laboratories and Library	Offices	Offices	Residential
Height (m)	21 m	30 m	23.9 m	10 m
No. of Floors	3	4	6	2
Gross Area (m^2)	63000 m^2	4000 m^2	37664 m^2	3000 m^2
Ventilation Type	Natural ventilation	Natural ventilation	Natural ventilation	Natural ventilation
Natural Ventilation Type	Cross	Stack	Stack	Stack
Night-time Ventilation	√	√	√	-
Annual Usage of Natural Ventilation	100%	100%	100%	95%
Annual Energy Saving	100%	57%	63%	79%
Annual Energy Consumption	–	13 kWh/m^2	125 kWh/m2	–

Table 3 Basic information for examples of high-rise buildings, based on (Alnusairat 2018; Pomeroy 2008; Jamala 2017; Raji et al. 2014; Lee et al. 2002; Wang et al. 2010)

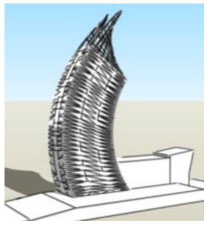
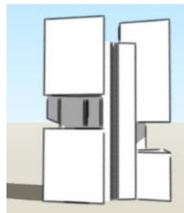
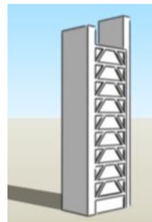
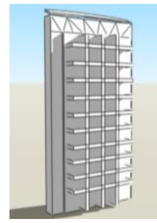
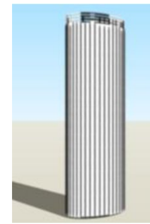
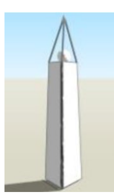
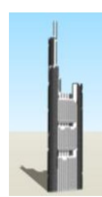
Building name	Phinisi tower	Torre cube	Century tower	GSW headquarters	1 Bligh street
Schematic					
Location	Makassar, Indonesia	Guadalajara, México	Tokyo, Japan	Berlin, Germany	Sydney, Australia
Climate	Humid and tropical	Warm and temperate	Hot and warm	Warm and temperate	Cold
Completion year	2012	2005	1991	1999	2011
Use	Education	Offices	Offices and apartments	Offices	Offices
Height (m)	97.5 m	70 m	136 m	81.5 m	139 m
No. of Floors	17	19	21	23	30
Gross Area (m^2)	–	17000 m^2	26600 m^2	48000 m^2	55000 m^2
Ventilation type	Mixed mode	Natural ventilation	Mixed mode	Natural ventilation	Mixed mode
Natural ventilation type	Stack and cross	Stack and cross	Stack and cross	Cross	Stack and cross
Night-time Ventilation	√	None	√	√	None
Annual usage of natural ventilation	60%	100%	65%	70%	100%
Annual Energy saving	13.7%	100%	75%	30–40%	63%
Annual energy consumption	–	–	26 kWh/m^2	–	–

Table 4 Basic information for examples of skyscrapers buildings, based on (Alnusairat 2018; Munro 2004; Headquarters et al. 2007; Parker 2013)

Building Name	Al Faisaliah Center	Swiss Re Tower	Commerzbank Headquarters	The Shard (London Bridge Tower)
Schematic				
Location	Riyadh, Saudi Arabia	London, United Kingdom	Frankfurt, Germany	London, United Kingdom
Climate	Hot and dry	Warm and temperate	Cold and temperate	Warm and temperate
Completion Year	2000	2004	1997	2012
Use	Office and restaurant	Offices	Offices	Residential, hotel, and office
Height (m)	267 m	180 m	259 m	309.6 m
No. of Floors	44	42	56	75
Gross Area (m^2)	240000 m^2	64500 m^2	85500 m^2	111000 m^2
Ventilation Type	Natural ventilation	Mixed mode	Mixed mode	Natural ventilation
Natural Ventilation Type	Stack and cross	Stack and cross	Stack and cross	Stack
Night-time Ventilation	√	None	√	√
Annual Usage of Natural Ventilation	100%	40%	85%	25%
Annual Energy Saving	45%	20%	63%	84%
Annual Energy Consumption	–	–	117 kWh/m^2	54 kWh/m^2

The Shard (London Bridge Tower; 25%). In addition, most buildings provided night ventilation.

