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A review of different phytoremediation methods and critical factors for purification of common indoor air pollutants: an approach with sensitive analysis

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Abstract

In recent decades, indoor air pollution has become a major concern due to its adverse health effects on the inhabitants. The presence of fine particles ($PM_{2.5}$) and hazardous volatile organic compounds (VOCs), such as formaldehyde and benzene, in indoor air and their proven carcinogenic effects, has raised the attention of health authorities. Their very difficult and expensive removal by chemical and mechanical methods has led researchers to seek an economical and environmentally friendly technique. The use of plants in different ways such as potted plants or green walls is considered as a potential green solution for the improvement of indoor air quality and the health level of its inhabitants. A review of the literature cited in this paper suggests that plants absorb some of the pollutants, such as particles directly and remove some pollutants such as VOCs indirectly through biological transfer or by using microorganisms. This review paper discusses the types of plants that have been used for the phytoremediation of airborne pollutants and the routes and mechanisms for removing the pollutants. Removal pathways of the pollutants by aerial parts of the plants, the growth media along with the roots and their microorganisms in the rhizosphere part were also discussed. Sensitive analysis of extracted data from the literature outlined the most useful types of plants and the appropriate substrate for phytoremediation. Also, it showed that factors affecting the removal efficiency such as light intensity and ambient temperature, behave differently depending on pollutants and plants types.

Keywords Building environment · Pollutant · Indoor air · Phytoremediation

Introduction

Today, indoor air quality has become a concern around the world due to its harmful effects on human health and the environment (Kabir and Kim 2012; Soreanu et al. 2013). With the onset of the energy crisis since 1973 and changes in the design of buildings to improve energy saving, the living environment has become confined spaces, which has led to the accumulation of indoor airborne pollutants resulting in an exacerbation of indoor air pollution (Orwell et al. 2006; Aydogan and Montoya 2011). As urban residents generally spend more than 80% of their time inside the buildings, this causes more exposure to indoor air pollutants (Klepeis et al. 2001; Xu et al. 2011). The World Health Organization (WHO) has identified a group of symptoms as "Sick Building Syndrome (SBS)," caused by the inhalation of accumulated indoor air contaminants, including headaches, dizziness, nausea, eye, and respiratory system irritation, as well as drowsiness, fatigue, and general impatience (Orwell et al. 2006; Aydogan and Montoya 2011; Soreanu et al. 2013).

Indoor air can be contaminated in a variety of ways. Combustion sources (e.g., gas, wood, or coal fireplaces and conventional gas ovens) emit a large number of particulates and gases pollutants (e.g., NO, NO_2, CO, SO_2, and hydrocarbons such as VOCs). In poor combustion conditions, these particles and gases will be in the form of soot. High-temperature combustion produces polycyclic aromatic hydrocarbons (PAHs) that are known as mutagens and/or carcinogens. Tobacco combustion produces more than 4500 compounds, 50 of which have carcinogenic or probably carcinogenic effects (Jeremy Colls 2002; Bernstein et al. 2008).

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Biological aerosols such as living aerosols (bacteria, viruses, and fungi) or originated from other living organisms (toxins or fragments of microorganisms) can also be emitted and accumulated inside the building at high concentrations and may act as a stimulant or toxic agent for residents (Jeremy Colls 2002; Kim et al. 2018a; Moustafa 2020).

Recently, fine particulate matter ($PM_{2.5}$) has been considered one of the most hazardous pollutants for human health, responsible for more than 3 million deaths per year worldwide (Vestreng et al. 2007; Silva et al. 2013). In the inside of buildings, $PM_{2.5}$ is emitted from household burners, heaters, fireplaces, frying, ironing, cleaning, plastic paints, presence and activity of family members, and pets. Several factors such as ventilation, air conditioning, buildings' physics, and structure play major roles in the concentration of indoor fine particles. Besides these, one of the main sources of indoor particles is infiltration from the outdoor (Ji and Zhao 2015). Studies have shown that the quality of outdoor air has a direct impact on indoor air quality, especially where outdoor fine particles is very serious (Chithra and Nagendra 2014; McGill et al. 2015). Because they cannot be filtered even with mechanical air condition systems (Mosley et al. 2001). Fine particles can remain in the released environment for hours to several days and transfer over long distances (Kobayashi et al. 2007; Gawrońska and Bakera 2015).

The levels of indoor air pollutants can be higher than outdoors because the air pollutants entered from outdoor mixes with other indoor pollutants such as CO_2 worsening indoor air quality, which is so observable in tight sealed and less spacious buildings. Although CO_2 is not considered a critical pollutant, due to its narcotic action and respiratory symptoms, it can make the inside environment more inconvenient (Stutte 2012; Torpy et al. 2017). Volatile organic compounds (VOCs) and black carbon or soot particles (BC) are among the most common indoor air pollutants (Bernstein et al. 2008; Berenjian et al. 2012). In addition, exhaled air also contains about 2000 $\mu g\ m^{-3}$ of acetone and ethanol, and several hundred $\mu g\ m^{-3}$ of isoprene, methanol and 2-propanol, which are endogenous products of metabolism that are produced in the human body. Cigarette smoking naturally increases the concentration of many substances in the respiratory air (Jeremy Colls 2002).

Monitoring of one hundred residential buildings in the UK showed that the average total concentration of 50–300 VOC types was 553 $\mu g\ m^{-3}$ and in 2% of the homes that reached to1777 $\mu g\ m^{-3}$, whereas that of in the outdoor air was 32 $\mu g\ m^{-3}$. The total concentration of VOCs in newly built houses may be around several thousand $\mu g\ m^{-3}$, but this concentration would decrease in houses with a lifespan of more than 3 months to a level of 1000 $\mu g\ m^{-3}$. This is probably due to the presence of VOCs in used materials such as paints, flooring, and furniture which are rich in VOCs in new buildings and spoils by the passage of time (Jeremy Colls 2002; Takigawa et al. 2010; Plaisance et al. 2017). The applicable federal standards for VOCs in non-industrial locations are not specified, but for each of the important VOCs such as benzene and formaldehyde which are more toxic at high levels, standards are specified for indoor air (Binetti et al. 2006; Nielsen and Wolkoff 2010; Gallego et al. 2011; Aydogan and Montoya 2011). Based on the WHO guidance for domestic pollutants, the exposure limit for formaldehyde to prevent sensory stimulation in ordinary people is 0.1 $mg\ m^{-3}$ for half an hour, and 0.2 $mg\ m^{-3}$ is prescribed to prevent long-term complications such as cancer (WHO 2010). However, no safe level has been proposed for exposure to benzene, which was classified as a group 1 pollutant (carcinogenic to humans) according to the International Agency for Research on Cancer (IARC) (Orwell et al. 2004; Wilbur et al. 2007; Mosaddegh et al. 2014; Parseh et al. 2018). Different studies have measured the concentration of benzene in the indoor air between 3.24 and 32.4 $\mu g\ m^{-3}$ (1–10 ppb), of which 95–99% is inhaled by exposure (Brunnemann et al. 1989; Pellizzari et al. 1999).

There are several ways to remove VOCs from the air, such as physicochemical methods that include activated carbon adsorption, absorption, catalytic burning, gas condensation to remove VOC vapors, and modern biological methods such as biofiltration (Mudliar et al. 2010; Huang et al. 2016). Although these methods have special potential for these purposes, the specific characteristics of the indoor environment create many problems, and it is difficult to find a simple, reliable, and cost-effective method of removal for the complex and different nature of the VOCs(Guieysse et al. 2008; Berenjian et al. 2012; Kabir and Kim 2012).

