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An experimental work to investigate the capabilities of plants to remove particulate matters in an enclosed greenhouse

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Abstract

Many studies, especially those conducted in laboratory chambers, have shown that plants are effective in removing indoor air pollutants. However, some researchers claim that laboratory results are not adequate evidence of validating the effectiveness of plants. Thus, an experimental work was designed and conducted by this research to investigate the capabilities of plants to remove particulate matters (PMs), given $PM_{2.5}$ and PM_{10} are the primary air pollutants in both indoor and outdoor environment in China. The experimental results have indicated that an enclosed space had a lower PM concentration than the outdoor environment. In addition, plants can further reduce the indoor PM concentrations because they increased the surface area of the space. Airflow speed has adverse effects on the efficiency of plants' PM removal. A relative slow airflow speed is beneficial to creating a stable indoor environment and to increase plants' efficiency in removing PMs. The experiment recorded removal efficiencies of plants were approximately 0.2–0.36 for $PM_{2.5}$ and 0.24–0.39 for PM_{10}, respectively. Moreover, measures, such as reducing infiltration rate, can further increase the removal efficiencies.

Keywords Plants · Indoor air quality · Particulate matters · Air pollution · Greenhouse

Introduction

China has experienced severe air pollution problems in recent years due to rapid industrialization and urbanization and increased energy consumption (Zhang et al. 2014). The Chinese economy still mainly depends on fossil fuels. In 2011, 69% of total energy consumption was linked to coal combustion, with 18% related to oil and 4% to natural gas use. As a result, the ambient air has been profoundly affected, especially in urban areas (Chung and Kim 2008). In 2012, only 5 cities out of 367 in China met the air quality standards recommended by the WHO. The primary air pollutant in Chinese cities is suspended particulate matters (PMs), specifically $PM_{2.5}$ and PM_{10} (PM_{10} denotes fine inhalable particulate matters with diameters that are generally 10 μm and smaller; $PM_{2.5}$ denotes fine inhalable particulate matters with diameters that are generally 2.5 μm and smaller) (Gao et al. 2016). The $PM_{2.5}$ concentrations in most urban areas have exceeded the acceptable national standards and are often worse in winter in North China due to increased fuel combustion for heating (Zhang and Crooks 2012; Gu et al. 2014). Shao et al. (2006) illustrated that over three-quarters of the population in urban areas is exposed to air quality levels that do not meet the Chinese National Air Quality Standard, and the primary contaminant in the ambient air is PM. Rohde and Muller (2015) found that high air pollutant levels are widespread throughout the northern and central parts of China, not only in the major cities and geologic basins but also in small cities and plain areas. They further noted that in the north-eastern corridor, which extends

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from Beijing to Shanghai, the air pollution is extremely severe.

In addition to PM, the concentrations of the other air pollutants, such as nitrogen oxide and carbon monoxide, have increased in recent decades. Data from the Chinese Ministry of Environmental Protection (2015) indicated SO_2 emissions had increased to 25.5 Mt/year in 2005, 27% higher than the emission level in 2000. Additionally, NOx emissions increased by over 150% between 2005 and 2015, due to the installation of new power plants and increases in the vehicle population.

The 13th Five-Year Energy Development Plan of China claimed that over the next 10 years, coal will remain the dominant energy source in China. Therefore, in the future, China will face more severe air pollution problems (NDRC and NEA 2016).

Since it is impossible to eliminate ambient air pollution in a short time, people have begun to implement air pollution mitigation measures inside their buildings. A market study showed that the sales volume of household air purification systems has dramatically increased since 2013 (Zhu 2013). In 2011 and 2012, 1.12 million and 1.26 million air purification systems were sold in China, respectively (Zhao 2014). Then, an extreme increase occurred in 2013, when the severe air pollution issue became well publicized and the total number of air purification systems sold reached 2.4 million. In 2017, over 7.69 million air purification systems were sold in China, three times the number in 2013. Moreover, a report from AskCI Consulting (2017) indicated that air purification systems are more popular in autumn and winter than in summer and spring, which is consistent with the air pollution trends in China.

However, some studies have verified that these air purification systems cannot completely clean the air to a level that meets the Chinese standards and the WHO indoor air quality standards (Li et al. 2015). Moreover, these products consume electricity and thus indirectly increase building energy consumption, which further contributes to ambient air pollution. In addition, cost is another barrier to installing air purification systems widely. For example, in December 2015, the Beijing government announced that they cannot install air purifier systems in all public primary school buildings due to financial restrictions (Wang 2016). In Hangzhou, the Education Department of the Hangzhou government rejected a proposal to install air purifiers in primary school classrooms due to a financial shortage (Wang 2016).

In view of the drawbacks of air purification systems, alternatively, passive methods, such as the use of plants, have gained increased recognition. Many studies have tested the efficiency of plants in removing various air contaminants (Darlington et al. 2001; Lohr 2010; Wood et al. 2003). Plants play a significant role in regulating climate changes. They have a considerable impact on the global climate and are highly related to the local weather conditions. Plants can lower temperatures, reduce energy use, and improve air quality mainly through two processes: evapotranspiration and photosynthesis. Evapotranspiration involves the absorption of water from the soil, ocean, or waterbodies and the subsequent release of water as vapor into the air through the stomata, which increases air humidity and decrease air temperature. This process is part of the water cycle and influences the thermal comfort level of the air, especially in dry climate regions. Photosynthesis is a process used by plants to convert light energy into chemical energy and simultaneously release oxygen. The atmospheric oxygen levels are maintained at a steady level by photosynthesis, and the energy necessary for life on Earth is provided (Bryant and Frigaard 2006).

The atmospheric CO_2 concentration has rapidly increased from 280 ppm to more than 380 ppm since the industrial revolution; moreover, this concentration is predicted to reach 700 to 1000 ppm by the end of the century (Team 2018). However, Berkeley Labs (2016) found that the CO_2 levels in the atmosphere have stabilized in recent years because plants are removing more carbon from the air than in the past. The Conversation (2014) stated that land plants absorb approximately 25% of the carbon emissions produced by human activities. Milcu et al. (2012) indicated that plants can remove much more CO_2 from the atmosphere than was previously believed. By absorbing CO_2, plants emit oxygen. Usman et al. (2014) stated that plants play a significant role in human life by maintaining atmosphere oxygen levels and that the oxygen production level of some plants is greater than the CO_2 absorption level. In addition to stabilizing the oxygen level and reducing the atmospheric CO_2 level, plants also affect indoor CO_2 levels. Tarran et al. (2007) indicated that among 55 city offices, rooms with three or more potted plants had 10% lower CO_2 concentrations in an air-conditioned building and 25% lower concentrations in a non-air-conditioned building. Pegas et al. (2012) conducted an empirical study by installing six plants in a classroom of 52.5 m2 in Aveiro, Portugal. The results indicated that this classroom had a lower CO_2 concentration by 50% compared to other classrooms without installing plants.

