The effectiveness of potted plants in improving indoor air quality: a comparison between chamber and field studies

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Abstract. People spend up to 90% of their time inside buildings, making indoor air quality an extremely important factor affecting public health and building design. Due to the inherent ability to absorb/filter pollutants, plants present a promising method for improving indoor air quality. In recent decades, many studies have quantified plants' effectiveness in removing indoor air pollutants using both chamber and field methods. This paper presents a review working covering these studies and discusses the differences between chamber and field studies, in terms of study methods and results. Through a meta-analysis of 41 chamber studies and 16 field studies, the effectiveness of 182 species in removing 25 pollutants has been estimated. From this work, a larger proportion of significant results were observed in chamber studies (88%), comparing to field studies (65%). Additionally, comparable studies revealed greater removal effectiveness of plants in chamber studies. These discrepancies could be attributed to many factors, such as the size and the airtightness of experimental setup, ventilation, gas exposure scheme, and environmental conditions. It is envisaged that these findings will help reduce the gap between chamber studies and field studies, and provide guidance for the future use of plants in buildings to improve indoor air quality.

1 Introduction

For buildings, indoor air quality is very important to occupants' health and productivity, as they generally spend up to 90% of their time indoors [1, 2]. The COVID-19 pandemic has further increased people's concerns pertaining to indoor air quality and its effects on public health [3]. From existing studies, significant correlations between air pollutants and people healthy issues, such as respiratory diseases, lung cancer, poor birth outcomes and premature death, have been well realized [4-6]. According to the Health Effects Institute [7], air pollution is the fourth greatest risk to premature death, and just in 2019 household air pollution has caused about 2.3 million deaths, accounting for 4.1% of the global deaths. Major indoor air pollutants include Volatile Organic Compounds (VOCs), such as formaldehyde and benzene, and Volatile Inorganic Compounds (VICs), such as carbon monoxide and nitrogen dioxide, and Particulate Matters (PMs) [8]. Additionally, Carbon Dioxide (CO_2) is an important indoor indicator for ventilation, high concentrations of which indicates poor indoor air quality [9]. The impact from air pollutants can be both short-term and long-term. For example, depending on exposure time and concentration, carbon monoxide may quickly cause mild symptoms, e.g. nausea and vomiting, or severe symptoms, e.g. respiratory failure, losing consciousness and death [10]. Long-time exposure to indoor pollutants may also cause chronic adverse health outcomes, such as irritation of airways [11], respiratory diseases (i.e. asthma) [12], leukemia [12], pulmonary diseases [11], diabetes [11], myocardial infarction [11], heart diseases [13], cancer [13], and premature death [12].

To improve indoor air quality, people can minimize/control indoor pollutant sources [14], improving ventilation [14], and utilizing purification technologies [15]. It is not possible to completely remove pollutants since they are not only emitted from chemical products, such as cleansers, disinfectants and furniture, but also from building materials and activities of occupants inside buildings [14, 16]. Good ventilation can reduce the prevalence of acute health conditions and adverse health effects, such as Sick Building Syndrome (SBS) symptoms [17], by diluting or removing pollutants. Meanwhile, ventilation may also result in the ingress of outdoor pollutants, which increase the requirement of filtration [18]. Additionally, when outdoor air is hot or cold, it will also increase the energy demand from the ventilation system to cool or heat the fresh air [18].

It is well known that plants have inherent ability in absorbing pollutants [19]. Therefore, they have been used as passive sinks for indoor air pollutants, working as an eco-friendly and cost-effective method for improving indoor air quality [15, 20, 21]. In a study

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carried out by Wolverton et al. [22], it was found that within 24 hours potted plants can reduce the levels of benzene, formaldehyde and trichloroethylene by 10% to 70%. Additionally, according to a study done by Gubb et al. [23], plants can achieve a removal rate for CO_2 at 1703 ppm·m^{-2}·h^{-1}. The study of Jang et al. [24] found plants can reduce 69.6% to 89.8% of $PM_{2.5}$ and 91.7% to 98.5% of PM_{10} after an eight-hour exposure. And the study of Ullah et al. [25] found plants can remove 98% of toluene within 48 hours.