The use of plants along with their associated microorganisms to remove contaminants from soil, water, and air has attracted more attention in recent decades. This is likely due to the economic, social, and environmental benefits of the plants, as well as its potential contribution to zero emissions (Xiaojing et al. 2006; Mudliar et al. 2010). Using the phytoremediation method in indoor areas, i.e., the placement of several potted plants in residential and office buildings, is an affordable way to absorb pollutants and clean up indoor air, in addition to its beauty and freshness. When sick building syndromes due to poor indoor air quality gained attention, the biological solution has been considered as a method to solve the problem, where NASA used plants for this purpose since 1980. Wolverton used Foliage plants for removing indoor air pollutants from energy-efficient homes in 1982 (Wolverton and McDonald 1982); afterward, phytoremediation studies has been expanded (Stutte 2012). Much research has been done on the phytoremediation of contaminated soil and water (Rostami et al. 2016, 2017; Egharevba et al. 2017; Rehman et al. 2018; Wei et al. 2021). Research in the field of air has shown that ornamental plants have the potential to eliminate indoor airborne contaminants. Nevertheless, more information in this area, such as the behavior of different plant species in different meteorological conditions and appropriate phytoremediation methods for different pollutants is not yet clear and sufficient to use them for the removal of contaminants of various concentrations. Further research is still required to verify the ability of different plant species in absorbing different indoor air pollutants under various environments.

The purpose of the current review is to provide information on how to remove common indoor air pollutants that threaten the health of residents by plants as well as to investigate the effects of different types of phytoremediation and critical factors on the removal efficiency of the plants. For better understanding, the materials are classified in several sections, which include a summary of phytoremediation studies and types of plants used, the pathways and mechanisms for removing pollutants by different parts of the plants. In the current study to select the best method and plants for specific indoor air pollutants to achieve the highest removal efficiency, sensitive analysis for different phytoremediation types, plants, and affecting factors (leaf surface area, light intensity, temperature, relative humidity, and flow rate) was conducted. As far as we know, this analysis was done for the first time and no phytoremediation review study dealt with sensitive analysis by now.

Types of indoor air phytoremediation

The purification of indoor pollutants can be carried out both by passive and active systems using potted plants and plant biofiltration, respectively. Air-purifying active systems operate using pressure to increase airflow to a biofilter or using an intermediate water transition phase where the contaminants are accumulated and transferred to the bioreactor, both of which increase the rate of removal of contaminants, whereas in the passive system, pollutants are eliminated only at a speed that penetrates the plant (Wolverton and McDonald 1982; Xu et al. 2011). Figure 1 represents different phytoremediation studies that have been used with different plant species, treatment types and growing media for indoor air purification.

Potted plants

In potted plants, the removal is carried out by the biological activity of the plant and microorganisms, as well as the growth medium of the plant (Aydogan and Montoya 2011). The root zone plays a very important role in the removal of contaminants. The rhizosphere microorganisms can decompose pollutants and the degradation can be increased by the root secretions (Xu et al. 2011). Although the purification of indoor air by potted plants has shown acceptable results, low concentration of pollutants in the air and inadequate exposure to plant and soil microorganisms affects the removal efficiency. Research indicates that static systems like pot plants may be ineffective for the purification of high-capacity pollutants. Therefore, technological advances such as using active biofiltration systems or green walls have been developed that can actively impact airflow to a high surface area of plants and their root zone resulting in a huge amount of pollutants contact with plants and their growth substrates (Llewellyn and Dixon 2011; Teiri et al. 2018b; Zhang et al. 2020).

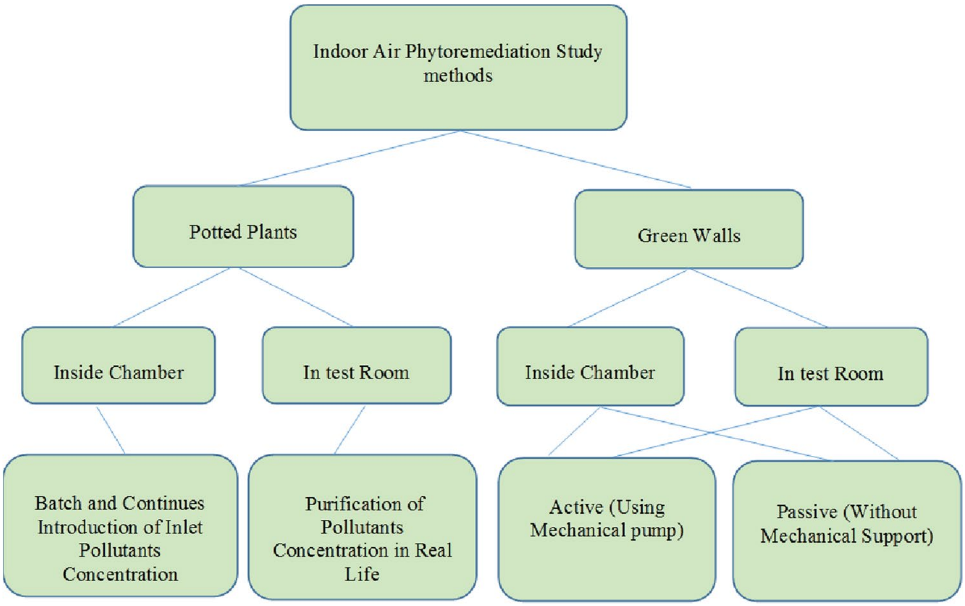

Fig. 1 Different study methods of phytoremediation

Green walls

Based on the research, green walls are preferred to potted plants due to their vertical design, high plant density, the need for less space, biomass growth, and ability to use different plant species in a single module. Removal mechanisms in green walls are the same as potted plants depending on the plants' microorganisms biological activity and the growth medium of the plant; however, some factors such as air flow rate influence green walls removal efficiency which is not applicable in potted plants systems (Bandehali et al. 2021). In the development of green wall systems for effective indoor air purification besides the beauty and growth of the plant determination of airflow rate and substrates types have been targeted. Because, various factors such as airflow rate, bed depth, and ventilation path's shape can affect the removal efficiency of these green walls (Li et al. 2019; Zhang et al. 2020). These characteristics make green walls more effective in eliminating particles and gaseous pollutants simultaneously (Torpy et al. 2014; Irga et al. 2019; Pettit et al. 2019), while potted plants are usually designed to remove particular pollutants (Li et al. 2019). Therefore, botanical systems can be a good alternative to potted plants with less energy consumption, less space occupied, less investment, and much more environmentally friendly (Bandehali et al. 2021).

Balancing the percentage of air flow that passes through the module is essential to maximize the capacity of the green wall biofiltration system. In higher flow rate, pollutants exit the system before having enough time to contact with the biofilter surface, and conversely, in very low flow rate, the volume of polluted air which reaches the biofilter is low that reduces the removal efficiency (Irga et al. 2017; Pettit et al. 2017). Therefore, to overcome this problem, researchers have examined different airflow rates versus different pressure drops using a variety of substrates and growing media to improve the efficiency of active green walls. Also, evaluating the role of irrigation has shown that more airflow passes through the wet modules than dry ones which result in more air purification due to the unifying of the growing media particles by water and increasing their porosity (Abdo et al. 2019).

Green walls have different types that include direct and indirect green facades and continuous and modular living walls. Green facades include plants that can grow upward or downward without any support, and stick on the wall. In these plants, the roots are directly "on the ground, but indirectly, a structure is needed as plant support" (Manso and Castro-Gomes 2015). Living walls (LWs) are the newest type of green walls in which materials and technologies are used to create a variety of plants uniformly on one surface. In continuous LWs, permeable and light plates are used, and each plant is placed on the plate separately. In modular LWs, which is the most common type used in phytoremediation, plates of the same size are used and the plant is placed on the plate with its growth bed (Coma et al. 2017; Radić et al. 2019; Liberalesso et al. 2020).

Phytoremediation of common indoor air pollutants

Volatile organic compounds

In 1985, NASA identified more than 300 types of VOCs inside a spaceship, a completely confined environment, where personnel were faced with health problems due to unhealthy indoor air (Wolverton and McDonald 1982; Aydogan and Montoya 2011). Consequently, NASA researchers have investigated the use of plants in an indoor environment to reduce the concentration of air pollutants and maintain a healthy environment. Similar studies found that the plants effectively reduce the levels of benzene, ammonia, formaldehyde, nitrogen oxides, and particles. They also modulate the humidity of the indoor air and increase the comfort of environments with a lower air exchange rate (Aydogan and Montoya 2011; Torpy et al. 2014; Fooladi et al. 2019). Various plants can remove pollutants, especially VOCs from the air, with different mechanisms, depending on the type of pollutant. Typically, the pollutants are absorbed by the stems or leaves of the plant, metabolized by plant cells using an enzymatic pathway, and decomposed by rhizosphere microorganisms (Xu et al. 2011; He and Zhou 2014; Gong et al. 2019; Pettit et al. 2019). In addition, plants' microbial populations living in the phyllosphere and rhizosphere are interacted with each other to purify pollutants from the air. It has been reported that inhabited microbes on the leaf surface and in leaves' bodies (endophytes) can detoxify part of adsorbed or absorbed pollutants from the air by degradation, transformation, or sequestration. Afterwards, the remaining pollutants are transferred down to the soil and contact with the microorganisms living in the plant's rhizosphere and roots to further detoxification. However, the potential role of the phyllosphere and endophytes for air purification needs to be further explored (Weyens et al. 2015; Wei et al. 2017; Lee et al. 2020).