Plants can also directly clean the atmosphere by intercepting PMs in three ways (Beckett et al. 2000; Freer-Smith et al. 2004). The first way is retention. Plants reduce the airflow velocity and PMs settle on the surfaces of leaves. The quantity that settles on the surfaces of leaves is based on the airflow velocity and PM concentration in the ambient air. However, PMs adsorbed by retention can return to the air easily if the airflow speed increases and deteriorate the stable surrounding environment. The second way is attachment based on the rough leaf epidermis and cuticle characteristics. PMs are fixed to the leaf surfaces by attachment, which is relatively stable, and it is difficult for the wind to blow away the PM. The third way for plants to adsorb PMs is adhesion by the leaf exudates. Adhesion is the most stable way of capturing PMs and fixing them to the surfaces of leaves. Chen et al. (2014) claimed that some garden plants have the ability to remove PMs from the air and significantly improve the urban environmental quality. At the local scale, the inner portions of forest patches in urban areas exhibited significantly reduced concentrations of PMs compared to those near forest edges (Cavanagh et al. 2009). McDonald et al. (2007) claimed that in the West Midlands area of the UK, 110 tons of PM_{10} was removed per year by increasing the total tree cover from 3.7 to 16.5%. In Glasgow, the PM_{10} concentration was reduced by 2%, accounting for almost 4 tons per year, by increasing the tree cover from 3.6 to 8%. Nowak et al. (2013) stated that trees remove 4.7 to 64.5 tons of $PM_{2.5}$ annually in Syracuse and Atlanta. In the Greater London area, almost 852–2121 tons of PM_{10} is annually removed by the urban tree canopy (Tallis et al. 2011). In the USA, urban trees remove approximately 214,900 tons of PM_{10} per year (Nowak et al. 2006). Trees can also indirectly reduce PM concentrations. For example, trees can alter the air temperature and influence building energy consumption (e.g., cooling the air temperature to reduce cooling energy consumption, shading buildings, and reducing solar heat gains), as well as subsequently affect the emissions from power stations (Nowak and Crane 2002; Beckett et al. 1998). Thus, plants both directly and indirectly play an essential role in the cleaning of the ambient air.

In addition to removing the PMs, plants also make a significant contribution to reducing chemical air pollutants, such as VOCs, ozone, NOx, and SOx. Tarran et al. (2007) performed laboratory studies and found that VOC load was significantly reduced by plants. Papinchak et al. (2009) stated that chambers containing snake plants, spider plants, and golden pothos had higher ozone depletion rates than chambers without plants. Takahashi et al. (2005) found that plants have a high capacity for the uptake of nitrogen dioxide.

Therefore, based on the benefits noted above, indoor planting is an important design factor that can improve energy savings, indoor air quality, and work performance. Table 1 lists some indoor plants that can reduce indoor air pollution.

Identification of problems

As previously discussed, plants contribute to removing indoor air pollutants, such as PMs, VOCs, and CO_2 (Pettit et al. 2017). Many studies, especially those conducted in chambers, have shown that plants can clean air. Orwell et al. (2006) indicated that plants have the capability to remove contaminants from the air based on a laboratory study in a small and sealed chamber. Wood et al. (2003) investigated the effectiveness of plants in removing benzene and hexane in a small sealed space and found that the concentrations of benzene and hexane were reduced by 80% and 70%, respectively.

However, many studies have claimed that the laboratory results are not adequate evidence for concluding that the use of plants indoors can result in significant reductions in indoor air pollutant levels. Dingle et al. (2000) performed a field study in office buildings in Perth, Australia, to investigate the effectiveness of plants in removing formaldehyde. The results showed “no change in the formaldehyde concentrations with the addition of 5 or 10 plants in the room and only an 11% reduction in formaldehyde concentrations with 20 plants in the room.” Wood et al. (2006) conducted a similar field study in Sydney, Australia. The study found that VOC concentrations in rooms with plants were randomly higher or lower than those in rooms without plants.

Therefore, conflicting conclusions were provided by different studies. On one hand, the reductions in pollutant concentrations by plants in chamber studies suggest that plants are capable of removing air contaminants. On the other hand, field

Table 1 Plants and target air pollutants (NASA 1989)

Scientific name of plants	Target air pollutants
Adiantum pedatum	Absorbs radiation from computer and printer
Aloe	Can “signal for help” when excessively
Hevea brasiliensis	Can be helpful in eliminating harmful substances
Asparagus officinalis	Can kill viruses and bacteria
Hedera helix	Absorbs formaldehyde
Cactaceae	Best in reducing radiation
Chlorophytum comosum	Filters air
Clivia miniata	Keeps air fresh in winter
Monstera deliciosa Liebm.	Improves air quality at night
Pachira aquatica	Absorbs smoke well
Nephrolepis obliterata	Formaldehyde, TVOCs
Aglaonema modestum	TVOCs, formaldehyde
Epipremnum aureum	Particulate matters

studies have indicated that plants are not efficient in cleaning air in practical settings. Two reasons are listed below.

- Firstly, most chamber studies were performed with many plants in a small space. Chambers can create a relatively stable environment for the plants. To observe the same effect in a real space, several times as many houseplants as required in the chamber may need to be included in the field study. Installing one or two plants for a large space will not make a significant difference in terms of air quality.
- The second reason for the differences between the laboratory and field studies is that air pollutants in real buildings are constantly affected by human activities. There may be not enough time for plants to completely absorb these pollutants. Therefore, laboratory studies and field measurements are very different cases.

Therefore, the key issue that should be considered in the use of plants to clean indoor air is the number of plants and the stability of indoor environments.

Research hypothesis

Plants play a significant role in building design and have been widely used in many ways, including green facades, garden atriums, vertical forests, and planted terraces. For example, the University of Guelph-Humber established a four-storey plant wall in their central atrium in early 2000s to recycle more inside air and reduce the need for heating and cooling. The plant wall was made up of over 1000 plants from 100 different species. In addition, it was fully integrated into the building's ventilation system and processes 1133 m^3 of air very minute, removing air pollutants, and decreasing the temperature (Guelphhumber n.d.). Another example is the Junglefy Breathing Wall developed by the company Junglefy Pty Ltd. and the Plants and Environmental Quality Research Group at the University of Technology Sydney. It is an active, modular green wall system that pulls the air through the leaves of plants by an electric axial impeller. Report published in 2016 indicates that a Breathing Wall of 10 m^2 in size can produce 1623.4 m^3 particle-free air per hour on average and balance-out CO_2 emissions from 4 to 5 occupants during normal working hours (Irga, et al. 2016).

Based on the literature review, this research proposed an integrated ventilation system designed for buildings (Fig. 1). The concept of the greenhouse with plants originated from laboratory studies involving small sealed chambers with many plants. Therefore, the sunspace in this system acts as an enlarged air storage chamber. The plants were placed inside the sunspace rather than scattering them randomly inside the buildings. Air flows into the greenhouse at a slow speed to ensure the stable inside environment. Therefore, the use of plants eliminated many factors that affect the plant cleaning efficiency, such as wind and occupant activities. Moreover, the sunspace provided a stable indoor environment for plants to remove air pollutants.

