A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach

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Abstract

Environmental pollution, especially indoor air pollution, has become a global issue and affects nearly all domains of life. Being both natural and anthropogenic substances, indoor air pollutants lead to the deterioration of the ecosystem and have a negative impact on human health. Cost-effective plant-based approaches can help to improve indoor air quality (IAQ), regulate temperature, and protect humans from potential health risks. Thus, in this review, we have highlighted the common indoor air pollutants and their mitigation through plant-based approaches. Potted plants, green walls, and their combination with bio-filtration are such emerging approaches that can efficiently purify the indoor air. Moreover, we have discussed the pathways or mechanisms of phytoremediation, which involve the aerial parts of the plants (phyllosphere), growth media, and roots along with their associated microorganisms (rhizosphere). In conclusion, plants and their associated microbial communities can be key solutions for reducing indoor air pollution. However, there is a dire need to explore advanced omics technologies to get in-depth knowledge of the molecular mechanisms associated with plant-based reduction of indoor air pollutants.

Keywords Pollutant · VOC · Indoor air · Phytoremediation · Botanical bio-filter · Potted plants

Introduction

Today, air pollution, especially indoor air quality (IAQ), has been a huge concern worldwide due to its adverse effects on both the surrounding environment and human health (Kabir and Kim 2012; Soreanu et al. 2013; Bhargava et al. 2021). The indoor and outdoor air are contaminated with a variety of man-made and natural substances that are hazardous to living beings, whether plants, animals, or humans. Since the beginning of the energy crisis in 1973, the design and construction of buildings have

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been changed to reduce energy consumption, which limits the living space, and subsequently generates several types of indoor air pollutants (Orwell et al. 2006; Aydogan and Montoya 2011). As per estimation, an urban population usually spends more than 80–90% of their time inside buildings (Klepeis et al. 2001; Xu et al. 2011). Furthermore, as a result of the COVID-19 global pandemic, people have recently experienced a national lockdown, which has increased people's reliance on indoor spaces, and as a result, this type of lifestyle has made people more vulnerable to massive exposure to indoor air pollution. According to the World Health Organization (WHO), 4.3 million early deaths occur every year due to exposure to indoor air pollution; however, 3.7 million deaths have been recognized due to outdoor air pollution (WHO 2015). The WHO has identified various symptoms caused by excess exposure to indoor air pollution, i.e., sick building syndrome (SBS). Such symptoms include headaches, eye and respiratory system irritation, dizziness, nausea, fatigue, drowsiness, and general impatience (Orwell et al. 2006; Aydogan and Montoya 2011; Soreanu et al. 2013). However, the biggest health effects due to indoor air pollution are respiratory and cardiovascular diseases. The previous result

showed that 10.2% of high-income countries and 33.7% of middle- and low-income countries are affected due to exposure to indoor air pollution (Feigin et al., 2016).

With an increasing population over the last three decades, urban growth has continued to rise, with an estimated annual growth rate of about 2.3% in well-developed and established countries (Brockherhoff 2000; United Nations 2000, 2004; UNFPA 2004). Rapid urbanization has been correlated with economic growth, energy consumption, and carbon dioxide emissions from the burning of fossil fuels, which consequently lead to an increase in air pollution. The presence of aerosols and chemicals in excess of their allowable limits, particularly particulate matter (PM), volatile organic compounds (VOCs), and aromatic hydrocarbons, is referred to as air pollution (Gawronski et al., 2017; Wei et al., 2017a). In 2021, WHO revised the permissible limit for various air pollutants as listed in Table 1. Anthropogenic activity also contributed to air pollution, such as the WHO's 2021 cutoff air quality with a minimum exposure and average concentration of various air pollutants. Because the urban population spends the majority of their time indoors, it has become imperative to find an effective solution to reduce indoor air pollutants. The initial step to minimizing air pollution is to remove or reduce the source of indoor pollution, like natural and anthropogenic activity, and the second step is to use appropriate and efficient air purification techniques that can remove or detoxify the existing pollutants (Wei et al. 2017b). So far, a variety of physiochemical methods or science-based technologies have been effectively implemented for the abatement of indoor air pollution (Wei et al. 2017b; Supreeth 2021). But due to the high maintenance costs, these existing conventional remediation technologies need to be replaced by cost-effective, eco-friendly, and non-invasive bioremediation approaches. Biological based remediation involves the use of plants and microbes to degrade or transform toxic pollutants into non-toxic ones (Lee et al. 2020; Supreeth 2021). A NASA (National Aeronautics and Space Administration) study in space shuttles in 1980 successfully demonstrated the role of plants in airborne pollutants removal (Wolverton et al. 1989; Chen et al. 2005). Several other recent investigations revealed that long-term exposure of pollutants to plants under both indoor and control chamber experiments led to the removal of maximum percent of pollutants from the indoor air (Cruz et al. 2014).