Phytoremediation of formaldehyde (as one of the dangerous and common available VOCs in indoor environments due to its sources) has attracted many researcher's attention (Kim et al. 2008, 2010; Xu et al. 2011; Teiri et al. 2018b; Li et al. 2019; Yang et al. 2020). Formaldehyde removal from indoor air using *Chamaedorea elegans* in a continuous flow pilot system with a volume of 375 L was conducted in 2018. The results showed that this plant could remove 65–100% of formaldehyde (with an elimination capacity of 1.47 mg m^{-2}. h^{-1}) from the contaminated air with its inlet concentration ranges of 0.66 to 16.4 mg m^{-3} and exposure time of approximately 1 h (Teiri et al. 2018a). Also, *Nephrolepis obliterata* was examined to remove formaldehyde from contaminated indoor air. In this study, the introduction of inlet formaldehyde concentration ranges of 0.6 to 11 mg m^{-3} to the pilot chamber resulted in 81–100% formaldehyde removal efficiency with an elimination capacity of 0.99 mg m^{-2}. h^{-1} (Teiri et al. 2018b). In addition, this plant represented a reduction of TVOCs under standard limits in a few hours in a green wall system (Suárez-Cáceres et al. 2021).

Removal of benzene as another hazardous airborne contaminant from the contaminated indoor air was evaluated, using the same methodology as described above, by *Schefflera arboricola* and *Spathiphyllum wallisii* plants. The average removal efficiency for benzene concentrations of 3.5–6.5, 10.5–16.3, and 25–30 μg m^{-3} were 97%, 94%, and 91%, respectively. The removal efficiency of the *S. arboricola* was slightly higher than that of the *S. wallisii* plant (Parseh et al. 2018).

Investigation of formaldehyde removal by three potted plants called *Chlorphytum comosum*, *Aloe vera*, and *Epipremnum aureum* in the soil bed during day and night under light intensities of 80, 160, and 240 μmol m^{-2} s^{-1} showed that *C. comosum* has the highest removal capacity, especially during the day. Probably, these results were achieved due to the high metabolism of the plant and rhizosphere microorganisms as well as the formaldehyde dehydrogenase activity of the leaves. Besides, the hydrophilic characteristic of formaldehyde which hardly pass through cuticles leads to a reduction of its absorption by the plants at night due to the closed stomata (Xu et al. 2011). These findings were in contrast with toluene removal efficiency by the *Dieffenbachia* plant. At low concentration, increasing light intensity had increased the toluene removal efficiency, but, in concentrations higher than 4000 (μg. m^{-3}) by increasing light intensity the removal efficiency was decreased may be due to toluene's self-inhibitory effect on its removal and probably due to toluene's toxicity to the systems that support metabolic capacity of the plant at higher toluene level (Porter 1994). The ability of the three mentioned potted plants' shoot was evaluated in removing combined benzene and formaldehyde from indoor air. The consistent removal efficiency of the plant shoot regardless of fumigation by formaldehyde represents that formaldehyde removal in plant shoots is mainly due to enzymatic metabolism of formaldehyde, by formaldehyde dehydrogenase activity (FDH). Therefore, the coexistence of benzene in the air induce the enzymes of the plants and increases formaldehyde conversion (Hou and Xu 2015).

Different physiological characteristics of plants show various behavior on the purification of pollutants throughout the air. *C. comosum* with green leaves represented a higher formaldehyde removal capacity by 84.66% ± 0.19 at natural daylight. Those species with combined green and white color and those with purple color showed removal efficiency of 71.07% ± 0.23, and 46.73% ± 0.15 at 1 ppm inlet concentration of formaldehyde, respectively (Li et al. 2019). Also, chlorophyll content, which is used for monitoring pollutant damage to plants, decreased from 6.95 up to 22.16% for all species which was comparable with some other reports (Teiri et al. 2018b; Li et al. 2019; Radić et al. 2019). In contrast, with increasing formaldehyde concentration, the free protein of all the three plant species was increased. Because during exposure to the pollutants, free proteins separate from phospholipids resulting in the damage of plants leaf tissues and reducing its resistance to the pollutants. Chlorophyll and free protein are the most important psychological indicators of plant growth and health which are monitored to help understand pollutant removal mechanism by the plant (Li et al. 2019). Among the 86 plant species tested for formaldehyde removal capacity, *Osmunda japonica* from the fern family was the most effective plant for purification of formaldehyde (6.64 μg m^{-3} per m^2 of leaf area for 5 h contact time with the inlet concentration of 2.0 μLL^{-1} in airtight chambers). In contrast, *Dracaena deremensis* from herbaceous foliage plants had the lowest removal efficiency (0.13 $\mu g m^{-3}$ cm^{-2} leaf area) (Kim et al. 2010).

Various parts of the plant have distinct contributions in phytoremediation; therefore, the removal capacity of aerial parts of the plant has been studied by sealing the plant roots and surface of the bed, and the removal capacity of the root zone along with the bed by cutting plant aerial or root zone alone by washing out the growing media. Although the removal contribution of plants' same parts was not in agreement in all studies, the results showed that the removal of VOCs by the plant root zone was much faster than that's removal by aerial parts of the plants (Aydogan and Montoya 2011).

The physicochemical properties of VOCs were also effective in eliminating them by the plant, e.g., investigation of BTEX (benzene, toluene, ethylbenzene, and xylene) removal by *Zamioculcas zamiifolia* demonstrated that benzene was removed earlier than the rest of the compounds, due to its lower molecular weight. Also, the findings proved that BTEX did not cause plant poisoning, and the concentration of 20 ppm of these vapors was not so high that would stop the plant's photosynthesis. About 73–80% of these pollutants were removed through the stomata and about 23–26% by the cuticle (Sriprapat and Thiravetyan 2013). These findings were in agreement with the phytoremediation of formaldehyde by *Chamaedorea elegans* and *Nephrolepis Obliterata* due to the plants' growth throughout the test even in fumigation concentrations of 16.4 mg m^{-3} and 11 mg m^{-3} respectively (Teiri et al. 2018b, a).

Carbon dioxide

With increasing tight and sealed buildings for energy saving purposes, besides the other common indoor air pollutant, the CO_2 concentration of the buildings is increased. Although CO_2 phytoremediation studies are not comparable with VOCs, much research demonstrated that interior plants are capable to purify indoor air from such pollutants (Raza et al. 1991, 1995; Park et al. 2010; Torpy et al. 2014, 2017; Salvatori et al. 2020). Using 6–9 potted plants of *Areca palm* species in a real-life setting could reduce CO_2 and CO by 52.33% and 95.70%, respectively, from polluted indoor air (Bhargava et al. 2021). Also, vertical farming of plants could absorb CO_2 from indoor air up to 9.2 times more than potted plants and therefore reduce 12.7–58.4% energy consumption due to ventilation (Shao et al. 2021).

As plants take in CO_2 during daylight hours and release about half of that at night through respiration, plants behavior has been investigated in different light levels. The photosynthesis function of common apartment plants in reducing CO_2 concentration from indoor air in low (10 ± 2 μmol m^{-2} s^{-1}) and high light intensity levels (90 ± 10 μmol m^{-2} s^{-1}) has been evaluated. The results represented that *Ficus benjamina* and *Dypsis lutescens* species had the highest capacity of CO_2 removal at both light levels. An interesting point was that, although the photosynthesis of the majority of plants under high light level was increased, three species, *Chamaedorea elegans*, *Aglaonema commutatum*, and *Howea forsteriana* had higher levels of photosynthesis at low levels of light. This is probably due to their exposure to a higher light intensity than optimum light level. The highest removal rate (657 mg m^{-2} h^{-1}) was obtained by *Dypsis lutescens* at a light intensity of 350 μmol m^{-2} s^{-1} (Torpy et al. 2014). However, some plants like *Zamioculcas zamiifolia* absorb CO_2 during the night and metabolize it during the day. This indicates that their stoma is open during the night and closed in the day, so light has no effect on increasing their pollutant removal efficiency. In these plants, due to the irregular Crassulacean acid metabolism (CAM), the stomata remain closed during the day to reduce evapotranspiration and open in dark conditions to collect CO_2 (Raza et al. 1991).