Although the greenhouse originated from chamber studies, a significant difference also should be emphasized. In chamber studies, normally, air pollutants were only introduced once, and the air was then monitored to observe the reductions in pollutant concentrations. In the greenhouse, air constantly flows into the greenhouse at a very slow speed. Thus, the cleaning efficiencies of plants in these two situations were also different.

To identify the potentialities of the ventilation system presented in Fig. 1 and also determine the capabilities of plants to remove air pollutants in a dynamic process (air constantly flows into the sunspace), an experimental work was

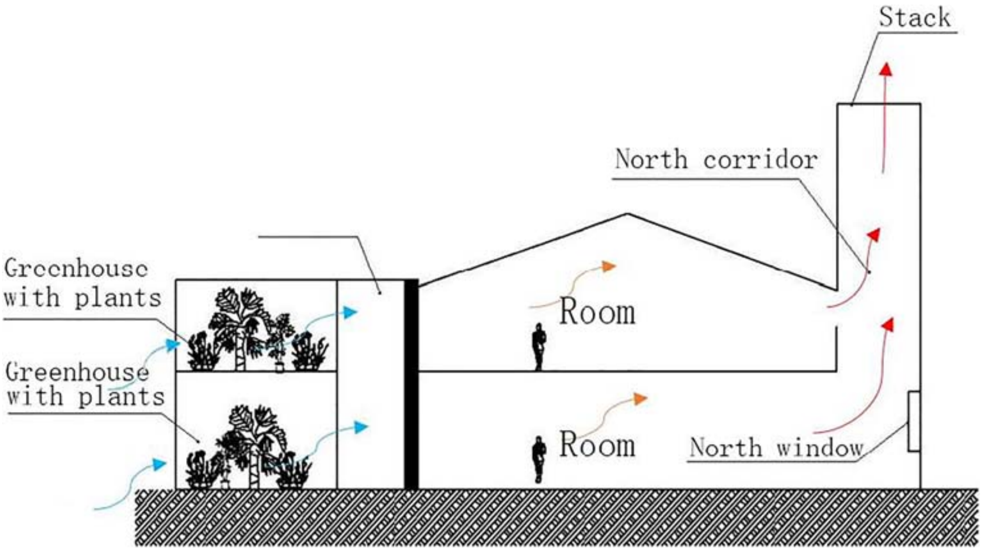


Fig. 1 Initial idea for plants' utilization in building design

Table 2 The quantity of leaves on selected plants

A	B	C	D	E	F	G	H	I	J
159	152	147	159	145	141	142	160	148	153
k	L	M	N	O	P	Q	I	S	T
148	152	151	158	155	154	144	158	158	159

conducted based on the financial and material resources currently available to this research.

Experimental setup

The experimental study established a greenhouse with a steel framework and polyethylene films to represent the sunspace designed in the ventilation system. Theoretically, the inside environment of the greenhouse was more stable than the ambient environment. The width, length, and height of the greenhouse were 1.4 m, 14 m, and 2 m, respectively. The primary air pollutants in China are currently $PM_{2.5}$ and PM_{10} (Peng et al. 2017); thus, the experimental work was mainly used to investigate the changing trends of PM concentrations. Moreover, the indoor PM concentrations were measured at four monitoring points (see Fig. 1 in the Supplementary Materials).

The greenhouse was located in Tai'an city. The city is part of the cold climate zone in China, which is bitterly cold in winter and hot in summer, indicating a large temperature variation. The coldest average monthly temperature was between − 10 and 0 °C in winter, while in summer, the highest air temperature usually was above 30 °C. It also has heavy ambient air pollution. Based on the data from the local environmental protection department, the daily highest ambient $PM_{2.5}$ and PM_{10} concentrations in 2019 were 195 $\mu g/m^3$ and 262 $\mu g/m^3$ on average, respectively (Environment Protection Department of Shandong Provincial Government 2019).

Based on the available financial resources, 20 potted plants (labeled from A, B, C…, to T) bought from the local market were placed inside the greenhouse (see Fig. 2 in the Supplementary Materials). The plants used were *Epipremnum aureum* because it is effective in removing PMs from the air (Zhou et al. 2009). The 20 plants were put in clay containers full of grow potting mix. Moreover, it is common in the plant market in the case study area of China and its number of leaves can be easily counted. The selected potted plants had similar heights, crown diameters, and ages.

Many methods, such as the graticulation method and regression equations, can be used to estimate the surface area of leaves. Some devices, such as portable leaf area meters, can also directly measure the surface area of leaves (Xu et al. 2002). In this study, due to resource limitations, only scanners and drawing software, including Photoshop and AutoCAD, were used to quantify the leaf surface area. The scanners scanned a single leaf and imported the scanned picture into Photoshop and AutoCAD. Then, AutoCAD can directly provide the surface areas of leaves (see Fig.3 in the Supplementary Materials).

To estimate the surface areas of leaves on each plant, the number of leaves should be determined. Table 2 summarizes the number of leaves on each plant. The maximum number of leaves was 160 for plant H. Leaves falling and growing are two natural processes that occur simultaneously. Within a specified period, it is assumed that the number of leaves and the leaf surface area is constant.

According to the empirical principles of the sampling survey, for a subject with a population less than 1000, the smallest number of viable samples should be at least 30% of the total population (Shao 2012). Therefore, for the selected 20 plants, 50 leaves from each plant were collected as samples. The samples of leaves were collected randomly from the bottom, middle, and top of each potted plant. Then, the overall leaf surface area was estimated based on these samples. Table 3 summarizes the average leaf surface area data for each

Table 3 Detail surface areas calculations of leaves from the selected plants (A-T) (m^2)

Plants	Leaves surface areas of plants (m^2)	Plants	Leaves surface areas of plants (m^2)
A	Plant A 0.0075 × 159 = 1.19	K	Plant K 0.0075 × 148 = 1.11
B	Plant B 0.0076 × 152 = 1.16	L	Plant L 0.0076 × 152 = 1.16
C	Plant C 0.0077 × 147 = 1.13	M	Plant M 0.0084 × 151 = 1.27
D	Plant D 0.0071 × 159 = 1.13	N	Plant N 0.0079 × 158 = 1.25
F	Plant E 0.0078 × 145 = 1.13	O	Plant O 0.0072 × 155 = 1.12
E	Plant F 0.0074 × 141 = 1.04	P	Plant P 0.0077 × 154 = 1.19
G	Plant G 0.0079 × 142 = 1.12	Q	Plant Q 0.0074 × 144 = 1.07
H	Plant H 0.0073 × 160 = 1.17	R	Plant R 0.0076 × 158 = 1.20
I	Plant I 0.0076 × 148 = 1.12	S	Plant S 0.0072 × 158 = 1.14
J	Plant J 0.0076 × 153 = 1.16	T	Plant T 0.0074 × 159 = 1.18
Average surface areas of one plant	(1.19 + 1.16 + 1.13 + 1.13 + 1.13 + 1.04 + 1.12 + 1.17 + 1.12 + 1.16 + 1.11 + 1.16 + 1.27 + 1.25 + 1.12 + 1.19 + 1.07 + 1.20 + 1.14 + 1.18)/20 = 1.16		

