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Phytoremediation potential of indoor plants in reducing air pollutants

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Indoor air quality (IAQ), specifically after the COVID-19 pandemic, has become an international issue, as humans spend 80–90% of their time in indoor microenvironments. Poor IAQ has been related to the sick-building syndrome, nasal and ocular irritations, allergies, and respiratory dysfunction, including premature deaths. Phytoremediation is a novel strategy to absorb, adsorb, assimilate or transfer/reduce air pollutants and improve the IAQ using plants. Hence, the current review aims to explore indoor plants' role in improving indoor air quality, including their purification capabilities. There is increasing evidence that various plant species (e.g., *Ficus benjamina, Chlorophytum comosum, Draceana*) or their parts can reliably reduce the concentration of numerous air pollutants in the indoor microenvironment and promote human wellbeing. However, the indoor air pollutants removal efficiency depends on the species of plant, various plant characteristics such as leaf size, thickness, area, photosynthetic activity, light intensity and part of plant involved, i.e., roots, leaves, wax, cuticle and stomata. Using indoor plants is one of the most cost-effective and reliable methods of making a healthier indoor environment. Better public health can be maintained at a lower cost, with less strain on the health care system, if more emphasis is placed on creating a biophilic atmosphere and increasing the use of indoor plants. However, there are no established criteria for the best indoor plants and the impact of indoor plants on various factors such as interior ventilation, temperature, humidity, etc. Therefore, further experimental research is needed that simulates the interior environment to monitor the impacts of indoor plants on factors such as humidity, temperature, ventilation, etc., in improving the microenvironment of a closed space/room.

KEYWORDS

indoor air quality (IAQ), air pollutants, removal efficiency, indoor plants, air remediation

Highlights

- Study examines the available evidence of the phytoremediation potential of indoor air pollutants.
- Indoor air pollutants removal efficiency depends on the parts of the plants involved: roots, leaves, wax, cuticle and stomata.

- Effect of plant-microbiome needs to be fully understood for indoor pollutants removal.
- Indoor plants offer an eco-friendly option for air purification with minimal energy consumption.

Introduction

Air quality is a crucial environmental factor affecting people's health, comfort and productivity. Air pollution has a negative impact on human health. Primary and secondary air pollutants like particulate matter (PM), volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, xylene (BTEX), formaldehyde, polyaromatic hydrocarbons (PAHs), and inorganic pollutants (O_3, NOx, CO_2, SO_2) remain present in ambient air in very high concentration specifically in lower and middle-income countries. There has been growing evidence that air pollutants are the root cause of the rise in the incidence of respiratory health issues in developing nations like China and India (Gulia et al., 2021; Zhang et al., 2022). These air pollutants could be present even at higher concentrations in indoor environments than outdoor ones (Myers and Maynard, 2005; Morawska et al., 2013).

In recent years, the energy crisis has led to the construction of air-tight, thermally insulated buildings, demanding less energy for heating. But in efforts to reduce energy consumption, less attention is paid to ventilation systems in the building. Due to reduced gaseous exchange, contaminants can accumulate up to toxic levels inside closed spaces leading to serious health concerns. Since most people in this modern time spend 85–90% time in indoor microenvironments such as schools, homes, or offices (Klepeis et al., 2001; Soreanu et al., 2013; Ravindra et al., 2020), the quality of indoor air become a major concern for better health.

Poor indoor air quality (IAQ) is known to be associated with the sick-building syndrome, which includes respiratory dysfunction, severe headache, ocular and cutaneous irritations, allergies, fatigue, and metabolic disorders (Brasche et al., 1999; Liu et al., 2016) and in some severe cases can lead to death (D'Amato et al., 2002). In addition to these health-related problems, indoor air pollution also decreases work efficiency and increases medical expenses, thus affecting the financially. According to the WHO report, indoor air contaminants accounted for 4.3 million premature deaths in 2012 (World Health Organization, 2014) and 3.8 million deaths in 2016, mainly in low- and middle-income countries (World Health Organization, 2016).

Pollutants present in indoor air come from different sources like outdoor air, fuel combustion, pets, furniture, paints, electronic equipment, etc. (Afshari et al., 2005; Yu et al., 2009; Clausen et al., 2011; Sharma et al., 2019; Ravindra et al., 2021a) as shown in Figure 1. Fungi and bacteria also contribute to lowering IAQ. Carbon dioxide (CO_2) is a common indoor pollutant released by occupants' breathing activity. Its concentration can rise several times higher than the standard value in air-tight spaces. A high concentration of CO_2 causes fatigue, drowsiness, headache, loss of concentration, nose and throat irritation, nasal discharge, cough and eye discharge (Seppanen et al., 2005; Llewellyn and Dixon, 2011; Ercan, 2012; Cetin and Sevik, 2016). Therefore, CO_2 concentration is typically used as a parameter to check the ventilation rate in closed spaces (Zhang and Smith, 2003).

Besides CO_2, PM and VOCs are the two primary pollutants in the indoor air. PM are hazardous as they can easily accumulate in the living cells and have high heavy metal content (Gawrońska and Bakera, 2015; Sonwani et al., 2022). Another class of pollutants, i.e., VOCs, are compounds with low molecular weight, such as aromatic, halogenated and oxygenated hydrocarbons with a 50–60°C boiling point at room temperature (Ravindra et al., 2008; Kim et al., 2018). In addition to other health-related issues, VOCs like and formaldehyde and benzene have also been reported to be carcinogenic (Nielsen and Wolkoff, 2010; Aydogan and Montoya, 2011). Prolonged exposure to these pollutants and their synergetic effect is the main reason behind health-related problems caused by poor IAQ (Soreanu et al., 2013).