C. comosum and *E. aureum* were identified as the most effective species for use in the green wall (as a method that requires a small amount of space for CO_2 removal) to remove CO_2 at a light intensity of more than 50 μmol m^{-2} s^{-1} (Torpy et al. 2017). *Apicra deltoidea* and *Sedum pachyphyllum* could remove CO_2 from a hospital room having a high level of CO_2 due to occupied people movement and respiratory metabolism and outdoors being a commercial and high traffic area even at night hours. These plants eliminated 61.9 and 80.95% of released CO_2 during nighttime, respectively (Raza et al. 1995). Using an external greenhouse consisting of 58–112 young plants of *Laurus nobilis* connecting to the HVAC ventilation system could control visitors' respiratory CO_2 emissions of the Leonardo da Vinci's painting museum (Salvatori et al. 2020). Therefore, the undeniable truth is that plants remain a net carbon sink, meaning that they absorb more than they emit.

The results of studying simultaneous removal of CO_2 and benzene by *Syngonium podophyllum* in a soil pot and a hydroculture medium (culture in water) indicated that the hydroculture growth medium could remove more CO_2 under normal indoor light conditions than the soil potted plant. However, the percentage of benzene removal in the hydroculture system was lower than that of the potted plant, which is attributed to a large bacterial population of the potted plant (Irga et al. 2013). Also, the results of some other research revealed that the net reduction of CO_2 by the hydroculture plants was higher than potted plants. These findings can be attributed to the fact that a larger proportion of plant respiration occurs in root and soil systems with potentially generate CO_2 (Darlington 2000; Gonzalez-Meler et al. 2004; Torpy et al. 2015).

Particulate matters

The ratio of indoor to outdoor PM concentration (I/O) indicates that indoor air PM is correlated with outdoor especially in the industrial urban area (Wang et al. 2016). Probably, using tight windows and HAVC-filter systems can be a solution for the problem but it is costly and not affordable for all people. Studying plants ability for anions emission via transpiration during an hour at the highest photosynthesis rate showed that they can eliminate 29–36% of tobacco particles from indoor air within 60 min, which was 1/13–1/17 of air cleaner filter efficiency (Yoon et al. 2009). Different types of activities such as gym, dentistry, and perfume bottling that take place in indoor environments can change particulate matter concentration in the air. Investigation of the ability of plants to remove all size fractions of particles ranging 0.01–100 μm revealed that they can remove coarse particles by the superficial method and through sedimentation on leaves, and fine particles through phytostabilization and trapping in the wax. The amount of accumulated PM on aluminum disks used as a control demonstrated that factors other than gravity are effective in the accumulation of particles on the leaves (Gawrońska and Bakera 2015; Pettit et al. 2019). However, PM removal efficiency of plants with high purification capacity used in botanical biofiltration such as green wall and greenhouse influenced by higher airflow rates due to rapid scape of particles, and speedy airflow rate showed a reverse effect on removal efficiency (Irga et al. 2017; Paull et al. 2017; Łukowski et al. 2020). Plant tolerance was evaluated to mix pollutants by exposing them for five weeks with a high concentration of diesel fuel combustion. The results represented that plants with healthy biochemical, morphological and physiological aspects can withstand high concentrations of pollutants over a short-term period. Specifically, the species of fig family such as *Ficuse lyrata* can be strongly recommended for purification of much polluted indoor environments (Fooladi et al. 2019).

Studied plant species

Most phytoremediation studies have been conducted on the removal of VOCs, especially formaldehyde and benzene due to their very hazardous properties and adverse health effects (Lin et al. 2017; Parseh et al. 2018; Teiri et al. 2018a; Torpy et al. 2018). However, different plant species have different behaviors in removing the contaminants. Several factors can cause these differences in the plant species; the most important of these is the thickness of the wax layer, roughness and softness of the leaf, stoma properties, leaf surface area, and villi growth (Wolverton and Wolverton 1993; Orwell et al. 2006; Popek et al. 2018; Łukowski et al. 2020). Also, differences in the growth ability of plant's roots and their ability to support soil microbial populations' growth are other factors that indirectly lead to a difference in the efficiency of removing VOCs by plants (Cruz et al. 2014; Manso and Castro-Gomes 2015).

Data extraction from all the reviewed literature in the current study for sensitive analysis revealed that the most common plants for removal of VOCs, CO_2, and PM were *C. comosum* (spider plants), *E. aureum* (golden pothos), *Hedera helix* (English ivy), *spathiphyllum* (peace lily), and *Schefflera* (umbrella) plants. Various species of spider plants showed high removal efficiency (about 90–95%) for formaldehyde from indoor air. High stomata density and metabolism, higher microbial degradation, and increased catalase were the main causes of the pollutant removal by these plants (Xu et al. 2011). Also, using a spider plant in a green wall system resulted in the purification of about 53% PM_{10} and 48% $PM_{2.5}$ from polluted indoor air (Irga et al. 2017). In addition, investigation of 86 plant species from general classes of plants (ferns, woody foliage, herbaceous foliage, Korean native plants, and herbs) for formaldehyde removal showed that fern and herbaceous plants have the highest removal efficiency (Kim et al. 2010; Teiri et al. 2018b). However, in some studies, a high concentration of outdoor particulate matter affecting the quality of indoor air, reduced the removal efficiency of rubber trees (*Hevea brasiliensis*), *Rhapis* (*Rhapis excelsa*), and happy trees (*Camptotheca acuminate*) in the indoor environment (Irga et al. 2017, 2018). Further phytoremediation studies for different indoor contaminant removal using different plant species and their removal efficiency were summarized in Table 1.

Contaminants removal pathways

The ability of a plant to remove contaminants from the environment is determined by the plant cells absorption capacity and its ability to metabolize the contaminant without harming its natural metabolism. Many studies have been conducted to identify the routes and mechanisms of entry, transfer, and removal of the contaminant by plants. The removal of contaminants by plants can be classified into three routes: (i) removal by aerial parts of the plant, (ii) removal by soil microorganisms, and (iii) removal by growing media and roots (Aydogan and Montoya 2011).

The entry of contaminants into the leaf occurs through an open stoma in the epidermis or via penetration into the wax cuticle (Thomas et al. 2015). Benzene and toluene are mainly absorbed by the plant through the stomata, but some studies have concluded that the stomata have no major role in the removal of volatile organic hydrocarbons (Sriprapat and Thiravetyan 2013; Popek et al. 2018). The cuticle wax layer allows both lipophilic and hydrophilic molecules to penetrate the plant. However, hydrophilic VOCs such as formaldehyde do not diffuse easily through the cuticle (Thomas et al. 2015). The amount and composition of the wax layer vary in plants, which affects the removal efficiency and the mechanism of removal. Lipophilic low molecular weight contaminants penetrate easily into the wax layer and accumulate to reach an extended level. then gradually penetrate to the leaf tissue (Kim et al. 2018b). The ability of the plant to remove benzene depends on the wax composition rather than the amount of wax in the leaf cuticle. However, the amount of xylene removal depends on both of these factors (Cruz et al. 2014). Also, It has been suggested that poisonous contaminants, in addition to stoma and cuticle, can enter the leaf through trichomes and ectodermal cells (Kim et al. 2008; Thomas et al. 2015).

Removal by the aerial parts of the plant

The aerial or above-ground parts of the plants include leaves and stems of the plant play an important role in the removal of contaminants, especially leaves that play a very significant role. In many studies, aerial parts of the plant have removed large amounts of contaminants such as formaldehyde (Kim et al. 2008; Aydogan and Montoya 2011; Teiri et al. 2018a) and benzene (Parseh et al. 2018) in comparison with soil and root parts. Leaves can receive contaminants from the air through the stoma, epidermis, or cuticle (Kim et al. 2018b; Parseh et al. 2018). Plants can remove particles from the air in both indoor and outdoor environments.