To obtain a thorough understanding on the ability of removing indoor pollutants by plants, this study has carried out a review on existing literature. Generally, the existing studies on the removal effectiveness of potted plants in indoor air pollutants were carried out in either laboratory chambers or real buildings. For example, chamber studies are generally carried out in sealed boxes, mainly made of either glass [26, 27] or acrylic polymer [24, 28], where plants were exposed to high level of pollutants and last from minutes [26] to days [29]. Field studies are generally carried out in real rooms, such as offices [30], class rooms [31], apartments [32] etc., lasting from days [33] to months [34].

The following contents of this paper have 1) summarized the number of tested plant species and pollutants in both chamber studies and field studies, 2) summarized the calculation of removal effectiveness in chamber studies and field studies, 3) compared the identified removal effectiveness in existing studies, by the number of significant results and level of removal effectiveness and analysed potential reasons behind the differences in terms of research methods.

2 Results

2.1 Review method

The literature search was conducted and screened in the process shown in figure 1. To collect articles within the scope of the study, keywords, such as potted plants, ornamental plants, houseplants, indoor plants, indoor air quality, phytoremediation, biofiltration, SBS, VOCs, CO_2, formaldehyde, and benzene, were defined as restrictions for the research. Then the backgrounds, including environmental science, Engineering, Botany and Chemistry, were applied to screen the search results. This review focused on empirical study articles that conducted laboratory or field experiments. Therefore, books, unpublished dissertations, and review articles were excluded. Articles were identified using the Web of Science and Google Scholar. The article collection was performed between 2020 and 2021, resulting in a solid database of 57 research papers published from 1995 to 2021.

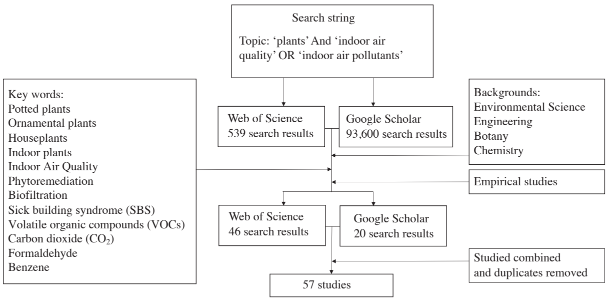

Fig. 1. Illustrated workflow of the screen process

2.2 Summary of reviewed studies

Of the 57 articles, 41 are chamber studies and 16 are field studies. In these studies, 182 plant species were investigated for their ability in removing air pollutants. To avoid misclassification on plant species, plant species were classified according to Angiosperm Phylogeny Group IV classification when scientific names are given in articles, instead of using common names. Figure 2 showed the number of tests for 18 most tested plant species in the review articles. The most frequently discussed plant species was *Epipremnum aureum*, which was tested 35 times, followed by *Ficus elastica* (28 times), *Spathiphyllum spp*. (28 times), *Dracaena deremensis* (18 times), *Chlorophytum comosum* (17 times), and *Asplenium nidus* (16 times). Additionally, as shown in figure 3, 25 pollutants were studied, consisting of VOCs and PMs, of which 64% were VOCs, and 24% were PMs. Benzene was tested the most (63 times), followed by formaldehyde (54 times) and CO_2 (49 times).