Thus, as an emerging bioremediation technology, phytoremediation gained enormous interest for the abatement of pollutants from different sources like soil, water, and air through the use of plants. Based on the metabolic activities of plants, the phytoremediation process involves the absorption and degradation of pollutants (Kim et al. 2020). Various plant metabolites, such as enzymes (catalase, dehydrogenase), are responsible for the decomposition of hazardous air pollutants (Rachmadiarti et al. 2019; Han et al. 2022). Previous research found that plants are efficient way to remove CO_2 through photosynthesis, degrade VOCs with the help of rhizosphere/phyllosphere microorganisms, and cause the dry deposition of PM on the plant surface (Orwell et al. 2006; Gawronska and Bakera 2015; Torpy et al. 2018). In this review paper, we have summarized the different studies on the potential of plants for bioremediation and purification of indoor air pollutants. Additionally, we have discussed the future research

Table 1 Permissible level of different indoor air pollutants and their impact on health

Air pollutant	Duration	Minimum exposure	Health effect	References
PM2.5	Annual 24-h mean	$5\mu g/m^3$ $15\mu g/m^3$	Eye, nose, throat and lung irritation, coughing, sneezing, runny nose and shortness of breath	WHO 2021
PM10	Annual 24-h mean	$15\ \mu g/m^3$ $45\ \mu g/m^3$	Coughing and wheezing to asthma attacks and bronchitis to high blood pressure, heart attack, strokes, and premature death	WHO 2021
O_3	8-h daily 8-h mean, peak season	$100\ \mu g/m^3$ $60\ \mu g/m^3$	Chest pain, coughing, shortness of breath, and throat irritation	WHO 2021
NO_2	Annual 24-h mean	$10\ \mu g/m^3$ $25\ \mu g/m^3$	Respiratory infections and asthma and chronic lung disease	WHO 2021
SO_2	24-h mean	$40\ \mu g/m^3$	Respiratory system, lung function, asthma and chronic bronchitis	WHO 2021
CO	24-h mean	$40\ \mu g/m^3$	Headache, fatigue, dizziness, drowsiness, or nausea	WHO 2021
VOC	NA	NA	Conjunctival irritation, nose and throat discomfort, headache, allergic skin reaction, dyspnea, declines in serum cholinesterase levels, nausea, and emesis	WHO 2021
Micro/nano plastic M/NPs	NA	NA	Toxicity through oxidative stress, inflammatory lesions, and increased uptake or translocation, metabolic disturbances, neurotoxicity, and increased cancer risk	WHO 2021: Liu et al. 2019

challenges regarding the mitigation of air pollution by the use of plants and plant-associated microbial communities.

Methodology for this review

Based on the survey, the authors thoroughly reviewed a huge literature related to indoor air quality and air pollution. This review paper mainly focuses on indoor air pollution, phytoremediation of indoor pollutants and summarizes the potential of different types of plant species for the removal of indoor pollutants. This review comprises following approaches: (1) urgency and seriousness of indoor air pollution, and the possible causes of indoor pollution, (2) the impacts of indoor air pollution and possible removal pathways, (3) the relationship between plant and microorganism for the removal of indoor pollution. This review paper also deals with future challenges that will be encountered in future research in this area. For the collection of data, we used the Scopus index, Sciences Direct, and Web of Science (https://www.webofscience.com). We used the following keywords in the online site of "the web of sciences" to search for research articles: indoor air pollution + plant, indoor air pollution + plant + phytoremediation, indoor air pollution + plant + microorganisms, indoor air pollution + plant + phytoremediation + microorganisms, indoor air pollution + living wall, and indoor air pollution + potted plants (Fig. 1). Most of the research and review articles have focused on the potential of plants in control chamber experiments for the removal of indoor pollution. There was no clear relationship between plants and microorganisms for VOC removal in any of the papers.

