

Article

Improving Comfort and Health: Green Retrofit Designs for Sunken Courtyards during the Summer Period in a Subtropical Climate

Gang Han ^{1,2,†}, Yueming Wen ^{1,2,†} , Jiawei Leng ^{1,2,*} and Lijun Sun ^{1,2}

¹ School of Architecture, Southeast University, Nanjing 210096, China; han_gang007@163.com (G.H.); wenyueming66@163.com (Y.W.); s-lijun@163.com (L.S.)

² Future Underground Space Institute, Southeast University, Nanjing 210096, China

* Correspondence: jw_leng@seu.edu.cn

† Gang Han and Yueming Wen contributed equally to this work.

Abstract: The sunken courtyard has long been used in underground spaces and provides an important outdoor environment. It introduces natural elements to create a pleasant space for human activities. However, this study measured a typical sunken courtyard and found potential problems of excessive solar radiation and accumulated air pollutants in summer when at an acceptable outdoor temperature for human activities. To improve the comfort and health of a sunken courtyard, this research proposes some green retrofit designs. Firstly, compared with green wall, water and a tree, sunshade is a primary measure to improve thermal comfort. Combining sunshade, a green wall and water reduces the temperature by up to 5.6 °C in the activity zone during the hottest hour. Secondly, blocking/guiding wind walls can effectively improve the wind environment in a sunken courtyard, but only when the wind direction is close to the prevailing wind. A blocking wind wall was better at affecting velocity and uniformity, while the guiding wind wall was more efficient at discharging air pollutants. This study initially discusses the climate-adaptive design of underground spaces in terms of green, thermal comfort and natural ventilation. Designers should generally integrate above/underground and indoor/outdoor spaces using natural and artificial resources to improve comfort and health in underground spaces.

Keywords: comfort; health; green; sunken courtyard; retrofit design; climate-adaptive design



Citation: Han, G.; Wen, Y.; Leng, J.; Sun, L. Improving Comfort and Health: Green Retrofit Designs for Sunken Courtyards during the Summer Period in a Subtropical Climate. *Buildings* **2021**, *11*, 413. <https://doi.org/10.3390/buildings11090413>

Academic Editor: Cinzia Buratti

Received: 14 July 2021

Accepted: 13 September 2021

Published: 16 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Urban intensification and vertical development are driving underground spaces towards becoming important activity spaces, particularly in downtown and railway areas. The sunken courtyard (or sunken plaza), which is a long-standing spatial form, plays a significant role in enclosing underground spaces in terms of connecting to the outdoors, improving thermal comfort, introducing natural elements and reducing traffic noise and energy consumption [1,2]. However, greening is disappearing from current sunken courtyards and being replaced by artificial materials, such as tiles, metals and plastic. Vernacular architecture and scientific studies have shown that soil, water and plants effectively modify sunlight, temperature, humidity and air quality [3,4]. In the summer, artificial materials with high albedo increase the radiant temperature, causing courtyards to be unsuitable for human activities. This situation also causes potential health risks, thereby preventing people from moving around outdoors during epidemics [5] and can cause health hazards, such as the release of total volatile organic compounds (TVOCs) and particulate matters (PMs) [6]. Therefore, there are research requirements and practical needs for monitoring environmental parameters and analyzing potential deficiencies in artificial sunken courtyards. Moreover, green retrofit designs can be developed purposefully and by scientifically combining microclimate simulations.

Existing research has indicated that location, orientation, form, geometry and construction affect the physical performances of sunken courtyards, including lighting, ventilation, energy and thermal comfort [1,4,7–9]. However, these factors are determined during the early design and construction phase. Subsequently, changing them would be extremely costly or even difficult because the construction of underground spaces is highly irreversible, particularly for those with other buildings or facilities aboveground. This study uses site measurements and environmental conditions as a basis for focusing on retrofit designs to improve the thermal comfort and air quality of existing sunken courtyards, including internal layout, building surface, greening and ventilation potential. In the summer weather, excessive radiation and air pollutants have been identified by analyzing the variation and correlation of air temperature, black-bulb temperature, relative humidity, wind velocity, CO₂, TVOCs and PMs, as the two most important problems. It has been identified that unshaded areas and building materials lead to high radiant temperatures. Physiological equivalent temperature (PET) is adopted by comparing several thermal comfort indicators. Furthermore, excessive TVOCs and PMs indicate that airflow in the courtyard is unable to discharge air pollutants. A wind vector is adopted to evaluate the ventilation potential driven by ground winds.

The simulation results supported the hypothesis that there is excessive solar radiation and accumulated air pollutants. The thermal effects of a sunshade, a green wall, water and the presence of a tree, as well as the natural ventilation effects of ground winds were simulated using ENVI-met Version 4 and Cradle scSTREAM Version 14. On the one hand, sunshades are a primary measure to improve thermal comfort in the summer, reducing the physiological equivalent temperature (PET) by up to 3 °C in the activity zone during the hottest hours. Green walls and shallow water reduce PET by up to 3 °C and 0.8 °C, respectively, when in specific positions. Combining a sunshade, a green wall and water reduce PET by up to 5.6 °C in the activity zone where the measured maximum of 39.5 °C drops to below 35 °C (which is hot for PET). On the other hand, a guiding wind wall introduced ground winds and created suitable and uniform wind fields in the activity zone and discharged air pollutants. A guiding wind wall can also be combined with a green wall and controllable louvers to provide controllable and comfortable ventilation. Actual measurements and retrofit designs indicate that underground spaces with good thermal performance often disregard climate-adaptive designs in the early stages. This study initially discusses the climate-adaptive design of underground spaces in terms of green, thermal comfort and natural ventilation. Introducing additional natural elements into sunken courtyards improves physiological comfort and also visual and psychological delight. This study is a direct reference for retrofit designs and newly built courtyards, providing numerous comfortable and healthy spaces for urban activities.

2. Methodology

2.1. Field Measurements

The measured sunken courtyard used in this research is located at an underground shopping mall in the center of Nanjing, China (Figure 1). Nanjing has a subtropical monsoon climate with an annual average temperature of 15.4 °C, an annual high temperature of 39.7 °C, and it belongs to the hot summer and cold winter climate zone in China. Nanjing is known as a hot summer city in China and is experiencing significant warming. Summer in Nanjing is also becoming longer and arrives in mid-May [10,11]. However, dates where the temperatures were above expected levels were not studied because, from observations during the previous summer, people were generally reluctant to stay in the sunken courtyard being measured for long periods when it exceeded 33 °C. Furthermore, China sets 35 °C as the threshold for high temperature warnings and outdoor work allowances. In the previous 140-day summer in Nanjing, only 19 days exceeded 33 °C. Three adjacent weekends, 29–30 May and 5 June 2021 (the weather was cloudless and sunny with a high temperature of 32 °C and a Beaufort Wind Force of 2–3), were selected in advance based on weather forecasts. The study period began at 10:00 (mall opening) and ended at 18:00 (dinner) when

solar radiation decreased significantly to a steady phase. Three measurements showed highly consistent patterns and characteristics, which were sufficient to support validity and representativeness. Data from 30 May were chosen because there were only a few unforeseen interferences and numerous evident interactions of environmental parameters.

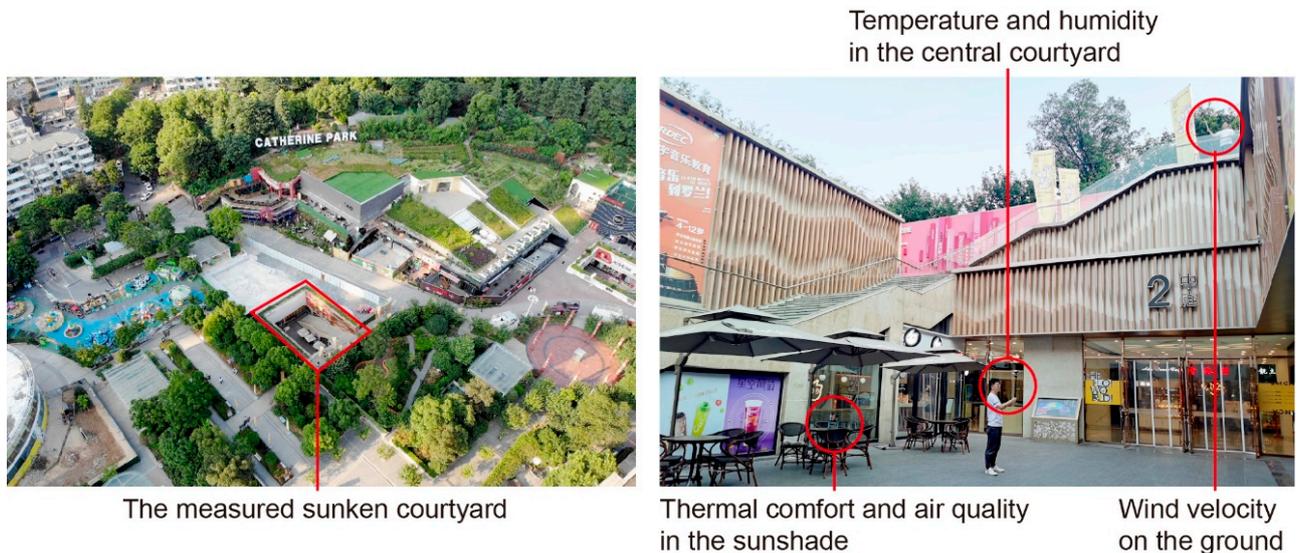


Figure 1. The measured sunken courtyard in Nanjing, China.

The measurement instrument was placed on a table and its probe was approximately 1.1-m high, which was also the height of the consumers' faces when sitting for a long time in the courtyard. Table 1 summarizes the specifications of the JT integrated monitor of thermal environment and air quality. The sampling interval was set at 10 s to sensitively determine the environmental effects of changing winds. A total of 2881 data sets were analyzed over an eight-hour period (i.e., 10:00–18:00). Meanwhile, environmental parameters required by ENVI-met were measured. Air temperatures, relative humidity (RH) and building surface temperatures were measured at a height of 2 m in the center of the courtyard. Air temperatures and RH were measured using a TANDD TR-72wf thermo recorder with a precision of 0.5 °C and 5% RH. Surface temperatures were measured using a Fluke 59 mini-infrared thermometer with a temperature precision of 2 °C. Wind velocities and directions were measured at a height of 10 m from the courtyard floor. Wind velocities were measured using Testo 405i hot-wire anemometer with a velocity precision of 0.1 m/s and temperature precision of 0.5 °C.