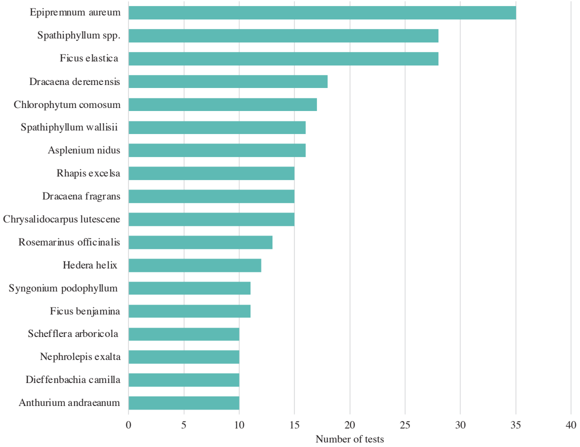

Fig. 2. The number of tests that 18 most tested plant species in review studies

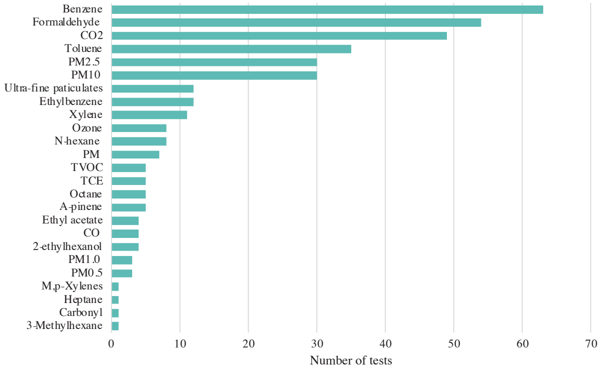

Fig. 3. The number of times that pollutants tested in review studies

2.3 Summary of calculation methods of removal effectiveness

To quantity their effectiveness of removing pollutants, nine evaluation methods have been adopted in previous studies:

- Change of concentrations ($mg \cdot m^{-3}$)

Quantifying temporal change of concentrations is the most popular method, used 35 times in existing chamber [26] and field studies [35]. It is a clear method to define the effectiveness, which describes relationships between the removal ability of plants and exposure time. Depending on durations of experiments, air samplers were set to automatically record the concentrations of pollutants in certain frequency.

- Removal efficiency (%)

The need for statistically accurate comparison enables the adaptation of parameters in defining effectiveness. Removal efficiency is the second most used parameters (20 times), representing the percentage of pollutants removed (per unit exposure time per leaf area) [27].

- Single-pass removal efficiency (%)

Single-pass removal efficiency (SPRE) is the removal efficiency for biofiltration, which shows the percentage of pollutants removed from the air stream passing through the botanical filter with a single direction [36].

- Infiltration factors (%)

Infiltration factors was used by Stapleton and Ruiz-Rudolph [37] for estimating removal efficiency to compare the reduction of ultrafine particulate matters by plants.

- Removal rate ($mg \cdot m^{-3} \cdot h^{-1} \cdot cm^{-2}$)

Despite representing the percentage removed by removal efficiency parameters, it is necessary to know how fast plants can achieve these reductions in pollutant amount. Removal rate was used 11 times, which is the third popular method, while it was hardly applied by field studies possibly due to long experimental period. Removal rate is defined as the amount of pollutant removed per unite exposure time per leaf area [38, 39], which helps to avoid errors caused by different leaf sizes.

- Change of removal rate ($mg \cdot m^{-3} \cdot h^{-1} \cdot cm^{-2}$)

Although the removal rate shows the average removal rate during whole exposure time, plants respond to environmental conditions that change constantly throughout the day [19]. As the exposure time of field studies ranges from minutes to days, the short-term changes of removal rate help to observe the trend of the removal rate during the response.

- Removal rate constant ($L \cdot m^{-2} \cdot h^{-1}$)

When aiming to make the removal rate more comparable with ventilation and scale up to reality, a standardized removal rate constant was introduced by Girman [40]. Hormann et al. [41] applied this parameter in their 48-hour research when found passive absorption is the dominant removal pathway on aerial plant surfaces for toluene and 2-ethylhexanol, as removal rate constant has the same unit as volumetric flow rates does.

- Deposition velocity ($m \cdot h^{-1}$)

Deposition velocity was also used for the removal effectiveness of particulate matters and ozone, showing the rate of the mass passing stopped by plant surfaces [42, 43].

- Accumulated amount ($\mu g \cdot cm^{-2}$)

Accumulated amount was used for calculation of deposited amount of PM by Gawronska and Bakera [32]. This practical method involves several experimental operations while requires less calculation than other methods.

2.4 Chamber studies

The removal ability of 169 plant species of 22 pollutants was studied in reviewed chamber studies. The number of three most tested species in chamber studies are: 1) *Spathiphyllum walliisi* (14 times), 2) *Epipremnum aureum* (12 times), and 3) *Hedera helix* (12 times). For pollutants, benzene (58 times), then formaldehyde (44 times) and CO_2 (38 times) are the most tested pollutants, which is in line with the overall tendency.

