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Evaluation of the effectiveness of common indoor plants in improving the indoor air quality of studio apartments

Shambhavi Sharma
Korea Railroad Research Institute KRRI
Ahtesham Bakht
Kumoh National Institute of Technology
Muhammad Jahanzaib
Korea Railroad Research Institute KRRI
Hyunsoo Lee
Kumoh National Institute of Technology
Duckshin Park (dspark@krri.re.kr)
Korea Railroad Research Institute KRRI

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Abstract

People spend most of their time indoors, and prolonged exposure to pollution can harm their health. The degradation of indoor air quality (IAQ) has raised serious issues. Botanical biofilters are an exciting solution for lowering indoor air pollution. However, plants cultivated inside under low light intensity (10–50 µ mole PAR m^{-2} s^{-1}) generate CO_2 in the indoor atmosphere. Combining C3 and CAM plants may be able to address this problem by lowering CO_2 emission levels and enhancing the efficiency of pollution removal by removing the primary indoor air pollutants from actual interior settings, including Carbon dioxide (CO_2), formaldehyde (HCHO), particulate matter ($PM_{2.5}$ and PM_{10}), and total volatile organic compounds (TVOCs). As a result, a successful botanical biofilter made of several plants was researched. Indoor plants can phytoremediate a variety of indoor contaminants. However, just a few studies have demonstrated its efficacy in practical contexts. Due to the harsh winter, apartments in South Korea are frequently closed, necessitating the measurement of interior air pollution concentration in real time. Four apartments (APT I through APT IV) with various ventilation and indoor plant setups were selected for this investigation. Various combinations of indoor environment (ventilation, low light) and a combination of C3 and CAM indoor plants as a botanical biofilter were used to study the sites over two months. Current research indicates that combining a botanical biofilter with ventilation can reduce levels of CO_2, TVOCs, HCHO, $PM_{2.5}$, and PM_{10} by 76%, 87%, 75%, 52%, and 51%, respectively. The current study concluded that different indoor potted plants provide an effective, affordable, self-regulating, sustainable option for enhancing indoor air quality and, consequently, human well-being and productivity in small, cramped places.

Introduction

Long-term research has been done on the harmful effects of exposure to outdoor air pollution. Numerous studies have connected various health effects to both short-term and long-term exposure to particulate matter (PM) with a diameter of less than 10 µm (PM_{10}) and particulate matter with a diameter of less than 2.5 µm ($PM_{2.5}$), VOCs, and formaldehyde(Brook et al. 2010; Crouse et al. 2015; Hoek et al. 2013; Jahanzaib, B. Irshad, D. Park 2022; Shuai et al. 2018; Zhang et al. 2020). A lesser amount of research has been done on exposure to indoor air pollution. Personal exposure depends on various factors, including behaviors that could increase the concentrations of the pollutants of concern, the amount of time spent in the environment, and the methods used to remove the pollutants. Since most people spend roughly 90% of their time indoors and at home, interior spaces are expected to be the source of the greatest exposure (Brasche and Bischof 2005; Schweizer et al. 2007). The bulk of indoor contaminants originates from outdoor air, which generally has an impact on the quality of indoor air. Infiltrations from the outdoors, emissions from interior-specific sources, and particle production from indoor chemistry are the dynamics causing elevated indoor air pollution levels(Chen and Zhao 2011; Vardoulakis et al. 2020). However, several indoor sources and occupant activities include furniture, paints, varnishes, waxes, carpets, solvents, cleaning supplies, office equipment including copiers and printers, gas cooktops, and cigarettes that generate potentially harmful gases and particular matter (PM) (Maisey et al. 2013). Carbon monoxide and dioxide (CO and CO_2), volatile organic compounds (VOCs; for example, formaldehyde and benzene), nitrogen oxides (NO and NO_2), and polycyclic aromatic hydrocarbons (PAHs) are among the air pollutants that are commonly found in various indoor situations (Geiss et al. 2011). Given that individuals in developed nations spend more than 80% of their time indoors, one of the top issues for human health today is the build-up of air pollutant concentrations to dangerous levels, particularly in new energy-efficient yet airtight homes(Bruce et al. 2002). The primary sources of interior PM pollution include tenant activities like cooking, lighting candles, incense, and almost any external PM pollution that enters the building through the ventilation systems. Burning incense during religious ceremonies, yoga, and meditation may have a tremendous impact on the indoor atmosphere because it has been a regular practice for decades. According to research, eco-friendly incense releases more polycyclic aromatic hydrocarbons and fine particulate matter ($PM_{2.5}$) than conventional incense(Lui et al. 2016). This increases the risk of cardiovascular diseases and seriously impacts the human lungs(Pan et al. 2015).

To maintain superior Indoor Environment Quality (IEQ), which primarily focuses on occupant thermal comfort, buildings are frequently outfitted with Air Conditioning and Mechanical Ventilation System (ACMV) systems. Modern technology has significantly improved the air filtration component of air conditioning (AC) systems, making it more effective in improving indoor air quality (IAQ) and offering optimum thermal comfort to building occupants. However, the high energy consumption of AC systems unintentionally increases greenhouse gas emissions that could impact global warming. The fresh air entering residential buildings is typically insufficient because they only have split air conditioners and no mechanical ventilation systems(Daghigh 2015).