Table 1. Specifications of JT integrated monitor of thermal environment and air quality.

Parameters	Range	Precision
Air temperature	−40–85 °C	±0.3 °C
Globe temperature	20–85 °C	±0.3 °C (20–40 °C)
Wet-bulb temperature	5–40 °C	±0.5 °C
Relative humidity	0–100% RH	±2%RH
Wind velocity	0.05–2 m/s	±(0.03 m/s + 2% reading)
PM _{2.5}	0–999 ug/m ³	±10% reading
CO ₂	0–5000 ppm	±30 ppm
TVOCs	0.1–0.6 ppm	±10% reading

2.2. Thermal Comfort Evaluation

Outdoor thermal comfort indices can be divided into three categories: (1) cold and hot thermal stress indices based on regression analysis, such as Wet-bulb globe temperature (WGBT) and predicted mean vote amended by Jendritzky (PMV*) [12]; (2) indices based on steady-state heat transfer models, such as OUT Standard Effective Temperature (OUT-

SET*) [13] and PET [14]; and (3) indices based on unsteady heat transfer models, such as the Universal Thermal Climate Index (UTCI) [15]. Table 2 summarizes the factors involved in some commonly used indicators. Based on the literature review, PET and UTCI have been recommended and widely used in recent years. Compared with UTCI, PET is considerably more sensitive to wind velocity and solar radiation [16,17]. Moreover, PET requires wind velocity to be measured at 1.1 m, whereas UTCI requires wind velocity to be measured at 10 m. Therefore, PET is better adapted to the requirements of the current study. At any given place, outdoors or indoors, PET is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism 80 W of light activity was added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed [14]. Table 3 shows PET ranges corresponding to different thermal sensations. In the current study, clothing insulation (0.6 clo) and metabolic rate (1.0 met or 60 W/m²) were predicted according to field observation and *ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy* [18].

Table 2. Commonly used outdoor thermal comfort indices.

Index	Physical Factor (Climatic Conditions)				Physiological Factor (Physiological Regulation)				
	Air Temperature	Humidity	Air Velocity	Radiation	Skin Temperature	Skin Wettedness	Core Wettedness	Clothing Insulation	Metabolic Rate
WGBT	+	+	+	+					
PMV*	+	+	+	+	+	+		+	+
OUT-SET*	+	+	+	+	+	+		+	+
PET	+	+	+	+	+	+	+	+	+
UTCI	+	+	+	+	+	+	+	+	+

Table 3. Thermal sensations and corresponding PET ranges.

Thermal Sensation	Very Cold	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot	Very Hot
PET range (°C)	<4	4–8	8–13	13–18	18–23	23–29	29–35	35–41	>41

The RayMan Version 1.2 model was applied to calculate PET from the measurement data. The RayMan model is a diagnostic micro-scale radiation model developed by the department of meteorology and climatology at the Albert Ludwigs University of Freiburg. This model is designed to calculate radiation fluxes in simple and complex environments [19]. Mean radiation temperature (T_{mrt}) is a key index for calculating PET and can be approximately calculated from the SkyHelios model and Sky View Factor in RayMan. However, the current study adopted a considerably accurate calculation by measuring the globe temperature which is explained in *ISO 7726:1998-Ergonomics of the thermal environment-Instruments for measuring physical quantities* [20]. It is obtained using the following equation:

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{1/4} - 273$$

where T_g = globe temperature (°C), v = wind velocity (m/s), ε = globe emissivity (0.95), D = globe diameter (mm) and T_a = air temperature (°C).

2.3. Simulation of Retrofit Designs

The microclimate effects of four retrofit designs were modeled using Rhinoceros software and simulated in ENVI-met software, including a water pond, a tree, wall greening and a sunshade. ENVI-met is widely used and validated for predicting microclimates for buildings and green areas. The courtyard in this study is 15 m × 23 m and has a calculation domain of 45 m × 69 m; the simulation results shown in similar medium-sized courtyards were satisfactory [21–24]. Furthermore, the ground environment of the measured courtyard

is a green garden. No large buildings are within three times the scale of the courtyard and as such do not affect the microenvironment [25].

Table 4 shows the environmental parameters at the heights required by the ENVI-met simulation. These measured parameters were added to the epw.weather file. The epw. file that is recommended for ENVI-met provided geographical location, solar angle and radiation in this study; this was downloaded from <https://www.ladybug.tools/epwmap/> (accessed on 12 September 2021) supported by the US Department of Energy. This study compared the simulation results of three grid sizes (i.e., 2 m, 1 m and 0.5 m, which are the smallest supported by ENVI-met) and found that a grid size of 1 m significantly balanced simulation precision and computation time. Figure 2 shows the sizes and materials of the original and modified courtyards.

Table 4. Environmental parameters required by ENVI-met simulation.

	Time	2-m Height (Courtyard Center)		10-m Height (Ground Surface)	
		Air Temperature (°C)	RH (%)	Wind Velocity (m/s)	Wind Direction (°)
Hourly averaged environmental parameters	09:00	31.6	58.2	2.5	202.5
	10:00	32.2	52.8	1.6	247.5
	11:00	32.8	48.5	2.3	202.5
	12:00	33.5	38.6	1.6	270.0
	13:00	34.9	35.8	2.7	270.0
	14:00	35.8	35.3	1.6	292.5
	15:00	37.0	31.7	2.4	225.0
	16:00	33.8	36.6	1.3	135.0
	17:00	32.7	39.1	2.1	292.5
	18:00	31.7	42.2	1.9	112.5
19:00	31.2	48.6	2.7	112.5	
Initial building temperature (09:00)			30.2 °C		

Note: 0-m height of the sunken courtyard floor.

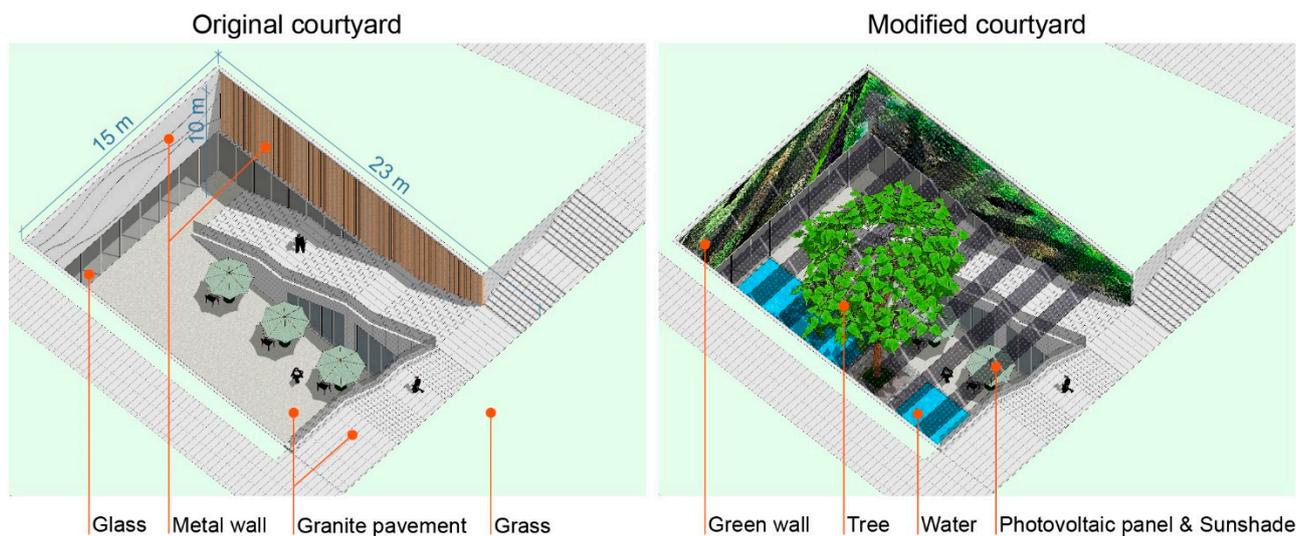


Figure 2. Models of original and modified courtyards.

Numerical models and settings were validated by comparing the simulated and measured temperatures and RH. However, the measurements of the hourly average wind velocities were 3–8 times that of those simulated (0.06 m/s–0.28 m/s), which seriously affects the calculation of PET. This result supported our assumption that the sunken courtyard was minimally affected by ground winds. Therefore, the measured wind velocity was used to modify the simulated PET. The comparative results showed that temporal trends are more consistent with errors of T_a (0.9–4.0%), RH (6.8–19.7%) and PET (6.0–15.6%)

(Figure 3). ENVI-met calculated high solar radiation and low humidity, which were also found in previous studies, but were at acceptable levels [22,26,27]. The effect of green renovation was mainly assessed by comparing the differences of the simulated PET.