Table 1 Phytoremediation studies with different plant species, treatment types and growing media for indoor air purification

No	Plant species	Type of treatment	Growing media	Pollutant	Pollutant concentrations (μg/m^3)	Type of exposure	Removal rate	Authors
1	*Epipremnum aureum*	Botanical indoor air biofilter (BIAB)	Kenaf fiber, corrugated cellulose sheets	PM2.5, PM10, VOCs	18,000–25,000	Batch	54.5%, 65.42%, 46% In 16 min	Ibrahim IZ et l. (2021)
2	*Areca palm*	Potted plant	Soil, sand, and well-decomposed farm yard manure	TVOCs, CO_2, CO	829.4, 1,545,092, 5728	Continuous	88.16%, 52.33%, 95.70% In 4 months	Bhargava B et l. (2021)
3	*Nephrolepis exaltata*	Green Wall	Coconut fibr and peat	TVOCs	3900–6600	Batch	12.8–77.3% In 3 h	Suárez-Cáceres GP et l. (2021)
4	*Laurus nobilis*	Potted Plant	Garden soil, slow releasing fertilizer	CO2	684,003–1,800,009	Continuous	360,002 μg/m^3/day/m^2	Salvatori E et l. (2020)
5	*Chlorophytum comosum*	Potted Plant	Soil	Formaldehyde	1228 ± 5%	Continuous	71.07% ± 0.23 in 7 days	Jian Li et l. (2019)
6	*Ruscus hyrcanus Danae racemosa*	Potted Plant	Soil	Benzene, toluene, ethylbenzene, xylene	31,947–217,097	Batch	8.5075–86.66 mg/m^3/h cm^2	Mahta Fooladi et l. (2019)
7	*Epipremnum aureum*, *Chlorophytum comosum*, *Hedera heli*, *Echinopsis tubiflora*	Potted Plant	Soil	Benzene	319,470 Then, 99.9% benzene (100 ppm, Weichuang Inc., Shenzhen, China) was injected into the chamber at 200 mL·min^{-1} for 120 s,	Batch	72% in 72 h	Yu Gong et l. (2019)
8	*Chamaedorea elegans*	Potted plant	Loamy soil: 30% sand, 30% silt, 15% clay, 25% humus	Formaldehyde	660–16,400	Continuous	65–100% in 48 h	Teiri et al.(2018a, b)
9	*Nephrolepis obliterata*	Potted plant	Loamy soil: 30% sand, 30% silt, 15% clay, 25% humus	Formaldehyde	600–11,000	Continuous	81–100% in 48 h	Teiri et al. (2018a, b)
10	*Schefflera arboricola Spathiphyllum wallisii*	Potted plant	Loamy soil: 30% sand, 30% silt, 15% clay, 25% humus	Benzene	3.6–29.5	Continuous	91–97% in 48 h	Parseh et al. (2018)
11	*Philodendron scandens*, *Philodendron scandens* "Brazil," *Asplenium antiquum*, *Syngonium podophyllum*	Active green wall	Inorganic growing media, activated carbon	Methyl ethyl ketone; MEK	101.63	Batch	56.6 ± 0.86% in 8 h	Torpy et al. (2018)
12	*Chlorophytom comosum*	Active green wall	Soil	Total suspend particles PM10 PM2.5	700	Batch	48.21–53.35%	Irga et al. (2017)
13	*Hedera helix*	Potted plant	Sterilized media	Formaldehyde	6,140,000	Batch	99.99% in 67.6 h	Lin et al. (2017)

Table 1 (continued)

No	Plant species	Type of treatment	Growing media	Pollutant	Pollutant concentrations (µg/m^3)	Type of exposure	Removal rate	Authors
14	*Dieffenbachia maculata, Spathiphyllum wallisii, Asparagus densiflorus*	Potted plant	Soil	2-Ethylhexanol Toluene	146,000 20,000	Batch	*D. maculata* 1.8 ± 0.2 *S. wallisii* 2.4 ± 0.2 *A. densiflorus* 2.0 ± 1 *D. maculata* 5.6 ± 1.8 *S. wallisii* 5.7 ± 1.5 *A. densiflorus* 4.0 ± 2.1 Unit [L h $^{-1}$ m $^{-2}$ leaf area	Hörmann et al. (2018)
15	*Neomarica* sp *Philodendron xanadu Peperomia* sp. large leaf *P* and small leaf *Gibasis* sp., Tahitian bridal veil, *Epipremnum aureum Golden pothos Chlorophytum comosum*	Active green wall	Coconut fiber with a slow release fertilizer (NPK 18:3:10)	CO_2	1,800,000	Batch	Best-performing species, Chlorophytum (20%), and Epipremnum (8%)	Torpy et al. (2016)
16	*Schefflera actinophylla*, *Ficus benghalensis*	Potted plant	Sun Gro Horticulture Bark humus and sand, sphagnum peat moss, perlite, dolomitic lime, gypsum, and a wetting agent	Toluene total xylene	43.0–62.3	Continuous	Toluene and xylene 13.3 and 7.0 µg·m − 3·m − 2 leaf area in *S.actinophylla*, 13.0 and 7.3 µg·m^{-3}·m^{-2} leaf area in *F. benghalensis*	Kim et al. (2016)
17	*Chlorophytum comosum*	Potted plant	Horticultural media	PM	PM available in the room environment (real life)	Continuous	13.62 to 19.79 µg·m^{-2} leaf blade in 2 months	Gawrońska and Bakera (2015)
18	*O. microdasys*	Potted plant	Soil	Benzene, toluene, ethylbenzene, and xylene	6389, 7537, 8684, 8683	Batch	100% in 48- 57 h	Mosaddegh et al. (2014)
19	*Zamioculcas zamiifolia*	Potted plant	Soil and coco coir	BTEX	63,894, 75,371, 86,845, 86,839	Batch	Benzene 0.96 ± 0.01, toluene 0.93 ± 0.02, ethylbenzene0.92 ± 0.02, xylene 0.86 ± 0.07 mmolm^{-2} leaf area	Sriprapat and Thiravetyan (2013)
20	*Dracaena sanderiana*	Potted plant	Soil	Benzene	63,894	Batch	46% by wax 54% by stomata In 72 h	Treesubsuntorn and Thiravetyan (2012)

Table 1 (continued)

No	Plant species	Type of treatment	Growing media	Pollutant	Pollutant concentrations (µg/m^3)	Type of exposure	Removal rate	Authors
21	*Hedera helix, Chrysanthemum morifolium, Dieffenbachia compacta, Epipremnum aureum*	Potted [lant	Grown stone (99% recycled glass bottles) Expanded clay Activated carbon	Formaldehyde	2000	Batch	88% 84% 96% 94% In 24 h	Aydogan and Montoya (2011)
22	*Chlorphytumcomosum, Aloe vera Epipremnum aureum*	Potted plant	Fluvo-aquic soil	Formaldehyde	4000	Continuous	95% 53% 84%	Xu et al.(2011)
23	*Fatsia japonica Decne.* and *Planch. Ficus benjamina* L	Potted plant	Sun Gro Horticulture Bark humus and sand,sphagnum peat moss, perlite, dolomitic lime, gypsum, and a wetting agent	Formaldehyde	2456	Batch	*F. japonica* 39% (day) and 98% (night) *F. benjamina* 57% (day) and 94%(night) In 5 h	Kim et al. (2008)
24	*Hedera helix Spathiphyllum wallisii Sygonium podophyllum Cissus rhombifolia*	Potted plant	Hydroball cley pellets	Benzene Toluene	3195 3769	Batch	*S. wallisii* 174.5 ± 3.8 *S. podophyllum* 103.4 ± 6.9 *C. rhombifolia* 50.3 ± 7 *H. helix* 102.8 ± 8.3 *S. wallisii* 203.7 ± 24 *S. podophyllum* 161.6 ± 19.2 *C. rhombifolia* 85.8 ± 6 *H. helix* 220.2 ± 31.8 (ng.m^{-3}.h^{-1}.cm^{-2} leaf area) In 6 h	Yoo et al. (2006)
25	*Spathiphyllum 'Petite'Howea forsteriana Dracaena marginata Epipremnum aureum Spathiphyllum 'Sensation'Schefflera 'Amate' Dracaena 'Janet Craig'*	Potted plant	Composted hardwood sawdust, composted bark fines, coarse river sand with Macracote "Green plus" 9-month fertilize	Benzene	80,000	Batch	40 to 88 mg m^{-3} day^{-1} Per pot	Orwell et al. (2004)
26	*Howea forsteriana*	Potted plant	composted hardwood sawdust, composted bark fines, coarse river sand with Macracote "Green plus"' 9-month fertilizer	n-Hexane	353,000	Batch	4032 mg/m^3/day/m^2	Wood et al. (2002)

