sustainability

MDPI

Article

The Impact of Indoor Living Wall System on Air Quality: A Comparative Monitoring Test in Building Corridors

Yiming Shao [1,*], Jiaqiang Li [1], Zhiwei Zhou [1], Fan Zhang [2] and Yuanlong Cui [3]

[1] School of Architecture, Nanjing Tech University, Nanjing 211816, China; 201861111024@njtech.edu.cn (J.L.); 201961111015@njtech.edu.cn (Z.Z.)
[2] School of Engineering and the Built Environment, Griffith University, Southport, QLD 4222, Australia; fan.zhang@griffith.edu.au
[3] Department of Built Environment, College of Engineering and Technology, University of Derby, Derby DE22 3AW, UK; Y.Cui@derby.ac.uk
* Correspondence: sym19851021@njtech.edu.cn; Tel.: +86-17712418192; Fax: +86-25-83410676

Abstract: Living wall systems have been widely recognized as one of the promising approaches for building applications due to their aesthetic value and ecological benefits. Compared with outdoor living wall systems, indoor living wall systems (ILWS) play a more vital role in indoor air quality. The aim of this study is to investigate the effects of ILWS on indoor air quality. In an office building, two parallel corridors were selected as comparative groups. A 10.6 m^2 ILWS was installed on the sidewall of the west corridor while the east corridor was empty. Some important parameters, including indoor air temperature, relative humidity, concentrations of carbon dioxide (CO_2), and particulate matter (PM) were obtained based on the actual environment monitoring. According to the statistical analysis of the data, there were significant differences in the concentrations of CO_2 and PMs in the corridors with and without ILWS, which indicated that CO_2 and $PM_{2.5}$ removal rate ranged from 12% to 17% and 8% to 14%, respectively. The temperature difference is quite small (0.13 °C on average), while relative humidity slightly increased by 3.1–6.4% with the presence of the ILWS.

Keywords: vertical greenery system; indoor living wall system; indoor air quality; carbon dioxide; particulate matter

check for updates

Citation: Shao, Y.; Li, J.; Zhou, Z.; Zhang, F.; Cui, Y. The Impact of Indoor Living Wall System on Air Quality: A Comparative Monitoring Test in Building Corridors. *Sustainability* **2021**, *13*, 7884. https://doi.org/10.3390/su13147884

Academic Editor: Ali Bahadori-Jahromi

Received: 11 June 2021
Accepted: 9 July 2021
Published: 14 July 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

Currently, city development trends in the vertical direction owing to the rapid increase in population, especially in developing countries [1,2]. The growth of density and reduction of green spaces has caused a series of urban environmental health problems including the heat island effect [3] and air particle pollution [4]. In recent years, the purification and thermal effects of green plants on the urban environment have received increasing attention in the academic community [5–7]. Their ecological effects have also been verified, such as pollution reduction [8,9], noise reduction [10–12], increase in biodiversity [13–15], and energy consumption reduction [16–22]. Relevant research studies are mostly focused on outdoor greening, such as three-dimensional greening in urban centers [23], greening of roofs [24], and building skins [25]. Hence, the vertical greenery system (VGS) becomes an ideal typology of greening in a crowded city, since it effectively uses the vertical space to accommodate the green plants. VGS can be categorized into green façade and the living wall system (LWS) based on structure configurations. A green façade refers to the climbing plants rooting at the ground level. The vegetation can either climb on the wall directly or indirectly with trellises. By contrast, an LWS refers to vegetation grown in felt or modular systems attached to the walls. The felt or modular system holds the substrate media which can be watered mechanically [26]. With a number of planting units, LWS can be flexibly

pixilated with species of colorful plants to form a green pattern which could add aesthetic value to the built environment [27].

Generally, LWS can be divided into two categories including outdoor living wall system (OLWS) and indoor living wall system (ILWS) [26]. In recent years, OLWS has been widely investigated and conducted to verify the potential in terms of thermal enhancement and energy-saving. Results show that the OLWS can effectively improve thermal comfort and decrease energy demand in summer and act as extra insulation in winter [28–31].

Compared with OLWS, the studies on ILWS are quite limited. Previous papers of ILWS focus on thermal comfort and energy-saving aspects [32]. There is little attention given to ILWSs' impact on the indoor physical environment, especially indoor air quality. López-Aparicio et al. [33] found that the deterioration of outdoor air quality could indirectly affect indoor air quality. The most prominent indoor air pollutants are carbon dioxide (CO_2), particulate matter (PM), and a range of volatile organic compounds (VOCs) [34]. An elevated level of CO_2 concentration has been associated with "sick building syndrome". When CO_2 concentration rises from 389 ppm to 1160 ppm, sick building symptoms will increase significantly [35]. The CO_2 concentration also has an effect on workplace productivity. Research shows that when the indoor CO_2 concentration reduced from 1515 ppm to 735 ppm, the human reaction time was shortened by 5.4% [36]. Long-term exposure to high concentrations of PMs (higher than 50 $\mu g/m^3$) could lead to the increasing of morbidity and mortality due to cardiovascular, respiratory, and venous thromboembolic diseases [37]. VOCs have also been associated with several health effects according to different main ingredients [34]. As a majority of citizens spend almost 90% of their time indoors every day [38], ensuring good indoor air quality becomes a prerequisite for people to maintain a healthy state of daily life. Although small in number, studies have been done to investigate the impact of green walls on indoor environmental quality, including CO_2 and PMs concentration, temperature, and humidity. Ghazalli et al. [39] studied the impact of IVGS installation in the north-south corridor on PMs, temperature, and humidity, and found that IVGS has no significant impact on temperature but can reduce particulate matter concentration and increase indoor humidity. Su and Lin [40] showed that a 5.72 m^2 ILWS could reduce the CO_2 concentration of a 38.88 m^3 room from 2000 to 800 ppm within 4 h. Torpy et al. [41] showed that a 1 m^2 ILWS was capable of significant room CO_2 reductions, but only with considerable supplementary lighting (250 $mmol/m^2/s$), whilst indoor light levels typically range between 5 and 12 $mmol/m^2/s$. Tudiwer et al. [42] tested a 5.88 m^2 ILWS installed on the sidewall of a classroom (8.5m Length × 6.5 m Width × 3.7 m Height) and found that compared with non-green classrooms, the relative humidity of the green classroom increased by 34.21%, and the indoor CO_2 concentration decreased by 3.5%. The comfort level was increased by 20.6% (the local comfort zone: temperature 17 °C to 25.5 °C, relative humidity 18% to 87%).

At present, there are only a few academic research studies on the effect of ILWS on indoor air pollutant removal and thermal comfort enhancement. Research in its impact on different parameters, including the concentration of CO_2, the concentration of PMs, temperature, and humidity, at different climatic zones is needed. The purpose of this paper is to fill this knowledge gap by providing a ten-month monitoring test and statistical analysis within an office building at Cfa climatic zone (the subtropical climate and the precipitation more evenly distributed throughout the year) in Köppen climate classification. Two parallel corridors, with and without ILWS, were investigated to assess the effects of ILWS on indoor air pollutant reduction (CO_2 and PMs concentration) and thermal condition (temperature and relative humidity).

2. Methods

2.1. Location of the Study

The site is located in Nanjing city (118°38′24″ E, 32°04′48″ N), which is situated in the hot summer and cold winter climatic zone. Based on the China Meteorological Data Network [43], as shown in Figure 1, the maximum ambient air temperature is about 37.2 °C

in July, while the minimum is −5.6 °C in January. In terms of relative humidity, despite the large fluctuations from 15% to 100%, most of the values are concentrated in the 60–90% range, with an average of over 70%.

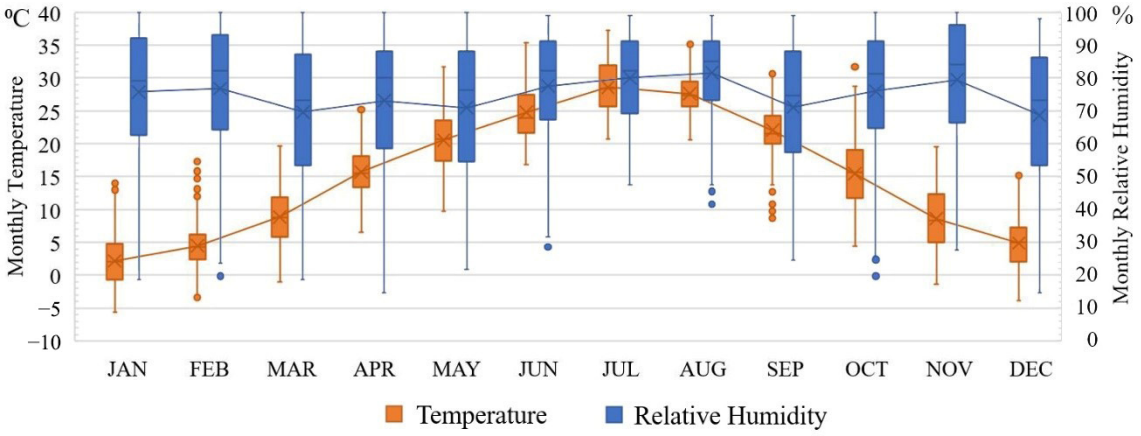


Figure 1. Monthly temperature and relative humidity statistics.

2.2. Monitoring Conditions

The monitoring test was carried out on the first floor of a six-story office building (built in 2010) at the university park as shown in Figure 2. To be more specific, the ILWS is arranged on the wall of the stairwell at the western end of the corridor, which has an area of approximately 10.6 m^2 as shown in Figure 3. The ILWS has been constructed and run for more than 2 years. The ILWS consists of a modular planting pot array, a drip irrigation network, and a light-emitting diode (LED) lighting system. Specifically, the water at the bottom of the tank is pumped to each level of the planting pot array, which is then distributed by the drip irrigation to each pot and finally circulated back to the water tank by gravity. The vegetation of ILWS consists of three shade-requiring landscaping plants (Table 1). By contrast, the wall without ILWS is at the eastern end of the corridor. The corridors are enclosed by glazing that separates the indoor corridor space from the courtyard. The building information can be found in Table 2.

Table 1. Plants on the indoor living wall system.

Name of the Plant	Light Requirement	Growth Cycle Category	Applied Area (m^2)/Proportion (%)
Schefflera octophylla (Lour.) Harms	shade-loving	Perennial	5.2/49.1%
Fatsia japonica (Thunb.) Decne. et Planch	shade-loving	Perennial	2.1/19.8%
Chamaedorea elegans Mart	shade-loving	Perennial	3.3/31.1%

Table 2. Building information.