Air pollution

Air pollution has been identified as the most serious environmental threat to global sustainability. There are approximately 200 different types of air pollutants in ecosystems that can harm the human respiratory system, which is regarded as the world's greatest environmental health risk (Orellano et al. 2020; Han et al. 2022). Globally, more than 80–90% of people spend their entire lives indoors, in places like schools, educational institutes, colleges, offices, homes, and other commercial structures (Mannan and Al-Ghamdi 2021). On a global scale, studies have revealed that air pollution is responsible for one out of every ten deaths (Gonzalez-Martin et al. 2020). Research studies revealed that air pollution is not only confined to outdoor air pollution but that indoor air pollution is much more contaminated than outdoor air pollution, so more studies should be focused on the risks associated with indoor air quality (EPA, 2014). The quality of the indoor environment is regulated by the outdoor air quality (Schieweck et al. 2018) and
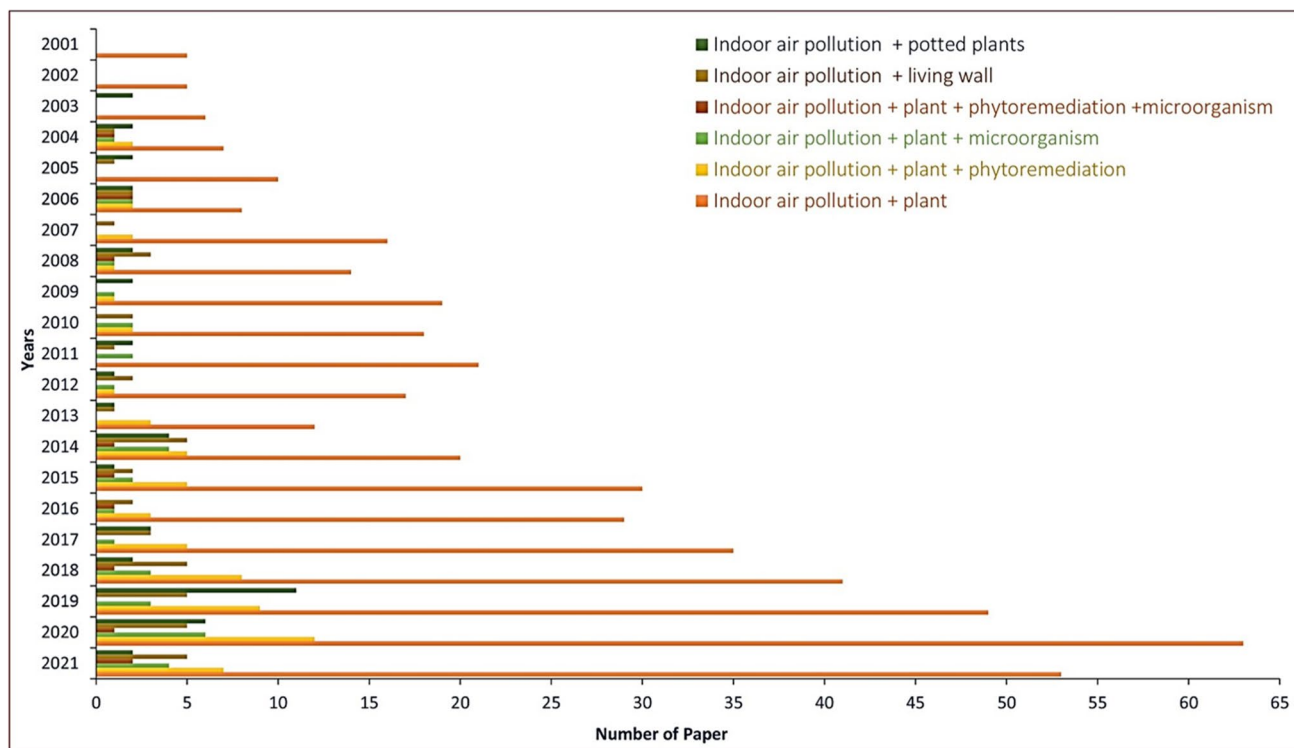