Thus, maintaining an indoor environment could be an essential criterion for human health and comfort. Numerous modern techniques have been developed to maintain the air quality in closed spaces, but none seem promising in maintaining the level of pollutants. None of the present air purifiers can remove all the contaminants to match the standards fixed by World Health Organization (WHO) and they are very expensive. It has also been reported that some air purifiers emit ozone which is also toxic for humans if it accumulates beyond a certain level (Britigan et al., 2006). Hence, continuous efforts are being made to develop economical and sustainable air-purifying techniques. Growing decorative plants in indoor environments can provide a much more efficient and natural approach to abate the concentration of different air pollutants in ambient air. Han and Ruan (2020) conducted a systematic review and found that indoor plants have the potential to improve the air quality, followed by a decrease in temperature and an increase in humidity. In contrast, Susanto et al. (2021) suggested that indoor plants can be used as an alternative way to reduce indoor air pollution.

Indoor plants purify the air and positively affect the occupant's work productivity and mental health (Shibata and Suzuki, 2004; Han, 2009; Park and Mattson, 2009; Raanaas et al., 2011; Deng and Deng, 2018; Saxena and Sonwani, 2020). Over the past three decades, various studies have elaborated that indoor plants may dramatically reduce the majority of indoor air pollutants. In the post COVID-19, people are shifting toward traditional and greener options and reducing the usage of artificial purifiers. Therefore, appropriate low-cost methods of changing indoor air quality and microclimate conditions should be researched.

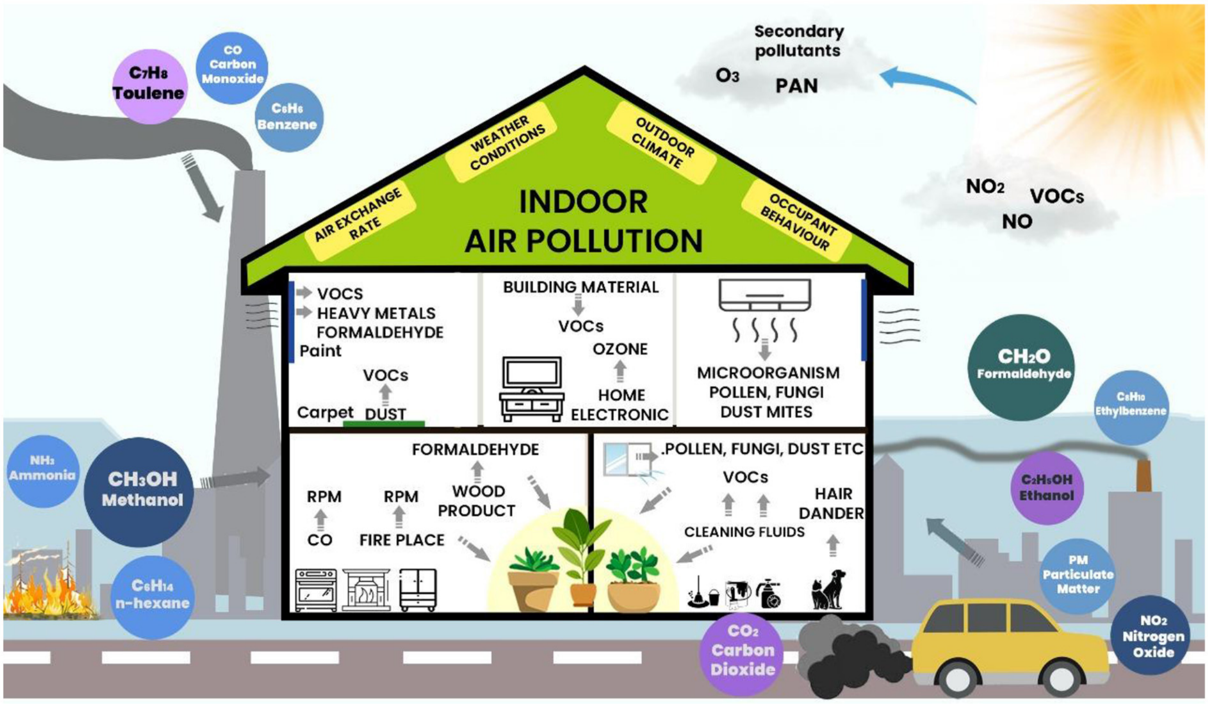

FIGURE 1
Major indoor air pollutants and their sources.

However, there have been no thorough assessments of the impact of indoor plants on air quality. To fill a gap in the literature, this study examines the existing literature to provide an overview of the effects of indoor plants on air quality, including identifying the main classes of indoor air pollutants and their impact on human health. The manuscript's key focus is to highlight the various mechanisms by which decorative plants take up indoor air pollutants and convert them into less toxic or harmless metabolites. The study also identifies the major plant species reported to be effective for indoor air phytoremediation and to regulate interior environmental comfort and air quality.

Methodology

This comprehensive literature review explores and discusses the role of indoor plants in improving indoor air quality for human health and comfort. The inclusion criteria for screening the existing literature were: (1) recent publication in an international peer-reviewed journal available on PubMed, Google Scholar, Scopus, or Science Direct database (irrespective of date); (2) emphasis on articles that review the main classes of indoor air pollutants and their impact on human health, plants involved in the uptake of indoor air pollutants and converting them into less toxic or harmless metabolites, related mechanism of action, parts of plants involved in improving air quality; (3) published in English (4) both *in-vivo* and *in-vitro* studies were also considered. The exclusion criteria include (1) thesis, dissertations, conference proceedings, letters to the editor and editorials; (2) language except for English. The keywords begin with "indoor air quality", followed by the search words and their combinations: "air pollutants", "phytoremediation", "indoor plants", "household air pollution" "indoor air quality" and "public health". The search was performed using Boolean logic searching methods (AND/OR/NOT/()/" "). A manual search for relevant articles was also conducted in the bibliography section of each article.