Skycourt configurations have contributed to reducing energy consumption by significant proportions. We did not reach the actual consumption of energy for some buildings. As for the buildings whose annual energy consumption has been reached, we notice a significant saving in energy consumption rates. Annual consumption in the Business Promotion Center was 13 kWh/m^2; Dongguan's Eco-Park Office Building, 125 kWh/m^2; Century Tower, 26 kWh/m^2; Commerzbank Headquarters, 117 kWh/m^2; and The Shard (London Bridge Tower), 54 kWh/m^2. For the remaining buildings, specific information on annual energy consumption was not found.

Skycourt attributes in selected buildings

The skycourt in the multi-story buildings of all building classifications; mid-rise, high-rise, and skyscraper had similar functions and spatial configurations in all specified climatic regions zones; dry, tropical, temperate, and cold. However, we observed differences in the façade envelope, such as the percentage of opening in the skycourt wall and shading. We found other differences in the selected examples, such as the skycourt type, the skycourts' environmental functions, and the skycourts' morphological composition. Tables 5, 6, 7 show the skycourt attributes in mid-rise buildings, high-rise buildings, and skyscrapers, respectively.

As shown in Tables 5, 6, 7, the skycourt and skygarden are the most observed types in mid-rise buildings, such as the Masdar Institute, Dongguan's Eco-Park Office Buildings, and The Courtyard House. For high-rise buildings, skycourts on typical floors and skycourts on final floors are the most observed types, and the skyroof is used as a restaurant, such as at Century Tower and 1 Bligh Street. For skyscrapers, the use of the skycourt on typical floors and the skyentrance on the first floor are merged, such as et al. Faisaliah Center and The Shard (London Bridge Tower).

In hot and cold climates, open skycourt walls were uncommon. By contrast, they were glazed and closed owing to the high wind speed and temperature variation between summer and winter and day and night. In addition, shading is required to reduce solar radiation in summer and allow it in winter. In humid climates, the skyentrance is widely used because it helps reduce humidity on upper floors, such as those of Dongguan's Eco-Park Office Buildings, Phinisi Tower, and 1 Bligh Street.

A skycourt located between the floors of a building was the most observed type, followed by a skyroof and skyentrance. A skygarden was commonly observed in residential models. Skycourts were mostly located between the office areas and the exterior walls.

Skycourt location is associated with its functionality. For instance, a skycourt between the floors of the building was the most observed type in high-rise buildings, followed by a skygarden and skyentrance. A skygarden was commonly observed in mid-rise buildings, followed by a skyroof, skycourt, and skyentrace. In skyscrapers, the most observed type is a skyroof, followed by a skycourt and skygarden.

Additionally, a hollowed-out design was the most observed prototype for skycourts in mid-rise buildings and high-rise buildings. This buffer zone is attached to the outside by one edge. Other commonly observed prototypes in mid-rise buildings and skyscrapers were corner and three-edged (sided) shapes.

In mid-rise buildings, for example, Dongguan's Eco-Park Office Buildings, the skycourt helped to achieve all the functions of the skycourt specified in the research. In Masdar City and Business Promotion Center, the skycourt fulfilled four of the specified functions. In high-rise buildings, the skycourt was widely used as a social space, transitional space, and passive design element. By contrast, in skyscrapers, the skycourt was used as a social space and passive design element, such as those in Swiss Re Tower, Commerzbank Headquarters, and The Shard (London Bridge Tower).

In mid-rise buildings and skygarden and skycourt acted as a buffer zone, capturing cold air from the interior, and exhaling hot air. In high-rise buildings, the skycourt was mostly used to capture cold air and expel hot air from another place. The role of other environmental functions of skycourts in mid-rise buildings, high-rise buildings, and skyscrapers was providing natural lighting for the surrounding spaces and inside the skycourt and a thermal buffer zone. In cold and hot climates, the thermal buffer zone helps reduce heat transfer from inside to outside and from outside to inside.

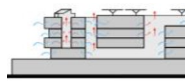
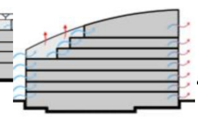
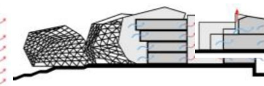
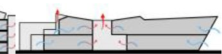
Results analysis

In this section, the results of the examples are presented and analyzed in terms of the role of the skycourt in promoting natural ventilation and reducing energy consumption, followed by a discussion of these results to determine the role of skycourts as transitional spaces that contribute to providing natural ventilation.