The removal effectiveness of plants varies from study to study, which will be further discussed in chapter 3.2. For example, the removal efficiency ranges from 39.96% [44] to 100% [45] for benzene. However, these differences in the results of chamber studies can be influenced by factors related to plants, pollutants, and the environment.

2.4.1 Removal effectiveness influenced by plant related factors

Plant traits have been well evidenced as key influential factors. Oh et al. [26] reported *Spathiphyllum clevelandii*, *Ficus benjamina* and *Chrysalidocarpus lutescens* reduced more CO_2 when the leaf area increased from 3,000 cm^2 to 15,000 cm^2. But the removal rate was limited by the ratio of leaf area to chamber volume. Besides leaf area, stomatal uptake and deposition on cuticle wax are the main pathways of leaf absorption [19, 46]. Crassulacean acid metabolism (CAM) plant led to a linear relationship between removal efficiency and exposure time because of opening stomata in the dark and *Epipremnum aureum* showed appreciably higher removal efficiency because of the higher density of cuticle wax per leaf area [27]. Meanwhile, the topography of the leaf is related to PM capture. For live plants, PM deposited more on midribs and veins rather than on sides, even for artificial plants, those with rough, hairy, and woven-thread leaves captured more PM than those with smooth and flat leaves [42].

2.4.2 Removal effectiveness influenced by external factors

External factors were found to influence plants in removing pollutants, such as light intensity and temperature. As light is indispensable for the photosynthesis process, it is one of the major external sources and factors that affect the removal behaviours of plants. Light has been well-documented to significantly affect the removal effectiveness of plants [15, 19, 46]. Higher light intensity, such as an increase from 15 PPFD (about 453 lux) to 300 PPFD (about 13043 lux), would positively affect the CO_2 absorption by plants [47]. Additionally, the light quality plays a crucial role in ontogenesis of plants, including photosynthesis, biomass accumulation and growth [48]. Setsungnern et al. [49] investigated the influence of light quality (blue LED light, red LED light and white fluorescent light) on the removal effectiveness of *Chlorophytum comosum* on benzene. *C. comosum* demonstrated significantly high removal efficiency (68.77%) under B:R = 1:1 light combination and the removal efficiency decreased when the ratio increased to B:R = 2:1 and 3:1. Additionally, the temperature factor was explored by Sevik et al. [50]. They observed that the pollutant removal efficiency of plant species varied with dry bulb temperature, and suggested both light and temperature should be considered to achieve optimal effectiveness of plants.

2.5 Field studies

The removal ability of 37 plant species of 12 pollutants was studied in reviewed field studies. The three most tested species in field studies are: 1) *Spathiphyllum spp.* (28 times), 2) *Epipremnum aureum* (23 times), and 3) *Ficus elastica* (18 times). However, only 13 species were studied individually in field studies as the field setup combines more than one species during experiments, focusing on quantity rather than species (table 1). Among 12 tested pollutants, CO_2 (16 times), formaldehyde (10 times) and toluene (7 times) are the most tested pollutants.

Table 1. The combination of plant species in field studies

Combinations	Species
Combination 1	*Spathiphyllum sensation, Nephrolepis exalta, Chrysalidocarpus lutescene, Dracaena deremensis*
Combination 2	*Nephrolepis exalta, Chlorophytum comosum, Ficus benjamina, Anthurium andreanum, Yucca filomentosa, Asplenium spp., Dieffenbachia spp., Spathiphyllum spp.*
Combination 3	*Citrus unshiu, Asplenium nidus , Gardenia jasminoides, Spathiphyllum spp., Epipremnum aureum, Rosemarinus officinalis*
Combination 4	*Chrysalidocarpus lutescene,Ficus elastica, Chamaedorea seifrizii Burret, Spathiphyllum spp., Epipremnum aureum, Portulacaria afra, Fatsia japonica, Rosemarinus officinalis*
Combination 5	*Howea forsterana, Rhapis excels, Ficus elastic co. robusta, Dracaera fragrans, Dieffenbachia camilla , Ficus elastica*
Combination 6	*Dracaena deremensis, Dracaena marginata, Spathiphyllum spp.*
Combination 7	*Rhapis excelsa, Ficus robusta, Chrysalidocarpus lutescene, Nandina domestica, Asplenium nidus, Spathiphyuuum spp., Epipremnum aureum, Ardisia pusilla*
Combination 8	*Ficus elastic, Ficus benghalensis, Rhapis excelsa, Fragrant Aralia, Schefflera arboricola Hayata*
Combination 9	*Asplenium nidus, Citrus unshiu, Gardenia jasminoides, Epipremnum aureum, Rosemarinus officinalis*
Combination 10	*Chamaeadorea elegances, Zamioculcas spp., Spathiphyllum spp., Epipremnum aureum, Dieffenbachia camilla, Rhapis Excelsa*