Fig. 1 Number of publications and citations regarding indoor air pollution in each year from 2001–2021

the indoor sources, viz., cooking, heating and burning (coal, wood, gas, oil, and kerosene), smoking, furniture, carpets, building materials, office equipment, and cleaning products (Destaillats et al. 2008; Cocarta et al. 2021).

Furthermore, some harmful indoor pollutants are those from biological sources such as pollen, animals, pathogens, water vapor, humidifiers, air conditioning systems, and carpets (De Gennaro et al. 2014). The dominant source of indoor air pollution is the combustion of solid fuels, viz., coal, fuelwood, cow dung, straw, used for indoor cooking, heating, and lighting, which directly or indirectly affect human health (McCarron et al. 2020; Luo et al. 2021). Solid fuels are used to meet the basic needs of 41% of households in low- and middle-income countries worldwide (Bonjour et al. 2013; Dickinson et al. 2019). Polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) such as benzene, toluene, acetaldehyde, acrolein, xylene, styrene, and formaldehyde, heavy metals, sulfur dioxide (SO_2), nitrogen dioxide, black carbon, carbon monoxide, ozone, PM 2.5, and PM 10 particles are all produced by inefficient and incomplete solid fuel combustion, which leads to serious health problems in living beings (Amegah and Jaakkola 2016; Chen et al. 2016). The constant evolution of living styles and the materials used in indoor environments has resulted in significant changes in nature and composition of indoor air pollutants, which must be thoroughly investigated (Agarwal et al. 2018; Khare and Shukla 2020; Bhargava et al. 2021; Han et al. 2022).

Sources of indoor air pollution

Aerosol air pollutants

Particulate matter (PM)