Results of examples analysis

The results of the analysis of the 13 examples of multi-story buildings indicated that all buildings enhance natural ventilation, and this facilitated high rates of energy consumption reduction, which reached 100% in several buildings. The skycourt also enhanced night ventilation.

Table 5 Comparative analysis of skycourts in selected mid-rise buildings, based on (Alnusairat 2018; Alsheghri et al. 2015; Bai et al. 2015; Abass et al. 2016)

Building Name			**Masdar Institute**	**Business Promotion Center**	**Dongguan's Eco-Park Office Buildings**	**The Courtyard House**
Skycourt attributes	Geometry	Shape	Semi- rectangular	Semi elliptical	Square	Semi- rectangular
		Form	Open-sided (two-sided)	Closed	Open (four-sided)	Open (four-sided)
		Central/sided	Central	Sided	Central	Central
		Open/closed	Open	2 walls closed/ open from external façade	Core/centralized/ open from 4 sides	Core/centralized/open from 4 sides
		Section				
	Type	Skygarden	–	√	–	√
		Skyroof	√	–	–	–
		Skycourt	√	–	–	√
		Skyentrace	–	–	√	–
	Spatial Morphology	Hollow space	√	√	√	√
		Corner space	√	√	–	–
		Lateral space	√	√	–	√
		Interstitial space	–	–	–	–
		Chimney	–	–	√	–
		Filling space	–	–	–	–
	Function	Social space	–	√	√	–
		Well-being	√	–	√	√
		Transitional space	–	√	√	√
		Environmental filter	√	√	√	√
		Biodiversity enhancer	√	–	√	–
		Passive design element	√	√	√	√
		Productivity enhancer	–	–	√	–
	Environmental Benefits	Air intake, extraction	√ (Only intake)	√ (Both)	√ (Both)	√ (Both)
		Inducing ventilation	√	√	√	√
		Stack ventilation	√	√	√	√
		Lighting	√	√	√	√
		Acoustics	–	–	–	√
		Thermal buffer zone	√	–	√	–

Notably, all types of ventilation were either cross-ventilation or stack ventilation patterns because the type of ventilation in skycourts is either cross or stack and does not depend on single ventilation.

The results also indicate the difference in the type of skycourt in the buildings and the diversity of the spatial morphology of the skycourt. In the mid-rise buildings, the most used type of skycourt was the skycourt and skygarden. In the high-rise buildings, most of the four types of skycourt buildings were used. In skyscrapers, the most used type was the skyroof, followed by the skycourt and the skygarden.

Regarding the spatial morphology of the skycourt types, they varied in each type of building. In mid-rise

Table 6 Comparative analysis of skycourt in selected high-rise buildings, based on (Alnusairat 2018; Pomeroy 2008; Jamala 2017; Raji et al. 2014; Lee et al. 2002)