The results from field studies showed both significant and insignificant removal effectiveness of plants. For example, Kim et al. [34] showed a significant reduction in concentrations of formaldehyde in a six-month period of placing 12 potted plants indoors. Gawronska and Bakera [32] investigated the accumulation of PM on *Chlorophytum comosum* and found plant leaves captured significantly more amount of PM than aluminium plates regardless of the size fractions of PM in all five different rooms. However, the study of Jung and Awad [35] showed insignificant results: CO_2 concentrations increased less in the case where 48 pots of indoor plants were placed (average 668 ppm) compared with the case where indoor plants were not placed (average 1205 ppm), but the difference is statistically insignificant (p-value=0.1).

Common field study locations are the offices and schools. Potential influential factors for pollutant removal efficiency were investigated in field studies as well. An early study by Dingle et al. [51] conducted field studies in 38 offices and found there was no reduction in formaldehyde until the density of plants reached 2.44/ m^2 when an 11% reduction was observed. Regarding this, there need to be 48.8 plants in a normal 20 m^2 office, which is not feasible in a real indoor environment. Han [33] also found that when the green coverage ratio was 31.5% (8 pots of plants in a 12 m^2 room), levels of $PM_{2.5}$ and PM_{10} were significantly lower than those in the room without plants, regardless of the presence or absence of occupants. Wood et al. [30] investigated VOC removal by plants in 60 offices, however, found there were no significant differences between the effect of locating 3 and 6 pots of plants, while found plants can effectively reduce up to 75% of TVOC from 280 ± 120 ppb to 65 ± 10 in non-air-conditioned rooms. The influence of ventilation on removal effectiveness was highlighted by Kim et al. [52]: ventilation can be more effective in maintaining indoor air quality in newly built offices with high indoor air pollutant concentration levels, while plants were more effective in formaldehyde removal in older offices. Lin [53] also investigated the influence of different layouts of 17 pots of *Asplenium nidus* on CO_2 removal and found that the layout of hanging plants on two sides of the wall reduced more CO_2 (180 ppm) than the layout of concentration in one location (104 ppm).

3 Comparison between chamber and field studies

3.1 Plant species and pollutants

Figure 4 compared the number of tests for the 11 most tested species between chamber and field studies. Chamber studies tested a greater number of plant species than field studies, but the number of tests for most tested plant species in field studies (28 times) is larger than that in chamber studies (14 times). Besides, species from the genus of *Spathiphyllum*, *Epipremnum aureum, Ficus elastica, Dracaena deremensis,* and *Chlorophytum comosum* are tested in both chamber studies and field studies.

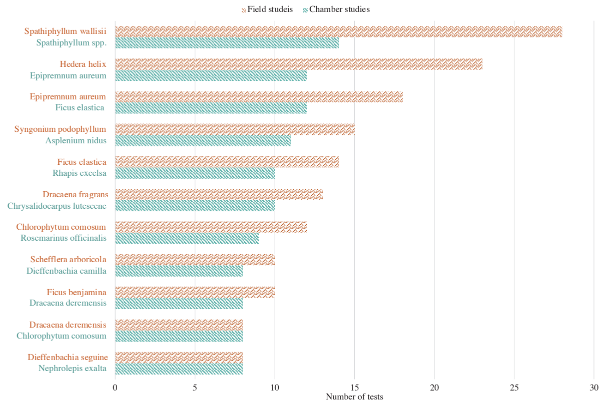

Fig. 4. The comparison of the number of tests for the 11 most test plant species between chamber studies and field studies

Figure 5 displayed the number of tests for pollutants in chamber studies and field studies, respectively. Chamber studies tested more types of pollutants than field studies, and the majority of pollutants tested are VOCs. Instead of focusing on VOCs, field studies tested CO_2 the most.