Building Components	Specifications
Floor height	4 m, floor to floor height
Wall	240 mm hollow concrete small blocks wall with paint finish
Ceiling	light steel keel asbestos board suspended ceiling
Floor	120 mm cast-in-place concrete with floor tile finish
Glazing	6 mm single glazing
HVAC system	no HVAC system in corridors and other public spaces, single air-conditioner in separated offices

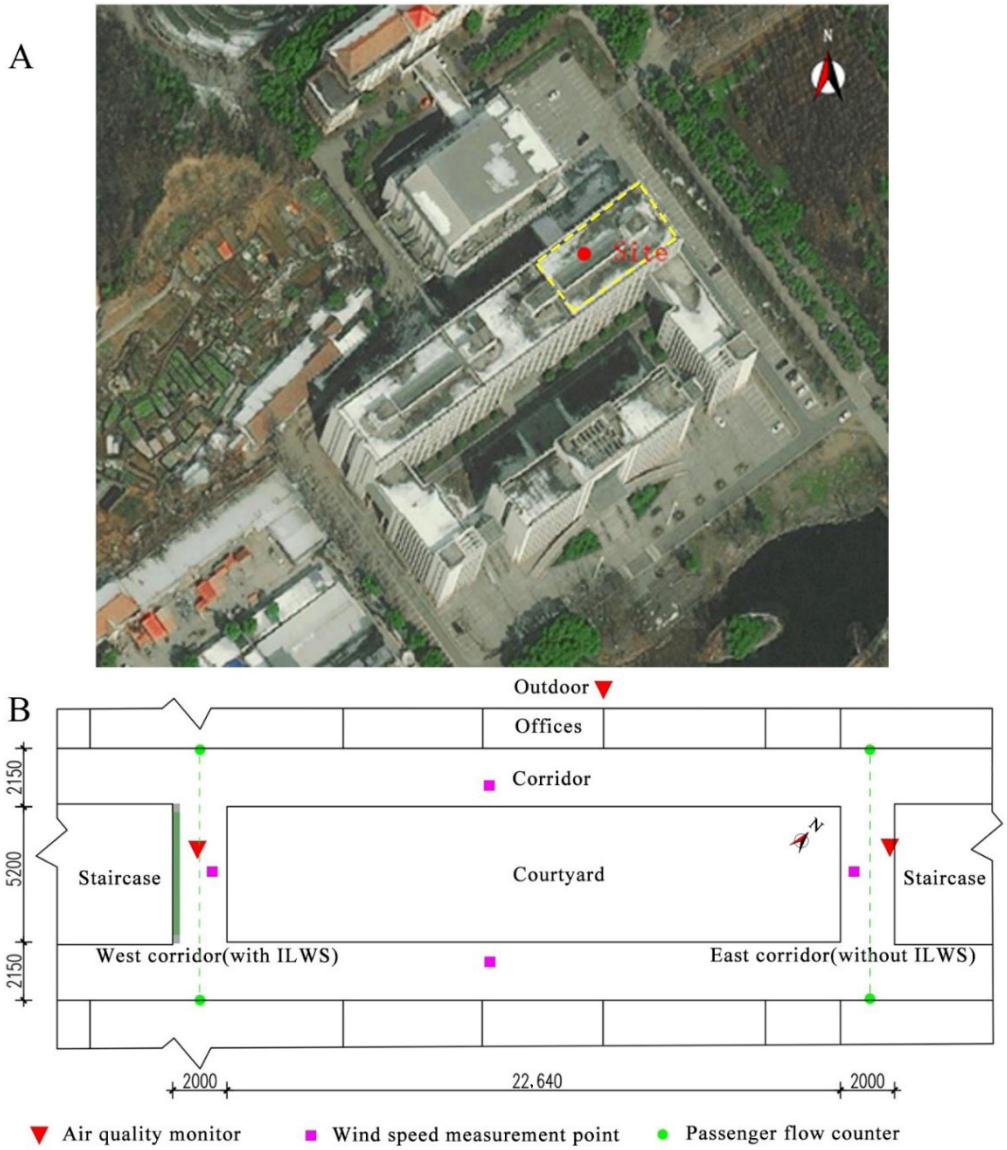


Figure 2. Monitoring location: (**A**): location of the site; (**B**): floor plan and the setup of measuring devices (Unit in mm).

2.3. Monitored Parameters and Sensors

A series of parameters, including CO_2 and PMs concentration, temperature, and relative humidity, of the two corridors, were compared using recorded monitoring data. In doing this, several devices were adopted, including three air quality monitors, a photosynthetically active radiation (PAR) meter, two anemometers, and two pairs of passenger flow counters, as presented in Figure 4. Table 3 summarized the measurement methods of the concentration of CO_2, PMs (average PMs concentration was recorded for three mutually exclusive PMs fractions: $PM_{0.3–1}$, $PM_{1–2.5}$, $PM_{2.5–10}$), temperature, and relative humidity. The three air quality monitors were located in two corridors and one outside the building. Monitors in each corridor were positioned at a 2 m height level where the air movement was relatively stable with minimum human interference. The third monitor was set outside the exterior window of the first floor (ground floor height: 4 m), at 2 m level to the floor, i.e., 6 m above the ground. The PAR meter measures the photosynthetic energy from natural and artificial light. It was placed at six measuring points on the surface of the ILWS (Figure 3C) in order to obtain the photosynthetic photon flux density (PPFD) values at each point on different sunny and cloudy days. These data were then used to calculate the average PPFD on each point. The four anemometers, setting at the middle of each corridor,

record the indoor wind speed. The number of people passing by the corridors was recorded by the passenger flow counters that were positioned at the midline of each corridor. All devices were checked and calibrated before use. The monitoring period was recorded from November 2018 to August 2019. Three independent measurements were conducted in both heating and cooling seasons, in which each measurement contains 15 days of records.

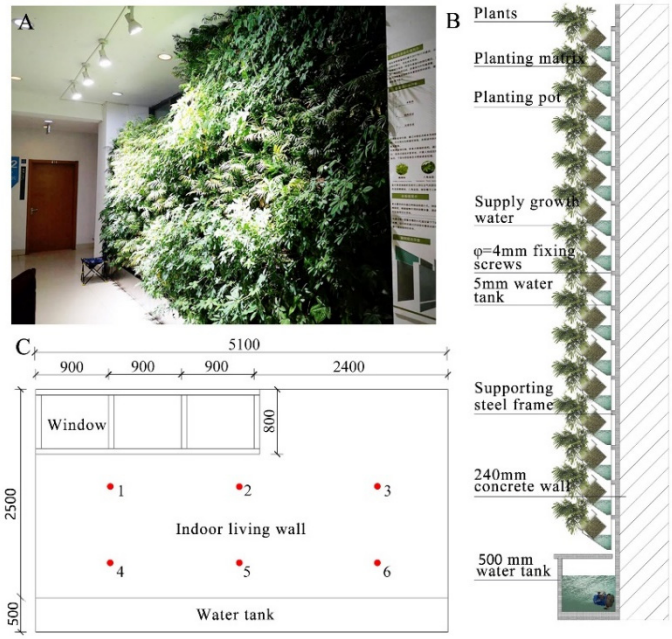


Figure 3. Photo and diagrams of the ILWS: (**A**): photo; (**B**): section; (**C**): PAR measuring points (Unit in mm).

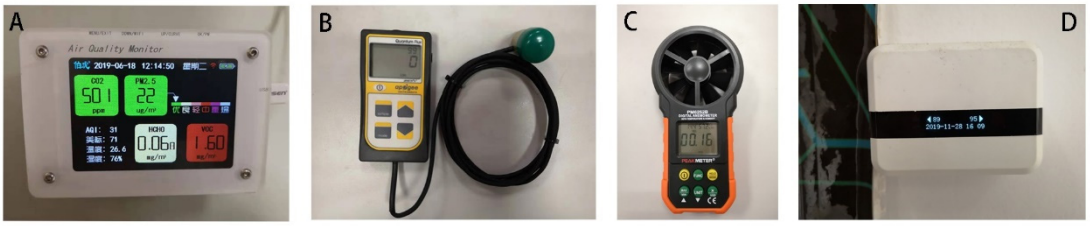


Figure 4. Monitoring equipment: ((**A**): air quality monitor; (**B**): PAR meter; (**C**): anemometer; (**D**): passenger flow counter).

Table 3. Parameters measurement and methods.

Parameters	Devices	Type	Measurement Method	Accuracy
CO_2 (ppm)	Air quality monitor (BohuBH-03)	SenseonAir S8	7/24 h, automatic recording frequency is 1 time/min	±3%
$PM_{0.3–1}$ (μg/m^3)		PMS7003		±2%
$PM_{1–2.5}$ (μg/m^3)				±2%
$PM_{2.5–10}$ (μg/m^3)				±2%
Temperature (°C)		Senseon SHT20		±0.2 °C
Relative humidity (%)				±2%
PPFD (μmol/s)	PAR meter	Apogee MQ-500	Manual measurement	±5%
Dimension (m)	Laser rangefinder	Bosch GLM30	Manual measurement	±1.0 mm
Wind speed (m/s)	Digital anemometer	PM6252B	7/24 h, automatic recording frequency is 1 time/15 min	±2%
Human traffic	Passenger flow counter	iDTK	7/24 h, automatic recording	N/A

2.4. Data Analysis

As the forms of the two corridors are the same, the air change rate of the corridors depends only on the air movement speed, considering no other mechanical ventilating device is used. The anemometers were set at the middle of each corridor at the height of 1.5 m. The statistical data of 15 days' records (15 min interval), with and without ILWS, were compared in heating and cooling seasons. Through independent sample *t*-test analysis (Table 4), there was no statistically significant difference in air movement speed between the compared corridors.

Table 4. Comparisons on indoor air movement speed between the corridors.

Season	Average Air Movement Speed (m/s)		Difference	MRE	*t*-Test Sig.	95% Confidence Interval of the Difference	
	With ILWS (C_W)	Without ILWS (C_E)	$C_E - C_W$	$(C_E - C_W)/C_E$	C_W&C_E	Lower	Upper
Heating season	0.0859	0.0871	0.0012	1.1%	0.377	−0.0039	0.0015
Cooling season	0.1187	0.1216	0.0029	2.4%	0.147	−0.0068	0.0010

The passenger flow counters were applied to check the equality of the intensity of use between the corridors. The counters recorded the daily and total numbers during June, July, and August in the cooling season and November, December, and January in the heating season. Then the average daily number was calculated and compared. Again, the independent sample *t*-test (Table 5) shows that there was no statistically significant difference in daily users between the compared corridors.