Table 4 The diameters of the selected pipes and the corresponding airflow speed

The air volume flow rate of the fan (m^3/h)	The diameters of the pipes (mm)	The corresponding air supplied speed (m/s)
0	0	Infiltration
225	300	0.9
	400	0.5
	250	1.3

Table 6 Measurement results (24-h average)

Scenarios	$PM_{2.5}$ (μg/m^3)			PM_{10} (μg/m^3)		
	Indoor	Outdoor	I/O ratios	Indoor	Outdoor	I/O ratios
1	65	87	0.75	73	94	0.78
2	53	136	0.39	61	156	0.39
3	182	219	0.83	213	263	0.81
4	74	135	0.55	84	157	0.54
5	153	192	0.80	182	232	0.79
6	39	78	0.50	44	90	0.49
7	55	71	0.77	71	89	0.80
8	38	78	0.49	48	98	0.49

plant. The average surface area for one plant was approximately 1.16 m^2.

To ensure that the air could pass through as many plants as possible, it flowed into the greenhouse from inlet A1 and through the outlet A2 (see Fig. 1 in the Supplementary Materials). A fan with a rated power of 50 W was used to generate an air flow rate of 225 m^3 per hour. Moreover, the diameter of the fan's outlet was 100 mm. Therefore, the supplied air flow speed at the outlet of the fan was 8 m/s. A connection between the fan and the pipes was created to generate different airflow speeds (see Fig. 4 in the Supplementary Materials). For example, when the fan was connected to a pipe with a diameter of 400 mm, an airflow speed of 0.5 m/s could be generated. The box in the middle acted as a connector between the pipes and the fan. The diameters of selected pipes were 250 mm, 300 mm, and 400 mm, and each pipe corresponded to one air flow velocity (Table 4). In addition, polyvinyl chloride (PVC) pipes with different diameters were used for the measurements (see Fig. 5 in the Supplementary Materials).

Totally, five portable hand-held detectors of BRAMC-SMART-126 models (see Fig. 6 in the Supplementary Materials), which have been certified by the Department of Environment Protection of Central Government of China, were used to measure the PM concentrations at the inside monitoring points of the sunspace and the outside PM concentrations, simultaneously. The detector is a high-precision dust sensor capable of detecting 0.5-μm particulate matters. It provides great airflow intake and generate consistent and accurate results.

To identify the influences of the plants on the inside PM concentrations, measurements of different scenarios were conducted (Table 5). Totally, 8 scenarios were created, and the duration of each measurement was 24 h. The plants were cleaned in advance before each measurement. For example, the plants' leaves were washed 1 day before the measurements.

Measurements results and discussion

Inside and outside PM concentrations

Table 6 indicates the indoor and outdoor PM concentrations and the ratios of indoor PM concentrations to outdoor PM concentrations (I/O ratios) of scenarios. The indoor PM concentrations were estimated based on the measurement results from the 4 monitoring points (see Fig. 1 in the Supplementary Materials). Figures 2, 3, 4, and 5 show the changing tendency of PM concentrations in both indoor and outdoor environments in scenarios 1, 2, 6, and

Table 5 A summary of the measurement

Scenarios	Air supply	Plants	Period	Values	Ventilation type	Air change rate (1/h)
1	No	No	24 h	Hourly	Infiltration	Rely on infiltration
2	No	Yes				
3	Yes, 1.3 m/s	No			Mechanical air supply	5.7/h
4		Yes				
5	Yes, 0.9 m/s	No				
6		Yes				
7	Yes, 0.5 m/s	No				
8		Yes				

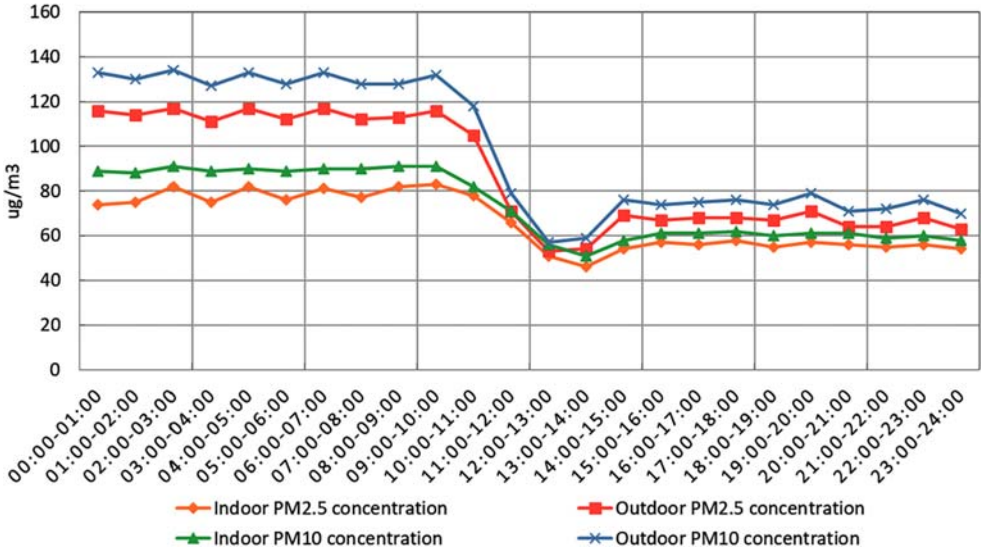


Fig. 2 Measurement results of scenario 1 (without air supply, and plants were placed inside greenhouse)

7. It was noted that in all scenarios, the indoor PM concentrations were all lower than the outdoor PM concentrations. Thus, in an enclosed space, the stable inside environment led to a lower inside PM concentration, as more PMs were retained, attached, or adhered on the leaf surfaces of the plants in the greenhouse.

In scenarios 1 and 7, there were no plants inside the sunspace. Therefore, the ambient PM concentrations were the sole factor that affected the inside PM levels. Moreover, it was also noted that the changing tendency for both the inside and outside PM concentrations was more consistent than those situations in scenarios 2 and 6. A similarly changing tendency also can be observed in scenarios 3 and 5.

However, at some points, the inside PM concentrations were closed to the outside PM concentrations. For example, in scenario 1, there was a rapid decline of the outside PM concentrations between the time 11:00–13:00, and then, it quick reversed before the inside PM concentrations could respond. Therefore, the inside PM concentrations reached a similar level as the outside PM concentrations. In scenario 7, the rapid decline of the ambient PM levels led a significant decrease of the inside PM levels of the sunspace.

In scenarios 2 and 6, plants were moved into the greenhouse. It was noted that the inside PM concentrations were more stable than outside PM levels because plants provided more inner surfaces for PMs to sunk. For example, in Figs. 4 and 5, the outside PM concentrations fluctuated greatly during 9:00–14:00, while the inside PM concentrations were maintained at a stable level. A similarly pattern also can be found in scenarios 4 and 8.