As in other cold nations, Korea experiences severe wintertime cold and snowfall. To keep indoor air clean and conserve energy for air conditioning, it is typical for residents to seal window and door openings. The sealing of windows and doors would result in the accumulation of indoor pollutants, air stagnation, and a decline in IAQ. To increase IAQ and supply fresh air inside of buildings, air purifiers are typically employed, along with the operation of ACs, to improve IEQ. Although air purifiers' initial performance appears compelling, (F. R. Torpy et al. 2014) reported that with time, dust particles could build up and clog air filters, decreasing the air purifier's single-pass efficiency (SPEs)(Zuraimi et al. 2017).

Removing VOCs and converting these harmful substances into a carbon source for plant and microbial growth are both highly prospective outcomes of phytoremediation(Kvesitadze et al. 2009; Liu et al. 2007; B. C. Wolverton et al. 1984; B. Wolverton and Wolverton 1993). It has been shown that several plant species have a high clearance rate for contaminants like formaldehyde and benzene. Active Botanical biofilters (ABB) systems effectively filter indoor air pollutants and have been identified as a way to improve IAQ in buildings(Moya et al. 2019).

The Ministry of Environment (MOE) passed the Indoor Air Quality Management Law in Multi-use Facilities in May 2004 to fully handle the IAQ issue. Before occupancy, IAQ data in residences must be measured and made available to the public. The MOE released updated housing guidelines for indoor air quality (IAQ) in December 2005. Additionally, contractors who build or remodel apartment buildings with more than 100 units must install ventilation systems with an air ventilation performance (air exchange rate) of over 0.7 times per hour, according to an update to the Ministry of Construction and Transportation's Regulations on the Facility Standards of Buildings. Despite this development, a Korean Consumer Agency investigation found that 14.5% of survey respondents had sick-house syndrome (Maisey et al. 2013) and lawsuits against building companies have continued to be based on poor indoor air quality. Additional fundamental investigations are required to comprehend better the development of IAQ improvement to combat indoor air pollution, and botanical biofilters have gained popularity (Darlington et al. 2001; Feng and Hewage 2014). Between phyto and bio-degradation, active airflow through the plant layer and growth media layer with microorganisms can increase the effectiveness of removing BTEX (Wang et al. 2014). Rhizospheric bacteria can increase pollutant removal effectiveness in addition to plants(Fr Torpy et al. 2017). Additionally, some contaminants can be absorbed by the chemical and physical characteristics of the plant development media(Soreanu et al. 2013). Therefore, using active botanical biofilters instead of standard passive potted plants delivers a better removal efficiency(Darlington et al. 2001).

Even while botanical biofilters may effectively remove indoor air pollution, plants can often create a high concentration of carbon dioxide (CO_2) during plant respiration, especially when inadequate light conditions are present (indoor settings) (F. R. Torpy et al. 2014). According to Satish et al. (Satish et al. 2012), considerable symptoms are produced by CO_2 at 4.5–9 g m^{-3} and several human symptoms and diseases are caused by high CO_2 concentrations over 1.08 g m^{-3} (Satish et al. 2012). The normal CO_2 guideline, according to ASHRAE (2011), shouldn't be more than 1.8 g m^{-3}. Therefore, it is crucial to consider the CO_2 generated by plants in low light situations before utilizing a botanical biofilter. Numerous studies have shown that plants can effectively absorb CO_2 when they receive adequate light, but they cannot do so when they do not receive enough light. (Satish et al. 2012). A combination of C3 and CAM plants in an efficient botanical biofilter can be a different approach to the issue of CO_2 production by botanical biofilters under poor light support or indoor settings.

According to botany principles, CAM plants generally absorb CO_2 at night, while C3 plants can leak CO_2 into the atmosphere.

Our study intends to examine the impacts of CAM and C3 plants, which are frequently implemented to reduce indoor air pollution in real-life scenarios. The objective was to investigate the concentration of significant indoor pollutants throughout the winter when interior household activities are typically conducted with windows closed due to the cold outside, including CO_2, $PM_{2.5}$, PM_{10}, TVOC, and HCHO. The effectiveness of the combination of these plants in lowering indoor air pollution was also monitored.

Material And Methods

2.1 Study location

Uiwang is a city in Gyeonggi Province, South Korea (see Fig S1). It lies just South of Seoul. Uiwang has an area of approximately 53.46 km^2 and a total population of 158482. The study was carried out in a typical Uiwang studio apartment home, which was a one-room, 10-pyeong-squared apartment with a kitchen slab and bathroom slab shared in the same living space (View Fig. 01). To conduct this study, four apartments (I-IV) were considered: APT I (without ventilation and interior plants), APT II (without ventilation, with indoor plants), APT III (with ventilation, without indoor plants), and APT IV (with ventilation and indoor plants). Additionally, an ambient air sample site (outdoor) was chosen to track changes in the external environment. All the selected units were single-occupancy, and each had a window. People were instructed to keep a record detailing all indoor activities and the times they opened windows.

Table 1
Detailed information about the apartments.

Experimental sites	Area, Door, Window No. of occupants	Ventilation	Indoor Plant
Apartment I (APT I)	10-Pyeong, 1, 1, 1	With Ventilation	With Indoor Plants.
Apartment II (APT II)	10-Pyeong, 1, 1, 1	Without Ventilation	With Indoor Plants (only CAM plants).
Apartment III (APT III)	10-Pyeong, 1, 1, 1	With Ventilation	Without Indoor Plants.
Apartment IV (APT IV)	10-Pyeong, 1, 1, 1	Without Ventilation	Without Indoor Plants

2.2 Plant Preparation

Sansevieria kirkii, Sansevieria trifasciata, Monstera deliciosa, Zamiifolia, and *Portulacaria afra*, five commonly used ornamental plants with comparable leaf area, size, and form (**see Table 02**), were bought from plant stores in South Korea. These plant species are frequently grown indoors. Plants having a total leaf area of 500 cm^2 that were pest-free were retrieved from the apartments to gauge how effectively they removed the indoor air pollutants. The plant development medium consisted of a potting mixture with a moisture content of 1.1 to 1.4%, a water retention capacity of 9.1 to 10.2 cm m^{-1}, and a composition of 58% sand, 28% silt, and 14% clay. Typically, this substance is used to grow decorative plants. The porosity of the potting material was in the range of 36-38%. All plants were cultivated in their native environments at 30-32 °C and 12/12 h day/night before the experiment.