Table 5. Comparisons on the number of people passing through the corridors.

Season	Average		Difference	MRE	*t*-Test Sig.	95% Confidence Interval of the Difference	
	With ILWS (C_W)	Without ILWS (C_E)	$C_E - C_W$	$(C_E - C_W)/C_E$	C_W&C_E	Lower	Upper
Heating season	586	559	−28	−5.0%	0.404	−37.76	91.09
Cooling season	338	327	−11	−3.7%	0.392	−15.20	37.60

The light intensity of natural sunlight varied from time to time, but the light intensity of artificial LED light was stable. In order to figure out which one dominated energy source in plants' photosynthesis, and quantitatively evaluate daily PAR from that source, PAR meters were used. They were positioned at six measuring points on the surface of ILWS to record the photosynthetic photon flux density (PPFD) value at daytime (sunlight only) and night (LED light only). Daily PAR can be calculated by multiply PPFD and 10 hours' photoperiod (8:00 AM to 18:00 PM).

The daily photosynthetically active radiation (PAR) values at each measurement point (Figure 3C) on the surface of the ILWS were measured, shown in Figure 5. Since the PAR received from the natural light was relatively small, whether on sunny or cloudy days, the ILWS mainly relied on the LED artificial light sources to provide energy for photosynthesis. The average photosynthetic photon flux density (PPFD) was 35.3 μmol/s and the daily PAR was calculated to be 1.3 mol/day at 10 hours' photoperiod from 8:00 AM to 18:00 PM.

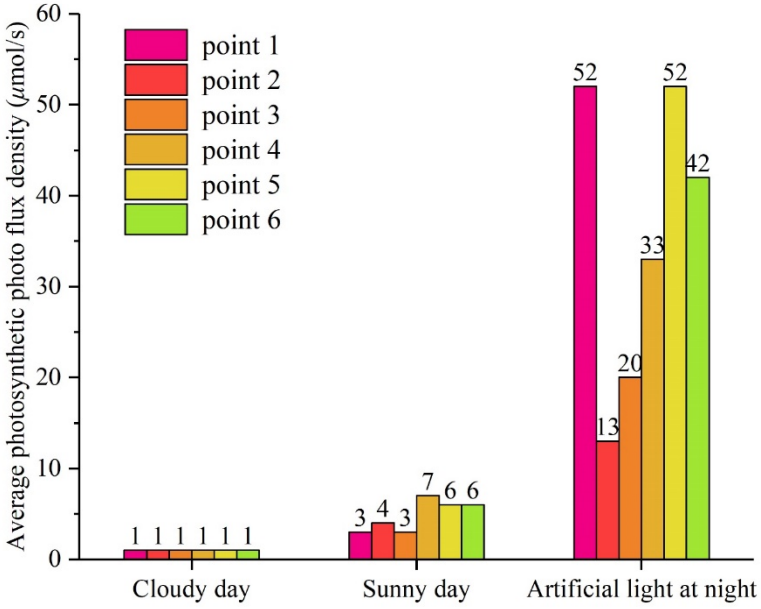


Figure 5. Average photosynthetic photon flux density (PPFD) under natural light and artificial light.

In this study, parameters of the indoor air quality on both sides of the corridors with and without ILWS were measured, including CO_2 concentration, PM concentration, temperature, and relative humidity. The obtained data of each parameter were then analyzed, using Mean, Mean Relative Error, and Independent Sample *t*-test, to examine whether there was a statistically significant difference. It can be inferred that the differences in parameters measured in the two corridors were caused by the ILWS, for the following reasons:

(1) The form of two corridors are completely the same and they are symmetrical in the floor plan;
(2) There was no statistically significant difference in the air change rate;
(3) There was no statistically significant difference in the intensity of use of people.

3. Results and Discussion

3.1. Comparison of CO_2 Concentration with and without ILWS

The daily average value of CO_2 concentration is shown in Figure 6. The outdoor CO_2 concentration fluctuates from 380 ppm to 450 ppm most of the time. However, in some scenarios, for example in measurement 1 in the heating season, it can even reach 550 ppm. It can be found that the CO_2 concentration at the west corridor (with ILWS) is lower than that of the east corridor (without ILWS), and sometimes it is even lower than the outdoor value. Specifically, as shown in Table 6, in the corridor using ILWS during the heating season, the CO_2 concentrations of measurement 1, measurement 2, and measurement 3 are 76.5 ppm, 63.6 ppm, and 66.2 ppm lower than those without ILWS. In the cooling season, the remaining three measured concentrations are 53.1 ppm, 49.3 ppm, and 47.3 ppm lower, respectively. Moreover, according to an independent sample *t*-test on C_W and C_E (with ILWS and without ILWS), the difference is statistically significant in most of the cases. Since the differences in air change rate and the number of people passing through the two corridors are not statistically significant (considered as equal), and there are no other objects that generate or absorb CO_2, the difference in CO_2 concentration in the two corridors were considered to be caused by the presence of ILWS. On average, the CO_2 concentration decreased by 16.7% in the heating season and 11.7% in the cooling season, respectively.

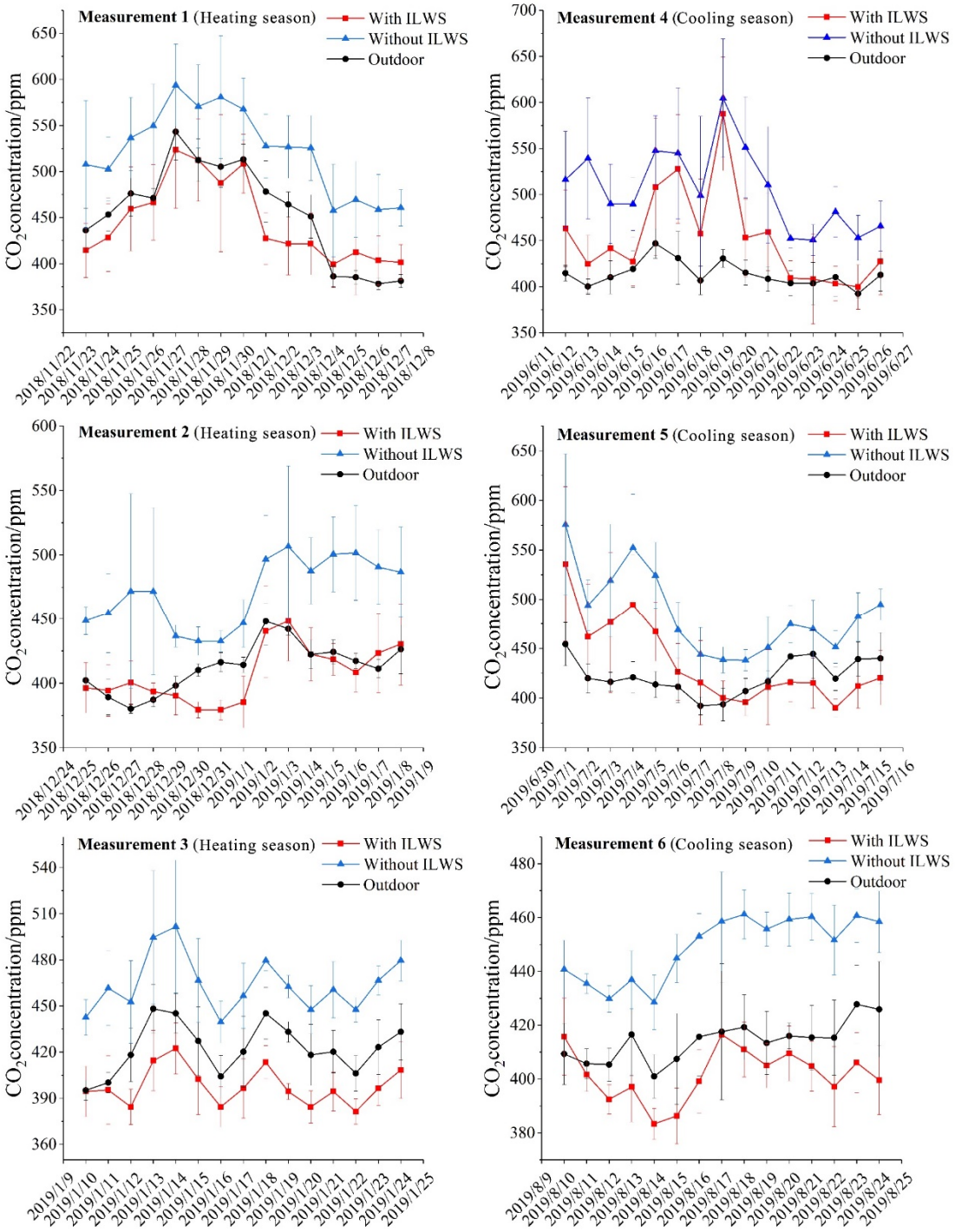


Figure 6. 15 days' record on CO_2 concentration.

3.2. Comparison of Particulate Matter Concentration with and without ILWS

The daily average value in $PM_{0.3–1}$, $PM_{1–2.5}$, and $PM_{2.5–10}$ concentration is shown in Figures 7–9. In all cases, the PMs concentrations are much higher in the heating season than in the cooling season. This trend is consistent with the national historical data [44,45]. The reasons for this trend are complicated. The main attributes that influence the concentration of PM are pollution source emissions and meteorological conditions. Coal-fired heating and incomplete combustion in vehicle engines at low temperatures may increase emissions in the heating season. The temperature inversion effect and less precipitation

in the heating season may also become adverse meteorological conditions for pollutants' diffusion and washout [46–49].

Table 6. Comparisons on indoor CO_2 concentration between the corridors.