Further, a bibliometric analysis was done to extract the snapshot of the research domain by objectively and statistically examining the bibliographic data. Swift collection of the database was done based on the keyword frequency using the dimensions website (https://www.dimensions.ai/). "Indoor air plants" AND "air pollution" AND "public health" AND "phytoremediation" were used as search terms to identify the most relatively matching publication. The retrieval was made on November 2, 2022. VOSviewer (version 1.6.10) was utilized to analyze citations and publications based on countries.

Bibliometric analysis

The global literature published between 1970 and 2021 on the influence of indoor plants on indoor air quality was analyzed through the dimensions database collection. The original

TABLE 1 Top 20 countries based on total link strength using bibliographic analysis approaches.

S.No.	Country	Documents	Citations	Total link strength
1.	China	245	9,279	621
2.	Australia	64	3,368	515
3.	United States	151	6,878	340
4.	United Kingdom	65	2,318	325
5.	India	118	5,279	288
6.	South Korea	44	2,055	273
7.	Germany	43	2,122	246
8.	Pakistan	37	2,018	167
9.	Malaysia	35	1,107	164
10.	Iran	36	555	163
11.	Canada	26	2,159	139
12.	Poland	33	1,699	111
13.	France	30	1,744	101
14.	Italy	43	803	95
15.	Egypt	23	918	91
16.	Belgium	19	1,242	89
17.	Spain	26	999	87
18.	Sweden	16	1,141	83
19.	Saudi Arabia	18	455	68
20.	Thailand	17	492	66

number of published articles revealed that 1,174 documents are available between 1970 and 2021. The information for the articles that met the requirements was exported in CSV format and included publication year, language, journal, title, author, affiliation, keywords, document type, abstract, and citation counts. The network and density of the countries based on relevant documents pertaining minimum of 10 citations/10 documents from the different geographic areas were viewed using VOSviewer.

The table generated by the VOSviewer software shows the prominent countries that published articles on the topics of indoor air quality. Table 1 depicts top 20 countries based on total link strength. According to the VOSviewer manual, each link carries a strength, which is represented by a positive numeric value. The greater this value, the greater the link's strength. The total link strength reflects the number of occurrences of search keyword queries in published articles. China has a total link strength (621), followed by Australia (515), the United States (340), and then the United Kingdom (325). India is at fifth position with 288 link strength. The origin seems far more global, spanning Europe, Asia, and America.

Figure 2 illustrates the Bibliometric analysis of citations and publications by country. The size of each circle corresponds to the number of co-citations. The distance between the two circles represents their correlation. On the basis of citations, various colors represent distinct groups. Scientific research plays a vital role in understanding the effects of indoor plants on indoor air quality.

Indoor air quality

The air quality within and around buildings and other structures impacts the health of the occupants. In urban areas, mechanical heating and cooling air ventilation systems (known as HVAC) are used to maintain the temperature and IAQ of closed spaces like offices, schools, homes, etc. In order to lower energy utilization, buildings are made as air-tight as possible to prevent the infusion of unconditioned outside air with conditioned air inside. The construction of thermally insulated buildings comparatively requires less energy for heating and air conditioning, which has increased the problem of indoor pollution worldwide. Moreover, in lower and middle-income countries, most rural populations depend on solid biomass burning as their primary source of household energy for their daily needs, including cooking and residential heating (Ravindra et al., 2020, 2021b).

In 2015 emission from the incomplete combustion of solid biomass fuel was reported to be associated with over 2.9 million premature deaths on a global scale and ranked as the 8th major risk factor contributing to the global burden of disease (Ravindra et al., 2020). Thus, indoor air pollution has emerged as an essential consideration to minimize the preventable burden of death and disability to improve public health (World Health Organization, 2014, 2016). Particulate matter pollution, biological pollution (such as pollen, fungi, molds, dust mites, etc.), physical pollution caused by agents such as temperature and electromagnetic fields, and chemical pollution, which includes volatile organic compounds in addition to radon, carbon monoxide, and other non-organic chemicals, are the four categories that can be used to classify indoor air pollution (Kim et al., 2018).

VOCs are considered an extensively studied class of indoor air pollutants. Their indoor levels can rise up to 10 times higher than the outdoor air levels (Žuškin et al., 2009). They are released from various sources building materials, paints, adhesives, cosmetics, furniture, carpets, electronic equipment, cleaning products and occupant activities (Yu and Crump, 1998; Llewellyn and Dixon, 2011; Agarwal et al., 2019). The concentration of VOCs also varies with time, occupant activities and depending on the type of indoor environment. During winters, their indoor amount is notably higher as most windows remain closed. Various VOCs are present in the indoor environment, among which formaldehyde, benzene, toluene, ethylbenzene, xylene, and polyaromatic hydrocarbons (PAHs) are most widely studied due to their hazardous nature.