Table 2. Details about selected Plant species

Plant	Family	Common name	Plant type
Sansevieria kirkii	Asparagaceae	Snake Plant	CAM carbon fixation.
Sansevieria trifasciata	Asparagaceae	Snake Plant	CAM carbon fixation.
Monstera deliciosa	Araceae	Swiss Cheese Plant	C3 carbon fixation.
Zamiifolia	Araceae	ZZ-plant	C3 carbon fixation
Portulacaria afra	Didiereaceae	Jade plant	C3 or CAM carbon fixation

2.3 Indoor Air Pollutants measurements

From December 2021 to January 2022, the units' indoor air quality (IAQ) was inspected. Each team was monitored for 24 hours spread over a regular two-week period. Table 01. describes the characteristics of each flat. The plants were positioned to prevent any obstructions to mobility. Since it was winter in Korea, the tenants kept the window closed. As their actions also contribute to the pollution, the residents were instructed to list all indoor activities in a notepad, such as sweeping, cooking, lighting candles, and smoking. All the indoor air pollutants were measured using the AirScan device from Sensoronic [See Fig 2]. Formaldehyde (HCHO), total volatile organic compounds (TVOC), carbon dioxide (ppm), PM_{10}, and $PM_{2.5}$ were all measured in real-time, along with temperature (°C) and relative humidity (%). The system was configured to record values every five minutes. Weekly readings were recorded. Before the experiment, TVOCs, CO_2, PM_{10}, HCHO, and $PM_{2.5}$ levels were pre-tested and measured to determine the levels and variability of these pollutants. Outdoor PM_{10} and $PM_{2.5}$ concentrations were also measured using the same device.

2.4 Data analysis

MATLAB 2021a was used to process and analyze the real-time mass concentrations of the indoor pollutants that were measured using the Sensoronic AirScan device [See Fig. 2]. The mean and standard deviation were calculated using a descriptive statistical method. For samples with more than two sample groups, the mean of each treatment was compared using a one-way analysis of variance (ANOVA) at a 95% level of confidence, and for samples with two sample groups, an independent t-test with (n_1+n_2)-2 and α a= 0.025 (two tails). Tukey's multiple comparison test with a 95% confidence level was used to classify groups after the one-way ANOVA. Data visualization and interpretation were made using MATLAB 2021a.

2.4 Calculation of Air Exchange Rate (AER), Deposition and emission rate

Using the CO_2 release mechanism and its decay rate as reported in (Claude-Alain and Foradini 2002) determined the sampling duration's air exchange rate (AER). The apartment was equipped with an Extech SD800 Datalogger, and the AirScan was used to gauge the CO_2 levels within. By releasing lab-grade CO_2 from a gas cylinder, the CO_2 levels were raised to between 5000 and 7000 ppm, making small fluctuations in the background levels inconsequential. The impact of the background CO_2 levels was minimized as a result. The location of the CO_2 monitor was changed in order to provide a clearer image of the average AERs. The mass balance equation was employed in this investigation to determine the indoor $PM_{2.5}$ emission rates, which is consistent with prior studies (Guo et al. 2008; C. He et al. 2005; L. Y. He et al. 2004). Numerous presumptions were made to simplify the mass balance equation. The penetration efficiency (P) was first considered to be one. The P, however, is a function of particle size and is less than one due to gravitational settling, especially for high particle diameters, which is crucial to mention (e.g., Ref. (Chen and Zhao 2011)) Outdoor sources were regarded as negligible since indoor concentrations during the activities were significantly more significant than

background levels. Using average values and the extra supposition of a well-mixed environment, the average emission rates were calculated from Equations (1) and (2) as follows:

$$\frac{dC_in}{dt} = PaCout + \frac{Q_s}{v} - (a+k)\,C_in \quad \text{(i)}$$

$$\overline{Q_s} = V * \left[\frac{C_in - C_in0}{\Delta_t}\right] + \overline{(a+k)\ c_i}n - aC_{in_0} \qquad \text{(ii)}$$

Where t is the difference in time between the initial and peak concentrations, is the AER, is the deposition rate, and C_{in} is the average indoor concentration. Qs is the average indoor particle emission rate, V is the room volume, and C_{in} and C_{in0} are the peak and initial indoor concentrations, respectively. The word (α + κ) denotes the average removal rate. As a result, dynamic aerosol processes that affect particle generation and removals, such as condensation, evaporation, and coagulation, are not considered. (Ref. (L. Y. He et al. 2004)) provides more information on the estimation of particle emission rates.

According to (Vicente et al. 2021) which assumes that the outdoor effect is minimal, the decay of interior particles after the source has stopped is characterized as follows:

$$\frac{dCin}{dt} = -(a+k)\,Cin \quad \text{(iii)}$$

Equation (iii) can be integrated to yield the following linear equation:

$$ln\frac{C_{in}t}{C_{in0}} = -(a+k)t \quad \text{(iv)}$$

Where the slope of the graph of ln ($\frac{Cint}{Cino}$) vs *t* is equal to (*a*+ *κ*).