Measurements	Average CO_2 (ppm)			Difference	MRE	*t*-test Sig.	95% Confidence Interval of the Difference	
	With ILWS (C_W)	Without ILWS (C_E)	Outdoor (C_S)	$C_E - C_W$	$(C_E - C_W)/C_E$	C_W&C_E	Lower	Upper
Measurement 1	445.8	522.3	455.7	76.5	17%	0.000	−12.91	−10.52
Measurement 2	407.4	471.0	412.6	63.6	16%	0.060	−0.03	1.51
Measurement 3	397.8	464.0	422.5	66.2	17%	0.039	0.02	1.01
Measurement 4	453.2	506.3	413.8	53.1	12%	0.000	12.08	15.03
Measurement 5	435.9	485.2	422.1	49.3	11%	0.000	16.90	19.17
Measurement 6	401.7	449.0	414.1	47.3	12%	0.000	18.55	19.16

Duration of the dataset: Measurement 1: 23 November 2018–7 December 2018; Measurement 2: 25 December 2018–8 January 2019; Measurement 3: 10 January 2019–24 January 2019; Measurement 4: 12 June 2019–26 June 2019; Measurement 5: 1 July 2019–15 July 2019; Measurement 6: 10 August 2019–24 August 2019.

Figure 7 shows that the outdoor $PM_{0.3–1}$ concentration varies from 20–80 μg/m^3 in the heating season and from 5–45 μg/m^3 in the cooling season. By comparison, the $PM_{0.3–1}$ in the corridor without ILWS is much higher. The maximum value reaches 120 μg/m^3 in the heating season and 55 μg/m^3 in the cooling season. In the case of the ILWS, the value is in-between. Figure 8 shows outdoor $PM_{1–2.5}$ ranges from 30–180 μg/m^3 in the heating season, 10–70 μg/m^3 in the cooling season. The maximum value in the cases without ILWS reaches 225 μg/m^3 in winter. Even in the cooling season, the maximum value can be as high as 85 μg/m^3. The same thing goes for $PM_{2.5–10}$ (Figure 9). Outdoor $PM_{2.5–10}$ fluctuates from 40–220 μg/m^3 in the heating season, 10–85 μg/m^3 in the cooling season. Without ILWS, the maximum value breakthroughs 260 μg/m^3 in the heating season and nearly 100 μg/m^3 in the cooling season.

The results are summarized in Table 7. The results from the independent sample *t*-test indicate that the differences in these groups are statistically significant in all the cases. During the three monitored periods in the heating season, the average $PM_{0.3–1}$ concentration in the corridor with ILWS is 11.1 μg/m^3, 6.6 μg/m^3, and 10.5 μg/m^3 respectively (measurement 1–3) lower than that without ILWS. In the cooling season, the average $PM_{0.3–1}$ concentration with ILWS is 0.1 μg/m^3, 0.6 μg/m^3, and 1.2 μg/m^3 respectively (measurement 4–6) lower than that without ILWS (Table 7, $PM_{0.3–1}$). During the three monitored periods in the heating season, the average $PM_{1–2.5}$ concentration in the corridor with ILWS is 18 μg/m^3, 8.8 μg/m^3, and 12.3 μg/m^3 respectively (measurement 1–3) lower than that without ILWS. In the cooling season, the average $PM_{1–2.5}$ concentration with ILWS is 4.8 μg/m^3, 5.4 μg/m^3, and 5.1 μg/m^3 respectively (measurement 4–6) lower than that without ILWS (Table 7, $PM_{1–2.5}$). During the three monitored periods in the heating season, the average $PM_{2.5–10}$ concentration in the corridor with ILWS is 10.7 μg/m^3, 5.3 μg/m^3, and 2.9 μg/m^3 respectively (measurement 1–3) lower than that without ILWS. In the cooling season, the average $PM_{2.5–10}$ concentration with ILWS is 4.9 μg/m^3, 6.6 μg/m^3, and 6.3 μg/m^3 respectively (measurement 4–6) lower than that without ILWS (Table 7, $PM_{2.5–10}$).

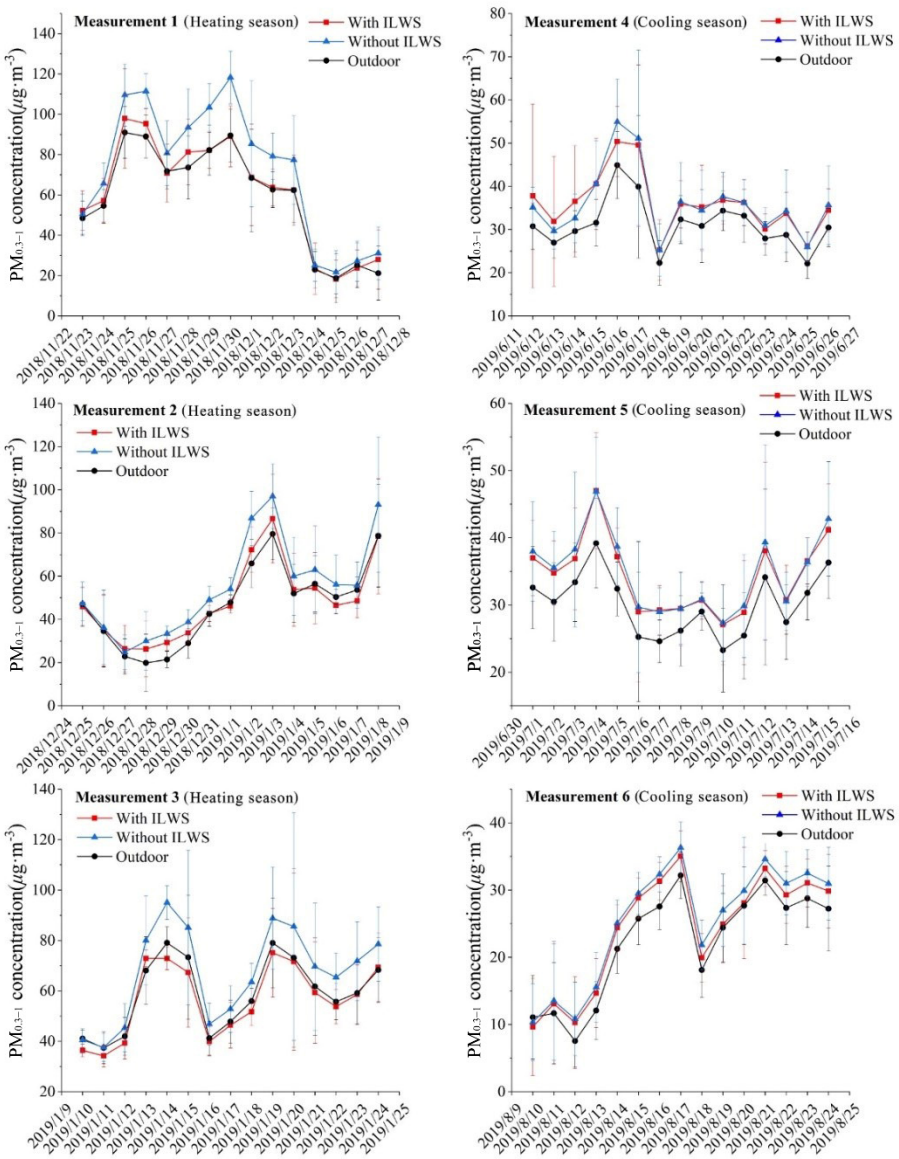


Figure 7. 15 days' record on $PM_{0.3–1}$ concentration.

3.3. Comparison of Indoor Air Temperature with and without ILWS

During the experimental period, the average indoor air temperature is approximately 12.3 °C with the relative humidity of 54% in the heating season whereas the mean indoor temperature reaches about 30.0 °C with the relative humidity of 65% in the cooling season.

As shown in Figure 10, the outdoor temperature fluctuates sharply, while the indoor temperature is relatively stable. The temperature difference between indoor and outdoor is 3–6 °C, but the temperature difference between corridors with or without ILWS is much smaller. Data analysis (in Table 8) shows that in most of the cases, the difference in air temperature between the corridors with and without ILWS is statistically significant. The average air temperature in the corridor with ILWS is 0.13 °C higher than that without ILWS in the heating season, and 0.33 °C higher in the cooling season. Given the accuracy of the experimental instrument (±0.2 °C), the ILWS just has a quite limited effect on indoor air temperature. However, further research is needed to rectify its effect on indoor air temperature.

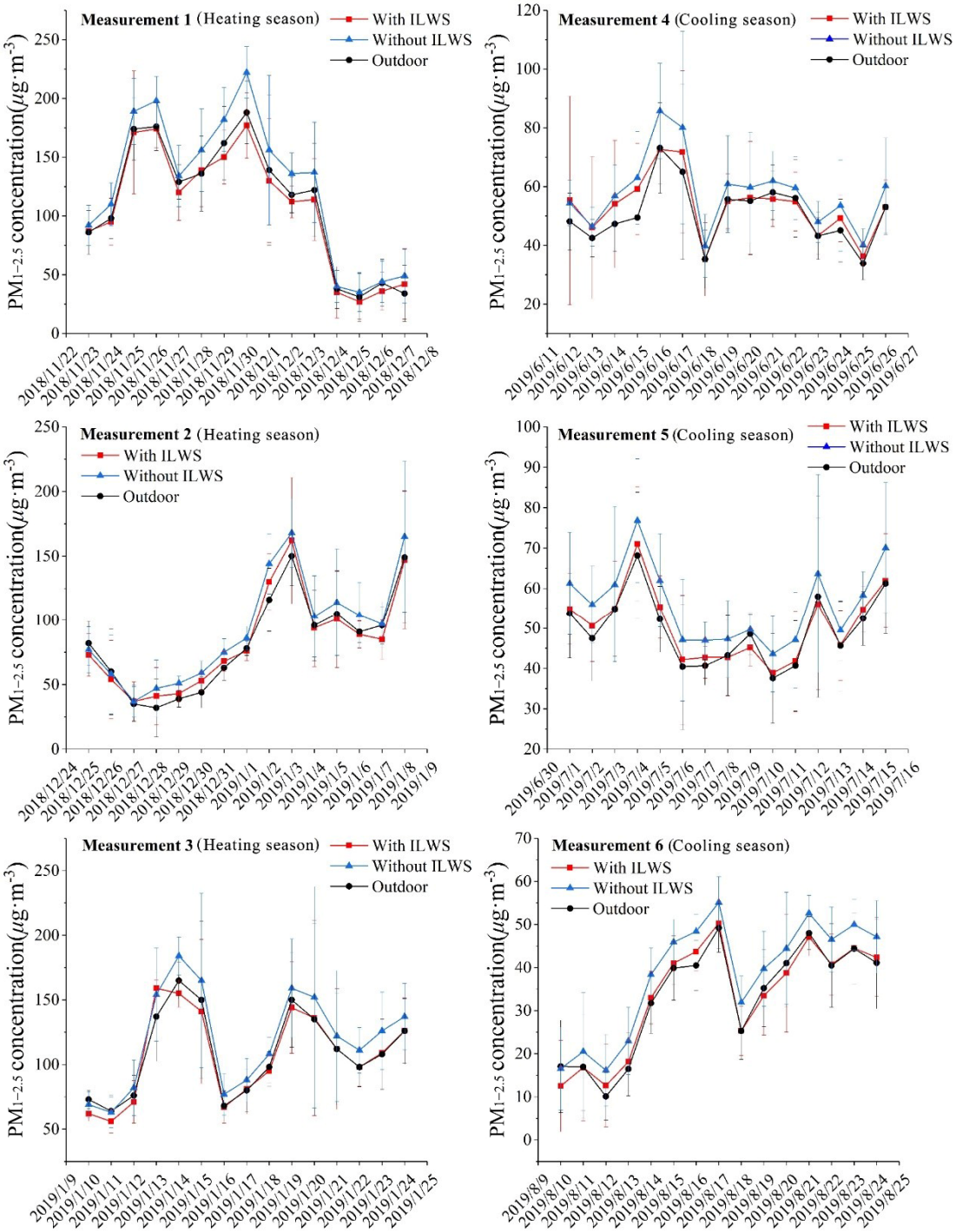


Figure 8. 15 days' record on $PM_{1–2.5}$ concentration.