In general, in an empty space, the ambient PM concentration was the only influential factor that affected the indoor PM concentrations. This finding was also proved by the field studies conducted by Peng et al. (2017),

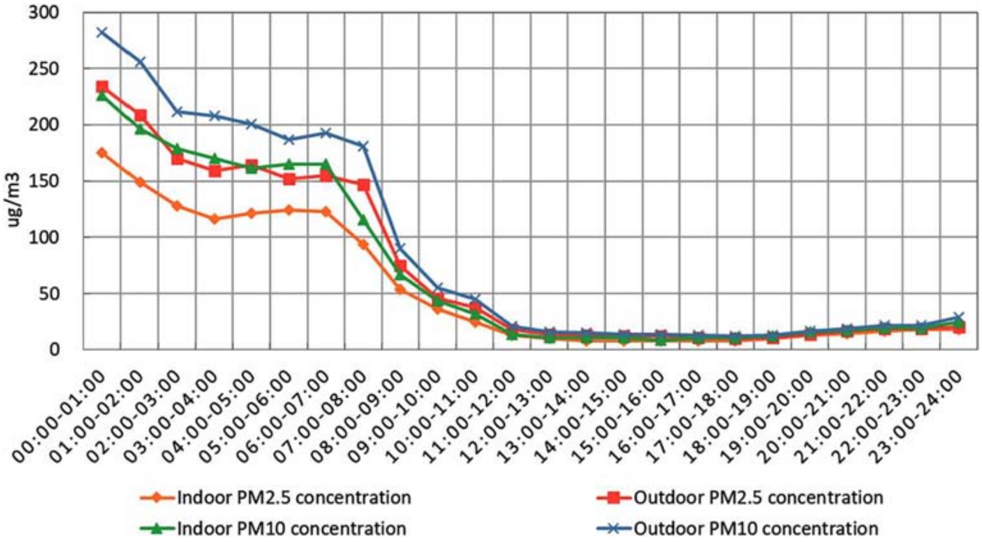


Fig. 3 Measurement results of scenario 7 (air supply at 0.5 m/s, and plants were not inside)

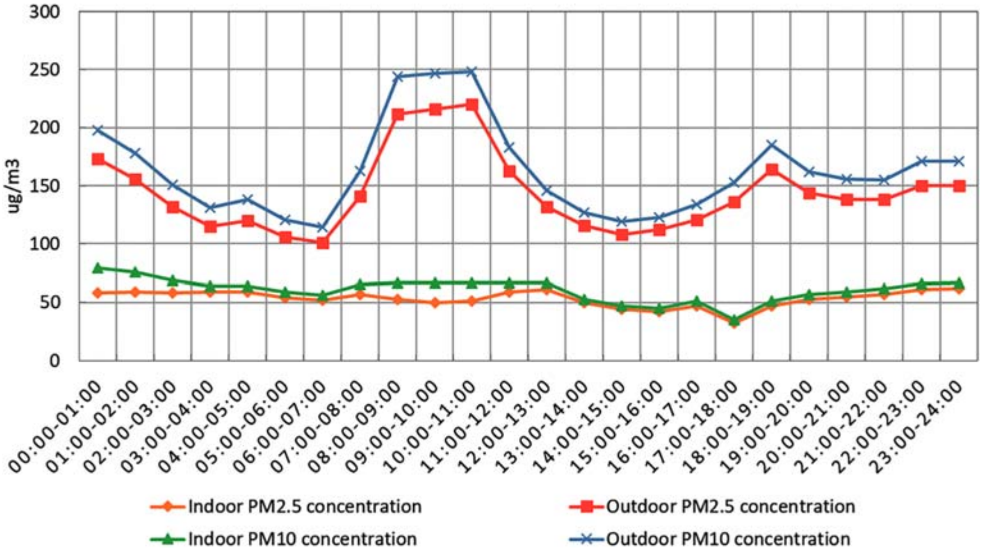


Fig. 4 Measurement results of scenario 2 (no air supply, plants were not inside)

which stated that, in unoccupied space, the inside PM concentrations are normally lower than the outside PM concentrations. In addition, plants inside the greenhouse provided more inner surfaces for PMs to be retained, attached, or adhered. Thus, the inside PM levels were more stable than that case of greenhouse without plants.

I/O ratios

Figures 6 and 7 describe the I/O ratios of different scenarios. Notably, the greenhouse with plants inside has lower I/O ratios than the sunspace without plants inside. I/O ratios of scenarios 1, 3, 5, and 7 were between 0.64 and 0.98. In scenarios 2, 4, 6, and 8, the values ranged from 0.23 to 0.66.

The I/O ratios of scenario 1 were much higher than those in scenario 2. The only difference between scenario 1 and scenario 2 was the presence of plants. Scenario 2 revealed that the plants can remove approximately 38% of PMs from the infiltration based on scenario 1. Thus, there is no doubt that the plants increased the surface areas of the greenhouse and more of the PMs originated from the outside were retained, attached, or adhered on the surfaces of leaves.

Figure 8 shows the comparison between scenarios 1, 3, 5, and 7. The airflow speed is the single variable in this comparison. It was noted that in scenario 1, the greenhouse without plants has approximately 77% of the PMs coming from the outside by infiltration on average. In scenarios 3, 5, and 7, the I/O ratios were slightly higher than that in scenario 1, since air comes inside not only by infiltration but also through the supply of the fans at speeds of 1.3 m/s, 0.9 m/s, and 0.5 m/s, respectively.

Scenarios 4, 6, and 8 suggested that when the air flows at a relatively slow speed, a greenhouse with plants still has a lower PM concentration than those of the ambient air.

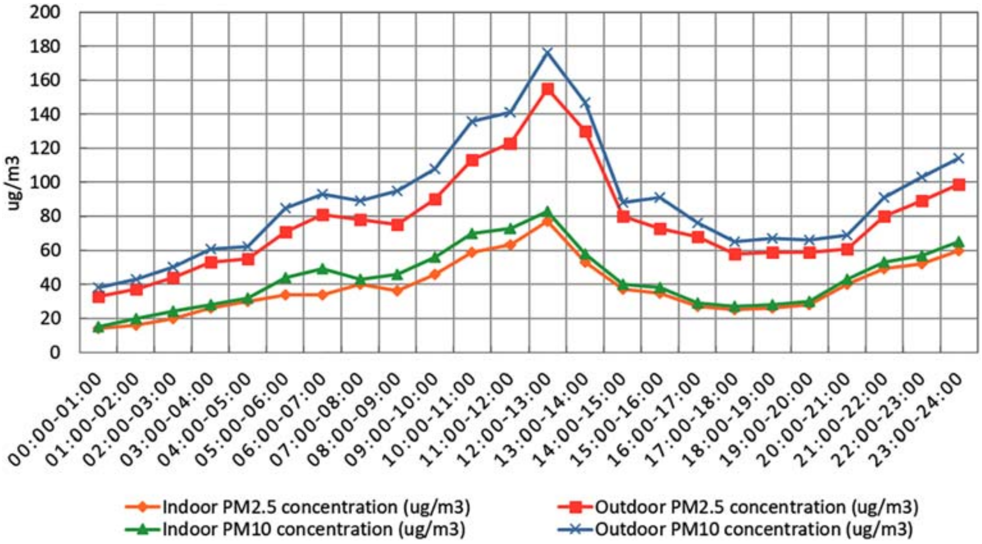


Fig. 5 Measurement results of scenario 6 (air supply at 0.9 m/s, plants were placed inside)