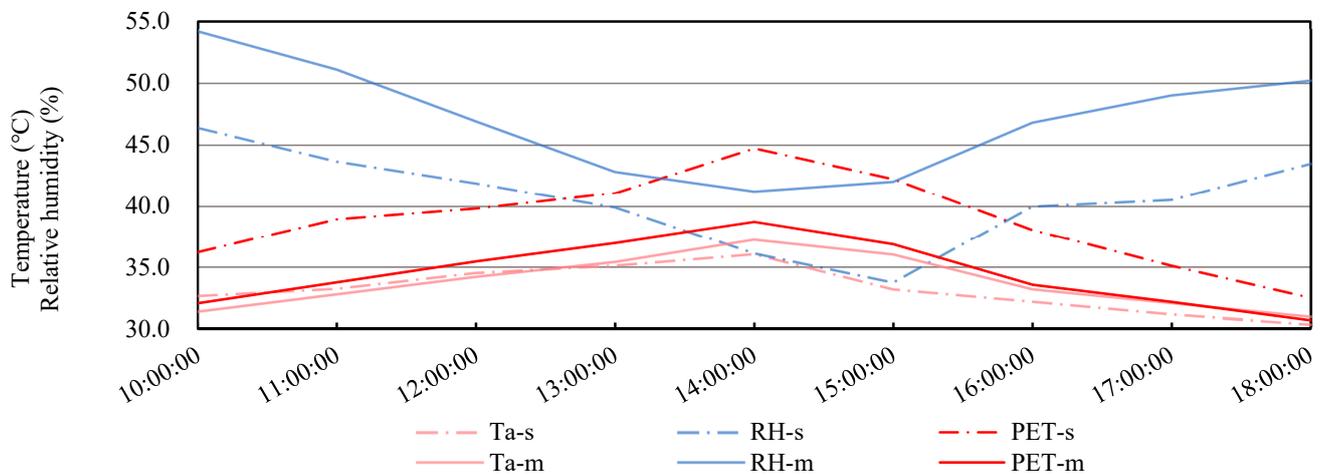


Figure 3. Model validation (s: simulation, m: measurement).

Given the shortcomings of ENVI-met in fine-scale computerized fluid dynamics (CFD) simulations, this study adopted Cradle scSTREAM Version 14, which is a specialized computational fluid dynamics software, to accurately simulate the wind environment in the sunken courtyard. Referring to Chinese standards, “GB 50736-2012, Design code for heating ventilation and air conditioning of civil buildings” [28], Table 5 summarizes the computational settings that meet the requirements of outdoor wind environment analysis.

Table 5. Computational settings of CFD simulations.

Computational Domain	
Material	Air (incompressible)
Analysis type	Turbulence flow, heat, solar radiation, steady state
Turbulence model	Renormalization group (RNG) k-ε model
Ambient temperature	31.6 °C
Initial solid temperature	30.2 °C
Boundary Condition	
Basic type	External flow (winds blowing through buildings)
Prevailing wind	2.6 m/s (10 m height), SSE
Roughness category	Urban area formed by medium-rise buildings (4–9 story) mainly
Flow boundary	Power law (inlet), static pressure (outlet)
Wall boundary	Noslip (power law or smooth)
Thermal boundary	Adiabatic (outer), heat transfer (fluid-solid), conduction (solids)
Solar Radiation	
Location	Nanjing, 32°00′ (Latitude), 118°48′ (Longitude)
Date and time	30 May, 9:00 a.m.
Solid absorptance	Architectural material

3. Results

3.1. Analysis of Measurement Data

3.1.1. Correlation Analysis

A correlation analysis was conducted using SPSS (Table 6). Firstly, PET was strongly positively correlated with T_a and T_g and strongly negatively correlated with RH. Secondly, TVOCs were strongly positively correlated with air temperature, which also led to a strong negative correlation with humidity. Thirdly, wind velocity has a limited effect on the concentration of air pollutants, which is contrary to common sense in ventilation. A

positive correlation amongst CO₂, PM2.5 and TVOCs initially proved that there was air stagnation in the sunken courtyard.

Table 6. Pearson correlation analysis of environmental parameters.

	PET	T_{mrt}	T_a	T_g	RH	v	CO ₂	PM2.5	TVOC
PET	1	0.982 **	0.986 **	0.988 **	−0.848 **	−0.227 **	0.374 **	0.290 **	0.495 **
T_{mrt}		1	0.941 **	0.999 **	−0.782 **	−0.108 **	0.275 **	0.273 **	0.396 **
T_a			1	0.953 **	−0.897 **	−0.262 **	0.462 **	0.300 **	0.579 **
T_g				1	−0.797 **	−0.134 **	0.295 **	0.277 **	0.416 **
RH					1	0.224 **	−0.495 **	−0.193 **	−0.596 **
v						1	−0.266 **	−0.092 **	−0.264 **
CO ₂							1	0.449 **	0.854 **
PM2.5								1	0.364 **
TVOC									1

Absolute	Correlation
0.0–0.1	Not
0.1–0.3	Weak
0.3–0.5	Moderate
0.5–1.0	Strong

** . Correlation significant at 0.01 level (two-tailed).

3.1.2. Excessive Solar Radiation

Temporal trends of the measured data showed a significant concordance amongst PET, T_{mrt} , T_a and T_g (Figure 4). Humidity showed a significant negative correlation with temperature in terms of overall trends and local changes. Given the effect of solar radiation on ambient temperature and humidity, solar radiation can be deduced as the decisive factor influencing the thermal environment in the sunken courtyard. Local changes in wind velocity had evident cooling effects but did not affect the overall trend of PET (Figure 5). From 10:00 to 15:00, solar radiation led to $T_{mrt} > T_g > PET > T_a$. Before 15:00, the four temperatures steadily increased and started to exceed 35 °C (the hot threshold for PET) at approximately 11:30. After reaching a maximum of 39.5 °C (PET) at 15:00, these temperatures decreased rapidly because of self-shading of the sunken courtyard and a reduction of direct solar radiation. Additionally, T_{mrt} and T_g were occasionally lower than PET, which may be related to increasing humidity. These temperatures decreased gradually and converged after 17:00. Therefore, controlling solar radiation is the primary means of improving thermal comfort, with relative potential for increasing humidity.

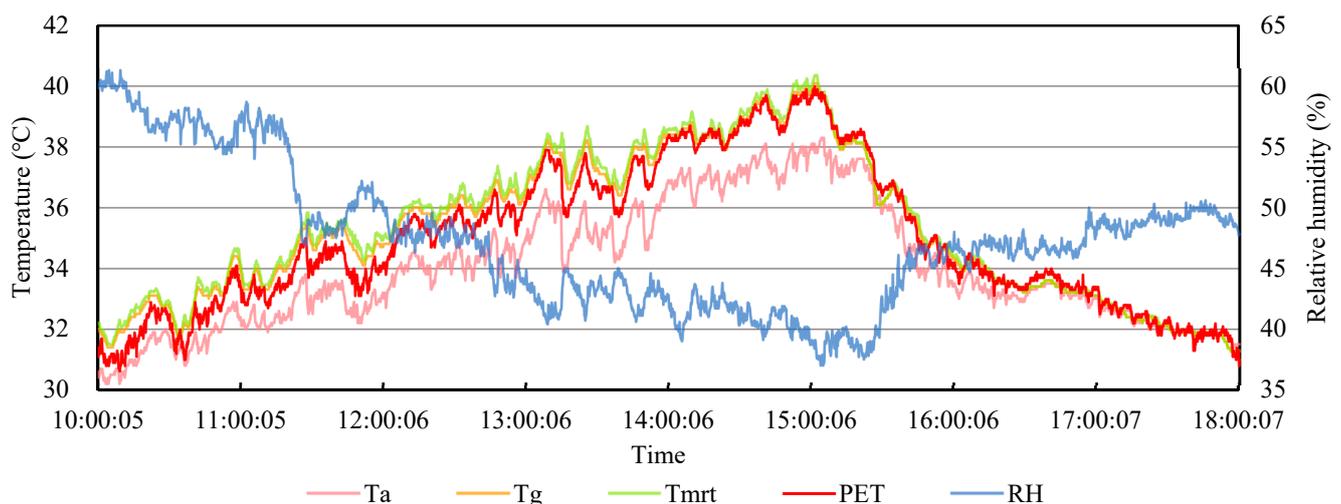


Figure 4. Temporal trend of strongly correlated thermal comfort parameters.

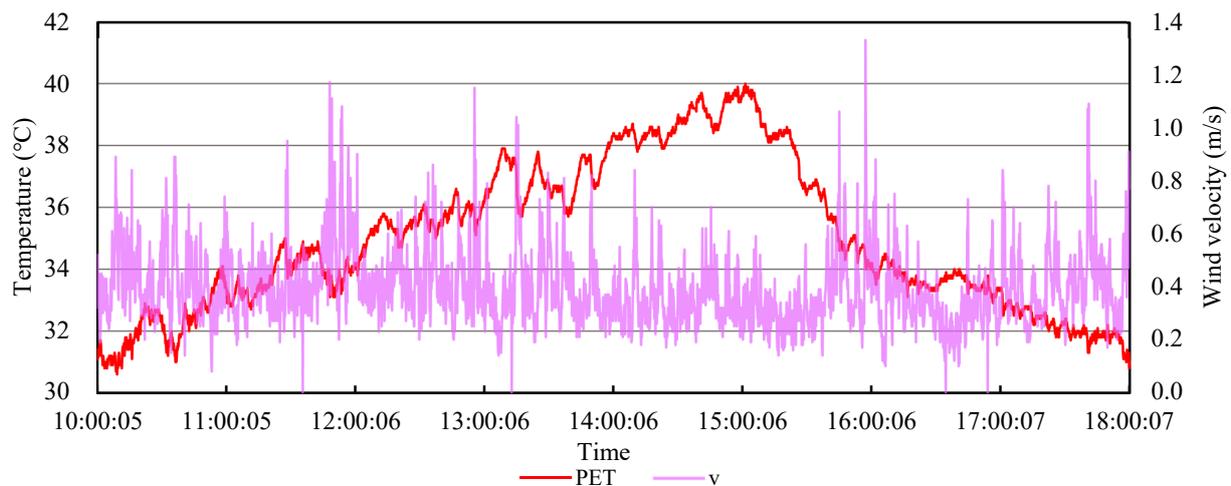


Figure 5. Temporal trend of weakly correlated thermal comfort parameters.