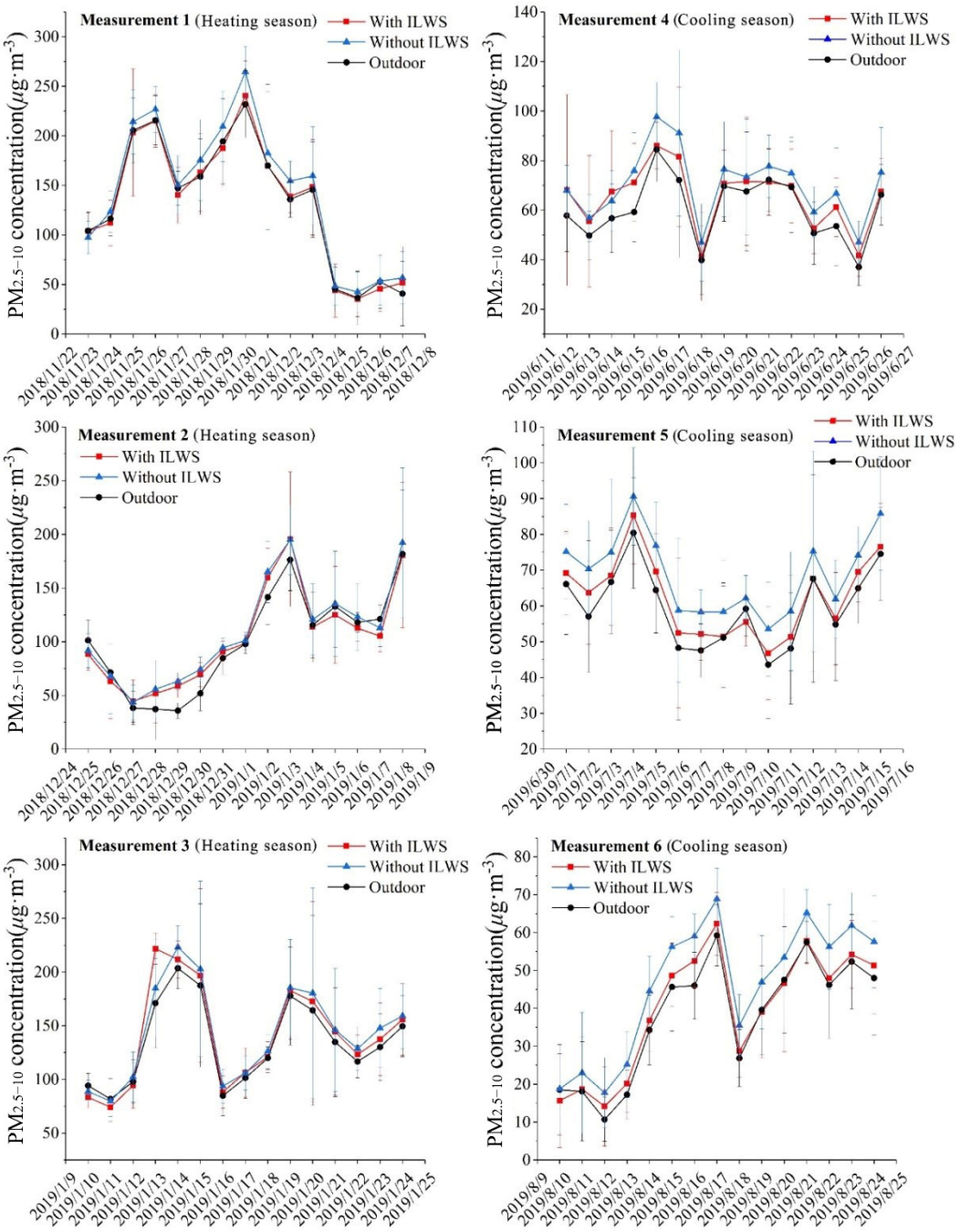


Figure 9. 15 days' record on $PM_{2.5–10}$ concentration.

Table 7. Comparison of PMs concentration between the corridors.

Parameter	Measurements	Average $PM_{0.3–1}$ ($\mu g/m^3$)			Difference ($\mu g/m^3$)	MRE	*t*-Test Sig.	95% Confidence Interval of the Difference	
$PM_{0.3–1}$		With ILWS (C_W)	Without ILWS (C_E)	Outdoor (C_S)	$C_E - C_W$	$(C_E - C_W)/C_E$	C_W&C_E	Lower	Upper
	Measurement 1	60.9	72.0	58.8	11.1	15%	0.000	−9.62	−8.35
	Measurement 2	48.4	55.0	46.8	6.6	12%	0.000	−6.50	−5.63
	Measurement 3	56.6	67.1	58.9	10.5	16%	0.000	−11.56	−10.62
	Measurement 4	36.0	36.1	31.1	0.1	0.3%	0.189	−0.41	0.080
	Measurement 5	34.2	34.8	30.1	0.6	2%	0.000	−0.80	−0.44
	Measurement 6	24.2	25.4	22.3	1.2	5%	0.000	−1.38	−0.98
$PM_{1–2.5}$									
	Measurement 1	107.3	125.3	111.6	18	14%	0.000	−13.84	−11.44
	Measurement 2	83.5	92.3	82.4	8.8	10%	0.000	−8.74	−7.06
	Measurement 3	107.5	119.8	109.3	12.3	10%	0.000	−16.19	−14.20
	Measurement 4	53.2	58.0	50.7	4.8	8%	0.000	−5.03	−4.23
	Measurement 5	50.6	56.0	49.7	5.4	10%	0.000	−5.72	−5.12
	Measurement 6	33.3	38.4	33.2	5.1	13%	0.000	−5.39	−4.78
$PM_{2.5–10}$									
	Measurement 1	133.2	143.9	133.3	10.7	7%	0.000	−5.97	−3.06
	Measurement 2	103.8	109.1	100.3	5.3	5%	0.000	−5.82	−3.85
	Measurement 3	140.9	143.6	134.3	2.7	2%	0.000	−8.84	−6.38
	Measurement 4	65.2	70.1	60.4	4.9	7%	0.000	−5.60	−4.69
	Measurement 5	62.4	69.0	59.6	6.6	10%	0.000	−7.00	−6.28
	Measurement 5	39.7	46.0	37.8	6.3	14%	0.000	−6.75	−5.96

Duration of the dataset: Measurement 1: 23 November 2018–7 December 2018; Measurement 2: 25 December 2018–8 January 2019; Measurement 3: 10 January 2019–24 January 2019; Measurement 4: 12 June 2019–26 June 2019; Measurement 5: 1 July 2019–15 July 2019; Measurement 6: 10 August 2019–24 August 2019.

Table 8. Comparisons on air temperature between the corridors.

Season	Measurements	Average Temperature (°C)			Difference (°C)	MRE	*t*-Test Sig.	95% Confidence Interval of the Difference	
		With ILWS (C_W)	Without ILWS (C_E)	Outdoor (C_S)	$C_E - C_W$	$(C_E - C_W)/C_E$	C_W&C_E	Lower	Upper
Heating season	Measurement 1	17.0	16.6	11.4	−0.4	−2.4%	0.000	0.45	0.51
	Measurement 2	10.2	10.1	4.5	−0.1	−1.0%	0.890	−0.04	0.05
	Measurement 3	9.9	10.0	5.2	0.1	1.0%	0.000	0.03	0.07
Cooling season	Measurement 4	28.6	28.3	25.3	−0.3	−1.2%	0.000	0.27	0.30
	Measurement 5	29.3	28.9	26.8	−0.4	−1.4%	0.000	0.41	0.45
	Measurement 6	31.6	31.3	28.8	−0.3	−1.0%	0.000	0.21	0.24

Duration of the dataset: Measurement 1: 23 November 2018–7 December 2018; Measurement 2: 25 December 2018–8 January 2019; Measurement 3: 10 January 2019–24 January 2019; Measurement 4: 12 June 2019–26 June 2019; Measurement 5: 1 July 2019–15 July 2019; Measurement 6: 10 August 2019–24 August 2019.