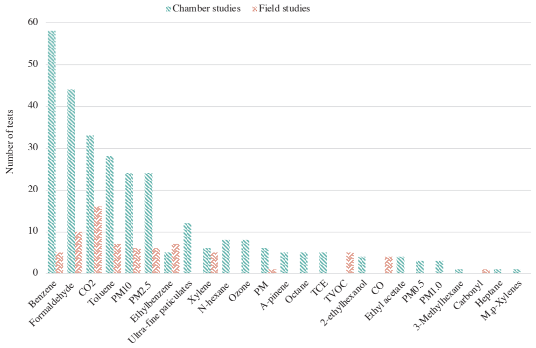

Fig. 5. The comparison of the number of tests for pollutants between chamber studies and field studies

3.2 Significance of removal effectiveness

As one study can conduct multiple substudies, the classification of significance depends on the substudies. There are 746 substudies and 114 substudies in chamber and field studies, respectively. Regarding different experimental conditions between chamber studies and field studies, several criteria were set to screen the chamber substudies available to compare with field substudies. They should:

- Show statistical significance with p-value, either confirmed removal effectiveness data that showed statistical significance,
- Conduct under common field thermal environmental conditions (e.g. temperature lower than 30 °C),
- Conduct under common field light conditions (e.g. substudies with the whole experimental process in dark will be removed),
- Not test plants with uncommonly used growing media in field studies (e.g. hydroculture),
- Not test plants in special development stages (e.g. epigeous period).

After the screening, figure 6 displayed the number of significant and insignificant results in available substudies from chamber and field studies, showing there is a larger number of significant substudy results in chamber studies than that in field studies. The classification 'significant' means the results of experiments showed a statistically significant reduction of pollutant concentrations; 'insignificant' means the results of experiments showed a statistically insignificant reduction of pollutant concentrations. Among 274 available chamber substudies, 240 (88%) showed statistically significant removal effectiveness, while 34 (12%) showed insignificant results. Among 105 available field substudies, 68 (65%) showed statistically significant removal effectiveness, while 37 studies (35%) had insignificant results.

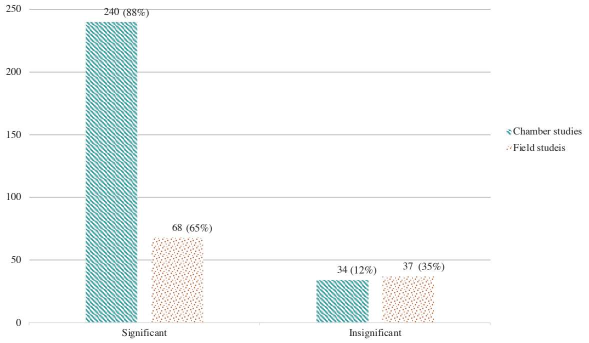

Fig. 6. The number of results showed significant and insignificant reduction of pollutants in available substudies from chamber and field studies

Besides, plants showed better removal effectiveness in chamber studies than in field studies. Table 2 summarized the removal effectiveness of plants in common indoor air pollutants, ranging from minor to superior. The removal effectiveness of plants in chamber studies is generally better than that in field studies. For instance, the removal of formaldehyde by

Chlorophytum comosum was studied in both chamber studies and field studies. The results from chamber studies showed *C. comosum* absorbed 90% of formaldehyde after 1 hour and 100% after 72 hours [45], revealing the high removal ability of *C. comosum*. However, in field studies, *C. comosum* uptook approximately 50% of formaldehyde after 90 days. Another example is the removal of CO_2 by *Epipremnum aureum*. A 13% reduction was found after 27 days in the field study [54], while a 6.5% reduction in CO_2 concentrations was found after only 8 hours in chamber studies [55]. The results of chamber studies represented the same species with great abilities in removing pollutants within hours, while results of field studies showed a gradual reduction of pollutants in a long term, even though it was significant but less promising. Therefore, it is crucial to compare the discrepancies in methodology.