3.1.3. Air Stagnation and Pollutant Accumulation

Concentrations of PM_{2.5}, CO₂ and TVOCs were consistently stable, even with evident winds (Figure 6). However, there was an unforeseen scenario: at approximately 15:30, a consumer stayed close to the instrument for 20 min smoking and eating, thereby leading to a sudden increase in these concentrations. Table 7 shows the healthy building standards in China and the US, in which PM_{2.5} (average 36.4 $\mu\text{g}/\text{m}^3$) and TVOC (0.65 ppm) were consistently exceeded, whilst CO₂ (522.8 ppm) was below the threshold. Specifically, TVOCs were nearly four times over the thresholds, which may be derived from the interior air in the mall and decoration materials in the courtyard. Although the sunken courtyard is an open outdoor space, it is not connected to the ground wind environment, thereby preventing the discharge of air pollutants. Additionally, fresh air from the above ground garden cannot enter the sunken courtyard. Occasional there were breezes in the measurements that were mainly caused by air convection between open doors. Therefore, the sunken courtyard should be modified to introduce substantial natural winds.

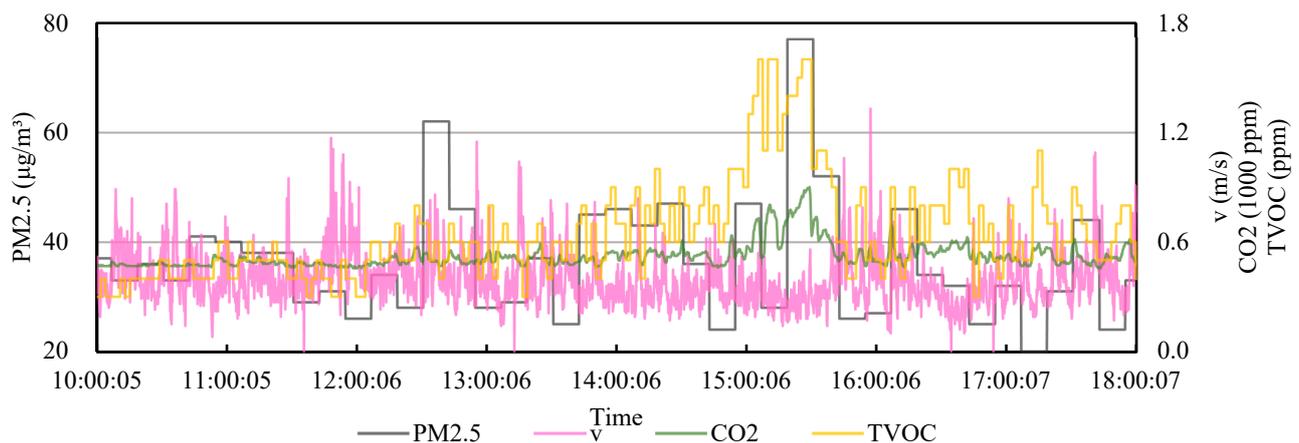


Figure 6. Temporal trends of wind velocity and air pollutants.

Table 7. Air pollutant thresholds in healthy building standards.

Air Pollutant	T/ASC 02-2016: Assessment Standard for Healthy Building	The WELL Building Standard-V2	Remark
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	35	35	24-h mean
CO ₂ (ppm)	1000	800	24-h mean
TVOC (ppm)	0.15	0.125	8-h mean

3.2. Simulation of Green Retrofit Designs

3.2.1. Retrofit Design for Thermal Comfort

Figure 7 shows the PET reduction when using a sunshade, a green wall, a tree, water and their combination in the middle section of the courtyard. Table 8 summarizes ENVI-met parameters of green retrofit measures. Firstly, the sunshade reduces PET throughout the courtyard, most noticeably immediately below the sunshade by 2–4 °C. In the activity zone (0–2 m high), it reduces the temperature by 1–3 °C. Secondly, the green wall increases the surrounding PET by 0–2 °C, which is caused by sunlight reflection and heat storage in the leaves. However, it reduces the temperature by 2–4 °C in the central activity zone. Thirdly, contrary to common experience, a tree with a dense canopy increases the PET in most of the courtyard, but reduces the temperature by 2–3 °C in the central activity zone. A comparison of 15 m and 20 m tall trees shows that the canopy should preferably be above ground level to avoid blocking surface winds. Fourthly, shallow water has a very limited cooling effect, only cooling its surroundings by less than 0.8 °C. Fifthly, combining the four designs reduces the temperature by up to 4.9 °C in the activity zone. Finally, considering the counteraction of the trees, the combination of a sunshade, a green wall and water reduces the temperature by up to 5.6 °C in the activity zone. This design integrates the cooling effects of three designs to reduce the measured maximum temperature of 39.5 °C to below 35 °C (which is hot for PET).

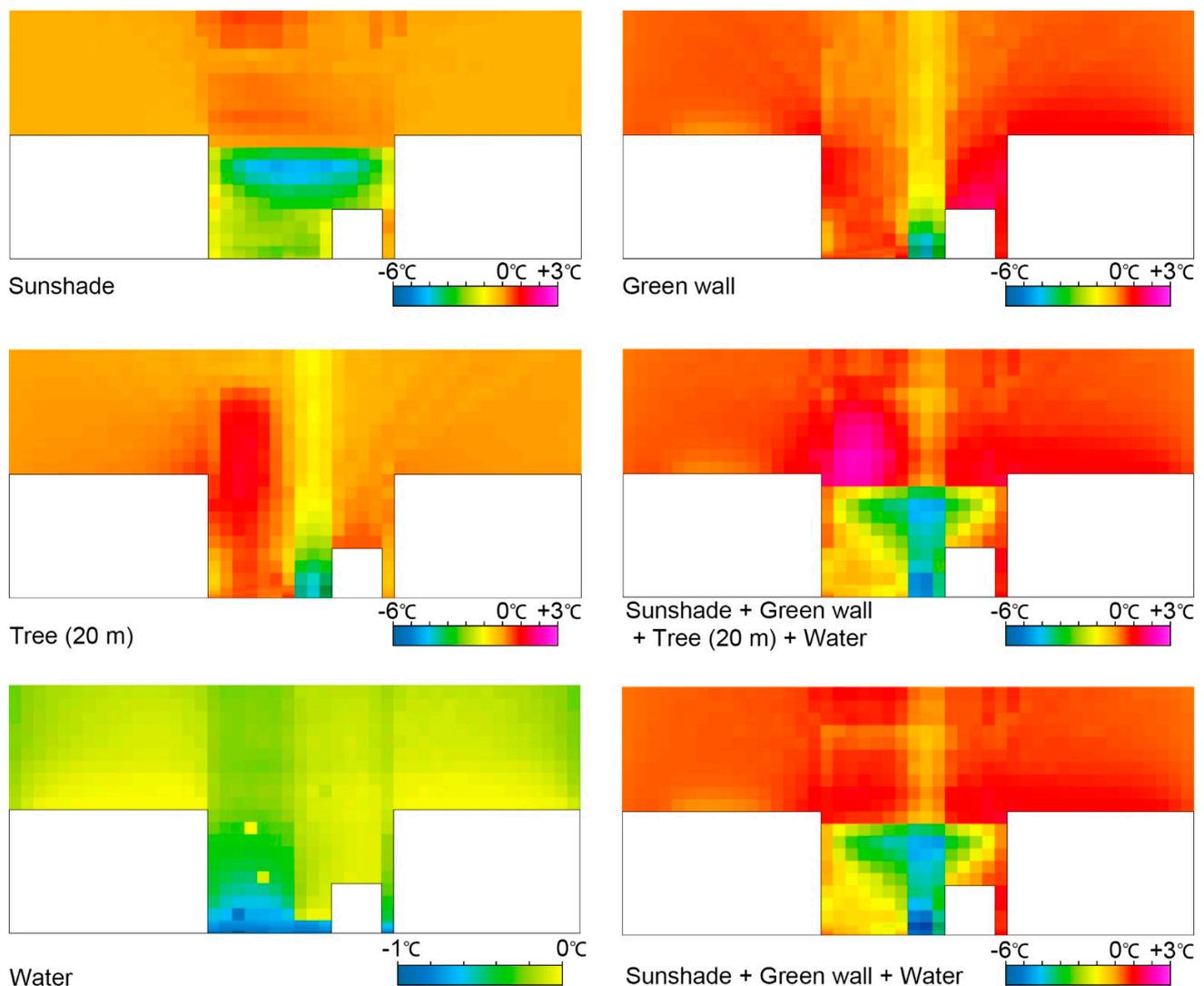


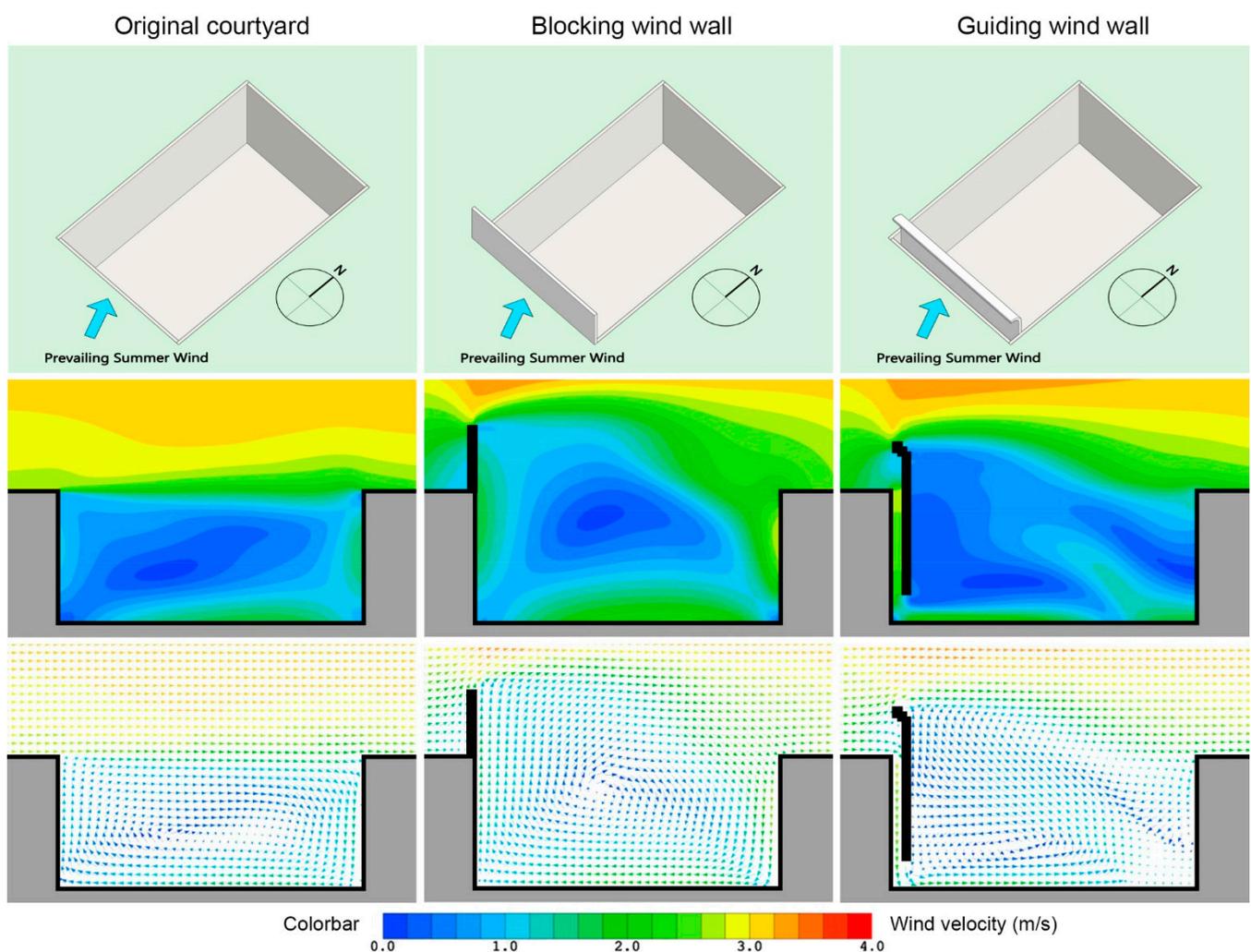
Figure 7. ENVI-met simulation results of improved designs for PET.