CO_2 is a common indoor air pollutant, present in very high concentrations in poorly ventilated rooms and buildings due

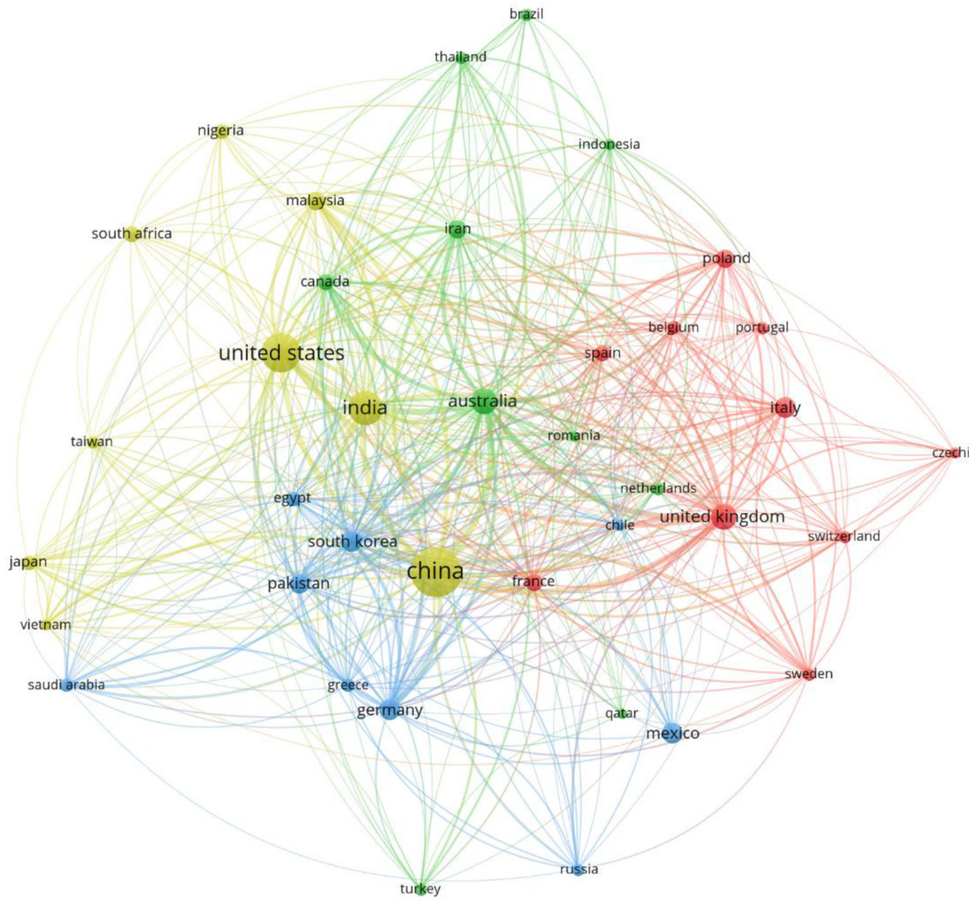

FIGURE 2
Countries' network and density based on relevant documents on phytoremediation of indoor air pollution using bibliographic analysis.

to continuous respiratory emissions by occupants (Llewellyn and Dixon, 2011; Kaur-Sidhu et al., 2020). Other sources of CO_2 inside closed spaces include gas stoves, fireplaces, cigarette smoking and microbial activities. All these activities can increase CO_2 concentration to a much higher level than its outside ambient environmental concentration. Usually, the average outdoor air concentration of CO_2 is ∼400ppm, as provided by World Meteorological Organization (WMO, 2018). However, this level may rise up to 2000-2500 ppm in crowded and under-ventilated rooms (Persily and Gorfain, 2004; Pettit et al., 2018). CO_2 concentrations are generally used to measure the ventilation rate in buildings and levels below 1,000 ppm indicate an adequate fresh air supply in the room. They are frequently used to examine and investigate a building's ventilation capacity to remove indoor air contaminants.

Particulate matter is generally classified based on its aerodynamic diameter ranging from 0.001 to 10 μm. The smaller the size, the deeper it can penetrate the human respiratory system; thus, fine and ultrafine particles affect health more severely than coarse particles. Fine particles in indoor air have been reported to be the most hazardous fraction of air pollutants leading to various human health impacts (Pandey et al., 2021; Sonwani et al., 2021). Particulate matter is emitted into the indoor air during cooking, ironing, cleaning, smoking, and other occupant activities and remains suspended in the air for a long time (D'Amato et al., 2002; Afshari et al., 2005). PM_{10} and $PM_{2.5}$ are the most extensively studied categories of particulate matter. There are various toxic components of air pollutants, such as heavy metals and organic compounds like PAHs, which remain absorbed/adsorbed on fine particles (Ravindra et al., 2001, 2006; Masiol et al., 2012). Further, environmentally persistent free radicals can also adhere to indoor particles, increasing their bio-availability and enhancing the accumulation of toxic fractions in the living cells (Saravia et al., 2013).

Health effects of indoor air pollutants

Several studies provide direct evidence of exposure to indoor fine particles and their association with various respiratory illnesses such as impaired lung function, asthma and chronic obstructive pulmonary disease (COPD) (Upadhyay et al., 2014; Wu et al., 2018; Shetty et al., 2021). It has been estimated that exposure to toxic indoor fine particles could contribute to around 10–30% of the global burden of disease (Morawska et al., 2013). Indoor air pollution has been related to various health effects, including irritation of the eyes and upper respiratory tract, chronic lung inflammation, cardiovascular disease, and, in extreme cases, cancer (Ravindra, 2019). Exposure to high particle concentration has been linked to increased morbidity and mortality due to cardiovascular, respiratory and venous thromboembolic disease (Bari et al., 2014; Ge et al., 2018).