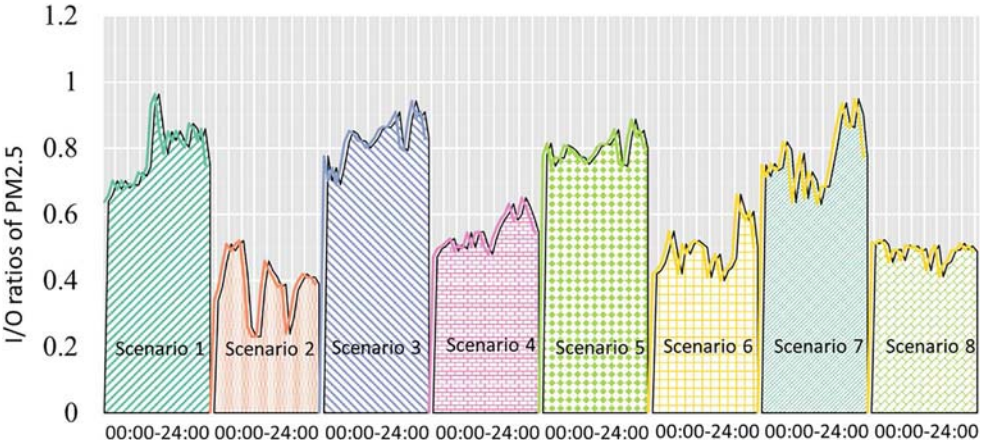


Fig. 6 Performance of I/O ratios of $PM_{2.5}$ in different scenarios

Scenario 6 performed similar I/O ratios to those of scenario 8. Scenario 4 has higher values than scenarios 6 and 8 on average.

Comparison between scenarios 3, 5, and 7 and 4, 6, and 8 suggested that plants can significantly reduce the inside PM concentrations although they have the same airflow speeds. For example, in scenarios 3 and 4 (airflow speed was 1.3 m/s), plants approximately removed 28% of the inside PMs based on the level of scenario 3. In scenarios 5 and 6, 7, and 8, this number was 30% on average.

Supported by findings from the field study conducted by Peng et al. (2017), a consistent conclusion was raised based on the analysis of I/O ratios in this research: an enclosed space with plants tends to have a lower PM concentration than the ambient environment. In addition, plants and slow airflow speed have a positive effect on the reduction of indoor PM concentration.

The designed experiment contains two variables: plants and airflow speed. Comparisons between scenarios revealed the significance of the plants in removing PM and the effects of the airflow speed on reducing PM concentrations. These comparisons have directly answered the research question raised earlier in the "Identification of problems" section. The key issue that should be considered in the use of plants to clean air is the number of plants and the stability of the indoor environments.

Discussion

Taking scenario 1 as a baseline, the removal efficiencies of plants in scenarios 2, 4, 6, and 8 were summarized in Table 7. Scenario 2 has the highest removal efficiency, as the values for $PM_{2.5}$ and PM_{10} were 0.36 and 0.39, respectively. Scenario 6 has similar removal efficiency to those of scenario 8. Scenario 4 has lower removal efficiency than scenarios 6 and 8, on average.

Compared with an earlier study from Irga et al. (2017), it was noted that only scenario 2 has removal efficiencies of PMs within the range determined by Irga et al. (2017). In contrast, scenarios 4, 6, and 8 have lower removal efficiencies (see Fig. 7 in the Supplementary Materials). The differences between these two studies may be explained as follows.

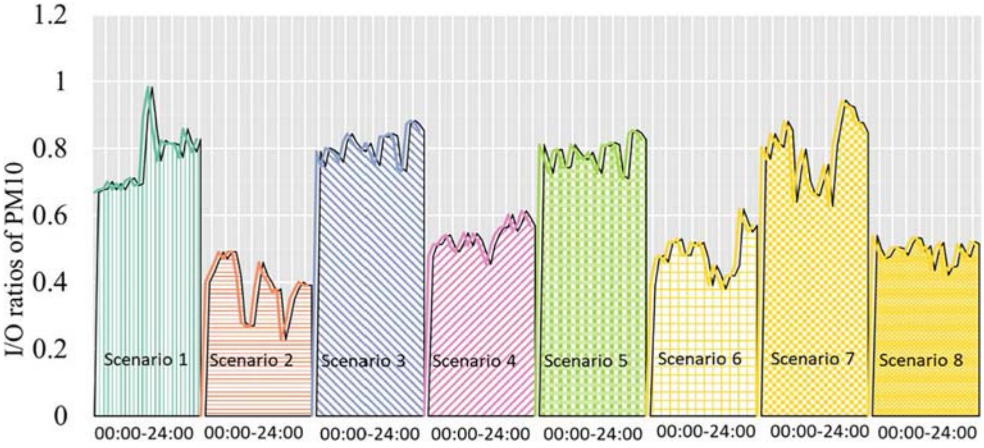
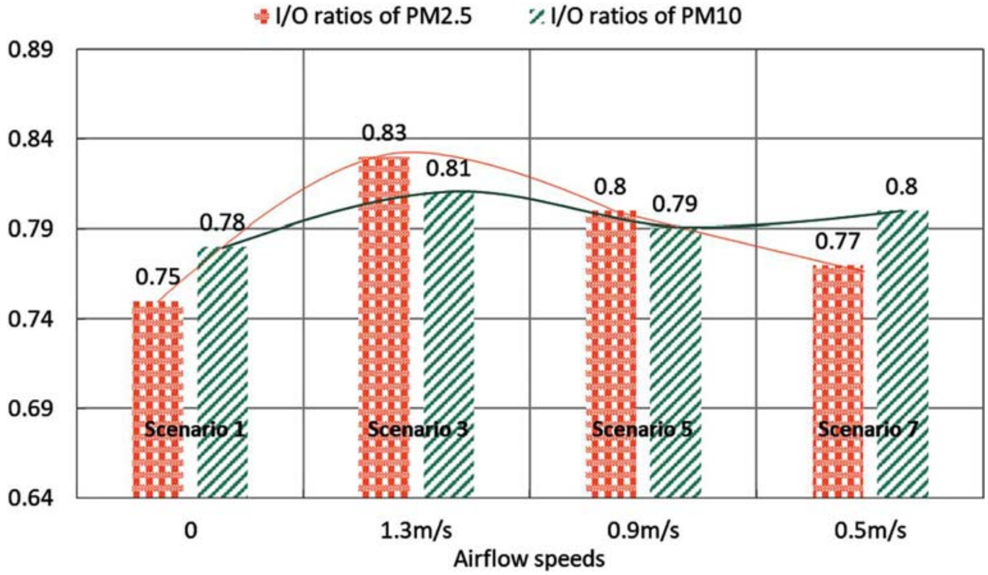


Fig. 7 Performance of I/O ratios of PM_{10} in different scenarios

Fig. 8 A comparison of I/O ratios of PMs between scenarios 1, 3, 5, and 7



- Firstly, the study from Irga et al. (2017) was carried out in a chamber which is relatively small compared to the greenhouse used in this work (see Fig. 8 in the Supplementary Materials).
- Secondly, the airflow rate in this work was much higher than the value used in the study from Irga et al. (2017) (62.5 L/s vs 11.25 L/s).