Table 1 (continued)

No	Plant species	Type of treatment	Growing media	Pollutant	Pollutant concentrations (μg/m^3)	Type of exposure	Removal rate	Authors
27	*Nephrolepis exaltata Chrysanthemum morifolium Phoenix roebelenii*	Potted plant	Soil	Formaldehyde	6140	Batch	*N. exaltata*: 1863 μg m^{-3} h^{-1} *C. morifolium*: 1450 μg m^{-3} h^{-1} *P. roebelenii*: 1385 μg m^{-3} h^{-1}	Wolverton and Wolverton (1993)

The coarse particles deposit and accumulate on the epidermis of the leaves. The smaller particles stick more on the leaves because of their smaller size (Pugh et al. 2012). The amount of particles that accumulate on the epidermis of leaves depends on the type of plant, the proximity of the plant to the release source, the type of activity that takes place in the room, and the location of the room (Gawrońska and Bakera 2015; Wei et al. 2017). The particle concentration in apartments where residents have high levels of physical activity and use devices such as fixed bicycles daily or in places where they use printers or copy devices are much higher than in other places (Gawrońska and Bakera 2015; Irga et al. 2017).

Contaminants such as formaldehyde, benzene, toluene, and many other VOCs are penetrated to the plant through the stoma and removed (Mosaddegh et al. 2014; Kim et al. 2016; Lin et al. 2017; Teiri et al. 2018a). Since plants are also able to remove contaminants from the air in the dark place and when the stoma is closed, this indicates that many contaminants are absorbed by the cuticle (Salthammer et al. 2010; Xu et al. 2011; Teiri et al. 2018a). The absorption pathways of VOCs by the plant depend on the characteristics of VOCs. Thus, hydrophilic contaminants such as formaldehyde can hardly enter the plant through the cuticle that is the adipose tissue, while lipophilic contaminants such as benzene can be easily absorbed through the cuticle, in addition to the stomata (Kim et al. 2008; Hörmann et al. 2018; Teiri et al. 2018a). However, some studies have concluded that the contribution of the aerial parts of plants on the removal of VOCs from indoor air is not significant (Girman et al. 2009; Llewellyn and Dixon 2011; Hanoune et al. 2013; Hörmann et al. 2018).

Removal by the root and surrounding microorganisms

Research has shown that microorganisms in the soil, especially those located in the root, play an important role in purifying the indoor air due to their ability to metabolize large amounts of organic contaminants (Weyens et al. 2015). The ability of plants to secrete substances from roots that stimulate the growth of many microorganisms in the rhizosphere is a well-known phenomenon. The initial opinion was "the foliage of plants is the main part in the removal of VOCs" (Torpy et al. 2014). It was later confirmed that the microbial activity of the rhizosphere is the main mechanism for reducing VOCs, and the foliage of the plants has the least role. In fact, in some cases, forming a boundary layer on the surface of the soil prevents the reduction of contaminants. Studies have proven that VOCs in the gas phase decomposes by soil microorganisms. Soil microorganisms can contribute to the degradation of 19–90.5% of formaldehyde from polluted air. By increasing formaldehyde transformation from air to rhizosphere solution, the removal efficiency rate significantly improves. This happens especially at night when the stomata are closed and the plant cannot easily metabolize through the stomata. So, rhizosphere microorganisms nourish from formaldehyde as a carbon source in addition to root exudates (Orwell et al. 2004; Kim et al. 2008; Zhao et al. 2019; Yang et al. 2020). Some of the microorganisms may produce VOCs for different reasons, such as metabolic end products of anaerobic fermentation processes. Due to the coexistence of anaerobic and aerobic microhabitats in soil, these products are consumed as nutrients by aerobic microorganisms that are finally converted to CO_2 and water (Owen et al. 2007; Delory et al. 2016).

Root structure plays important role in plants removal efficiency, especially when accompanied by active airflow, coarse plant roots, such as spider plant roots decrease the single-pass removal efficiency (SPRE) of biofilters by creating pores that strengthen the airflow pathway and allows unfiltered air to pass through the biofilter (Pettit et al. 2017). Also, roots with different structures may modify the physicochemical characteristics of plants or substrate structure and increase biofiltration capacity. Likely, plants with shallow root system due to the rhizomatous growth of roots and producing dens biomass toward the surface of the substrate increases the removal efficiency (Park et al. 2010; Pettit et al. 2019).

Although the effect of temperature on the removal efficiency is not well defined and various studies have reported different results about increasing or reducing the removal efficiency due to temperature changes (Raza et al. 1991, 1995; Torpy et al. 2017; Teiri et al. 2018a), some researchers concluded that with increasing temperature, the growth of microorganisms in the soil and the possibility of consuming organic contaminants by them increases (Mosley et al. 2001). In addition, by increasing temperature, penetration of the contaminants from the cuticle increases, which also leads to an increase in the removal efficiency (Pugh et al. 2012).

Removal by growing media

The growth bed used for plants can affect the absorption rate and efficiency of pollutant removal. When contaminants such as VOCs enter the soil or other growth bed, they can deposit in the three phases of gas, liquid, and solid at the bed surface. They absorb in the liquid phase, sticks to the surface of the bed in the solid phase, and presents in void spaces in the gas phase (Yang et al. 2020). The soil is the most common growth bed for potted plants. Both organic and mineral particles of the soil can absorb contaminants from the air, but the soil used to grow plants mostly contains organic particles. Several studies have examined the role of the growth bed of potted plants in the removal of contaminants. Evaluation of soil contribution to formaldehyde removal by potted plants represented that, despite the limited surface of contact with the pollutant, about 45% of formaldehyde can be removed by soil (Xu et al. 2011; Teiri et al. 2018a). It has been also postulated that the removal efficiency of contaminants by soil may be increased by introducing air into the bed (Kim et al. 2016). The contribution of rhizosphere microorganisms in formaldehyde removal has been investigated by *Ficus benjamina* plant after cutting the aerial parts of the plant and destroying soil microorganisms by thermal sterilization at 120 °C and 0.13 MPa pressure for 30 min in the autoclave. The results showed that soil sterilization reduced its contribution in formaldehyde removal efficiency by 90% compared to the results obtained before sterilization which highlights the role of rhizosphere microorganisms in air purification (Kim et al. 2008).

Research has shown that the purification capacity of green walls can be improved by modifying the substrate. Using the *Leca* granules and *Nmix* substrate along with activated carbon to remove some of VOCs from indoor air showed that *Nmix* has a higher removal efficiency compared to the other two substrates. This was attributed to the superiority of soil-free beds to chemical properties and activated carbon adsorption or microbiological properties of *Nmix* substrates (Mikkonen et al. 2018). The results of evaluating the ability of green walls for the removal of particles and VOCs using coconut shells activated carbon and a mixture of activated carbon and coconut shells as a substrate revealed that the coconut shells alone have no significant effect on the removal efficiency, but activated carbon showed very high efficiency in the removal of VOCs (Irga et al. 2017; Paull et al. 2017). However, it did not show any increase in the removal efficiency of the particles, even in some cases, activated carbon resulted in the release of extra particles, which may be due to its compact composition and the release of aerosols by the airflow (Gong et al. 2019). Despite this, the findings of this study and some other studies suggested that the combination of coconut shells and activated carbon is a desirable substrate choice for the removal of VOCs. It was also suggested that the selection of activated carbon as a substrate should be done according to the target contaminant (Pettit et al. 2018).