Simoni et al. (2002) discovered a relationship between indoor $PM_{2.5}$ exposure and the onset of bronchitis and asthma symptoms, particularly during the winter months, in northern-central Italy. Moreover, 51% of the global death ratio and 50% of disability-adjusted life years were reported to be linked with $PM_{2.5}$ exposures in India and China (World Health Organization, 2016). In India, particulate matter was found to be responsible for 1.1 million premature deaths in 2015. Prolonged exposure to PM_{10} and $PM_{2.5}$ can cause inflammation of the alveoli. This could lead to blood coagulation and the release of harmful inflammatory cytokines. Further, severe exposure to fine indoor particles has been reported to be associated with bronchitis, asthma and neuron damage, including myocardial infarction and ischemic heart disease (Rai, 2015; Manisalidis et al., 2020).

Moreover, most indoor VOCs are identified as human carcinogens and their exposure has been associated with respiratory problems, including asthma. Formaldehyde is a ubiquitous indoor pollutant and is classified as a Group I carcinogen by International Agency for Research on Cancer (IARC) (2006). There is sufficient epidemiological evidence that stipulates that formaldehyde causes cancer in humans. According to IARC, formaldehyde causes nasopharyngeal cancer in human beings. Among BTEX hydrocarbons, benzene is also reported to induce cancer and is considered one of the most toxic VOCs. It can potentially produce hematological illnesses such as acute and chronic lymphocytic leukemia, acute myeloid leukemia, non-lymphoma, Hodgkin's multiple myeloma, and aplastic anemia (Snyder, 2012). Further, various studies have linked VOC exposure to respiratory, hepatic, nervous and renal problems (Mendell, 2007; Sriprapat et al., 2014a; Mozaffar and Zhang, 2020).

Poor indoor air quality also causes sick building syndrome known as SBS, including multiple chemical sensitivity and new house syndrome (Shinohara et al., 2004). Indoor air pollutants can act as a carrier of allergens, respiratory and eye irritants, and toxicants (Bernstein et al., 2008; Ravindra, 2019; Ravindra et al., 2021a). The most common indicators of poor IAQ are ocular, nasal and cutaneous irritation, severe allergies, headache, fatigue and respiratory dysfunction, symptoms collectively known as SBS (Aydogan and Montoya, 2011; Lu et al., 2016).

Role of plants for absorption and removal of indoor pollutants

Plants kept indoors serve as a component of the three-dimensional environment and interact with humans in a wide variety of ways. Numerous studies discuss the different aspects of plant characteristics, such as leaf area, number, sunlight intensity, respiration, and photosynthesis, to remove air pollutants effectively. Irga et al. (2013) estimated that 57 m^2 of leaf area would be able to absorb/remove around 13% of CO_2 generated per person in an average room without ventilation. The greater the leaf area, the more CO_2 is removed by indoor plants. Previous studies have also suggested that leaf characteristics significantly remove pollutants, as shown in Table 2. Various other leaf characteristics, i.e., leaf roughness, thickness and leaf villi, were also important aspects concerning dust retention ability (Jia et al., 2012; Lu et al., 2018; Jeong et al., 2020).

At the same time, Fujii et al. (2005) reported an increase in the removal efficiency of CO_2 with increasing illuminance. Also, Burchett et al. (2011) found that low light intensities (~10 PAR $\mu mol\ m^{-2}\ s^{-1}$) showed no or less CO_2 removal. The removal rates were quite inadequate, even with a reasonable number of plants to improve indoor air quality. This lower efficiency of CO_2 removal was due to the respiration process taken place by non-green parts of plants and pot microorganisms. Therefore, for potted plants, the increased light intensity with reduced pot mix microorganisms is required (Burchett et al., 2011). Hörmann et al. (2018) showed that the value of toluene varied between 3.4 and 5.7 $L\ h^{-1}\ m^{-2}$ leaf area with no significant differences between selected plant and light conditions (light/dark). (Orwell et al., 2004) observed that the removal rate of benzene per pot ranged from 12 to 27 ppm d^{-1} and microorganisms of the potting mix rhizosphere were the primary agents of removal.

Some air-purifying houseplants are depicted in Figure 3. During photosynthesis, the photoelectric effect in the leaf produces a large number of negative air ions (NAIs), which is responsible for absorbing dust and improving air quality (Wu and Lee, 2004; Perez et al., 2013; Yan et al., 2015). Shiue et al. (2011) also reported that NAIs effectively reduce the aerosol pollutants in average-sized rooms. Moreover, the production of NAIs during photosynthesis is beneficial to the health of individuals. However, using plants to produce fresh air with

TABLE 2 Plant characteristics and their role in removing indoor air pollutants.

Parameters	Pollutant		Removal efficiency	References
Leaf surface area	687 m^2	CO_2	145.6 mg CO_2/day	Fujii et al., 2005
	763 m^2		27.5 mg CO_2/day	
	796 m^2		44.7 mg CO_2/day	
	10.2 m^2		79.5 ppmv h^{-1}	Deng and Deng, 2018
Leaf thickness and surface area	0.14–0.80 mm, 123–4,270 cm^2	PM	3.3–286.2 $\cdot m^{-2}$ leaf	Jeong et al., 2020

FIGURE 3
List of selected air-purifying house plants.

abundant NAIs indoors is still a major challenge. Hence, there is a need to understand the optimization of the relationship between them.