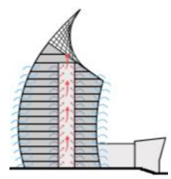
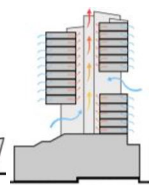
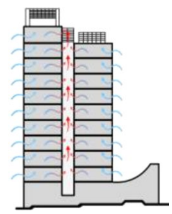
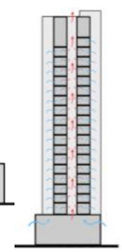
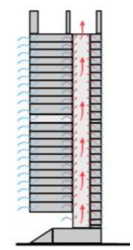
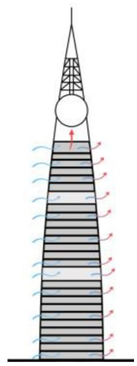
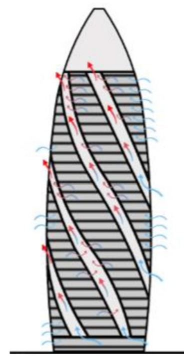
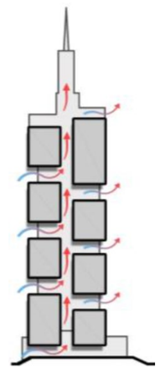
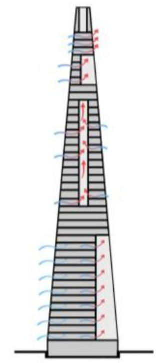
Building Name			**Phinisi Tower**	**Torre Cube**	**Century Tower**	**GSW Headquarters**	**1 Bligh Street,**
Skycourt attributes	Geometry	Shape	Semi-circular	Semi-triangular	Rectangular	Semi-rectangular	Semi-triangular
		Form	Open-sided (two-sided)	Open-sided (two-sided)	Closed	Open (four-sided)	Open-sided (two-sided)
		Central/sided	Central	Central	Sided/Central	Central	Central
		Open/closed	2 walls closed/open from the external façade and to the atrium	2 walls closed/open from the external façade and to the atrium	Core/centralized/Open from 4 sides	Core/centralized/Open from 4 sides	2 walls closed/open to the atrium
		Section					
	Type	Skygarden	√	√	–	–	–
		Skyroof	√	–	–	√	–
		Skycourt	–	√	√	–	√
		Skyentrace	–	–	√	–	√
	Spatial Morphology	Hollow space	√	√	√	√	√
		Corner space	–	–	–	–	–
		Lateral space	–	–	–	–	–
		Interstitial space	√	–	√	√	√
		Chimney	√	√	–	–	–
		Filling space	–	–	–	–	–
	Function	Social space	–	√	√	–	√
		Well-being	√	–	–	√	–
		Transitional space	√	√	√	√	√
		Environmental filter	√	–	–	√	–
		Biodiversity enhancer	√	–	–	√	–
		Passive design element	√	√	√	√	√
		Productivity enhancer	–	–	–	√	–
	Environmental Benefits	Air intake, extraction	√ (Only intake)	√ (Only intake)	√ (Both)	√ (Both)	√ (Only intake)
		Inducing ventilation	√	–	√	√	√
		Stack ventilation	–	–	–	–	–
		Lighting	√	√	√	√	√
		Acoustics	–	–	–	√	–
		Thermal buffer zone	–	√	–	√	–

Table 7 Comparative analysis of skycourt in selected skyscrapers buildings, based on (Alnusairat 2018; Munro 2004; Headquarters et al. 2007; Parker 2013)

Building Name			**Al Faisaliah Center**	**Swiss Re Tower**	**Commerzbank Headquarters**	**The Shard (London Bridge Tower)**
Skycourt attributes	Geometry	Shape	Triangular	Triangular	Semi-triangular	Semi-rectangular
		Form	Open	Open-sided (two-sided)	Open-sided (two-sided)	Open-sided (two-sided)
		Central/sided	Sided	Sided	Central	Sided
		Open/closed	2 walls closed	2 walls closed/ open from external façade	2 walls closed / open to the atrium	2 walls closed/ open from external façade
		Section				
	Type	Skygarden	√	–	–	√
		Skyroof	√	√	–	√
		Skycourt	–	–	√	√
		Skyentrace	–	–	–	√
	Spatial Morphology	Hollow space	√	√	√	√
		Corner space	√	√	–	√
		Lateral space	–	–	–	–
		Interstitial space	–	–	–	√
		Chimney	–	–	√	–
		Filling space	–	–	–	–
	Function	Social space	–	√	√	√
		Well-being	–	–	√	√
		Transitional space	√	√	√	√
		Environmental filter	–	–	√	√
		Biodiversity enhancer	√	–	–	√
		Passive design element	√	√	√	√
		Productivity enhancer	–	–	√	–
	Environmental Benefits	Air intake, extraction	√ (Only intake)	√ (Both)	√ (Both)	√ (Both)
		Inducing ventilation	√	√	√	√
		Stack ventilation	√	√	√	√
		Lighting	√	√	√	√
		Acoustics	–	–	√	–
		Thermal buffer zone	–	√	–	–

and high-rise buildings, hollow space, interstitial space, and chimney space were the most used formations. In skyscrapers buildings, hollow spaces, and corner spaces were the most used formations.

The results also indicate the high effect of the skycourt types on enhancing the natural ventilation of multi-story buildings, which contributed to reducing energy consumption. In mid-rise buildings, the dependence on natural ventilation reached 100%, such as that for the Masdar Institute, the Business Promotion Center, and Dongguan's Eco-Park Office Buildings; in reducing energy consumption at high rates, reaching 100% in the Masdar Institute; and in the remaining buildings, the percentage of exceeded 50%. Regarding high-rise buildings, they depended on natural ventilation at rates that reached 100% for Torre Cube and 1 Bligh Street, a city building's adoption of 100% natural ventilation reduced energy consumption by 100%, and the percentage of energy savings of Century Tower reached 75%.