Particulate matter (PM) is made up of liquid droplets and solid particles that are suspended in the air with different shapes, sizes, origins, and chemical compositions; various of them are hazardous (Davidson et al. 2005; Yadav and Devi 2019). The PM is classified into four fractions based on its aerodynamic diameter: ultrafine (< 0.01 μm), fine (0.01–2.5 μm), coarse (2.5–10 μm), and large (10–100 μm) (Chen et al. 2020; Teiri et al. 2021). Globally, on an annual basis, fine and superfine (PM 2.5) particles alone are causing over 2 million deaths (Silva et al. 2013; Teiri et al. 2021). The sources of PM are diverse and can be broadly classified as either natural (storms, volcanic eruptions, forest fires, rock debris, salt spray, gaseous emissions) or anthropogenic (fuel combustion, steel industry, industrial processes, cement, petroleum foundries, glass manufacturing industry, emissions from power plants, mining operations, burning of coal) (Ukaogo et al. 2020). In the indoor environment, such things as paints, varnishes, solvents, cleaning products, and office equipment like photocopiers, printers, and gas cooktops release PM (Maisey et al. 2013) (Fig. 2). However, it is also generated by cleaning fibers, combustion-based
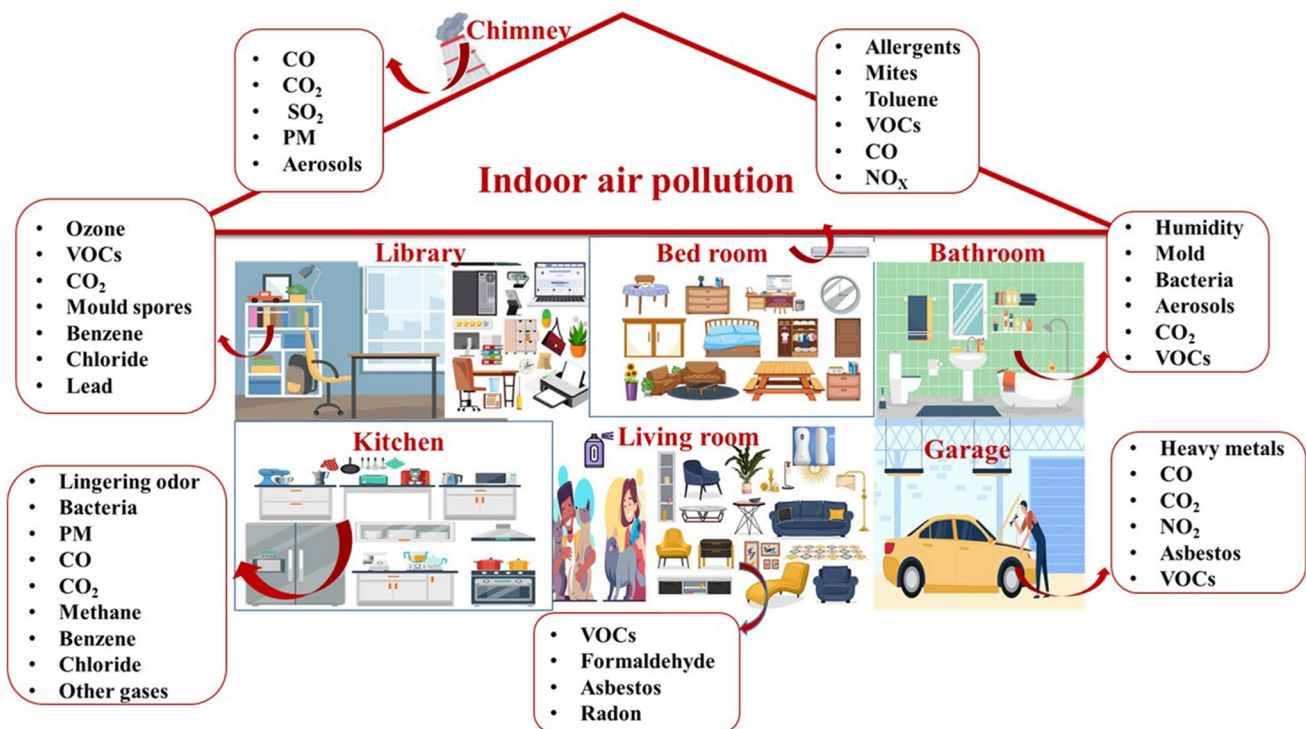

Fig. 2 Pictorial representation of various indoor air pollutants and their sources

appliances (heaters, ovens, fireplaces, tobacco, and smoke), and reactions between some VOCs and ozone (Royal College of Physicians 2016; Lin and Zhu 2018; Gonzalez-Martin et al. 2021). It has been seen that coal-burning houses have higher PM concentrations than non-solid fuel-burning houses (Adesina et al. 2020). Levels of PM are found to be very high in habitations around heat and power plants, cement plants, wood processing plants, welding workshops, power plants, and hookah lounges (Sanchez-Soberon et al. 2015; Cichowicz and Dobrzanski 2021). Indoor pollutant PM10 contains elements such as Ni, As, Cd, Al, Pb, Zn, B, Mg, F, Cl, SO42, and NO3; however, indoor pollutant PM2.5 contains metal content (1%), elemental carbon (3%), ammonium ion and water (15%), sulfates and nitrates (30%), and organic carbon (50%) (Park et al. 2018). Indoor PM concentrations are directly related to outdoor concentrations, and seasonal differences in home concentrations can be observed (Sanchez-Soberon et al. 2015; Priyamvada et al. 2018). If the PM concentration in the atmosphere is significantly high, it will have a direct negative impact on the health system. The size of PM in the air ranges from 2.5 mm (PM 2.5) to 10 mm (PM 10). The upper respiratory tract is mostly affected by PM 10, while the lower respiratory tract, lung, and alveoli are damaged by ultrafine particles of size 0.1 mm (Gonzalez-Martn et al. 2021). Long-term exposure to airborne particles below the permissible limit has been shown to increase the risk of lung cancer (Trostl et al. 2016; Han et al. 2022). It can harm the immune system and cause variety of respiratory and cardiovascular diseases (ranging from nose, eye, and throat, and asthma to fibrosis, bronchial irritation, and lung cancer) (Puett et al. 2009; Gonzalez-Martin et al. 2021; Huang et al. 2021) (Table 1).