Table 2. Summary of plant removal effectiveness for common pollutants in chamber studies

Pollutants	Removal effectiveness (Removal efficiency %)	
	Chamber studies	Field studies
Benzene	38.66% to 100.00%	15.00% to 75.50%
CO_2	20.8% to 92.40 %	-33.8% to 52.33%
Formaldehyde	65.63% to 100.00%	33.06% to 64.60%
Toluene	70.00% to 100.00%	48.16% to 79.55%

Table 3 compared the methodologies in chamber and field studies. In chamber studies, glass chambers are more airtight than testing rooms. The known materials and texture of the chambers offer the possibility of measuring or calculating leakage and deposition in chamber studies [56]. Because of this, the gas exposure scheme can be controllable [57]. But due to uncontrolled ventilation or usage of rooms in real life, it is not possible to fully control air exchange, pollutant concentrations, and deposition of pollutants in field studies, which could potentially influence the effect of plants as ventilation could affect indoor air quality [18]. Additionally, the exposure duration in chamber studies ranges from 40 mins to 8 days, while the exposure duration in field studies mostly ranges from weeks to months, during which environmental factors changed. As it has been evidenced in chamber studies that some environmental factors, such as temperature and light, can significantly affect the removal effectiveness of plants, it is necessary to compare the final pollutant concentrations with not only initial concentrations but also the results of control experiments. For instance, Kim et al. [58] found there were no distinct differences in PM levels between a household with and without plants. Therefore, the long exposure duration in field study could potentially affect the removal effectiveness and the change of environmental factors should be considered in the methodology. Moreover, the green coverage ratio has been evidenced to significantly influence plant removal effectiveness in both chamber and field studies [26, 33, 51]. Because of the smaller chamber size, the green coverage ratio is higher than in field studies even if placing only one pot plant in the chamber, while it is infeasible to reach an excessively high green ratio in real-life settings.

Table 3. The comparison between methodologies of chamber studies and field studies.

Methodologies	Chamber studies	Field studies
Chamber/Room size	Small (10.5 L to 29.25 m^3)	Large (Volume: 30 m^3 to 240 m^3, area: 14 m^2 to more than 130 m^2)
Duration of experiments	Short (40 mins to 8 days)	Long (19 hours to 16 months)
Airtightness	Airtight or calculatable leakage	Natural ventilated or unventilated, air conditioned or air unconditioned
Initial concentrations	High (e.g. VOCs: 350 $\mu g \cdot m^{-3}$ to 1,620,000 $\mu g \cdot m^{-3}$, CO_2: 410 ppm to 3310 ppm)	Low (e.g. VOCs: 1.09 $\mu g \cdot m^{-3}$ to 518 $\mu g \cdot m^{-3}$, CO_2: 371.13 ppm to 2004 ppm)
Sources of pollutants	One-off injection or discrete injection	Natural sources and occupants
Light and temperature	Controllable	Uncontrollable

4 Conclusion

This paper reviewed the effectiveness of potted plants in improving indoor air quality in both chamber and field studies. Potted plants have been shown in chamber studies to have a great ability in removing indoor air pollutants. The internal factors of plants, such as leaf area and cuticle wax, and external factors, such as light and temperature, can significantly influence the removal effectiveness. In field studies, plants showed less significant ability than chamber studies in removing indoor pollutants. The layout of plant placement and the number of plants were investigated and concluded to be potential influence factors on removal effectiveness. The reasons behind this discrepancy between the results of chamber studies and field studies could be addressed to different airtightness, exposure durations, and green coverage ratios. Airtightness determines the air exchange between the inside and outside of chambers/rooms, which is related to the gas exposure scheme and the leakage of pollutants. Long exposure duration in chamber study leads to the inevitable change of environmental factors, which could affect research outcomes. A high green coverage ratio is hard to achieve in real life, which could influence the layout of plants as well. In the future, these findings could help the design of field studies to adapt more comprehensive methodologies and provide useful guidance for using plants in buildings.

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