Pathways and mechanisms for indoor air pollutants removal by plants

Phytoremediation strategies

Phytoremediation is a bioremediation technique using plants and associated microorganisms to remove, transfer, stabilize or destroy pollutants (Newman and Reynolds, 2004). Plants are well known for their ability to absorb and metabolize toxic compounds from air, water and soil. Using green plants to improve IAQ offers a comparatively less expensive and environmentally friendly option than modern high-energy consuming techniques. Indoor plants eliminate harmful pollutants and have a positive psychological effect on occupants, thus enhancing human health and wellbeing (Fjeld et al., 1998; Han, 2009). Several studies focus on describing the role of plants in remediating poor IAQ, such as Darlington et al. (2001), Wood et al. (2002), and Aydogan and Cerone (2021).

Plants can absorb and assimilate air pollutants through regular gas exchange *via* the stomatal opening. Some indoor contaminants are known to be removed by microorganisms associated with plants or through direct adsorption to the plant surface (Son et al., 2000; Orwell et al., 2004). There have been different techniques used for phytoremediation based on their physical properties, type of the plant and medium of remediation, i.e., Phytoextraction, Phyto filtration, Phyto stabilization, phytodegradation, rhizodegradation and phytovolatilization, shown in Figure 4 (Moya et al., 2019). All these techniques use different metabolic processes to filter the pollutants. Figure 5 shows the contribution of

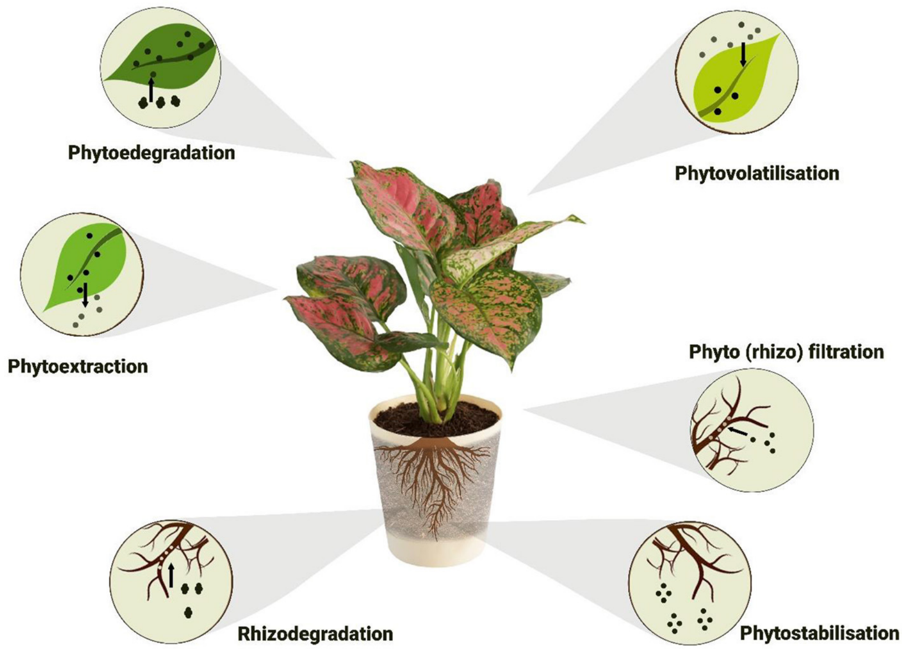

FIGURE 4
Depicting different phytoremediation techniques.

different plant parts in removing indoor pollutants from the surrounding air.

Entry of pollutants into the plants and mechanism of action

Photosynthesis is the primary process responsible for lowering the amount of indoor CO_2. Plants uptake CO_2 and releases O_2 in the surrounding atmosphere. They utilize CO_2 as a source of carbon to synthesize organic compounds by using sunlight and water as a source of energy. Hence, the rate of photosynthesis depends upon the conditions like availability of sunlight, amount of CO_2 and temperature (Zeiger and Field, 1982; Cure and Acock, 1986). The rate of photosynthesis increases with the increase in the concentration of CO_2 under vigorous light intensity, releasing more O_2 into the air.

NASA conducted a series of experiments that proved that green plants could efficiently remove VOCs from the air (Wolverton et al., 1989). Plants remove toxicants from the air either through stomatal uptake (Newman and Reynolds, 2004) or by adsorbing them on their leaf surface (Orwell et al., 2004). Plants can metabolize these chemicals into non-toxic compounds, either utilized by them or released into the surrounding atmosphere (Newman and Reynolds, 2004; Liu et al., 2007). Transpiration is a normal process of water evaporation from plant parts, mainly leaves, that increase the level of humidity in closed spaces, thus making the indoor environment more comfortable for the occupants (Aydogan and Montoya, 2011; Llewellyn and Dixon, 2011; Kichah et al., 2012; Deng and Deng, 2018).

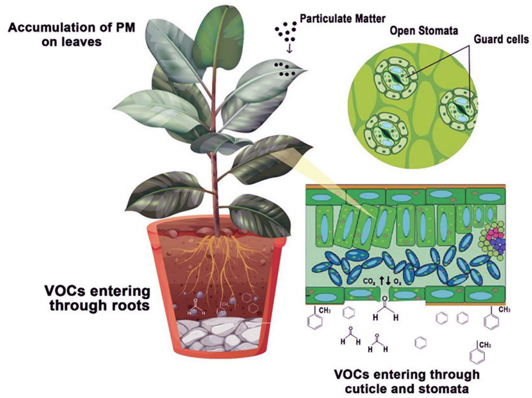

FIGURE 5
Parts in the removal of indoor pollutants from the surrounding air.