Result

3.1 Indoor and Outdoor $PM_{2.5}$ and PM_{10} concentration

According to our findings, there are substantial differences in the component concentrations for each apartment (see Table 1), with apartment 4 having the lowest pollutant level due to ventilation and specially chosen indoor plants. The lowest and highest average indoor $PM_{2.5}$ levels were recorded for APTI and APTIV, respectively. The PM_{10} content of APTI was found to vary from 6 to 68 µg m^{-3}, with an average value of 19.4 µg m^{-3}, whereas APTIV had a range of 4 to 679 µg m^{-3}, with the highest average value being 58.81 µg m^{-3}. These standards cover typical indoor activities, including frying, cleaning, lighting candles, etc. PM_{10} and $PM_{2.5}$ are both present, with $PM_{2.5}$ having a range of 4-42 µg m^{-3} and an average of 12.64 µg $m^{-3}$for APTI and APTIV, respectively, and a range of 3-49 µg $m^{-3}$and 35.72 µg m^{-3}. For each apartment, the interior PM_{10} and $PM_{2.5}$ readings exhibit greater variation than the outdoor concentrations (see Table S1). The study's indoor PM concentrations are within the range of those noted in the literature. According to earlier research (Chen and Zhao 2011; Guo et al. 2008; C. He et al. 2005; L. Y. He et al. 2004; Vicente et al. 2021), indoor $PM_{2.5}$ levels can reach 9.5µg m^{-3} and 34.6 µg m^{-3} and indoor PM_{10} levels can reach 23.0µg m^{-3}, 18.3µg m^{-3}, and 47.2µg m^{-3}, respectively (Amouei Torkmahalleh et al. 2021; Aquilina and Camilleri 2022). There is a difference between interior and outdoor PM concentration for each apartment, with the apartment with ventilation and inside plants having the lowest concentration (see Fig 03).

The results also made it abundantly clear that apartments with indoor plants and ventilation can significantly lower $PM_{2.5}$, up to 64.61%, as opposed to apartments with only CAM plants, which only show a reduction of 52.09%. These apartments

also have higher reduction efficiencies than apartments without indoor plants and ventilation (see Table 03) (p-value< 0.0001). The outcomes demonstrated plants' capacity to adsorb or absorb $PM_{2.5}$. Prior research has suggested that plants can lower the amount of $PM_{2.5}$ in the air (Gawrońska and Bakera 2015; Mo et al. 2015).

3.2 Indoor TVOC, HCHO, and CO_2 concentration

Total Volatile Organic Compounds (TVOC) concentration

Fig. 04 shows the total volatile organic compound (TVOC) rates throughout the complete two-month study. Fig.04 plot shows the variation in average TVOC concentration over time for several sets of circumstances, APTI, APTIV, APT II, and APT III (refer to table 1). Indoor average TVOC concentrations without indoor plants and ventilation can reach 800.41 µg m^{-3}, but they were found to be 56.35 µg m^{-3} and 190.93 µg m^{-3} in APTI and APT II, respectively (see Table S1). In the indoor testing settings, a general decreasing pattern for average TVOC concentration was seen with the indoor plant (p-value < 0.0001). (APTI–APTIV). The following increase in average TVOC concentration can be noticed for APT II compared to APT I. We also discovered a decrease in TVOC level, with APT I having the lowest average TVOC level compared to APT II when both C3 Cycle and CAM plants were combined. (see Fig 04).

Sansevieria species and other commonly used indoor plant species have been shown in prior research to be able to remove a variety of VOCs (Bhargava et al. 2021; Lee et al. 2021; Permana et al. 2022; Zhao et al. 2019). Still, we discovered that the apartment with both C3 and CAM plants, or APT I, had a substantially greater TVOC removal effectiveness than APT II, which only had CAM plants. When comparing the removal efficiency of TVOCs for APT I and APT III, respectively, and using Apartment IV as the control apartment, devoid of any indoor plants and ventilation, as a standard for comparison (see Table 04). The removal of indoor air pollutants such as formaldehyde, acetone, benzene, and xylene by CAM plants and C3 plants has also been reported in earlier research (Khaksar et al. 2016; Kim et al. 2010; Setsungnern et al. 2017; Siswanto et al. 2020; Treesubsuntorn and Thiravetyan 2018). However, in this case, we found the average concentration of TVOCs.

Formaldehyde (HCHO) concentration

The average formaldehyde (HCHO) rates for the whole two-month study are depicted in Fig.05. The variation in average HCHO concentration over time is depicted in the Fig.05 plot for several different sets of conditions, such as APTI, APTIV, APT II, and APT III (refer to table 1). Average indoor HCHO concentrations are higher in apartments lacking indoor plants and ventilation than in apartments with these features. For example, APTI has a value of 6.023 µg m^{-3}, APT II has a value of 5.98 µg m^{-3}, while APT III and APTIV were found to have values of 34.67 µg m^{-3} and 23.99 µg m^{-3} (see Table S1). A general decreasing pattern for average HCHO concentration was seen with the indoor plant in the indoor testing circumstances (p-value < 0.0001). (APTI–APTIV). Because the plants used in APT II have already demonstrated their ability to reduce the HCHO content, similar average formaldehyde concentrations can be found for both I and APT II. (Khaksar et al. 2016; Kim et al. 2010; Setsungnern et al. 2017; Siswanto et al. 2020; Treesubsuntorn and Thiravetyan 2018). (see Fig. 05) The reduction rates for APT I and APT II are identical, at 75% and 74%, respectively. Although the average HCHO level for each apartment was found to be within the ASHRAE-recommended range, there is a noticeable difference in the concentration of HCHO for the units with plants. (see Table 3)

Carbon dioxide (CO_2) concentration

Fig. 06 plot illustrates the variation in average CO_2 concentration over time for a variety of various combinations of settings, APTI, APTIV, APT II, and APT III (refer to table 1). Similar to other contaminants, it has been found that indoor average CO_2 concentrations are higher in apartments without indoor plants and ventilation than in those that do. Previous studies have also shown few Indoor plants reducing CO_2 concentration. (Aquilina and Camilleri 2022; Bhargava et al.