In addition, the contribution of other media types could improve the removal rate of PM in phytoremediation treatment. Using evaporative hard media made of corrugated cellulose sheets in a botanical system could enhance removal efficiency and reduction rate of fine particulate matter and VOCs from indoor air due to its high ability of water absorption and consequently higher dust adhesions (Ibrahim et al. 2021). Hydroponic systems with different soil-free beds are used for plant growth. The most important properties of the hydroponic growth bed for root formation is water holding capacity and air-filled porosity (Irga et al. 2013). They show higher removal efficiency for polar and hydrophilic contaminants, which may not reflect the actual removal capacity of the plants. Three hydroponic growing media including grow stone, expanded clay, and activated carbon were investigated to remove formaldehyde under three conditions: growing medium alone, dry medium in a pot, and wet medium in a pot. Activated carbon showed the highest removal efficiency (88–97%) in all the conditions (Aydogan and Montoya 2011). Different type of growth bed which applied in the phytoremediation studies, represented in Table 1. All these findings demonstrate that growth media has an important role in phytoremediation and the type of media is so effective in pollutant removal rate.

Contaminant removal mechanisms

Removal mechanisms of pollutants may differ depending on the type and chemical characteristics of the pollutants, including absorption or adsorption by leaf, biodegradation, assimilation of pollutants, and transformation (Wei et al. 2017). When plants expose to air contaminants, the surface of plant leaves can adsorb the pollutants and act as a sink for some of them such as PM. Leaves with different compositions and waxes represent the various capacity for removal. Leaf-associated microbes can transform pollutants such as benzene into less harmful and fewer toxicant derivatives or nontoxic ones (Vacher et al. 2016; Wei et al. 2017). If pollutants are absorbed and entered the leaves of the plants through the stomata or cuticle, transfer through the xylem and phloem (plant's vascular system from leaf edges to root tips) to other parts of the plant and decompose or metabolize (Wei et al. 2017). The transfer of pollutants through leaves to the various parts of the plant depends on their concentration in the indoor air (Kim et al. 2008; Thomas et al. 2015).

In addition, plants can assimilate and store pollutants. However, excessive storage due to the accumulation of deadly concentrations will result in damage to the plant. Eventually, some contaminants can move to the root and remove through the root and can be decomposed by microorganisms in the soil or absorb into the soil (Orwell et al. 2004, 2006; Wood et al. 2006; Treesubsuntorn and Thiravetyan 2012). In other words, plants can oppose toxic compounds through removal, combination with molecules or decomposition of them into cellular metabolites, and carbon dioxide in some cases, in which the latter is the best way for phytoremediation purposes (Thomas et al. 2015). In the case of formaldehyde as one of the most toxic VOCs, its decomposition into harmless compounds is most desirable. Formaldehyde can be carried from the air, through leaves and roots to rhizosphere water contents (Salonen et al. 2009; Huang et al. 2016). Phytoremediation of formaldehyde with or without rhizosphere microorganisms showed that in the absence of root microorganisms, formaldehyde mainly reduces from the air by active tissue components of the plants like reactive oxygen species (ROS) and enzymes (Hou and Xu 2015; Liang et al. 2019; Kim et al. 2020).

The oxidative degradation of benzene, toluene, and xylene (BTX) begins with the scission of a ring, followed by muconic acid production in benzene, toluene, and 3-methyl-2-butanol formation in xylene (Huang et al. 2016). Further oxidation may lead to the formation of fumaric acid, which is a key intermediate in the tricarboxylic acid cycle or the Krebs cycle for organic acid biosynthesis (Raza et al. 1995; Mosley et al. 2001). The role of microorganisms, especially root microorganisms due to their ability to metabolize organic matter, has been proved by various studies (Weyens et al. 2015). In a study, among several isolated microorganisms, *Arthrobacter aurescens* TC1 was able to remove 86% formaldehyde from the test chamber with advanced enzyme metabolism and decomposition by bacteria (Wolverton and McDonald 1982; Xu et al. 2011). Root secretions are used as a carbon source for many rhizosphere microorganisms that decompose VOCs into constituent material that can enter the TCA cycle (Kim et al. 2016). Some fungi also lead to the transformation and consumption of aromatic hydrocarbons (Teiri et al. 2018b). Therefore, in general, increasing plant–microbe interaction for indoor air purification can be a good strategy for improving the efficiency of indoor plants in phytoremediation (Irga et al. 2018).

The number of plants required per unite area of indoor places

Knowing the plant elimination capacity, the pollutant removal rate per unit surface area of plant leaf (mg m^{-2}.h^{-1}), gives an accurate estimate of the plant's ability to remove contaminants. Also, it can be used to estimate leaf surface and thereby how many pots are needed for air purification. The EPA estimates that in a building with $32m^3$ of room, assuming the formaldehyde emission of 2.5 mg per 32 m^3, two potted ferns can completely purify the air. Also, the results of our previous study represented that with the average removal capacity of 0.5 mg/m^2.h, 2–3 pots of ferns with $2m^2$ leaf surface area per pot, will be enough for air purification of 12 m^2 room surface (Teiri et al. 2018a, b).

NASA scientists provided some insight into the number of plants per room is needed to purify indoor air. Wolverton recommends at least two good-sized plants for every $9.3m^2$ of indoor space (Wolverton et al. 1989). Hort Innovation found that even just one houseplant in an average room (4 × 5 m) improved air quality by 25%, two plants produced a 75% improvement, and five or more plants produced even better results. Of course, plants with more leaf surface area, as well as larger pots, will produce the best results (Raffaele Di Lallo 2021).

Most of the ornamental plants do not need higher light intensity than room natural light, even some of them are vulnerable to higher light intensity than their optimum light level and some others stomata open at night to purify indoor air like *Zamioculcas zamiifolia* (Sriprapat and Thiravetyan 2013; Torpy et al. 2014). However, in indoor environments with low or without natural light, low energy–consuming lamps or luminescent solar concentrators can be used (Pedron et al. 2021).

Sensitivity analysis of factors affecting removal rate

Sensitivity analysis determines how different values of an independent variable affect a particular-dependent variable and determines how the target variables are affected based on changes in other variables known as input variables. According to the conflicting results of the factors affecting the removal efficiency of pollutants from the air by plants in literature, sensitivity analysis was performed to determine the accuracy and sensitivity of these results. Pearson correlation coefficient and SPSS software with 95% confidence interval were used for this purpose, the result represented by tornado graph in Fig. 2. According to the results, 5 plant types were the most common plants used for removal of the VOCs from the air including *C. comosum*, *E. aureum*, *H. helix, Spathiphyllum*, and *Schefflera*. To compare the yield of 5 evaluated plants, ANOVA sensitivity analysis was performed and no significant difference was observed between different plants (P-value = 0.101 > 0.05).

According to the tornado graph, Fig. 2(a), the most effective parameters on VOCs removal efficiency from polluted indoor air were leaf surface area, temperature, relative