However, due to the limited financial resources, the greenhouse was built with a steel framework and polyethylene films. Moreover, the connection of the polyethylene films of the sunspace only relies on the transparent adhesive tape (see Fig. 9 in the Supplementary Materials), which might lead to a low level of airtightness. Therefore, the greenhouse might have a high infiltration rate allowing more outdoor PMs penetrations, resulting in high I\O ratios and low removal efficiencies, even though plants can remove parts of them. Moreover, a high infiltration rate also leads to a high indoor pollution load, which might accelerate the process of adsorption saturation of plants since their adsorption capacity is certain. Supported by the findings of Peng et al. (2017), if materials such as glass were used to build the greenhouse, the airtightness levels would be significantly improved. Hence, the removal efficiencies can be further improved.

Table 7 Removal efficiency of plants in different scenarios

Scenarios	Airflow rate	Plant removal efficiency	
		$PM_{2.5}$	PM_{10}
2	62.5 L/s	0.36	0.39
4		0.20	0.24
6		0.25	0.29
8		0.26	0.29

Conclusions

This research provided information about an experiment designed to evaluate the capabilities of plants to remove PMs. The measuring results have generated the following conclusions.

- An enclosed greenhouse has a lower PM concentration than the outside environment as the ventilation only relies on infiltration.
- Plants can further reduce the indoor PM concentrations, since they increase the surface area of the greenhouse. Therefore, more PMs coming from outside can sink on the surfaces of leaves.
- Airflow speed has adverse effects on the efficiency of plants' PM removal. A relatively slow air supply speed is beneficial to create a stable indoor environment and to increase plants' efficiency in reducing PM concentrations.

This research focused on plants' capabilities to remove PMs ($PM_{2.5}$ and PM_{10}). The changes in the concentrations of other air pollutants inside the sunspace were excluded from this research. For example, plants could reduce the CO_2 concentrations and increase the oxygen level by photosynthesis. Other air pollutants, such as VOCs, NO_x, and SO_x, could also be removed from the air. Future work could focus on the potential cleaning performance of the plants regarding CO_2 and other air pollutants. Due to the limited financial resources, the sunspace in the experiment was built with a steel framework and polyethylene films. The airtightness could be significantly improved if glass was used and the reduction of PM inside the sunspace could be different.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Dr. Zhen Peng and Dr. Wu Deng. The first draft of the manuscript was written by Dr. Zhen Peng and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

AskCI Consulting (2017) Market size analysis of China air purifier. AskCI, Beijing, pp 1–30

Beckett K, Freer-Smith P, Taylor G (1998) Urban woodlands: their role in reducing the effects of particulate pollution. Environ Pollut 99(3): 347–360. https://doi.org/10.1016/s0269-7491(98)00016-5

Beckett K, Freer-Smith P, Taylor G (2000) Effective tree species for local air quality management. J Arboric 26(1):12–19

Berkeley Lab (2016) Study: carbon-hungry plants impede growth rate of atmospheric CO_2. Berkeley Lab. http://newscenter.lbl.gov/2016/11/08/atmospheric-CO_2-pause/. Accessed 1 Dec 2019

Bryant DA, Frigaard NU (2006) Prokaryotic photosynthesis and photo trophy illuminated. Trends Microbiol 14(11):488–496. https://doi.org/10.1016/j.tim.2006.09.001

Cavanagh J, Zawar-Reza P, Wilson J (2009) Spatial attenuation of ambient particulate matter air pollution within an urbanised native Forest patch. Urban For Urban Green 8(1):21–30. https://doi.org/10.1016/j.ufug.2008.10.002

Chen L, Fan Y, Yang S, Wu J, Li Z, Chen H (2014) Investigation of PM concentrations in public faculties of Nanchang. J Hyg Res 43(1): 146–148

Chung YS, Kim HS (2008) Observations of massive air-pollution transport and associated air quality in the Yellow Sea region. Air Qual Atmos Health 1(2):69–79. https://doi.org/10.1007/s11869-008-0014-y

Darlington A, Dat J, Dixon M (2001) The biofiltration of indoor air: air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. Environ Sci Technol 35(1):240–246. https://doi.org/10.1021/es0010507

Dingle P, Tapsell P, Hu S (2000) Reducing formaldehyde exposure in office environments using plants. Bull Environ Contam Toxicol 64(2):302–308. https://doi.org/10.1007/s001289910044

Environment Protection Department of Shandong Provincial Government (2019) Urban ambient air quality platform-Tai'an air quality information. http://58.56.98.78:8801/AirDeploy.Web/AirQuality/MapMain.aspx. Accessed 2 Feb 2020. https://doi.org/10.1007/978-3-030-11149-6_8

Freer-Smith P, El-Khatib A, Taylor G (2004) Capture of particulate pollution by trees: a comparison of species typical of semi-arid areas (Ficus Nitida and Eucalyptus Globulus) with European and North American species. Water Air Soil Pollut 155(1–4):173–187

Gao J, Yuan Z, Liu X, Xia X, Huang X, Dong Z (2016) Improving air pollution control policy in China—a perspective based on cost–benefit analysis. Sci Total Environ 543:307–314

Gu J, Du S, Han D, Hou L, Bai ZP (2014) Major chemical compositions, possible sources, and mass closure analysis of $PM_{2.5}$ in Jinan, China. Air Qual Atmos Health 7(3):251–262. https://doi.org/10.1007/s11869-013-0232-9

Guelphhumber (n.d.) The plant wall, the University of Guelph-Humber. Retrieved 4 February 2020, from https://www.guelphhumber.ca/about/plant-wall

Irga PJ, Paull N, Abdo P, Huynh BP, Avakian V, Nguyen T, Torpy FR (2016) Developing the Junglefy Breathing Wall for enhanced indoor air quality remediation. Plants and environmental quality research group. Report prepared for Junglefy Pty Ltd. University of Technology Sydney, Australia. https://doi.org/10.1007/s11046-016-0013-8

Irga PJ, Paull NJ, Abdo P, Torpy FR (2017) An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system. Build Environ 115:281–290. https://doi.org/10.1016/j.buildenv.2017.01.035

Li W, Zhu C, Yu J, Xu J, Liu F (2015) Field test and analysis on air purifiers' effect on indoor air purification. Green Building 1:59