Promoting passive strategies matrix

Based on the analysis of the skycourt as a passive cooling design strategy via various global examples in different climates, this section proposes the reference matrix. Designers and decision-makers can refer to this matrix in designing the facades of multi-story buildings to enhance their natural ventilation, which is beneficial in reducing energy consumption. This matrix mainly constitutes the interrelationship in the design of the skycourt as a passive cooling design strategy, on the horizontal axis, and the vertical axis determines the classifications of the 13 multi-story buildings; mid-rise, high-rise, and skyscrapers, in our sample in each of the four main climate zones; dry, tropical, temperate, and cold. Some relationships are strong, and others are weak. In Table 8, these

Table 8 Weighted relations between building type and skycourt attributes

Building type	Climate region	Skycourt attributes as a passive cooling strategy																										
		Type/ style				Spatial Morphology						Function							Environmental Benefits						Geometry			
																									Central sided		Open closed	
		Skygarden	Skyroof	Skycourt	Skyentrace	Hollow space	Corner space	Lateral space	Interstitial space	Chimney space	Filling space	Social space	Well-being	Transitional space	Environmental filter	Bio-diversity enhancer	Passive design element	Productivity enhancer	Air intake, extraction	Inducing ventilation	Stack ventilation	Lighting	Acoustics	Thermal buffer zone	Central	Sided	Open	Closed
Mid-rise	Hot dry	◑	◑	●	○	●	◑	●	○	○	○	○	●	◑	●	◑	●	○	◑	●	●	●	○	○	○	●	◑	◑
	Tropical	○	○	○	●	●	○	○	○	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	◑	◑
	Temperate	●	○	○	○	●	●	●	○	○	○	●	○	●	●	○	●	○	●	●	●	●	○	●	○	●	◑	◑
	Cold	NA																										
High-rise	Hot dry	○	○	●	●	●	○	○	●	○	○	●	○	●	○	○	●	○	●	●	○	●	○	○	◑	◑	●	○
	Tropical	●	●	○	○	●	○	○	●	●	○	○	●	●	●	●	●	○	◑	●	○	●	○	○	◑	●	◑	◑
	Temperate	◑	◑	◑	○	●	○	○	◑	◑	○	◑	◑	●	◑	◑	●	◑	○	◑	○	●	◑	●	●	○	●	◑
	Cold	○	○	●	●	●	○	○	●	○	○	●	○	●	○	○	●	○	◑	●	○	●	●	●	●	○	◑	◑
Skyscrapers	Hot dry	●	●	○	○	●	●	○	○	○	○	○	○	●	○	●	●	○	◑	●	●	●	○	○	◑	●	◑	◑
	Tropical	●	●	●	●	●	●	○	●	○	○	●	●	●	●	●	●	○	●	●	●	●	○	○	●	●	◑	◑
	Temperate	○	◑	◑	○	●	◑	○	○	◑	○	●	◑	○	◑	○	●	◑	●	●	●	●	◑	●	◑	◑	◑	◑
	Cold	○	○	●	○	●	○	○	○	●	○	●	●	●	●	○	●	●	●	●	●	●	●	●	●	○	◑	◑

○ Weak relationship ◑ Medium relationship ● Strong relationship relationships are shown in different colors. The relationship strength varied between weak, medium, and strong relationships.

As shown in Table 8, the standards and criteria for the design of skycourts vary significantly by building height classification and the local climate. For the hot climate, in all building classifications, the most used type was the skycourt, followed by the skygarden and skyroof; the least used type was the skyentrance. For the tropical climate, the two most used types were the skyroof and the skygarden, and the use of the skycourt and the skyentrance were the same. For the temperate climate, the most used type was the skygarden, followed by the skyroof and the skycourt; the skyentrance was not used. For the cold climate, for high-rise buildings and skyscrapers, the most used type was the skycourt, followed by the skyentrance.