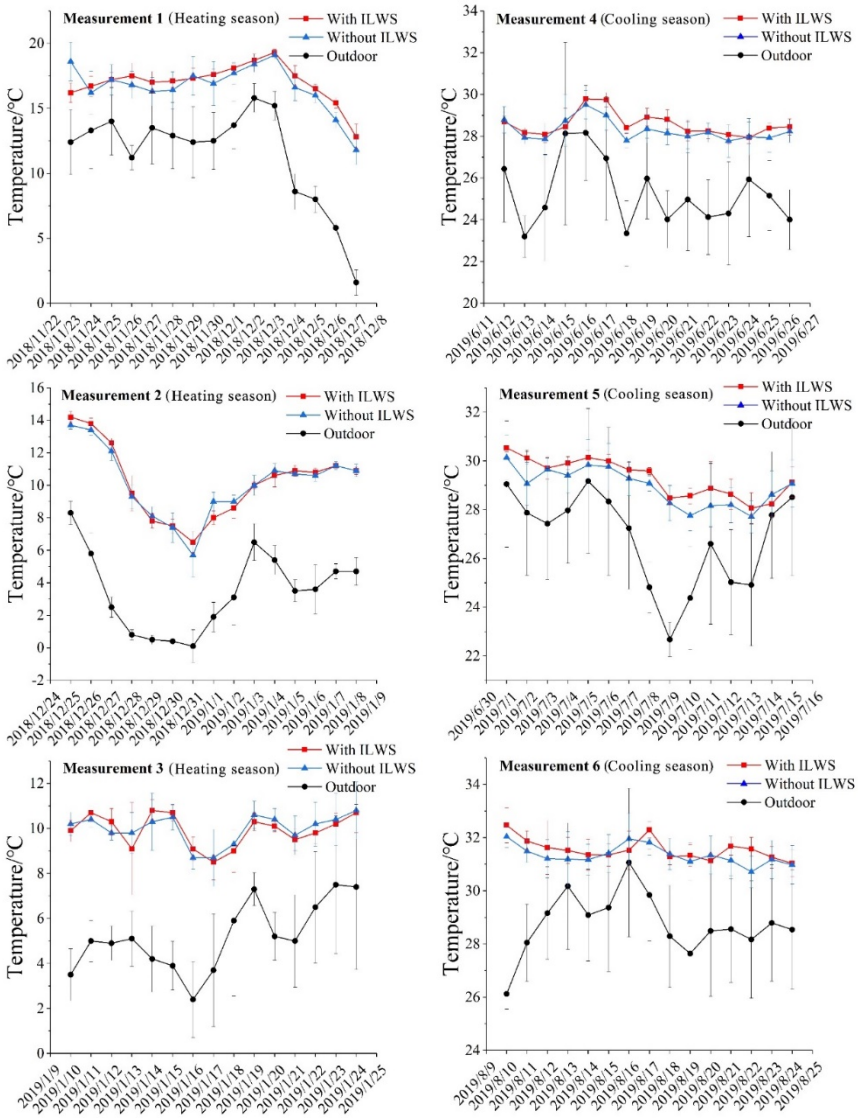


Figure 10. 15 days' record on air temperature.

3.4. Comparison of Indoor Relative Humidity with and without ILWS

The daily average relative humidity is plotted in Figure 11. It can be seen that in most of the days, whether in the heating season or in the cooling season, outdoor relative humidity is 10–30% higher than indoors. Relative humidity in the cases with the ILWS is slightly higher than that without ILWS. The data in Table 9 show that in the three monitored periods in the heating season, the average relative humidity in the corridor with ILWS is 3.3%, 7.5%, and 8.3% higher than that without ILWS (6.4% higher on average). In the cooling season, the values are 3.1%, 2.6%, and 3.6% higher (3.1% higher on average). The increase in relative humidity should be related to the transpiration of plants.

Table 9. Comparisons on relative humidity between the corridors.

Season	Measurements	Average Relative Humidity (%)			Difference	MRE	*t*-Test Sig.	95% Confidence Interval of the Difference	
		With ILWS (C_W)	Without ILWS (C_E)	Outdoor (C_S)	$C_E - C_W$	$(C_E - C_W)/C_E$	C_W&C_E	Lower	Upper
Heating season	Measurement 1	63.5	61.5	73.4	−2.0	−3.3%	0.000	2.40	2.65
	Measurement 2	54.2	52.3	69.1	−3.9	−7.5%	0.000	3.80	4.25
	Measurement 3	57.1	52.7	71.0	−4.4	−8.3%	0.000	3.01	3.30
Cooling season	Measurement 4	63.5	61.3	71.6	−1.9	−3.1%	0.000	2.07	2.34
	Measurement 5	67.6	65.9	75.2	−1.7	−2.6%	0.000	1.44	1.65
	Measurement 6	63.2	61.0	67.5	−2.2	−3.6%	0.000	2.15	2.38

Duration of the dataset: Measurement 1: 23 November 2018–7 December 2018; Measurement 2: 25 December 2018–8 January 2019; Measurement 3: 10 January 2019–24 January 2019; Measurement 4: 12 June 2019–26 June 2019; Measurement 5: 1 July 2019–15 July 2019; Measurement 6: 10 August 2019–24 August 2019.

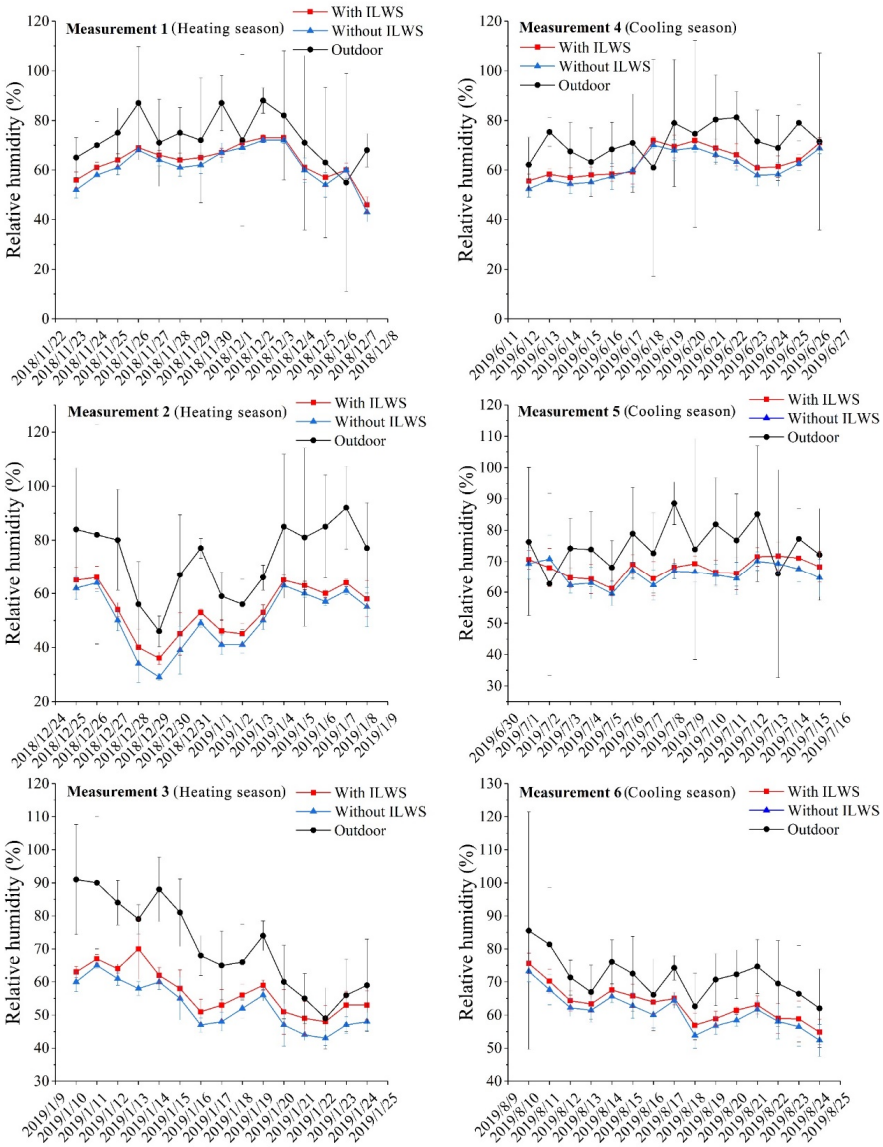


Figure 11. 15 days' record on relative humidity.

4. Discussions

In this study, the method of field monitoring was adopted. Since the confounding variables were not perfectly controlled, the causal relationship between the living wall system and indoor air quality cannot be directly revealed. However, through the monitoring of the actual environment and statistical analysis of the data, it has been found that there are statistically significant differences in the CO_2 concentration, PM concentration, and relative humidity between the corridors with and without ILWS. However, since the form of the two corridors are the same, and the difference in air change rate, as well as intensity of use, between the two corridors, were not statistically significant, it can be inferred that the differences were caused by the ILWS. Indoor CO_2 and PMs concentration reduced, while temperature and relative humidity slightly increased. Results from this study were compared with other studies (Table 10). Currently, the number of studies on ILWS is quite small, and the most studied climatic zone is Cfa in the Köppen classification. The impact of ILWS on CO_2 concentration reduction has been confirmed in studies, although the performance varies from case to case. Only two studies (this study and [39]), within the same climatic zone and similar space volume, investigated the impact of ILWS on PMs. Qualitatively, they draw the same conclusion that ILWS could reduce PMs concentration. However, quantitatively, the discrepancies in effectiveness are quite large. The influence of ILWS on temperature shows no obvious trend. In all the studies, relative humidity increases with the presence of ILWS. The increase in dry climatic zones is greater than that in humid regions.

Table 10. Results comparisons with other studies.

Reference	Köppen Climatic Zone	Area of ILWS (m^2)	Function & Volume of Space (m^3)	Impact on CO_2 Concentration ($\mu g/m^3$/%)	Impact on PMs Concentration ($\mu g/m^3$/%)	Impact on Temperature (°C/%)	Impact on Relative Humidity
This study	Cfa	10.6	Corridor 30.6	49.9–68.8↓ 12–17%↓	$PM_{0.3–1}$: 1.9–9.4↓ 2.4–14.3%↓ $PM_{1–2.5}$: 5.1–13.3↓ 10.3–11.3%↓ $PM_{2.5–10}$: 5.9–6.2↓ 4.7–10.3%↓	0.1–0.4↑ 1–2.4%↑	3.1–6.4%↑
Ghazalli et al. [39]	Cfa	3.2	Corridor 27	Not tested	$PM_{2.5}$: 48.5%↓ PM_{10}: 82.6%↓ >PM_{10}: 65.5%↓	→	2–3%↑
Su and Lin [40]	Cfa	5.72	Laboratory 38.88	21.3%↓	Not tested	2.5 °C↓ 11% ↓	2–4%↑
Gunawardena et al. [50]	Cfb	91	Atrium Not mentioned	Not tested	Not tested	0.2–0.7 °C↑ 1–3.1%↑	2.3–2.4%↑
Tudiwer et al. [42]	Cfb	5.5	Classroom 202	3.5%↓	Not tested	→	25.5%↑
Urrestarazu et al. [51]	Csa	8	Main hall 351	Not tested	Not tested	0.8–4.8 °C↓ 2.6–19.6%↓	6–21.3%↑
Rafael et al. [52]	Csa	7.74	Hall 195.4	Not tested	Not tested	4 °C↑	15%↑
Poorova et al. [53]	Dfb	3	Classroom 207.2	127.9↓ 14%↓	Not tested	1.7 °C↓ 4.6%↓	1.4%↑
Shao et al. [54]	Cfa	6.86	Office 88.92	25.7%–34.3%↓	Not tested	Not tested	Not tested

Note: ↑: increase; ↓: decrease; →: no significant change.