Lohr VI (2010) What are the benefits of plants indoors and why do we respond positively to them? Acta Hortic 88:675–682. https://doi.org/10.17660/ActaHortic.2010.881.111

McDonald A, Bealey W, Fowler D, Dragosits U, Skiba U, Smith R, Donovan R, Brett H, Hewitt C, Nemitz E (2007) Quantifying the effect of urban tree planting on concentrations and depositions of PM_{10} in two UK conurbations. Atmos Environ 41(38):8455–8467. https://doi.org/10.1016/j.atmosenv.2007.07.025

Milcu A, Lukac M, Subke J, Manning P, Heinemeyer A, Wildman D, Anderson R, Ineson P (2012) Biotic carbon feedbacks in a materially closed soil–vegetation–atmosphere system. Nat Clim Chang 2(4):281–284. https://doi.org/10.1038/nclimate1448

Ministry of Environment Protection of the People's Republic of China (2015) National environmental protection 13th Five-Year Plan. Beijing: MEP p2 http://wwwzhbgovcn/gzfw_13107/ghjh/wngh/ Accessed 28 Dec 2019

NASA (1989) NASA clean air study. En.wikipedia.org. https://en.wikipedia.org/wiki/NASA_Clean_Air_Study. Accessed 1 Dec 2019

NDRC N, NEA N (2016) The 13th China Energy Development Plan. NDRC and NEA, Beijing, pp 4–10

Nowak D, Crane D (2002) Carbon storage and sequestration by urban trees in the USA. Environ Pollut 116(3):381–389. https://doi.org/10.1016/S0269-7491(01)00214-7

Nowak D, Crane D, Stevens J (2006) Air pollution removal by urban trees and shrubs in the United States. Urban For Urban Green 4(3–4):115–123

Nowak D, Hirabayashi S, Bodine A, Hoehn R (2013) Modeled $PM_{2.5}$ removal by trees in ten U.S. cities and associated health effects. Environ Pollut 178:395–402. https://doi.org/10.1016/j.envpol.2013.03.050

Orwell RL, Wood RA, Burchett MD, Tarran J, Torpy F (2006) The potted-plant microcosm substantially reduces indoor air VOC pollution: II. Laboratory study. Water Air Soil Pollut 177(1–4):59–80

Papinchak H, Holcomb E, Best T, Decoteau D (2009) Effectiveness of houseplants in reducing the indoor air pollutant ozone. Hort Technol:286–290. https://doi.org/10.21273/HORTSCI.19.2.286

Pegas P, Alves C, Nunes T, Bate-Epey E, Evtyugina M, Pio C (2012) Could houseplants improve indoor air quality in schools? J Toxicol Environ Health A 75(22–23):1371–1380

Peng Z, Deng W, Tenorio R (2017) Investigation of indoor air quality and the identification of influential factors at primary schools in the north of China. Sustainability 9(7):1180. https://doi.org/10.3390/su9071180

Pettit T, Irga P, Abdo P, Torpy F (2017) Do the plants in functional green walls contribute to their ability to filter particulate matter? Build Environ 125:299–307. https://doi.org/10.1016/j.buildenv.2017.09.004

Rohde RA, Muller RA (2015) Air pollution in China: mapping of concentrations and sources. PLoS One 10(8). https://doi.org/10.1371/journal.pone.0135749

Shao Z (2012) The method of determining the number of samples in sampling survey. Statistics and Decision-making (22): 14. http://www.doc88.com/p-773863934557.html. Accessed 11 Dec 2019

Shao M, Tang X, Zhang Y, Li W (2006) City clusters in China: air and surface water pollution. Front Ecol Environ 4(7):353–361. https://doi.org/10.1890/1540-9295(2006)004[0353:CCICAA]2.0.CO;2

Takahashi M, Higaki A, Nohno M, Kamada M, Okamura Y, Matsui K, Morikawa H (2005) Differential assimilation of nitrogen dioxide by 70 taxa of roadside trees at an urban pollution level. Chemosphere 61(5):633–639. https://doi.org/10.1016/j.chemosphere.2005.03.033

Tallis M, Taylor G, Sinnett D, Freer-Smith P (2011) Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. Landsc Urban Plan 103(2):129–138. https://doi.org/10.1016/j.landurbplan.2011.07.003

Tarran J, Torpy F, Burchett M (2007) Use of living pot-plants to cleanse indoor air – research review. In: Sixth international conference on indoor air quality, Ventilation & energy conservation in buildings – sustainable built environment Sendai: Clean Air:2–3. http://www.plantsolutions.com/documents/PlantsCleanseIndoorAir.pdf. Accessed 28 Dec 2019

Team E (2018) ESRL global monitoring division - global greenhouse gas reference network. Esrl.Noaa.Gov. https://www.esrl.noaa.gov/gmd/ccgg/trends/. Accessed 31 Dec 2019

The Conversation (2014) Plants absorb more CO_2 than we thought. The Conversation. http://theconversation.com/plants-absorb-more-CO_2-than-we-thought-but-32945. Accessed 1 Dec 2019

Usman AB, Abubakar S, Alaku C, Nnadi O (2014) Plant: a necessity of life. Int Lett Nat Sci 20:151–159. https://doi.org/10.18052/www.scipress.com/ILNS.20.151

Wang X (2016) Discussion on installing air cleaners in kindergartens and primary schools in Beijing to protect children's health in heavy smog. Environ Prot 44(2):63–64

Wood R, Orwell R, Tarran J, Torpy F, Burchett M (2003) Potted plant/growth media interactions and capacities for removal of volatiles from indoor air. In: proceedings of health buildings 2003. Singapore: 441-445

Wood R, Burchett M, Alquezar R, Orwell R, Tarran J, Torpy F (2006) The potted-plant microcosm substantially reduces indoor air VOC pollution: I. office field-study. Water Air Soil Pollut 175(1–4):163–180

Xu G, Mao H, Hu Y (2002) Measurement of blade area based on computer vision technology reference object method. Trans CSAE 18(1)

Zhang Q, Crooks R (2012) Toward an environmentally sustainable future: country environmental analysis of the People's Republic of China. Asian Dev Bank:4–18

Zhang L, Yuan Z, Maddock JE, Zhang P, Jiang Z, Lee T, Lu Y (2014) Air quality and environmental protection concerns among residents in Nanchang, China. Air Qual Atmos Health 7(4):441–448. https://doi.org/10.1007/s11869-014-0255-x

Zhao (2014) Air purifier market: sales say unidentified users buy comfort. Cheaf.hc360.com. http://www.cheaf.hc360.com/2014/02/211657985279.shtml. Accessed 31 Dec 2018, https://doi.org/10.17226/21683

Zhou J, Yan W, Wang J (2009) Study on indoor dust retention ability of seven potted ornamental plants. Mod Agric Technol 2009(8):7–10

Zhu D (2013) Air purifiers step into warring states. Modern Household Appliances (13): 61. https://www.xzbu.com/2/view-4627197.htm. Accessed 28 Dec 2019