In plants, both the aboveground and belowground plant parts play a role in purifying indoor air. Stomata present on the leaf surface provide a natural gateway for gaseous pollutants into the plant body. The cuticle also plays an essential role in adsorbing air contaminants. For example, in Z. zamiifolia, cuticular absorption accounted for 20% of benzene, 23% of toluene, 25 % of ethylbenzene, and 26% of xylene uptake (Sriprapat and Thiravetyan, 2013). After entering into the leaf, contaminants can be degraded, retained, or excreted either at the uptake site or after translocation to other sections. Kondo et al. (1995) showed that increased stomatal conductance of *Nerium Indicum* was linearly related to the increased formaldehyde removal from the surrounding. Benzene can penetrate more quickly due to its hydrophobic nature toward the cuticle, while formaldehyde enters more rapidly through the stomatal opening as shown in Figure 6 (Cruz et al., 2014).

The actual pathway or uptake of indoor pollutants depends on their physicochemical properties. Hydrophilic pollutants (such as formaldehyde) cannot quickly diffuse/penetrate through the cuticle (as it is made up of lipids) and often enter through the stomatal openings. Roots are also involved in decontaminating the indoor air. Roots take up pollutants by themselves from the surrounding air and increase pollutant's bioavailability for the microorganisms (Wenzel, 2009). Once taken up by roots, pollutants are either metabolized or translocated to the aboveground parts for further processing or storage. Removal of aboveground parts affects the efficiency of the root zone for pollutant uptake. In the absence of photosynthesis, no root exudation occurs, which is mainly responsible for increasing the bioavailability of pollutants. Transpiration pull will also be lacking; therefore, absorbed pollutants cannot be transported to the other parts. These factors reduce the ability of roots to remove pollutants from the indoor air. Table 3 shows the list of indoor plants involved in air pollutant removal.

Several enzymes, such as formate dehydrogenase, cytochrome P450 monooxygenase, and dioxygenase, also play an essential role in plant cellular detoxification pathways (Rylott and Bruce, 2009). They are actively involved in the oxidation of the BTEX (xylene) group of pollutants. BTEX mainly enters the plant body through the stomata. After entering into the leaf, they are targeted to intracellular compartments for transformation. Cytochrome P450 enzymes are present on the membranes of the endoplasmic reticulum. Hydroxylation and cleavage of the aromatic ring are the main steps in BTEX transformation. Phenol is the first intermediate metabolite formed during benzene metabolism, which is then converted into catechol. Finally, cis-cis muconic acid is formed through the cleavage of an aromatic ring, with o-quinone formation, as an unstable intermediate. Muconic acid is the first organic acid formed during benzene metabolism, which can be further oxidized to fumaric acid.

Since fumaric acid is an intermediate of the Tricarboxylic Acid (TCA) cycle, it can directly enter into the TCA cycle. Studies using ^{14}C-labeled benzene indicate that benzene degrades into both high and low-molecular-weight compounds.

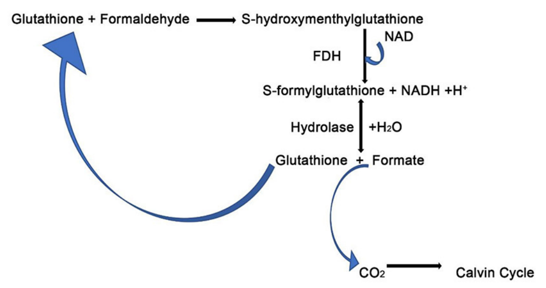

FIGURE 6
Steps in the formaldehyde metabolism by formaldehyde dehydrogenase enzyme.

Still, the maximum radioactivity was found in low molecular weight molecules such as organic acids and amino acids, as shown in Figures 6, 7, which depict formaldehyde metabolism and pathway of benzene metabolism in plants.

Microflora and indoor air pollutants

Microflora associated with plant parts also plays a vital role in removing pollutants (Orwell et al., 2004; Weyens et al., 2015). Numerous bacteria and fungi have been found to be symbiotically associated with the roots (rhizosphere) and leaves (phyllosphere) of plants which help the host plant in nutrient and water uptake, provide protection against pathogens and withstand biotic and abiotic stress (Weyens et al., 2009, 2015; Bulgarelli et al., 2013). Plant microcosm also assists the host plant in detoxifying air by increasing the bioavailability of pollutants to different parts, thus removing them from the air (Claudio, 2011).

Plant-microbe interaction is critical in phytoremediation because it sequesters and degrades contaminants while promoting plant growth (Weyens et al., 2009, 2015). Microorganisms living in the rhizosphere and phyllosphere have the ability to absorb pollutants from the ambient atmosphere (Sorkhoh et al., 2011). In fact, the removal capacity of plants for VOCs is now mainly attributed to the activity of microflora associated with the roots of plants (Llewellyn and Dixon, 2011). However, the effect and complexity of the plant microbiome need to be fully understood to remove indoor pollutants effectively.

Future perspective

Scholarly articles published on indoor plants affecting air quality indicate IAQ is drawing more attention. Indoor plants are the best-suited eco-friendly approach toward air purification/remediation with minimal energy consumption.

TABLE 3 List of indoor plants and their parts involved in air pollutant removal.