Table 8. ENVI-met parameters of green retrofit measures.

Green Retrofit Measure	Number	Parameter
Sunshade	000001	Single wall, SunSail, material (PV), thickness (0.2)
Green wall	01AGDS	Greenings with air gap, green and mixed substrate
Tree	0000BS	20 m height, dense, distinct crown layer, albedo (0.2), transmittance (0.3)
Water	0000WW	default

3.2.2. Retrofit Design for Natural Ventilation

Pressure difference is fundamental for organizing natural ventilation. This study aims to promote wind-pressure ventilation to introduce ground wind into the sunken courtyard and exhaust accumulated air pollutants. The two retrofit designs and original courtyard were compared by CFD simulation (Figure 8) in a prevailing SSE wind.

**Figure 8.** CFD simulation results of improved designs for natural ventilation.

First, the original courtyard had a wind velocity of 0.2–1.4 m/s in the activity zone, which was just perceptible but has a limited cooling effect in the summer. The vector diagram showed airflows circulating in the courtyard without being noticeably carried by ground winds. Therefore, the sunken courtyard becomes an outdoor ventilation “dead zone” and accumulates air pollutants, thereby confirming the uncertainties of previous measurements and ENVI-met simulation.

Thereafter, the 5-m high wall blocked ground winds to create a negative pressure zone in the courtyard and promote ground winds that sucked out underground airflows. The airflow field was effectively increased to 0.8–2.2 m/s in the activity zone. This condition was inspired by the upward wind in the surrounding area induced by the windward side of buildings in an urban wind environment. A blocking wall on the south side of the courtyard improved wind velocity, airflow exchange and the ventilation area better than the north side according to a comparison simulation. Furthermore, airflows were steadily circulated from the sunken courtyard to the ground, although many polluted airflows enter the courtyard again.

Lastly, guiding surface winds into the courtyard to create a positive pressure zone enables effective and consistent ventilation. This condition was inspired by widely used wind towers and wind deflectors in both aboveground and underground buildings. The 3-m high guiding wind wall increased the airflow field to 0.8–1.8 m/s in the activity zone. The guiding wind wall was installed 1 m from the original wall and did not encroach on a significant area. Although the guiding wind wall did not create a more uniform and faster wind than the blocking wind wall, it directed ground winds into the sunken courtyard more directly and with less circulation of polluted airflows.

In addition, both wind walls can be combined with greening or water cooling to reduce airflow temperature and upward buoyancy in the summer. Guiding wind walls can also be combined with controlled louvers in the top opening to avoid winter wind and undesirable airflow. Figure 9 shows ventilation performances of guiding wind walls for north, south and west (similar to east) ground winds with the same velocity as the prevailing wind (2.6 m/s). For wind direction close to the prevailing wind, there was a better performance on increasing wind velocity and discharging air pollutants. For wind direction contrary to the prevailing wind, it was no better than the effect of a slight discharge passage. For wind direction perpendicular to the prevailing wind, it was ineffective but had no negative effect.

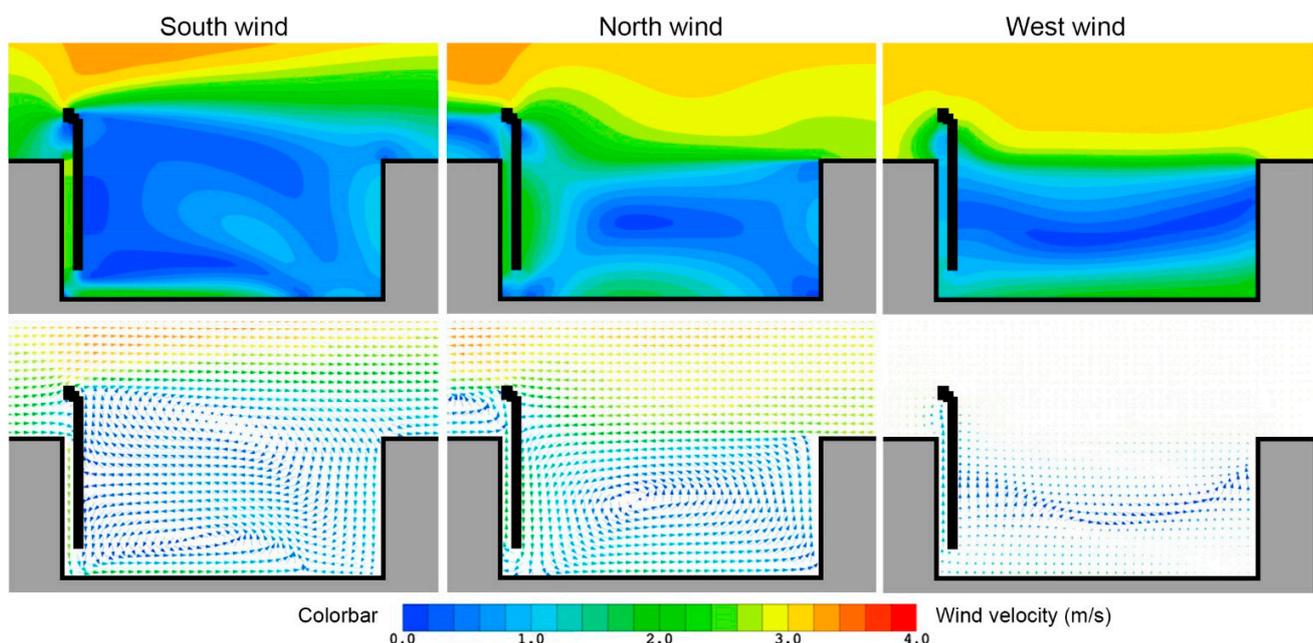


Figure 9. Ventilation performance of guiding wind wall in different wind directions.

Both wind walls can effectively improve the wind environment in the sunken courtyard, but only in wind directions close to the prevailing wind. A blocking wind wall was better at improving the wind environment for velocity and uniformity, while the guiding wind wall was more efficient at discharging air pollutants. When controlled louvers are closed, the blocking wind wall became a prevailing wind wall as well.

3.3. Summary

The main microclimatic problems in the measured sunken courtyard, that is, excessive solar radiation and accumulated air pollutants, were identified through analyzing field measurement and software simulations. First, compared to a green wall, water and a tree, sunshade was the primary measure to improve thermal comfort. When applying the findings to other sunken courtyards, position, size and angle of a sunshade should be adapted to local climate in order to balance summer shading with winter heating. Deciduous liane and photovoltaic panels can be combined with a sunshade to improve shading effects and ecological benefits. Secondly, large trees that provide partial shade for courtyards not only cause solar radiation to accumulate under the crown layer, but also weaken natural ventilation above and underground. Therefore, the traditional and empirical design concept of “more trees is better” may not apply. Appropriate plants should be chosen for different architectural interfaces to address corresponding environmental problems. Lastly, this study only applied the default setting of water in ENVI-met and found little effect on the courtyard microclimate. This requires further research on water of different depths, sizes and volumes. The design implications described above are further extended in Section 4.

4. Discussion

From this study of the thermal environment and air quality of the sunken courtyard, a classic underground space, it is clear that many empirically well and comfortably built environments conceal comfort and health problems, such as bad thermal conditions, accumulated pollutants and a lack of natural elements. In the early stages of building design, the designer should incorporate modeling and simulation to predict environmental quality. In turn, building design and environmental control should be adapted to the climatic conditions and usage requirements. This facilitates energy savings, natural access and reduces potential risks of the equipment used in the spaces. To counter global warming and the health crises, underground spaces cannot simply be artificially designed, due to the difficulties of construction and management, but should, as much as possible, be naturalized and healthy. The following section provides extended discussions on “greening underground spaces” and “adaptive designs for thermal environments”.

4.1. Greening Underground Spaces

4.1.1. Multiple Benefits

Greening underground spaces can enhance vitality and positive impressions. It can also help to regulate the microclimate in order to improve thermal comfort and air quality and promote healthy urban and social environments.