2021). The average CO_2 emissions from plants at night are a significant issue when considering phytoremediation in indoor areas. Combining CAM and C3 plants can dramatically lower the system's CO_2 emissions (Treesubsuntorn and Thiravetyan 2018). APT III with simply a CAM plant and APT I with combined CAM and C3 plants appeared to maintain low CO_2 concentrations in the apartment, while apartments without indoor plants and ventilation released higher CO_2 (p-value<0.0001) (see Fig. 6). Table 03 shows the reduction rate for each apartment, with APT I having the lowest average CO_2 concentrations of 615.5ppm whereas APTIV has the highest average CO_2 concentration of 2616.36ppm (see Table S1). In CAM plants like S. trifasciata, moderate light intensity appeared to cause stomata to open, enhancing CO_2 uptake. The C3 plant may produce CO_2 simultaneously due to the moderate light intensity (Treesubsuntorn and Thiravetyan 2018). Therefore, it's possible that the atmosphere in APT I experienced CO_2 emission and absorption when CAM and C3 Plants were mixed.

Discussion

Interior plants will increasingly be used in indoor areas as people's awareness of sustainability grows. A solution for treating indoor air that has the potential to be both efficient and sustainable is phytoremediation. However, the quantity of plants utilized as well as their mix affect how well they may reduce indoor air pollution. Total Volatile organic compounds (TVOCs), particulate matter, and oxidants and irritants are some of the several elements that make up indoor pollution (PM). People dwell indoors for up to 90% of the time in every country on earth. The interior air quality is therefore crucial to limiting human exposure to pollutants. The ability to lower indoor air pollutants was demonstrated by potted plants. According to our knowledge, this study is the first to perform real-time monitoring of indoor and outdoor PM and different indoor air pollutants concentration (TVOC, HCHO, and CO_2) in a typical Korean apartment throughout the winter. We emphasize the distinct indoor and outdoor sources by differentiating between different diurnal patterns for indoor and outdoor PM levels. The main contributors to indoor formaldehyde, TVOC, and PM pollution are cigarette use, building materials, and furniture. Furthermore, there is no association between interior and outdoor PM concentrations, particularly for $PM_{2.5}$. The effectiveness of commonly used indoor ornamental plants and ventilation in eliminating the primary indoor air contaminants is also discovered. Current research has shown that C3 and CAM plants work well together to reduce $PM_{2.5}$, PM_{10}, HCHO, TVOCs, and CO_2 to greater extents, up to 64%, 67%, 75%, 93%, and 76%, respectively (Table 3).

Active botanical biofilters are a recent innovation that has gained popularity for reducing indoor air pollution(Darlington et al. 2001; Feng and Hewage 2014). This approach involves passing tainted air through a layer of plants and growth material harboring advantageous bacteria(Sandhu et al. 2007). Therefore, this technique could be able to control the CO_2 content in indoor environments and lower the quantity of plants(Fraser Torpy et al. 2018). According to the principles of the botanical biofilter, microorganisms growing on plant growth material can be crucial in the removal of pollutants in a botanical biofilter(Wang et al. 2014), since some pollutants can be adsorbed on the planting material (Soreanu et al. 2013). In contrast to this, very few research have focused on lowering indoor air pollution in actual settings (Ghate 2021; Han et al. 2022; Jung and Awad 2021). More research and field tests are required to fully understand the capability of absorption by house plants in practical situations. The potential of a mixture of typical CAM and C3 house plants to absorb indoor air pollutants is explained in this study. The results demonstrate that the average concentration of all indoor air pollutants caused by diverse daily indoor activities was significantly greater in the APT IV (without ventilation and plants) than in the APT I (with ventilation and plants). Even with ventilation and without plants (APT III), there was a significant variation in the levels of several pollutants, demonstrating that ventilation cannot completely reduce pollution. The average value of several pollutants inside APT II is still greater than that of APT I, which also implies that the combination of both CAM and C3 plants may reach the highest removal effectiveness.

Conclusion

A solution for treating indoor air that has the potential to be both efficient and sustainable is phytoremediation. However, using plants to remove interior pollutants instantly still presents difficulties. Furthermore, having many plants especially C3 plants in a room with air conditioning might also be problematic because they release CO_2 into the atmosphere at night. Mixed plants (CAM and C3) exhibited high pollution removal efficiency with low CO_2 output than single plant species. In this study, we created a system that showed real-time indoor air phytoremediation in a typical Korean apartment during the winter, with little CO_2 emissions despite activities like cooking, cleaning, lighting candles, etc. Condensation, evaporation, and coagulation, dynamic processes that affect the production and removal of aerosols, were not considered since they were deemed negligible in this study when indoor sources were present. Reducing indoor air pollution levels by using plants may be a simple way to lower lifetime risk and exposure to a wide range of chemicals.