Regarding spatial morphology, in all climates, the most used forms were hollow space, followed by interstitial space; the least used formations were corner space, lateral space, and chimney space. Filling space was not observed. Considering the benefits provided by the types of skycourts in the examples, the skycourt in all the buildings helped provide natural ventilation. The skycourt provided other benefits in different proportions. This finding helped us achieve the main objective of the research, determining the role of the skycourt in promoting natural ventilation and contributing to reducing energy consumption.

Discussion

Concerning the importance of passive design strategies in reducing energy consumption and preserving the environment, the effect of skycourt spaces in multi-story buildings and the environmental effects, especially in enhancing natural ventilation, is discussed in this section.

The types of court spaces in the facades, especially the skycourt, which is located between the typical floors in multi-story buildings, provide many benefits for the building from an environmental, social, and economic perspective. The research emphasized the environmental aspect, especially natural ventilation. In several examples, natural ventilation reached 100%, which led to a high reduction in energy consumption.

The different configurations of the skycourt, especially the hollow space, interstitial space, and chimney, provided natural ventilation for the multi-story buildings, which helps to reduce energy consumption. Such formations also help to provide an external social space that increases well-being and serves as a transitional space, ecological filter, biodiversity enhancer, and productivity enhancer. Skycourt spaces provide many benefits other than the role of enhancing natural ventilation in most buildings. They serve as a transitional space that contributes to social interaction and well-being, improves productivity, provides natural lighting, and acts as an environmental filter and a sound and heat insulator.

In this study, the effect of the skycourt configurations in the existing multi-story buildings was examined. Furthermore, a limited number of configurations were selected in the sample of buildings; thus, in further research, additional test cases can be developed according to real microclimate conditions. In addition, the limitations regarding the small sample size cannot be generalized to all skycourt architectural configurations. However, such results are influential in the development of skycourt configurations to allow for outdoor social contact and enhance the natural ventilation of buildings, reducing energy consumption.

These findings help to clarify the impact of the skycourt as a passive cooling strategy for natural ventilation in multi-story buildings. These results can be used to help provide an improved design for skycourt spaces, allowing for improvements in ventilation, the comfort of interior environments, and occupant satisfaction. Improving the design of the skycourt space can provide social, psychological, economic, and quality of life benefits.

Conclusions

Multi-story buildings present a challenge regarding high energy consumption owing to the extensive use of air conditioning systems to provide thermal comfort to occupants. Skycourts are increasingly becoming integrated into the design of multi-story buildings to generate a more comfortable and livable environment than without them. These spaces act as transition nodes and spaces for social interaction. The literature indicates that skycourts could play a promising role in enhancing natural ventilation, which helps to reduce the energy consumption of buildings. However, few studies have provided evidence of their effect on total natural ventilation and the amount of cooling energy they provide in buildings.

This research contributes to proving the role of skycourts in enhancing the natural ventilation of multi-story buildings, in addition to achieving an acceptable level of thermal comfort in these spaces. The positive effect of skycourts on multi-story buildings in all climates was confirmed. Common skycourt prototypes have been identified as transitional buffer spaces in multi-story buildings; (a) hollow space, (b) lateral space, (c) corner. We observed that ventilation has a significant impact on indoor thermal conditions and energy consumption. However, a satisfactory indoor environment can be achieved not by introducing extravagant concepts but by developing a balanced approach to identifying ventilation needs and applying the tools to manage these requirements. This study contributes to literature by providing new insights into low-energy designs with a focus on ventilation. One of the main objectives of the study was to outline design guidelines for multi-story buildings in four climates to ensure maximum utilization of natural ventilation. The study succeeded in achieving this goal by creating a skycourt design and performance matrix. These results allow designers and decision-makers to decide on the appropriate prototype and geometrical properties of skycourt spaces.

Further research should emphasize detailed analyses of the role of the skycourt in allowing daylight to penetrate and prevent direct solar heat gain and consider the potential of these spaces to improve daylight and reduce glare. Also, it may be important for future studies to complement what this study raised and find a possible combination of daylight and heating and cooling demand for buildings with large voids. Concerning the social and environmental aspects of the skycourt, it needs many studies and experiments to reach the extent of the impact of the skycourt on it. Plants can be a primary characteristic of skycourts in multi-story buildings because plants can improve the environmental performance of skycourts, the well-being of their occupants, the thermal comfort of buildings, and urban scales. Therefore, further research investigating the effect of green space incorporation on skycourt performance would be worthwhile.

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