Firstly, greening revitalizes underground spaces into pleasant, comfortable and lively public spaces. The public has negative impressions of underground spaces, mostly from traditional cultures or unpleasant experiences, such as gloomy, damp, stuffy or lost environments. The sunken courtyard connects to the ground, bringing in natural elements, such as light, wind and water, which naturalize the underground environment and show the weather and time of day. This condition enhances multi-sensory experiences and also eliminates the unsafe and unhealthy psychological cues of underground spaces [29]. Furthermore, sunken courtyards enhance a sense of place and identity by providing external views and attractive images, which also echoes vernacular architecture and traditional context [30].

Secondly, plants and water effectively regulate the microclimate to enhance environmental quality whilst reducing energy consumption and carbon emissions. Plants enhance thermal comfort through transpiration, the absorption of carbon dioxide and the release of oxygen through photosynthesis. Plants can also absorb air pollutants (e.g., Vanda against nicotine and Tortoise against formaldehyde). Water acts as an efficient heat sink owing to its high thermal capacity and enhances absolute humidity and thermal comfort [31]. Meanwhile, these measures reduce operational loads for environmental control equipment, thereby reducing energy consumption and carbon emissions.

Thirdly, planted spaces in urban areas are beneficial to healthy environments in numerous ways [32]. Green spaces directly contribute to public health, notably because they enable citizens to engage in various activities that reduce obesity and prevent diseases, such as cardiovascular and lung disease. Additionally, outdoor activities are promoted to reduce the risk of indoor infections during epidemics.

4.1.2. Greening Design

The use of limited underground space to create a green atmosphere requires an elaborate design. Floors, walls and ceilings are available for plant design, creating a green underground space for a surrounding, immersive experience. Firstly, plants on the floor are easily accessible to people and provide spatial orientation. Fixed planting beds provide the soil depth required for plant growth. However, it inevitably takes up the already insufficient underground space and affects space availability. Removable containers can be arranged flexibly to meet different spatial requirements and can also be changed for seasonal scenes and various experiences. Secondly, a green wall does not encroach on horizontal spaces and provides an evident greening effect and recognizability. Modular green walls can easily be removed and replaced, providing a green underground space throughout the year. A green wall is also a widely used measure for regulating the microclimate and has been studied for its effectiveness in reducing radiation, enhancing thermal comfort and air quality and blocking noise [4,33,34]. Thirdly, a green ceiling contributes to the surrounding natural atmosphere, does not encroach on spaces available for human activities and provides coherent orientations. Additionally, a green ceiling can be combined with an outdoor pergola or sunshade to create a markedly pleasant environment in sunken courtyards. Lastly, water can be used in three spatial interfaces and with plants and has superior effects on thermal comfort. Note that water can provide animated landscapes and pleasant soundscapes. Water curtain walls, fountains and water spray [35,36] increase the thermal comfort, liveliness and vitality of underground spaces, giving occupants multi-sensory experiences.

Sunlight, air and water limit plant selection in underground spaces. Sunlight determines the photosynthesis and transpiration of plants. Outdoors, natural light is introduced as much as possible whilst balancing thermal temperatures and daylight [37]. Indoors, natural light can be supplied through direct, reflected or light-guided techniques, as well as by lighting that simulates the natural spectrum. Air movement affects temperature and humidity, which affect the root health and bacterial growth of plants. Poor air movement increases indoor carbon dioxide during plant respiration and affects human health. Water can be flexibly regulated through rainwater collection, grey water and irrigation systems. Therefore, drought-loving, shade-loving and cryptogamous plants are suited to underground greening, particularly in environments lacking in natural elements. Table 9 lists some plants suitable for underground spaces.

Table 9. Some plants suitable for underground spaces.

Green Methods	Plant Types	Plants
Green floor	Arbor	Royal palm, hemp palm, ficus lyrata
	Shrub	Octophylla, monstera, rohdea
Green wall	Herbage, liane, pteridophyta	Scindapsus, begonia cathayana hemsl, ophiopogon japonicus, moss
Green ceiling	Herbage, liane	Euphorbia humifusa, ivy, wisteria
Green water	Herbage, liane	Scindapsus, ivy, chlorophytum comosum
		Eichhornia crassipes, iris hexagonus, lotus

4.2. Adaptive Designs for Thermal Environments

Thermal environments cannot simply be designed to meet certain environmental standards. A healthy and energy-efficient thermal environment requires an adaptive design and flexible regulation. On the one hand, standard thermal comfort indicators should be modified according to the characteristics of underground spaces and the target

population. On the other hand, energy-efficient-oriented thermal design should integrate indoor and outdoor environments. Moreover, energy-oriented thermal regulation should integrate indoor and outdoor environments to fully use natural and artificial cooling and heat sources. Traditional designs focus on the interior and only consider using outdoor wind and light to reduce energy consumption of indoor environmental controls. Air and light between indoor and outdoor environments can be organized to maximize energy efficiency. For example, excessive cold air can penetrate from the indoors to the courtyard through open doors rather than mechanical exhaust systems, thereby reducing the energy consumption of equipment and also enhancing the thermal comfort of a sunken courtyard. Therefore, after analyzing the thermal demands generated by the environment and people, designers should integrate the surrounding environment and resources to design buildings, facilities, greening and operations with adaptive approaches.

4.2.1. Demand Analysis for Thermal Environment and Ventilation

The two common methods of thermal comfort are the predicted mean vote (PMV) and percentage of people dissatisfied (PPD) methods developed by Fanger [38], and the adaptive model proposed by Nicol and Humphreys [39]. Adaptive thermal comfort models combine field studies and linear regression to obtain specific temperatures adapted to location, climate and population [40]. Li et al. conducted a long-term and comprehensive study of underground thermal environments in various climatic zones in China. Firstly, four climatic zones for underground engineering in China were classified. Secondly, thermal comfort models and recommended temperature ranges for the different climate zones are proposed by regression analysis through field measurement and thermal sensation survey [41,42]. The current study classified Nanjing in the humid climate zone and suggested an indoor neutral temperature (25.43 °C) and an indoor acceptable temperature (23.80–27.65 °C). Lastly, the effects of temperature, relative humidity, wind velocity and the length of time that people dwell in the space, on thermal comfort in an underground mall were analyzed. The high temperature of transitional spaces between indoors and outdoors positively affected thermal comfort and energy consumption [43]. The research has been instructive for sunken courtyards as transitional spaces. The acceptable temperatures indoors are substantially lower than outdoor temperatures. Cool indoor air can naturally exhaust from the courtyard to enhance thermal comfort during hot times. Furthermore, an adaptive temperature gradient can provide dynamic thermal pleasure from the ground, to a courtyard, to the interior [44]. This condition also reduces cardiovascular and respiratory diseases caused by sudden exposure to hot and cold.

High thermal inertia of the surrounding soil provides a stable and delayed thermal environment to reduce the effects of outdoor climate fluctuations. The air-conditioning load of underground buildings is less than that of aboveground. However, excessive humidity in the summer, which causes condensation and insufficient sunlight, increases the dehumidification load of air-conditioning systems [45,46]. Humid air indoors also moderates dry environments in the sunken courtyard on summer afternoons.

Typical indicators of indoor air quality in underground buildings include concentrations of formaldehyde, TVOCs, CO₂ and radon, which are the main risk factors for sick building syndrome (SBS) and building-related illness (BRI) [45]. The most significant air pollutants in underground malls are TVOCs and formaldehyde from indoor decorations, catering and merchandise. These pollutant concentrations are significantly correlated with wind velocity and significantly positively correlated with air temperature and relative humidity [6]. Additionally, radon is a common problem for underground building air quality. Ventilation, coating level, decorating materials and geological formation are the main influencing factors [47]. Air pollutants infiltrate and accumulate in sunken courtyards, making them an environment which has a greater health risk than indoor environments with mechanical exhaust systems. Therefore, promoting ventilation using natural or artificial resources is key to the environmental health of courtyards.

4.2.2. Adaptive Design for Sunken Courtyard Microclimates

Site layout, building form, building configuration, building surfaces, greening and amenities of the built environment design significantly affect the thermal environment and energy efficiency. Vernacular experience and passive design of traditional buildings can be adapted to contemporary architectural design using innovation [48–50]. Even the built environment determines the long-term problems faced by microenvironments. Common problems in underground spaces include high humidity, lack of sunlight and views, poor air circulation and air quality and difficulty diffusing out noise. Considerable equipment, energy and space are required to compensate for the health and comfort deficiencies caused by the built environment [51–53]. The sunken courtyard is a significant solution that ideally connects and regulates indoor and outdoor microclimates and introduces the two most important natural elements: sunlight and wind.

Several studies have extensively explored adaptive solar, wind and thermal designs. Orientation, form, geometry and movable sunshade can be designed to provide substantial shadow in the summer and receive extensive sunlight in the winter. Reducing solar radiation in the summer should be balanced with heating in the winter, because sunken courtyards may not provide sufficient sunlight and acceptable thermal comfort in the winter [2]. Li studied, measured and simulated the ventilation and lighting performance of a sunken courtyard and found that its height and width are positively correlated with a ventilation effect. Furthermore, the height–lighting relationship suggested a north–south orientation and 5-m height adapted to the research field [54]. For additional daylighting and energy saving, Omrani et al. studied how the depth (D), width (W) and length (L) of sunken courtyards affect daylighting performance inside rooms and showed a Well Index (WI) = 0.5 that refers to D/W for a square plan or $D(W + L)/2$ for a rectangular plan [9]. Additionally, some studies on building surfaces and greening have been instructive. Ghafarianhoseini et al. evaluated the ability of unshaded courtyards to provide thermally comfortable outdoor spaces according to different design configurations and scenarios, including orientation, height and wall albedo and vegetation [55]. Similarly, high albedo surfaces, a water pond and vegetation were suggested to mitigate heat loads and moderate the microclimate of courtyards [23,56].