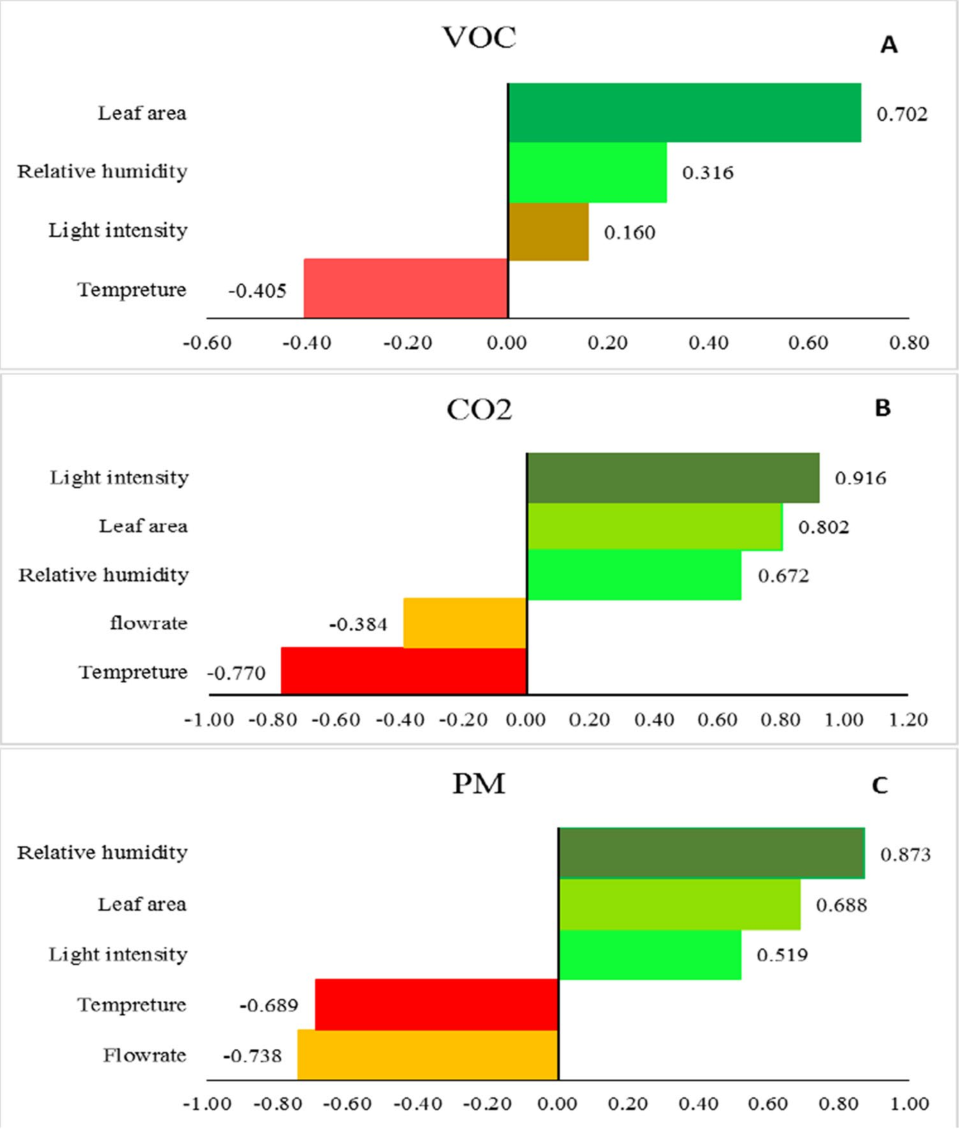

Fig. 2 Tornado graph for Pearson and ANOVA correlation coefficient between factors affecting removal rate, **A** VOC, **B** CO_2 and **C** PM Removal rate

humidity, and light intensity, respectively. Leaf surface area, humidity, and light intensity had a direct effect on the removal efficiency of VOCs and with the increase of these parameters, the removal rate also increased; however, the temperature had an inverse effect and with increasing temperature, the removal efficiency decreased. Likely, the effect of light intensity on the removal efficiency of VOCs is low, because a different range of light intensity was not evaluated in the studies. Phytoremediation by potted plants was the preferred method to remove VOCs from indoor polluted air. Therefore, the flow rate was not involved in VOCs removal by potted plants.

As Fig. 2(b) shows, light intensity, leaf surface area, and relative humidity had a positive effect on CO_2 removal efficiency, while temperature and flow rate showed a negative effect. An independent *t*-test was performed to compare the performance of two common evaluated plants in CO_2 removal and no significant difference was observed between plants (*P*-value = 0.982 > 0.05). Both potted plant and green walls were frequently used for purification of CO_2 from indoor air, to compare the performance of the two treatment methods in CO_2 removal, an independent *t*-test was performed and no significant difference was observed between the two methods (*P*-value = 0.109 > 0.05).

In the case of particulate matter in the air, the humidity was the most effective factor on PM removal efficiency followed by flow rate, temperature, leaf area, and light intensity. Leaf surface parameters, humidity, and light intensity had a direct effect on PM removal and with the increase of these parameters, the removal rate also increased, but the temperature and flow rate parameters had the reverse effect and with their increase, the removal efficiency decreased Fig. 2(c). ANOVA sensitivity analysis was performed to the comparison of the commonly used plants performance in the elimination of pollutants from the air. However, no significant difference was observed between different plants (*P*-value = 0.502 > 0.05). Independent *t*-test represented that no significant difference was between the results achieved by potted plants and green walls in the purification of PM from the air (*P*-value = 0.598 > 0.05).

Research has shown that the purification capacity of plants can be improved by modifying the substrate. Therefore, in this review, sensitivity analysis using ANOVA was conducted for evaluating the effect of various growth substrates studied in the removal of pollutants. Figure 3 illustrated the mean removal rate of the pollutants according to the type of media. The amount of calculated *P*-value (0.044 < 0.05) showed that there are significant differences in removal efficiencies of different substrates. Therefore, based on post hoc analysis, type 1 (soil) and 2 (commercial potting mix) substrates were put in one group and type 3 (coco coir) with 4 (coco coir + activated carbon) were made another group. The group including types 3 and 4 showed higher efficiency than the other group in removing VOCs. Independent *t*-test analysis between VOCs removal efficiency and potted plant as well as green wall purification methods with different substrates was performed separately but no significant difference was observed between the two purification methods (*P*-value > 0.05).

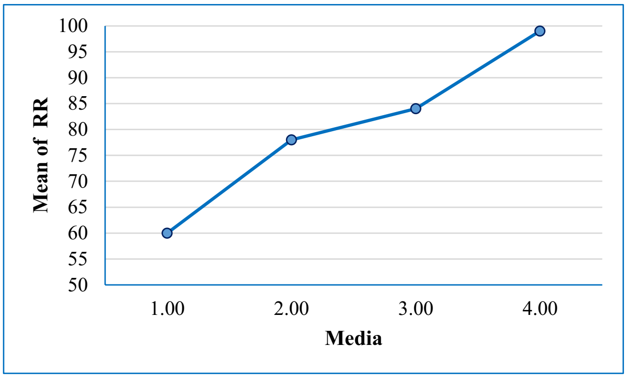

Fig. 3 Mean removal rate of the pollutants according to the type of media, type 1 (soil), type 2 (Commercial potting mix), type 3 (coco coir), type 4 (coco coir + activated carbon)

Conclusions and future challenges:

The main purpose of this review study was to provide information and discuss the removal of indoor air pollutants by plants, which is a convenient, affordable, environmentally friendly, and accessible method for all communities. According to the studies, removal of contaminants from indoor air by plants has been carried out mostly through passive filtration using potted plants or through active filtration using plant filters or green walls. These studies have concluded that the specific plant species have the potential to absorb and remove harmful contaminants inside the building, including VOCs. Sensitive analysis conducted in the current study revealed that the factors affecting phytoremediation efficiency show different behavior depending on the type of plant and pollutant. In addition, this analysis represented that using a mixture of coco coir and activated carbon as growing media significantly increases the removal efficiency of VOCs (*P*-value > 0.05).

Because the concentration of most contaminants in the indoor air is not clear, it is not possible to estimate the accurate number and size of plants needed to purify indoor air effectively. Therefore, determining the concentration of pollutants in indoor air is very important. Another major challenge is the difference in photosynthesis between plant species. In many plants, higher levels of light intensity than their optimal light levels can reduce the rate of photosynthesis. Therefore, the most appropriate light levels for plants should be selected, and this requires extensive studies with a variety of plant species to determine their desired light levels. Most phytoremediation studies have been conducted with species that grow slowly. Thus, studies on a variety of plants with fertility and high growth rate are recommended to assess the removal potential of contaminants. As different cultures and lifestyles of residents has created a variety of pollutants in the indoor spaces, it is recommended to study the simultaneous removal of a mixture of contaminants. Another challenge in using plants is the need for a large number of them to be effective in improving indoor air, given the fact that the majority of living places and offices are small and it is not possible to use a large number of potted plants. Therefore, it is suggested that studies on phyto-biofiltration systems or green walls with different plant species be conducted and expanded, because plants in living walls can simultaneously remove a mixture of contaminants in a single system with the need for less space. As, there are a few studies about the removal of contaminants such as particles, CO and NO_2 by plants, it is suggested to perform further phytoremediation research using common indigenous plants to remove all indoor contaminants that threaten human health.

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Author contribution The individual contributions of authors to the manuscript are specified as follow: A A: supervision, methodology, data curation; Y H: conceptualization, methodology, supervision, writing—review and editing; H T: investigation, methodology, literature review, writing—original draft; all authors read and approved the final manuscript.

Data availability All the necessary data generated or analyzed during this study are included in this published article. However, the datasets for statistical analysis are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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