Pollutant	Indoor plant species	Plant part involved	Removal rate	References
Formaldehyde	*Chrysanthemum morifolium, Epipremnum aureum*	Roots	81–96%	Aydogan and Montoya, 2011
	Chlorophutum comosum, Dieffenbachia amoena, Epipremum aremum		11%	Dingle et al., 2000
	Ficus benjamina		80%	Kim and Kim, 2008
	Chlorophytum comosum		60%	Xu et al., 2011
Benzene	*Chlorophytum comosum*	Leaves	95% in 7days	Zhou et al., 2011
	Asparagus densiflorus Hemigraphis alternata, Hoya carnosa, Tradescantia pallida	Leaves	2.61–5.54 mgh^{-1} m^{-3} m^{-2}	Yang et al., 2009
	Chlorophytum comosum	Shoots	88%	Giese et al., 1994
	Dracaena sanderiana	Wax and stomata	66–70% in 24 h	Treesubsuntorn and Thiravetyan, 2012
Ketones	*Epipremnum aureum, Spathiphyllum clevelandii*	Leaves	50–65%	Tani and Hewitt, 2009
Toluene	*Asparagus densifloru Hemigraphis alternata, Hoya carnosa*	Leaves	5.81–9.63 mg m^{-3} m^{-2} h^{-1}	Yang et al., 2009
	Draceana		2.2–549 mg m^{-3} d^{-1}	Orwell et al., 2006
	Sansevieria Hyacinthoides, Zamioculcas zamiifolia	Wax	85%	Sriprapat et al., 2014b
	Zamioculcas zamiifolia	Cuticle and stomata	95%	Sriprapat and Thiravetyan, 2013
Xylene	*Draceana*	Leaves	90% in 5 days	Orwell et al., 2006
	Zamioculcas zamiifolia		95% in 72 h	Sriprapat et al., 2014a
Trichloro ethylene (TCE)	*Hemigraphis alternata, Hedera helix, Tradescantia pallida, Asparagus densiflorus, Hoya carnosa*	Leaves	5.79–11.8 mg m^{-3} m^{-2} h^{-1}	Yang et al., 2009
	Ficus elastica		9.8% h^{-1}	Cornejo et al., 1999
Ethylbenzene	*Zamioculcas zamiifolia*	Cuticle and stomata	95%	Sriprapat and Thiravetyan, 2013
	Sansevieria hyacinthoides	Wax	90%	Sriprapat et al., 2014a

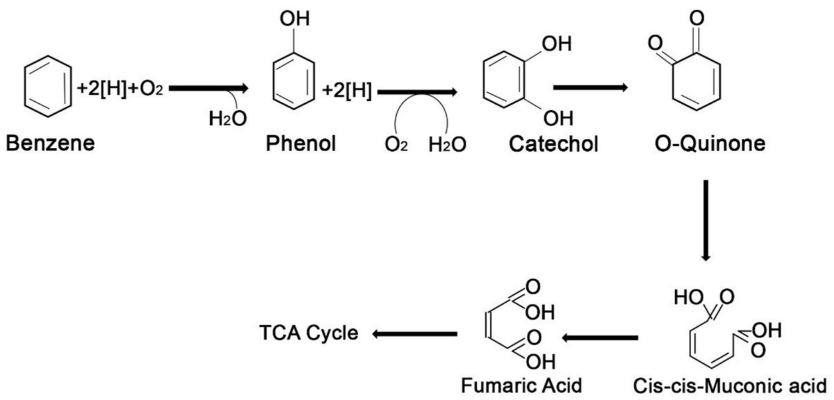

FIGURE 7
Pathway of benzene metabolism in plants.

But more in-depth studies are required to quantify the reduction in the actual amount of energy consumption due to plants. Moreover, various plant species that are likely candidates for use as house plants further need to be identified. Therefore, there is a significant window of opportunity for researchers, botanists, environmentalists, health and medicine experts to collaborate and investigate a specific plant's species, its criteria for indoor plants and their benefits.

More empirical research is needed to determine how indoor plants mitigate pollutants like formaldehyde, benzene, and toluene that are not in the air. Furthermore, as a consistent benchmark for transparency, ease of replication, and direct comparison, more complete and accurate information should be provided regarding the experimental protocols, especially on acclimation, plant quantity, ventilation, climate conditions, sampling frequency or period, and replication. In order to compare plant performance in pollutant absorption, consistent experimental techniques and measurement units are required.

Further research is needed on plant characteristics such as leaf size, thickness, surface area, the efficacy of specific species, and the plant part involved in removing air pollutants. Future interventions for air pollutants must concentrate on human behavior in response to indoor plants and enhanced ventilation. Further, short- or long-term exposure to indoor pollutants may result in the development of possible allergies or diseases. Hence, there is a need to establish a safe list of plants that can be used to minimize indoor air pollutants.

Limitation

This study is predominately based on a scoping/narrative approach, but we aimed to comprehensively provide the role of indoor plants in reducing air pollution. However, systematic reviews detailing each aspect, e.g., Indoor air pollution and health risk, mechanism of phytoremediation, economic viability and various aspects of the built environment, could further help to explore the use of the plant in reducing the exposure of indoor air pollutants.

Conclusions

Indoor plants appear to show pronounced improvement in IAQ and promote human well-being. Numerous studies showed a substantial decline in the concentration of air pollutants in the presence of indoor plants. This review enhanced knowledge of the detoxification pathways involved in removing various pollutants (such as plant roots, effectively removing VOCs). The extent to which indoor plants mitigate or reduce the adverse effects of air pollution differs from species to species. Therefore, the plant microbiome's effect and complexity still need to be fully understood. Further, the removal capacity of indoor plants needs to be fully clarified to establish and understand the actual pollutant removal mechanism. Moreover, the ability to remove air pollutants needs to be quantitatively assessed based on research trials and actual modeled-based mechanisms. Especially in low- and middle-income countries, there are several challenges and stress in the field of the health sector. Shifting to indoor greenery and adapting a biophilic environment can help reduce the pressure on the health sector and help sustain better public health.

Author contributions

KR and SM conceptualized and co-designed the framework and reviewed and edited the manuscript. Both authors contributed equally and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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