Environmentally persistent free radicals (EPFRs) are a new class of emerging pollutants that comes under the category of atmospheric PM 2.5 (Vejerano et al. 2018; Chen et al. 2019). These are chemical substances with relatively low reactivity, strong durability, and high toxicity (Cruz et al. 2012). EPFRs are highly stable because they do not easily decompose after formation, and they are highly persistent, lasting from few minutes to several months (Vejerano et al. 2018). The sources of EPFRs are mainly released from various anthropogenic activities (metallurgical processes, soil contaminants, waste incineration, biomass burning, engine exhaust, and industrial processes of organic materials that interact with metal-containing particles to form a free radical-particle pollutant) and precursors of secondary pollutants such as PAHs and reactive oxygen species (ROS): hydroxyl radicals, hydrogen peroxide (H_2O_2), and superoxide anion radicals (Wang et al. 2018; Li et al. 2020; Chen et al. 2019). Particles emitted from such sources undergo photo-oxidation and uptake another gas phase, such as VOCs (Wang et al. 2009). Quinones (PM 2.5) and semiquinones (cigarette smoke) are emitted from combustion processes

(Ruan et al. 2019). In the presence of hydrogen peroxide, the adsorbed organic carbon on PM 2.5 produces reactive oxygen species (ROS) because of the metal-mediated formation of superoxide, which further reacts with transition metals (Vejerano et al. 2018). These particles cause biological damage to cells such as myeloid leukemia cells, human lung epithelial cells, pulmonary inflammation, and cardiac inflammation (Squadrito et al. 2001).

Incomplete combustion of fossil fuels (especially diesel, wood, and coal) and other fuels releases black carbon, a carbonaceous component of soot particles (PM 2.5) (Smith et al. 2009; Boogaard et al. 2011). Due to the small size of black carbon, it is a matter of concern for public health because it can be inhaled and deposited directly in the lungs, causing serious health problems. It is used as a measure of exposure to diesel soot, a toxic air contaminant that contributes to human-induced climate change in a variety of ways (Fruin et al. 2004). Globally, Africa, Asia, and Latin America account for approximately 88% of global black carbon emissions from open biomass due to burning and fossil fuel combustion (Ito and Penner 2005). Air pollution regulations focus on PM 2.5; however, higher exposure to black carbon is a serious health threat that can cause heart attacks and strokes. In addition, it is also associated with asthma, hypertension, bronchitis, and chronic obstructive pulmonary disease (Shindell et al. 2012).

Volatile organic compounds (VOCs)

At room temperature, volatile organic compounds (VOCs) have a high vapor pressure and a low boiling point, which causes a large number of molecules to evaporate into the surrounding air (Wei et al., 2017a). A subset of VOCs is green leaf volatiles, also known as biogenic VOCs, which are emitted exclusively from plant leaves, particularly through stomata, and are responsible for the strong odor. VOCs are carbon compounds that participate in atmospheric photochemical reactions but do not include carbon monoxide, carbon dioxide, carbonates, carbonic acid, or ammonium carbonate (Gan et al. 2022; Zhang et al. 2017). VOCs are numerous and ubiquitous as they are released from both natural activities (volcanic eruptions, forest fires, etc.) and anthropogenic activities (exploitation, storage, refining, transport, and usage of fossil fuels, viz., cooking, asphalt blowing, and catalytic cracking processes). Isoprene, terpenes, and alkanes, as well as chemicals like formaldehyde, PAHs, and BTX (benzenes, toluene, and xylenes), are all examples of biogenic VOCs (Gan et al. 2022). Among all VOCs, formaldehyde, benzene, toluene, ethylbenzene, and xylene (BTEX) are the most abundant compounds in the air (Weyens et al. 2015). Different sources of indoor benzene as given in Fig. 2 include combustion devices, new or renovated buildings,