The results from this study could be used as a reference for other research and development in a similar climatic zone. In this study, the ILWS was considered as a whole system to influence the monitored environmental parameters, which provided an understanding of the overall effect of a typical ILWS in the particular climatic zone, although the weight of each attribute within the system was still unknown. For example, as the results indicated that there was a statistically significant reduction in PMs caused by the presence of the ILWS, the main attributes could not be quantitatively or even qualitatively identified. Whether the pollutants were adsorbed by the plants' leaves or by the water in the growing pods or by the water vapor produced by plants' transpiration could not be separated out and given weight. In order to figure out the causal relationship, a number of strictly controlled experiments in sealed chambers are needed. Of course, this is very time-consuming. However, from the perspective of the built environment, more attention should be paid to the overall performance of a typical system to evaluate its effectiveness and feasibility. In addition, studying the overall impact could achieve even more accurate prediction results than studying the effects of individual attributes and then adding them up. Since, under real-world conditions, it is almost impossible to control all influencing factors, extract the weight of each one from a whole system, and eliminate the possibility of mutual influence between attributes. Real-world tests can be used as references for other projects or studies, where an analogy method could be used with a large database to predict the potential impact of a new ILWS. A number of tests of different ILWS projects from different climatic zones with different combinations of plants are needed to build such a database. When an analogy method is used, the higher the matching degree of parameters, the higher the accuracy of prediction results will be. Area of ILWS to space volume ratio could be used as a key parameter for such an analogy evaluation, along with other parameters, such as plant type, the proportion of plants' combination, daily PAR on the ILWS, and so forth. In order to match the parameters from a new ILWS to those from a database, a training sample dataset is needed for machine learning, using a computer algorithm to determine the weight of each parameter. This study is just the first step, as one of the important case studies in many, towards this target.

The idea of introducing ILWS to the indoor environment starts from improving indoor air quality and environmental aesthetic value for human well-being [33]. However, the benefits do not stop here. The potential of using ILWS to reduce building energy consumption in heating and cooling seasons cannot be ignored [28]. The direct impact of ILWS on indoor air temperature is still inconclusive. It may be also influenced by some exterior factors, such as the orientation of the building, the location of openings on the building, or even the function of space. Further studies on these factors are needed. The indirect effect of ILWS on building energy saving could be mainly reflected in ventilation energy consumption. Currently, the main method of removing indoor air pollutants still relies on diluting the indoor pollutants by ventilating the fresh air from the outside [55]. During the spring or autumn seasons, when the outside temperature fluctuates within the temperature comfort zone, usually 18–26 °C, natural ventilation can be used directly [56]. However, in cooling or heating seasons when the temperature is beyond the comfort zone, the fresh air needs to be pre-heated or pre-cooled before it is ventilated mechanically to the indoor space in order to reach the indoor designed temperature. Therefore, in such scenarios, the ventilation rate, determined by the fresh air requirement, has a proportional relationship with the building energy consumption in ventilating sector. Introducing ILWS into buildings may improve the air quality, thus equivalently reduces the fresh air requirement and the ventilation rate when the outside temperature is beyond the comfort zone for natural ventilation. Apart from indoor and outdoor temperature and humidity differences, the performance of energy consumption reduction in ventilation is mainly determined by the CO_2 absorption rate of ILWS instead of the adsorption rate of PMs or VOC. It is because PMs and VOC can be adsorbed by various artificial porous materials, but there is currently no low-cost practical method for massive CO_2 conversion [57]. Plants' photosynthesis is still the most extensive process of carbon dioxide to oxygen conversion on

earth. Consequently, if working with other artificial filters, ILWS may reduce the building energy consumption through ventilation heat loss/gain in heating or cooling seasons. The effectiveness of this mechanism still needs further study.

5. Conclusions

In this study, a field monitoring test of the ILWS was implemented in order to evaluate the system performance for the Cfa climate zone (Köppen climate classification) from November 2018 to August 2019. The influences of the ILWS on indoor air quality with and without ILWS between two parallel corridors were studied in an office building based on different parameters such as CO_2 concentration, PM, atmospheric temperature, and relative humidity. Some key findings are concluded as follows:

- ILWS could be a promising opportunity in the eco-design of the buildings considering its aesthetic value and purification function of indoor air.
- Based on the results from the statistical analysis, the differences in CO_2 and PM concentration in the two corridors are statistically significant—this indicates the positive effect of ILWS on improving indoor air quality.
- In terms of the CO_2 concentration, the average indoor air temperature of the corridors with ILWS can be reduced to the same level of outdoor condition, or even slightly lower than outdoor levels.
- The purification performance of CO_2 and PMs in the heating season is better in comparison with that in the cooling season due to the local seasonal climate condition and pollutant emission.
- The effect of ILWS on indoor air temperature is quite limited. However, the relative humidity in the corridor with ILWS is slightly higher (3.1–6.4%) than that without ILWS.

Author Contributions: All authors contributed substantially to this study. Individual contributions are: conceptualization, Y.S.; writing—original draft preparation, Y.S. and J.L.; writing—review and editing, Y.S., J.L., Z.Z. and Y.C.; methodology, Y.S. and F.Z.; formal analysis, J.L., Y.S. and Z.Z.; project administration, Y.S.; funding acquisition, Y.S. 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 51708283]; the Natural Science Foundation of Jiangsu Province [grant number BK20171011], and the Ministry of Education Key Laboratory (Tongji University) Open Project Funding [grant number 2019030101].

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Nomenclature

VGS	Vertical greenery system
LWS	Living wall system
ILWS	Indoor living wall system
OLWS	Outdoor living wall system
CO_2	Carbon dioxide
PM	Particulate matter
VOC	Volatile organic compound
PAR	Photosynthetically active radiation
LED	Light emitting diode
PPFD	Photosynthetic photon flux density
MRE	Mean Relative Error
$PM_{0.3–1}$	The particle size is between 0.3 μm and 1 μm

$PM_{1–2.5}$	The particle size is between 1 μm and 2.5 μm
$PM_{2.5–10}$	The particle size is between 2.5 μm and 10 μm
$\bar{c}$	average value of each measured parameter
C_W	15 days' mean in the corridor with ILWS
C_E	15 days' mean in the corridor without ILWS
C_s	15 days' mean of outdoor environment
$C_{W,i}$	concentration with ILWS by minute
$C_{E,i}$	concentration without ILWS by minute
$C_{S,i}$	outdoor concentration by minute
m	daily reduction of the corresponding pollutants per square meter
R_r	pollutant reduction ratio

References

1. Wilson, T. Population Growth. In *International Encyclopedia of Human Geography*, 2nd ed.; Kobayashi, A., Ed.; Elsevier: Oxford, UK, 2020; pp. 1–6.
2. Liu, C.H.; Rosenthal, S.S.; Strange, W.C. The vertical city: Rent gradients, spatial structure, and agglomeration economies. *J. Urban Econ.* **2018**, *106*, 101–122. [CrossRef]
3. Bek, M.A.; Azmy, N.; Elkafrawy, S. The effect of unplanned growth of urban areas on heat island phenomena. *Ain Shams Eng. J.* **2018**, *9*, 3169–3177. [CrossRef]
4. von Schneidemesser, E.; Steinmar, K.; Weatherhead, E.C.; Bonn, B.; Gerwig, H.; Quedenau, J. Air pollution at human scales in an urban environment: Impact of local environment and vehicles on particle number concentrations. *Sci. Total Environ.* **2019**, *688*, 691–700. [CrossRef] [PubMed]
5. Vieira, J.; Matos, P.; Mexia, T.; Silva, P.; Lopes, N.; Freitas, C.; Correia, O.; Santos-Reis, M.; Branquinho, C.; Pinho, P. Green spaces are not all the same for the provision of air purification and climate regulation services: The case of urban parks. *Environ. Res.* **2018**, *160*, 306–313. [CrossRef] [PubMed]
6. Cai, M.; Xin, Z.; Yu, X. Particulate matter transported from urban greening plants during precipitation events in Beijing, China. *Environ. Pollut.* **2019**, *252*, 1648–1658. [CrossRef]
7. Deng, S.; Ma, J.; Zhang, L.; Jia, Z.; Ma, L. Microclimate simulation and model optimization of the effect of roadway green space on atmospheric particulate matter. *Environ. Pollut.* **2019**, *246*, 932–944. [CrossRef]
8. Charoenkit, S.; Yiemwattana, S. Living walls and their contribution to improved thermal comfort and carbon emission reduction: A review. *Build. Environ.* **2016**, *105*, 82–94. [CrossRef]
9. Marchi, M.; Pulselli, R.M.; Marchettini, N.; Pulselli, F.M.; Bastianoni, S. Carbon dioxide sequestration model of a vertical greenery system. *Ecol. Model.* **2015**, *306*, 46–56. [CrossRef]
10. Klingberg, J.; Broberg, M.; Strandberg, B.; Thorsson, P.; Pleijel, H. Influence of urban vegetation on air pollution and noise exposure–A case study in Gothenburg, Sweden. *Sci. Total Environ.* **2017**, *599–600*, 1728–1739. [CrossRef]
11. Lacasta, A.M.; Penaranda, A.; Cantalapiedra, I.R.; Auguet, C.; Bures, S.; Urrestarazu, M. Acoustic evaluation of modular greenery noise barriers. *Urban Urban Green.* **2016**, *20*, 172–179. [CrossRef]
12. Van Renterghem, T.; Forssén, J.; Attenborough, K.; Jean, P.; Defrance, J.; Hornikx, M.; Kang, J. Using natural means to reduce surface transport noise during propagation outdoors. *Appl. Acoust.* **2015**, *92*, 86–101. [CrossRef]
13. Madre, F.; Clergeau, P.; Machon, N.; Vergnes, A. Building biodiversity: Vegetated façades as habitats for spider and beetle assemblages. *Glob. Ecol. Conserv.* **2015**, *3*, 222–233. [CrossRef]
14. Oh, R.R.Y.; Richards, D.R.; Yee, A.T.K. Community-driven skyrise greenery in a dense tropical city provides biodiversity and ecosystem service benefits. *Landsc. Urban Plan.* **2018**, *169*, 115–123. [CrossRef]
15. Mayrand, F.; Clergeau, P.; Vergnes, A.; Madre, F. Chapter 3.13–Vertical Greening Systems as Habitat for Biodiversity. In *Nature Based Strategies for Urban and Building Sustainability*; Pérez, G., Perini, K., Eds.; Butterworth-Heinemann: Oxford, UK, 2018; pp. 227–237.
16. Dahanayake, K.W.D.K.; Chow, C.L. Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program. *Energy Build.* **2017**, *138*, 47–59. [CrossRef]
17. Poddar, S.; Park, D.Y.; Chang, S. Simulation Based Analysis on the Energy Conservation Effect of Green Wall Installation for Different Building Types in a Campus. *Energy Procedia* **2017**, *111*, 226–234. [CrossRef]
18. Morakinyo, T.E.; Lau, K.K.; Ren, C.; Ng, E. Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving. *Build. Environ.* **2018**, *137*, 157–170. [CrossRef]
19. Coma, J.; Pérez, G.; de Gracia, A.; Burés, S.; Urrestarazu, M.; Cabeza, L.F. Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades. *Build. Environ.* **2017**, *111*, 228–237. [CrossRef]
20. Yaghoobian, N.; Srebric, J. Influence of plant coverage on the total green roof energy balance and building energy consumption. *Energy Build.* **2015**, *103*, 1–13. [CrossRef]
21. Lee, L.S.H.; Jim, C.Y. Energy benefits of green-wall shading based on novel-accurate apportionment of short-wave radiation components. *Appl. Energy* **2019**, *238*, 1506–1518. [CrossRef]