Furthermore, as most of society spends most of its time indoors, the current research is essential to improving indoor air quality. The results also show a sustainable and affordable indoor air pollutant bioremediation system that is simple to integrate into engineering measures for any building infrastructure, including workplaces, research facilities, schools, and urban families. Given that plant growth conditions and the effectiveness of the plant species being employed in pollution removal influence how quickly plants digest air pollutants. It is necessary to conduct more research on the selection of indoor plant species based on their morphological, anatomical, and physiological characteristics that have the potential to phytoremediate air. This will ensure that indoor living has positive health benefits and will promote learning, productivity, and quality of life. This work sheds light on the significance of this understanding, particularly in light of its implications for human health.

Declarations

Data availability statement

Authors will provide data on request.

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Credit authorship contribution statement

The study was designed and developed by Shambhavi Sharma and Muhammad Jahanzaib. Shambhavi Sharma and Muhammad Jahanzaib also helped with data collection, and Shambhavi Sharma and Ahtesham Bakht handled data visualization and analysis. The complete study process was managed and funded by Duckshin Park. DuckShin Park and Hyunsoo Lee reviewed the manuscript and revised it. The published version of the manuscript has been read and approved by all authors.

Declaration of competing interest

The authors certify that they have no known financial or interpersonal conflicts that might have influenced the research presented in this study.

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Table 3

Table 3 is available in the Supplementary Files section.

Figures

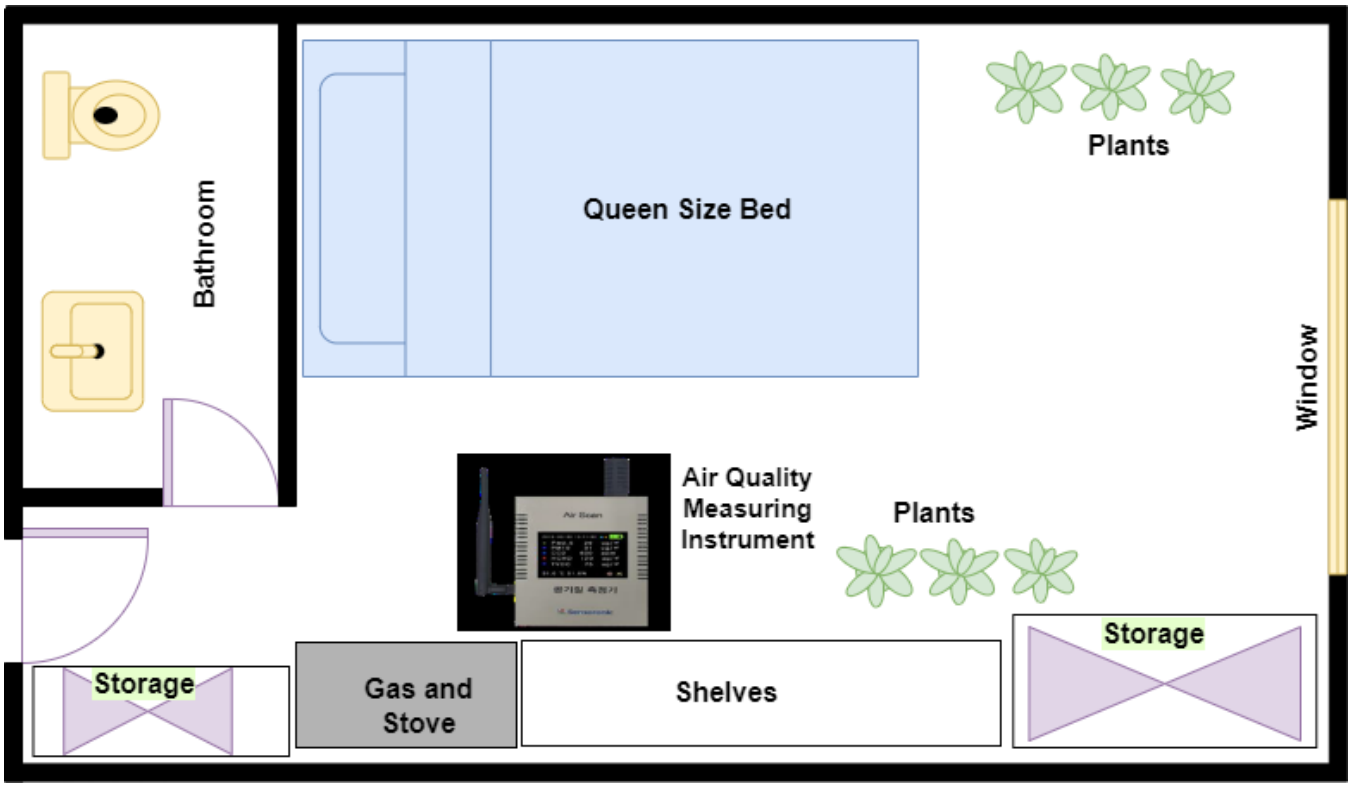


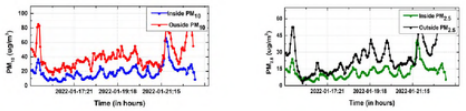
Figure 1

Diagram of the apartment showing the doors, windows, Kitchen shafts, indoor air pollutants (IAP) monitors, and the entry and exit path.

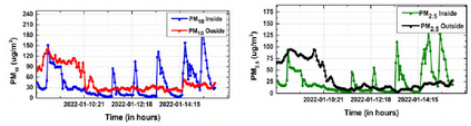


Figure 2

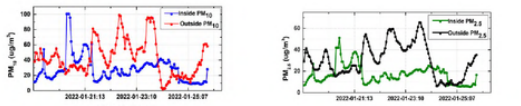
AirScan Device used for monitoring the Indoor Air Pollutant level



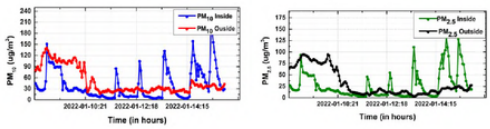
(a) Apartment with indoor plants and ventilation (APTI)



(b) Apartment without indoor plants and ventilation (APTIV).