Natural ventilation can effectively improve thermal comfort and air quality in daily life and during epidemics and has the immense potential to control efficiency and save energy [57–59]. However, adequate and stable natural ventilation in a separate underground space is difficult to obtain. In shallow underground spaces and hot-humid climates, the generation of buoyancy by the vertical temperature difference between underground and aboveground is not evident [60,61]. Thermal pressure ventilation needs stable temperature differences, which can be obtained by active and passive designs. Firstly, solar chimneys and photovoltaic–thermal collectors can collect solar energy to create temperature differences and promote stable ventilation [62]. Secondly, earth–air–heat exchanger systems use the constant temperature of the subsoil to heat or cool outdoor air [63]. Underground water cooling and spray cooling can be applied adaptively to reduce the length of cooling ducts. Thirdly, temperature differences created by connected courtyards or atria, which are widely used in traditional group buildings, can also create stable natural ventilation. Lastly, the previously discussed wind pressure ventilation can be further enhanced by the design of wind towers, wind ducts and wind catchers [8,58]. Figure 10 presents some concepts for active and passive designs to promote natural ventilation in underground spaces.

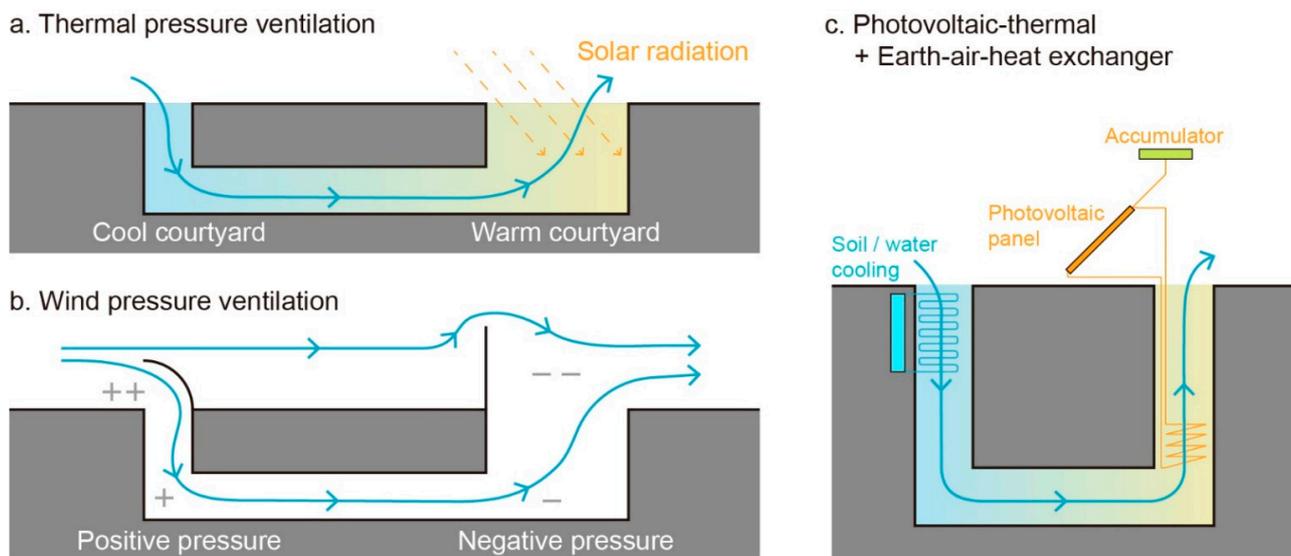


Figure 10. Active and passive techniques for natural ventilation in underground spaces.

5. Conclusions

Sunken courtyards, as major outdoor spaces underground, can provide comfortable, healthy and natural environments. Sunlight, wind and greening are the key factors to improving thermal comfort, air quality and usage experience. This study identified the existing problems of excessive summer solar radiation and accumulated air pollutants in a sunken courtyard through field measurements and simulations.

1. Measurements showed that excessive solar radiation caused PET to peak at 39.5 °C in the sunken courtyard when the weather forecast was below 33 °C. Increasing humidity and wind velocities can reduce PET to a limited extent.
2. Ground wind conditions hardly affected the sunken courtyard causing poor thermal comfort and accumulated pollutants. PMs and TVOCs consistently exceeded health standards and were likely to originate from artificial building materials, catering and merchandise.
3. In the activity zone, the sunshade most effectively reduced PET by 1–3 °C. The green wall reduced the temperature by 2–4 °C in the central zone. The shallow water only cooled its surroundings by less than 0.8 °C. Contrary to common experience, the tree with a dense canopy increased the PET in most of the courtyard but reduced the temperature by 2–3 °C in the central zone. Combining a sunshade, a green wall and water reduced the temperature by up to 5.6 °C and reduced the maximum temperature of 39.5 °C to below 35 °C (which is hot for PET).
4. Blocking/guiding wind walls can effectively improve the wind environment in the sunken courtyard, but only in wind directions close to the prevailing wind. A blocking wind wall was better at velocity and uniformity, while the guiding wind wall was more efficient at discharging air pollutants.
5. Climate-adaptive designs have immense potential and demand in underground spaces. Green-adaptive design considers the growth characteristics and environmental effects of plants to avoid a negative impact on an underground microclimate. Thermal-adaptive design balances daylight and heating to increase building self-shading in the summer and provide additional light in the winter. Wind-adaptive design integrates indoor and outdoor spaces to improve thermal comfort and passive ventilation through the use of natural and artificial sources.

The limitations of this study are the simulation errors of solar radiation and humidity in ENVI-met, and its grid sizes and greening functions. The potential of wind pressure ventilation in underground courtyards was only discussed initially and lacked realistic

simulations. Future research and engineering should combine significantly accurate environmental simulations with comprehensive adaptive design to improve the comfort and health of underground spaces.

Author Contributions: Conceptualization, J.L. and G.H.; methodology, G.H. and Y.W.; software, G.H. and Y.W.; validation, J.L. and L.S.; formal analysis, J.L.; investigation, G.H., Y.W. and L.S.; resources, J.L.; data curation, Y.W.; writing—original draft preparation, G.H. and Y.W.; writing—review and editing, J.L.; visualization, G.H., Y.W. and L.S.; supervision, J.L.; project administration, J.L.; funding acquisition, J.L. and Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52178009, the Postgraduate Research and Practice Innovation Program of Jiangsu Province, grant number KYCX20_0112, and the open fund for Jiangsu Province Key Laboratory of Intelligent Building Energy Efficiency, grant number BEE201902.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Al-Mumin, A.A. Suitability of sunken courtyards in the desert climate of Kuwait. *Energy Build.* **2001**, *33*, 103–111. [CrossRef]
- Amirbeiki Tafti, F.; Rezaeian, M.; Emadian Razavi, S.Z. Sunken courtyards as educational environments: Occupant's perception and environmental satisfaction. *Tunn. Undergr. Space Technol.* **2018**, *78*, 124–134. [CrossRef]
- Soflaei, F.; Shokouhian, M.; Mofidi Shemirani, S.M. Traditional Iranian courtyards as microclimate modifiers by considering orientation, dimensions, and proportions. *Front. Archit. Res.* **2016**, *5*, 225–238. [CrossRef]
- Fatemeh, V.; Siavash, R.; Reza, A. Investigating the cooling effect of living walls in the sunken courtyards of traditional houses in Yazd. *Eur. J. Sustain. Dev.* **2016**, *5*, 27. [CrossRef]
- Venter, Z.S.; Barton, D.N.; Gundersen, V.; Figari, H.; Nowell, M. Urban nature in a time of crisis: Recreational use of green space increases during the COVID-19 outbreak in Oslo, Norway. *Environ. Res. Lett.* **2020**, *15*, 104075. [CrossRef]
- Tao, H.; Fan, Y.; Li, X.; Zhang, Z.; Hou, W. Investigation of formaldehyde and TVOC in underground malls in Xi'an, China: Concentrations, sources, and affecting factors. *Build. Environ.* **2015**, *85*, 85–93. [CrossRef]
- Guo, H.; Deng, M.; Li, Y. Effect of sunken plaza on ventilation performance of underground commercial buildings. *J. South China Univ. Technol.* **2014**, *42*, 114–120.
- Wen, Y.; Leng, J. A spatial prototype of natural ventilation in underground public spaces combining courtyard with wind tower. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *703*, 12003. [CrossRef]
- Omran, M.; Lian, Z.; Xuan, H. Effects of the courtyard's geometry in dig pit underground dwellings on the room's daylighting performance. *Build. Simul.* **2019**, *12*, 653–663. [CrossRef]
- Xu, C. Nanjing Official Declares Summer Lasts 140 Days Longest in This Century and Enters Autumn. Available online: http://jsnews.jschina.com.cn/hxms/202010/t20201010_2641923.shtml (accessed on 4 September 2021).
- Wu, L. Simulation capacity assessment of the start date and length of the four seasons in Nanjing. *Technol. Innov. Appl.* **2021**, *11*, 52–54.
- Jendritzky, G.; Bucher, K.; Laschewski, G.; Walther, H. Atmospheric heat exchange of the human being, bioclimate assessments, mortality and thermal stress. *Int. J. Circumpolar Health* **2000**, *59*, 222–227. [PubMed]
- de Dear, R.; Pickup, J. (Eds.) An Outdoor Thermal Comfort Index (OUT-SET*): Part I-The Model and Its Assumptions. In Proceedings of the 5th International Congress of Biometeorology and International Conference on Urban Climatology, Sydney, NSW, Australia, 1 January 1999; Macquarie University: Macquarie Park, NSW, Australia, 1999.
- Höppe, P. The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. *Int. J. Biometeorol.* **1999**, *43*, 71–75. [CrossRef] [PubMed]
- ISB Commission 6. Universal Thermal Climate Index. Available online: <http://www.utci.org/> (accessed on 8 July 2021).
- Fröhlich, D.; Gangwisch, M.; Matzarakis, A. Effect of radiation and wind on thermal comfort in urban environments—Application of the RayMan and SkyHelios model. *Urban Clim.* **2019**, *27*, 1–7. [CrossRef]
- Fang, Z.; Lin, Z.; Mak, C.M.; Niu, J.; Tse, K.-T. Investigation into sensitivities of factors in outdoor thermal comfort indices. *Build. Environ.* **2018**, *128*, 129–142. [CrossRef]
- ASHRAE Standard 55-2017. *Thermal Environmental Conditions for Human Occupancy*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2017.
- Andres, M.; Fröhlich, D. RayMan. Available online: <https://www.urbanclimate.net/rayman/> (accessed on 8 July 2021).
- ISO 7726. *Ergonomics of the Thermal Environment: Instruments for Measuring Physical Quantities*, 2nd ed.; International Organization for Standardization: Geneva, Switzerland, 1998.
- Nasrollahi, N.; Hatami, M.; Khastar, S.R.; Taleghani, M. Numerical evaluation of thermal comfort in traditional courtyards to develop new microclimate design in a hot and dry climate. *Sustain. Cities Soc.* **2017**, *35*, 449–467. [CrossRef]
- Forouzandeh, A. Numerical modeling validation for the microclimate thermal condition of semi-closed courtyard spaces between buildings. *Sustain. Cities Soc.* **2018**, *36*, 327–345. [CrossRef]