and building materials such as paints, carpets, solvents, various plastics, and wooden furniture (Campagnolo et al. 2017; Gonzalez-Martin et al. 2021). Health risks for chronic exposure are carcinogenic and also include blood illnesses, reproductive problems, and neurological problems (Fernandez et al. 2013; Gonzalez-Martin et al. 2021; Leung 2015). The most common sources of toluene are paints, gasoline, resins, cosmetics, adhesives and coatings, renovated buildings, combustion devices, tobacco smoke, fingernail polish, and a variety of other household products (Gonzalez-Martin et al. 2021; Singh et al. 2016; Zhong et al. 2017b). Long-term exposure to toluene causes respiratory diseases and can affect the central nervous system (Gonzalez-Martin et al. 2021).

Paints, plastics, solvents, combustion, dyes, polymers, lacquers, insecticides, cleaning products, pharmaceuticals, adhesives, and other products are all sources of ethylbenzene and xylene in the indoor environment (Campagnolo et al. 2017; Gonzalez-Martin et al. 2021). The higher concentration and long-term exposure to this pollutant are associated with problems related to dizziness, headache, the gastrointestinal, central nervous systems, leukemia, and respiratory and reproductive system problems (Xu et al. 2016). Sources of naphthalene in indoor air include tobacco smoke, combustion devices, rubber materials, herbicides, and insect repellents (Kotzias, 2005). Intoxication with naphthalene can induce cataracts and hemolytic anemia (Zhong et al., 2017b). Short-term exposure to VOCs emitted from building materials can cause dizziness, headaches, and irritation of the eyes or skin; however, long-term exposure results in pulmonary disease, leukemia, tumors, etc. (Richard 2012).

Formaldehyde is a colorless flammable liquid or gas, with a pungent and suffocating odor that is found in engineered wood products made with adhesives containing urea-formaldehyde (UF) resins (Leung 2015). Formaldehyde and BTX are the main indoor VOCs contributing to the so-called "sick building syndrome" (Wieslander et al. 1996; Orwell et al. 2006; Soreanu et al. 2013). This compound enters the body through the skin, respiratory system, and gastrointestinal tract, causing headaches, asthma, respiratory symptoms, and decreased lung function, as well as effects on the nervous system, nasopharyngeal cancer, and myeloid leukemia (Mandin et al. 2020; Bandehali et al. 2021).

Aromatic compounds

Aromatic hydrocarbons are harmful persistent organic pollutants; however, the compounds' high molecular weight can make them even worse for human health and the environment (Adetona et al. 2017). These compounds are produced from anthropogenic sources like incomplete combustion generated through coal, wood, oil, and gas burning, petrol, and diesel oil combustion, industrial power generation, and waste incineration (Kliucininkas et al. 2011; Orecchio et al. 2016). Polyaromatic hydrocarbons (PAHs) are produced from industrial and domestic food processing like popular beverages, (coffee and tea), heating (Duedahl-Olesen et al. 2015), roasting, toasting, grilling, frying, baking, and barbecuing (O'Connor et al. 2022; Rose et al. 2015). These compounds are also found in products like bathing shoes, toys, mousepads, many sports items, and bicycle handles. (Brandt and Einhenkel-Arle, 2016). PAHs can also be produced from natural activities like forest fires, waste burning, volcanoes, and hydrothermal processes (Pongpiachan 2015; Domingos et al. 2015; Kong et al. 2015; Thai et al. 2016). Among the PAHs, the Environmental Protection Agency (EPA) includes pollutants like naphthalene, benzene, phenanthrene, anthracene, acenaphthylene, acenaphthene, phenanthrene, 7-fluorene, fluoranthene, and pyrenec (Raza et al. 2019). Benzo(a) pyrene (BaP) and 7,12-dimethylbenzo anthracene (DMBA), which are found in newspaper ink, are the most thoroughly studied PAHs (Paschke et al. 2015). Low vapor pressures (such as benzo(a)pyrene) sorb to particles, whereas higher vapor pressures (such as naphthalene) are associated with the vapor phase (Hussein and Ahmed, 2016).