(c) Apartment with indoor plants (only CAM plants) and without ventilation (APT II)



(d) Apartment with indoor plants and ventilation (APT III).

Figure 3

Average $PM_{2.5}$ and PM_{10} concentrations for Different Apartments (APTI–APTIV): Indoor and Outdoor Diurnal Variations.

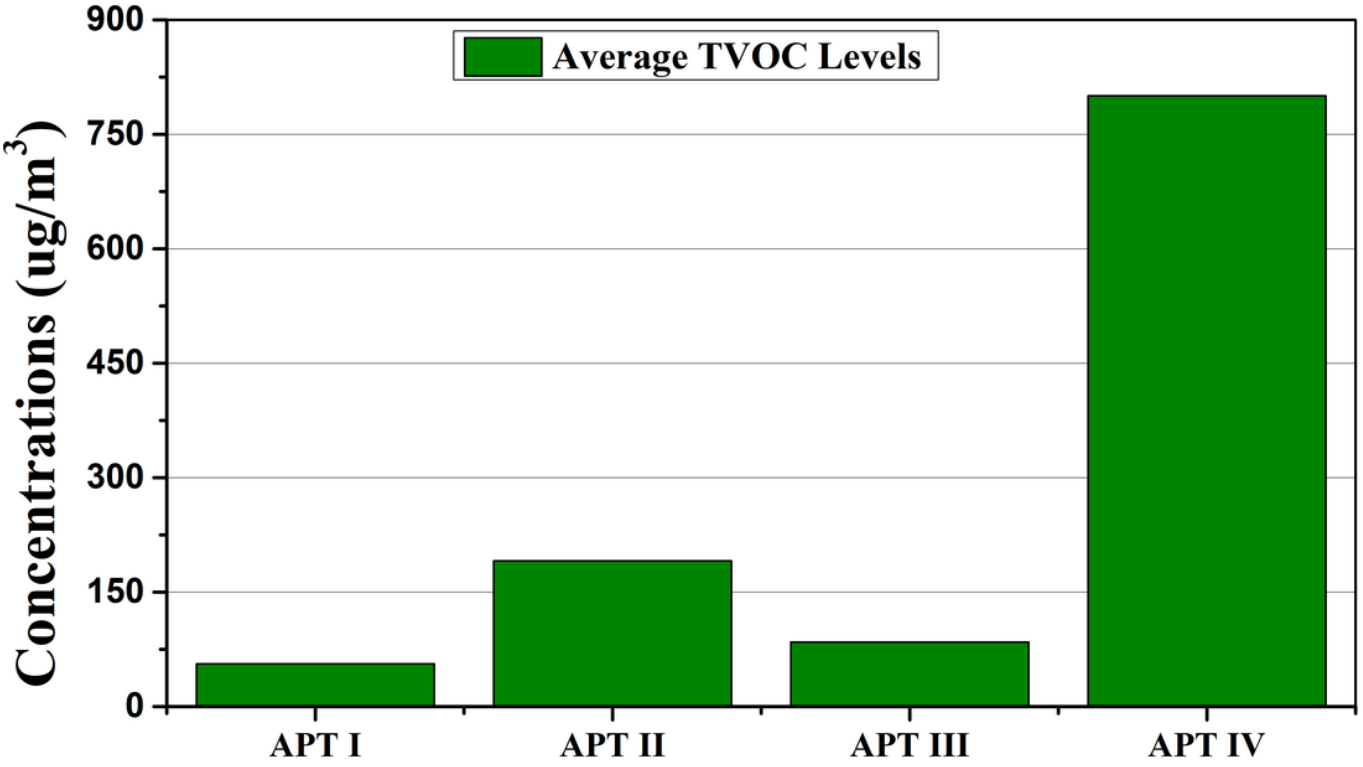


Figure 4

Variations in average TVOC concentration at the indoor apartments (APTI–APTIV)