23. Taleghani, M.; Tenpierik, M.; van den Dobbelsteen, A.; Sailor, D.J. Heat in courtyards: A validated and calibrated parametric study of heat mitigation strategies for urban courtyards in the Netherlands. *Sol. Energy* **2014**, *103*, 108–124. [CrossRef]
24. Soares, R.; Corvacho, H.; Alves, F. Summer Thermal conditions in outdoor public spaces: A Case study in a Mediterranean climate. *Sustainability* **2021**, *13*, 5348. [CrossRef]
25. Liu, S.; Pan, W.; Zhao, X.; Zhang, H.; Cheng, X.; Long, Z.; Chen, Q. Influence of surrounding buildings on wind flow around a building predicted by CFD simulations. *Build. Environ.* **2018**, *140*, 1–10. [CrossRef]
26. Acero, J.A.; Herranz-Pascual, K. A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques. *Build. Environ.* **2015**, *93*, 245–257. [CrossRef]
27. Salata, F.; Golasi, I.; de Lieto Vollaro, R.; de Lieto Vollaro, A. Urban microclimate and outdoor thermal comfort. A proper procedure to fit ENVI-met simulation outputs to experimental data. *Sustain. Cities Soc.* **2016**, *26*, 318–343. [CrossRef]
28. GB 50736-2012. *Design Code for Heating Ventilation and Air Conditioning of Civil Buildings*; Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2012. Available online: <http://www.jianbiaoku.com/webarbs/book/16582/1663584.shtml> (accessed on 12 September 2021).
29. Breton, E. Underground vegetal scenography: Benefits and installation conditions. *Procedia Eng.* **2016**, *165*, 369–378. [CrossRef]
30. Sun, L.; Wang, Y.; Leng, J. A study of museum courtyard space in eastern China. *J. Asian Archit. Build. Eng.* **2019**, *18*, 28–42. [CrossRef]
31. Imam Syafii, N.; Ichinose, M.; Kumakura, E.; Jusuf, S.K.; Chigusa, K.; Wong, N.H. Thermal environment assessment around bodies of water in urban canyons: A scale model study. *Sustain. Cities Soc.* **2017**, *34*, 79–89. [CrossRef]
32. Elliott, H.; Eon, C.; Breadsell, J.K. Improving City vitality through urban heat reduction with green infrastructure and design solutions: A systematic literature review. *Buildings* **2020**, *10*, 219. [CrossRef]
33. Tan, C.L.; Wong, N.H.; Jusuf, S.K. Effects of vertical greenery on mean radiant temperature in the tropical urban environment. *Landsc. Urban Plan.* **2014**, *127*, 52–64. [CrossRef]
34. Lau, S.-K.; Zhu, X.-F.; Lu, Z. Enhancing the acoustic absorption of vegetation with embedded periodic metamaterials. *Appl. Acoust.* **2021**, *171*, 107576. [CrossRef]
35. Farnham, C.; Emura, K.; Mizuno, T. Evaluation of cooling effects: Outdoor water mist fan. *Build. Res. Inf.* **2015**, *43*, 334–345. [CrossRef]
36. Wai, K.-M.; Xiao, L.; Tan, T.Z. Improvement of the outdoor thermal comfort by water spraying in a high-density urban environment under the influence of a future (2050) climate. *Sustainability* **2021**, *13*, 7811. [CrossRef]
37. Yu, F.; Wennersten, R.; Leng, J. A state-of-art review on concepts, criteria, methods and factors for reaching 'thermal-daylighting balance'. *Build. Environ.* **2020**, *186*, 107330. [CrossRef]
38. Fanger, P.-O. *Thermal Comfort: Analysis and Applications in Environmental Engineering*; Danish Technical Press: Copenhagen, Denmark, 1970.
39. Nicol, J.F.; Humphreys, M.A. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy Build.* **2002**, *34*, 563–572. [CrossRef]
40. Toe, D.H.C.; Kubota, T. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database. *Front. Archit. Res.* **2013**, *2*, 278–291. [CrossRef]
41. Li, Y.; Geng, S.; Yuan, Y.; Wang, J.; Zhang, X. Evaluation of climatic zones and field study on thermal comfort for underground engineering in China during summer. *Sustain. Cities Soc.* **2018**, *43*, 421–431. [CrossRef]
42. Li, Y.; Geng, S.; Zhang, X.; Zhang, H. Study of thermal comfort in underground construction based on field measurements and questionnaires in China. *Build. Environ.* **2017**, *116*, 45–54. [CrossRef]
43. Li, Y.; Geng, S.; Chen, F.; Li, C.; Zhang, X.; Dong, X. Evaluation of thermal sensation among customers: Results from field investigations in underground malls during summer in Nanjing, China. *Build. Environ.* **2018**, *136*, 28–37. [CrossRef]
44. Liu, S.; Nazarian, N.; Hart, M.A.; Niu, J.; Xie, Y.; de Dear, R. Dynamic thermal pleasure in outdoor environments-temporal alliesthesia. *Sci. Total. Environ.* **2021**, *771*, 144910. [CrossRef]
45. Yu, J.; Kang, Y.; Zhai, Z. Advances in research for underground buildings: Energy, thermal comfort and indoor air quality. *Energy Build.* **2020**, *215*, 109916. [CrossRef]
46. Dong, X.; Wu, Y.; Chen, X.; Li, H.; Cao, B.; Zhang, X.; Yan, X.; Li, Z.; Long, Y.; Li, X. Effect of thermal, acoustic, and lighting environment in underground space on human comfort and work efficiency: A review. *Sci. Total. Environ.* **2021**, *786*, 147537. [CrossRef]
47. Li, X.; Zheng, B.; Wang, Y.; Wang, X. A survey of radon level in underground buildings in China. *Environ. Int.* **2006**, *32*, 600–605. [CrossRef]
48. Paramita, B.; Fukuda, H.; Perdana Khidmat, R.; Matzarakis, A. Building Configuration of low-cost apartments in bandung—Its contribution to the microclimate and outdoor thermal comfort. *Buildings* **2018**, *8*, 123. [CrossRef]
49. Sun, F. Chinese Climate and vernacular dwellings. *Buildings* **2013**, *3*, 143–172. [CrossRef]
50. Santy; Matsumoto, H.; Tsuzuki, K.; Susanti, L. Bioclimatic Analysis in pre-design stage of passive house in Indonesia. *Buildings* **2017**, *7*, 24. [CrossRef]
51. Wen, Y.; Leng, J.; Yu, F.; Yu, C.W. Integrated design for underground space environment control of subway stations with atriums using piston ventilation. *Indoor Built Environ.* **2020**, *29*, 1300–1315. [CrossRef]

52. Wen, Y.; Leng, J.; Shen, X.; Han, G.; Sun, L.; Yu, F. Environmental and health effects of ventilation in subway stations: A Literature review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1084. [[CrossRef](#)] [[PubMed](#)]
53. Leng, J.; Wen, Y. Environmental standards for healthy ventilation in metros: Status, problems and prospects. *Energy Build.* **2021**, *245*, 111068. [[CrossRef](#)]
54. Li, K. Research and Optimization on Sunken Courtyard Building Natural Ventilation and Lighting in Xi'an. Master's Thesis, Xi'an University of Architecture and Technology, Xi'an, China, 2013.
55. Ghaffarianhoseini, A.; Berardi, U.; Ghaffarianhoseini, A. Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Build. Environ.* **2015**, *87*, 154–168. [[CrossRef](#)]
56. Taleghani, M.; Sailor, D.J.; Tenpierik, M.; van den Dobbelsteen, A. Thermal assessment of heat mitigation strategies: The case of Portland State University, Oregon, USA. *Build. Environ.* **2014**, *73*, 138–150. [[CrossRef](#)]
57. Chenari, B.; Dias Carrilho, J.; Gameiro da Silva, M. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1426–1447. [[CrossRef](#)]
58. Mukhtar, A.; Yusoff, M.Z.; Ng, K.C. The potential influence of building optimization and passive design strategies on natural ventilation systems in underground buildings: The state of the art. *Tunn. Undergr. Space Technol.* **2019**, *92*, 103065. [[CrossRef](#)]
59. Leng, J.; Wang, Q.; Liu, K. Sustainable design of courtyard environment: From the perspectives of airborne diseases control and human health. *Sustain. Cities Soc.* **2020**, *62*, 102405. [[CrossRef](#)]
60. Khan, N.; Su, Y.; Riffat, S.B. A review on wind driven ventilation techniques. *Energy Build.* **2008**, *40*, 1586–1604. [[CrossRef](#)]
61. Liu, P.-C.; Lin, H.-T.; Chou, J.-H. Evaluation of buoyancy-driven ventilation in atrium buildings using computational fluid dynamics and reduced-scale air model. *Build. Environ.* **2009**, *44*, 1970–1979. [[CrossRef](#)]
62. Xiang, B.; Yu, T.; Yuan, Y.; Sun, L.; Cao, X. Study on influencing factor of solar chimney effect in underground space based on photovoltaic-thermal. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 141–147.
63. Agrawal, K.K.; Misra, R.; Agrawal, G.D.; Bhardwaj, M.; Jamuwa, D.K. The state of art on the applications, technology integration, and latest research trends of earth-air-heat exchanger system. *Geothermics* **2019**, *82*, 34–50. [[CrossRef](#)]