22. Zazzini, P.; Grifa, G. Energy Performance Improvements in Historic Buildings by Application of Green Walls: Numerical Analysis of an Italian Case Study. *Energy Procedia* **2018**, *148*, 1143–1150. [CrossRef]
23. Cui, Y.; Zheng, H. Impact of Three-Dimensional Greening of Buildings in Cold Regions in China on Urban Cooling Effect. *Procedia Eng.* **2016**, *169*, 297–302. [CrossRef]
24. Ávila-Hernández, A.; Simá, E.; Xamán, J.; Hernández-Pérez, I.; Téllez-Velázquez, E.; Chagolla-Aranda, M.A. Test box experiment and simulations of a green-roof: Thermal and energy performance of a residential building standard for Mexico. *Energy Build.* **2020**, *209*, 109709. [CrossRef]
25. Coma, J.; Chàfer, M.; Pérez, G.; Cabeza, L.F. How internal heat loads of buildings affect the effectiveness of vertical greenery systems? An experimental study. *Renew. Energy* **2019**, *151*, 919–930. [CrossRef]
26. Bustami, R.A.; Belusko, M.; Ward, J.; Beecham, S. Vertical greenery systems: A systematic review of research trends. *Build. Environ.* **2018**, *146*, 226–237. [CrossRef]
27. Veisten, K.; Smyrnova, Y.; Kl Boe, R.; Hornikx, M.; Mosslemi, M.; Kang, J. Valuation of Green Walls and Green Roofs as Soundscape Measures: Including Monetised Amenity Values Together with Noise-attenuation Values in a Cost-benefit Analysis of a Green Wall Affecting Courtyards. *Int. J. Environ. Res. Public Health* **2012**, *9*, 3770–3788. [CrossRef]
28. Safikhani, T.; Abdullah, A.M.; Ossen, D.R.; Baharvand, M. Thermal Impacts of Vertical Greenery Systems. *Environ. Clim. Technol.* **2014**, *14*, 5. [CrossRef]
29. Kingsbury, N. *Planting Green Roofs and Living Walls*; Timber Press: Portland, OR, USA, 2008.
30. Cameron, R.W.F.; Taylor, J.E.; Emmett, M.R. What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. *Build. Environ.* **2014**, *73*, 198–207. [CrossRef]
31. Mårtensson, L.L.; Wuolo, A.A.; Fransson, A.A.; Emilsson, T.T. Plant performance in living wall systems in the Scandinavian climate. *Ecol. Eng.* **2014**, *71*, 610–614. [CrossRef]
32. Gunawardena, K.; Steemers, K. Living walls in indoor environments. *Build. Environ.* **2019**, *148*, 478–487. [CrossRef]
33. López-Aparicio, S.; Smolík, J.; Mašková, L.; Součková, M.; Grøntoft, T.; Ondráčková, L.; Stankiewicz, J. Relationship of indoor and outdoor air pollutants in a naturally ventilated historical building envelope. *Build. Environ.* **2011**, *46*, 1460–1468. [CrossRef]
34. Pettit, T.; Irga, P.J.; Torpy, F.R. Towards practical indoor air phytoremediation: A review. *Chemosphere* **2018**, *208*, 960–974. [CrossRef]
35. Jafari, M.J. Association of Sick Building Syndrome with Indoor Air Parameters. *Tanaffos* **2015**, *14*, 55–62.
36. Myhrvold, A.; Olesen, E. Pupil's Health and Performance due to Renovation of Schools. In Proceedings of the Healthy Buildings/IAQ, Washington, DC, USA, 27 September–2 October 1997; Volume 1, pp. 81–86.
37. Dzierzanowski, K.; Popek, R.; Gawrońska, H.; Saebø, A.; Gawroński, S.W. Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. *Int. J. Phytoremediation* **2011**, *13*, 1037–1046. [CrossRef]
38. El Hamdani, S.; Limam, K.; Abadie, M.O.; Bendou, A. Deposition of fine particles on building internal surfaces. *Atmos. Environ.* **2008**, *42*, 8893–8901. [CrossRef]
39. Ghazalli, A.J.; Brack, C.; Bai, X.; Said, I. Alterations in use of space, air quality, temperature and humidity by the presence of vertical greenery system in a building corridor. *Urban Urban Green.* **2018**, *32*, 177–184. [CrossRef]
40. Su, Y.; Lin, C. Removal of Indoor Carbon Dioxide and Formaldehyde Using Green Walls by Bird Nest Fern. *Hortic. J.* **2015**, *84*, 69–76. [CrossRef]
41. Torpy, F.R.; Zavattaro, M.; Irga, P.J. Green wall technology for the phytoremediation of indoor air: A system for the reduction of high CO_2 concentrations. *Air Qual. Atmos. Health* **2016**, *10*, 1–11. [CrossRef]
42. Tudiwer, D.; Korjenic, A. The effect of an indoor living wall system on humidity, mould spores and CO_2 concentration. *Energy Build.* **2017**, *146*, 73–86. [CrossRef]
43. National Meteorological Science Data Center. National meteorological Observation Data. Available online: http://data.cma.cn/data/online/t/1 (accessed on 5 January 2020).
44. Li, J.; Liao, H.; Hu, J.; Li, N. Severe particulate pollution days in China during 2013–2018 and the associated typical weather patterns in Beijing-Tianjin-Hebei and the Yangtze River Delta regions. *Environ. Pollut.* **2019**, *248*, 74–81. [CrossRef]
45. Zhang, Y.; Cao, F. Fine particulate matter (PM2.5) in China at a city level. *Sci. Rep.* **2015**, *5*, 1–12. [CrossRef] [PubMed]
46. Bollasina, M.A.; Ming, Y.; Ramaswamy, V. Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon. *Sci. Am. Assoc. Adv. Sci.* **2011**, *334*, 502–505. [CrossRef] [PubMed]
47. Yin, Z.; Wang, H. Seasonal prediction of winter haze days in the north central North China Plain. *Atmos. Chem. Phys.* **2016**, *16*, 14843–14852. [CrossRef]
48. Cheng, X.; Zhao, T.; Gong, S.; Xu, X.; Han, Y.; Yin, Y.; Tang, L.; He, H.; He, J. Implications of East Asian summer and winter monsoons for interannual aerosol variations over central-eastern China. *Atmos. Environ.* **2016**, *129*, 218–228. [CrossRef]
49. Yin, X.; Sun, Z.; Miao, S.; Yan, Q.; Wang, Z.; Shi, G.; Li, Z.; Xu, W. Analysis of abrupt changes in the PM2.5 concentration in Beijing during the conversion period from the summer to winter half-year in 2006–2015. *Atmos. Environ.* **2019**, *200*, 319–328. [CrossRef]
50. Gunawardena, K.R.; Steemers, K. Living wall influence on microclimates: An indoor case study. *J. Phys. Conf. Ser.* **2019**, *1343*, 12188. [CrossRef]
51. Pérez-Urrestarazu, L.; Fernández-Cañero, R.; Franco, A.; Egea, G. Influence of an active living wall on indoor temperature and humidity conditions. *Ecol. Eng.* **2016**, *90*, 120–124. [CrossRef]

52. Fernández-Cañero, R.; Urrestarazu, L.P.; Franco Salas, A. Assessment of the Cooling Potential of an Indoor Living Wall using Different Substrates in a Warm Climate. *Indoor Built. Environ.* **2012**, *21*, 642–650. [CrossRef]
53. Poorova, Z.; Vranayova, Z. *Humidity, Air Temperature, CO2 and Well-Being of People with and Without Green Wall*; Springer International Publishing: Cham, Switzerland, 2020; pp. 336–346.
54. Shao, Y.; Li, J.; Zhou, Z.; Hu, Z.; Zhang, F.; Cui, Y.; Chen, H. The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings. *Build. Environ.* **2021**, *195*, 107766. [CrossRef]
55. Ahmed, K.; Kurnitski, J.; Sormunen, P. Demand controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams. *Energy Build.* **2015**, *109*, 115–126. [CrossRef]
56. Zhang, F.; Haddad, S.; Nakisa, B.; Rastgoo, M.N.; Candido, C.; Tjondronegoro, D.; de Dear, R. The effects of higher temperature setpoints during summer on office workers' cognitive load and thermal comfort. *Build. Environ.* **2017**, *123*, 176–188. [CrossRef]
57. Kim, M.K.; Choi, J. Can increased outdoor CO2 concentrations impact on the ventilation and energy in buildings? A case study in Shanghai, China. *Atmos. Environ.* **2019**, *210*, 220–230. [CrossRef]