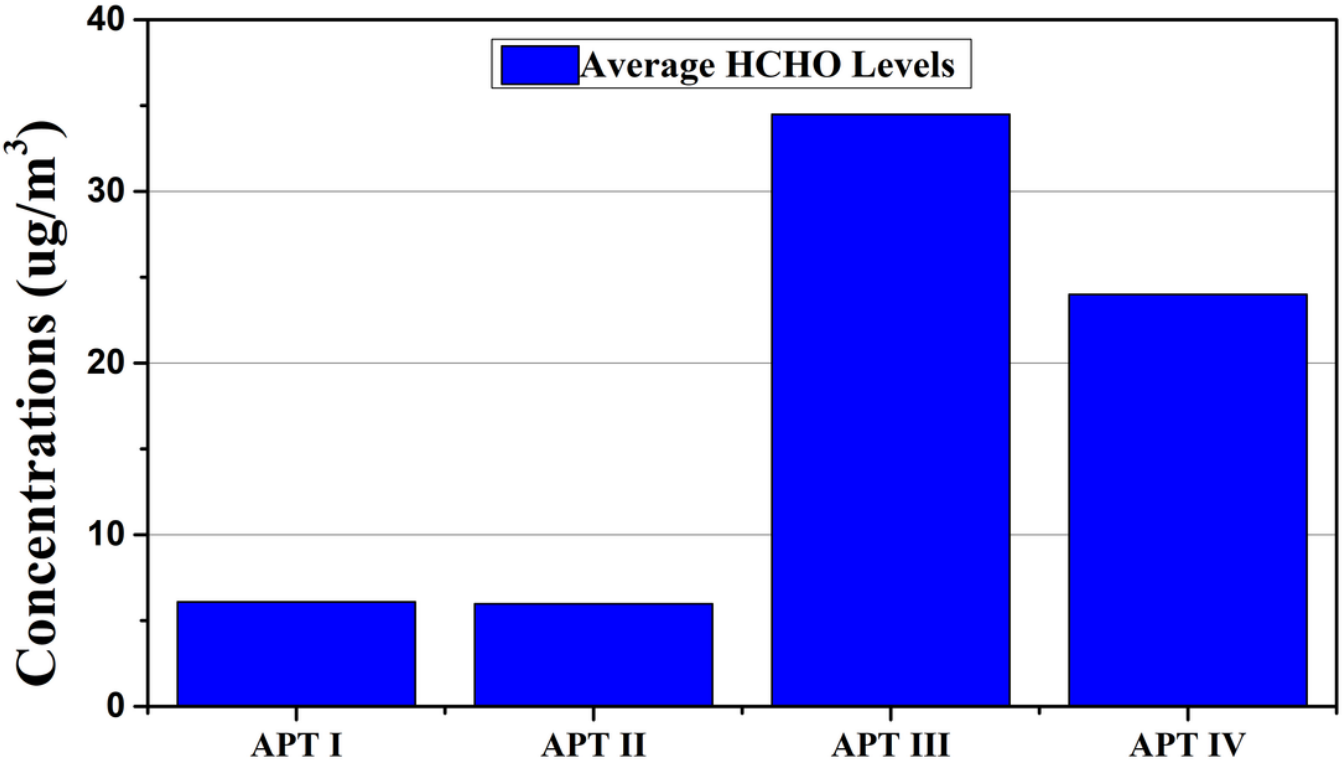


Figure 5

Variations in average HCHO concentration at the indoor apartments (APTI–APTIV)

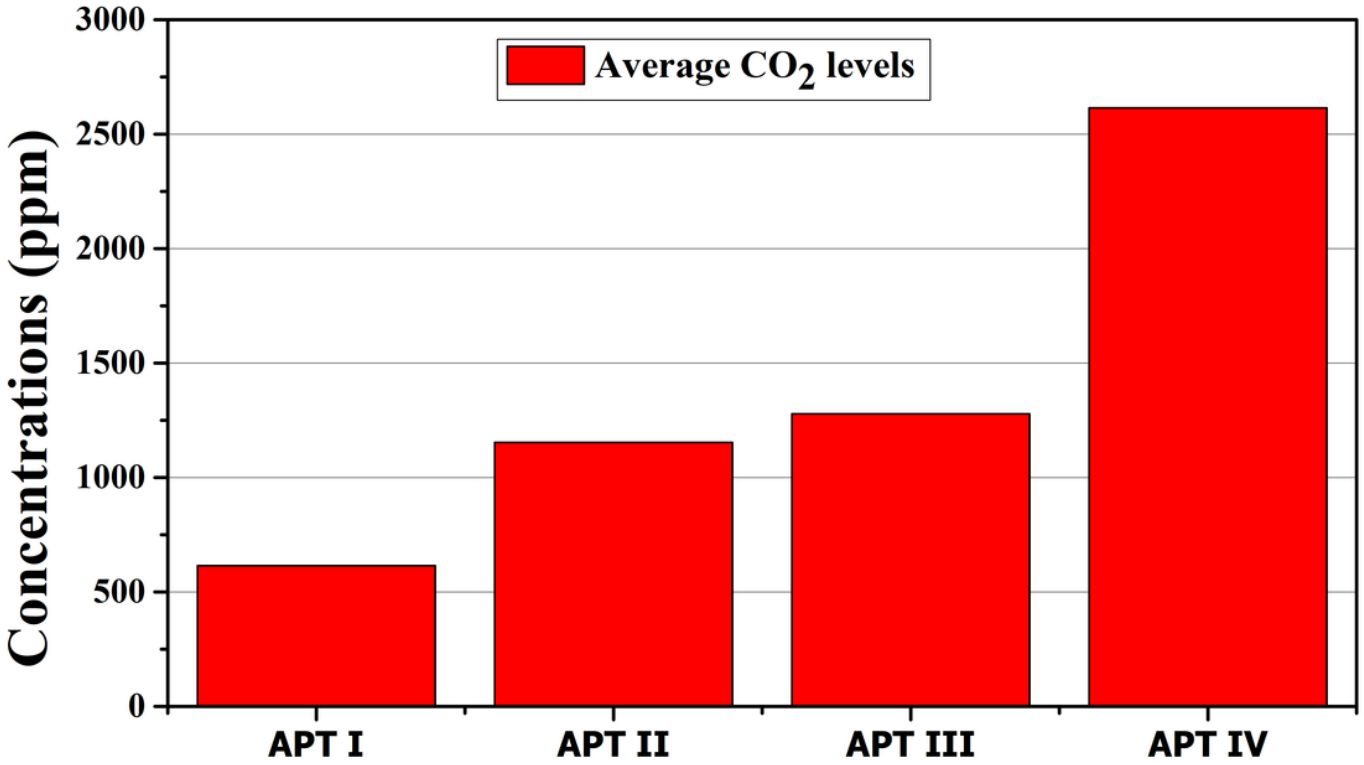


Figure 6

Variations in average CO_2 concentration at the indoor apartments (APTI–APTIV)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementaryfile.docx
- Table3.docx