In the chemical industry, naphthalene is a white crystalline solid that is produced by tobacco smoke, defective combustion devices, rubber materials, herbicides, and insect repellents (Gonzalez-Martin et al. 2020; Patel et al. 2020). Acute naphthalene intoxication can cause irritation in the eyes and respiratory system, hemolytic anemia, and cataracts (Kotzias, 2005). Anthracene and benzo(a) pyrene hydrocarbons, on the other hand, are direct skin sensitizers and irritants for animals and humans and can cause chronic health problems such as cataracts, breathing problems, asthma, kidney and liver damage, immune function loss, and lung malfunctions (Abdel-Shafy and Mansour 2016; Patel et al. 2020). In addition, benzopyrene can cause infertility in the male reproductive system (Smith et al. 2007). Lubricants, varnishes, paint removers, adhesives, typewriter correction fluids, cleaning agents, bleach household products, contaminated waters, and soil are all indoor sources of trichloroethylene (TCE) (Singh et al. 2016; Kraakman et al. 2021). It is a carcinogenic chemical that can have an acute effect on the central nervous system, reducing sensory capacity; however, long-term exposure can lead to liver, kidney, and bile duct cancer (Campagnolo et al. 2017; Pohanish, 2017). Terpenes, viz., pinene and limonene, are used in perfumery products, deodorizers, room fresheners, shampoos, fragrances, cleaning products, and wooden materials (Campagnolo et al. 2017). Acute exposure to high concentrations of these pollutants can cause irritation and inflammation (Zhong et al. 2017b).

Gaseous pollutants

Inorganic air pollutants are carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), nitrogen oxides (NOx), and sulfur dioxide (SO_2) (Liu et al. 2019). Anthropogenic activities such as greenhouses, garages, ventilated kitchens, and the combustion of fossil fuels (ovens, stoves, heaters, and tobacco smoke) produce gases such as CO_2 and CO; however, these gases are naturally produced by natural sinks such as forests, wetlands, and the sea (Weyens et al. 2015). Long-term exposure to these gases causes coughing, dizziness, fatigue, sneezing, eye irritation, and respiratory, cardiovascular, and neurological problems (Kotzias, 2005; Broderick et al. 2017; Yip et al. 2017). Nitrogen (N), a building block of proteins, is the second most important element for plants after carbon (Gawronski et al. 2017). Oxides of nitrogen, viz., nitric oxide (NO) and nitrogen dioxide (NO_2), are frequently released into the atmosphere by combustion processes such as ovens, furnaces, stoves, heaters, unvented gas appliances, burning kerosene, and fireplaces (Luengas et al. 2015). Long-term exposure to these gases can cause respiratory problems such as coughing, wheezing, bronchospasm, dyspnea, bronchoconstriction, pulmonary edema, chronic lung diseases, and loss of the senses of smell and taste (Vasile et al. 2016). The sources of ammonia are cleaning products, tobacco smoke, cooking by-products, concrete, and human emissions (Wang et al. 2020a). Sulfur dioxide (SO_2) is produced from the combustion of fossil fuels, greenhouses, acid rain, and industrial processes, and hydrogen sulfide (H_2S) is emitted by both natural and human activities, such as wetlands, hot and cold sulfur-rich springs, manure, coal pits, oil and gas reservoirs, hydrothermal systems, and volcanic eruptions. The sources of anthropogenic activity are concentrated animal feeding, sewage treatment plants, geothermal power plants, paper mills, oil refineries, groundwater containing sulfur dioxide, septic tanks, and landfills (He et al. 2013; Venturi et al. 2016; Kumar et al. 2021a; Kumar et al. 2021b).

These gases irritate the respiratory tract and cause a burning sensation, leading to asthma and bronchitis symptoms (shortness of breath, wheezing, and chest tightness), as well as lung infection. Ozone in the troposphere is one of the most serious threats to plants that are ozone-sensitive, and it is dependent on the presence of a genetically determined efficient antioxidant system (Paoletti et al. 2011). Tropospheric ozone is produced when sunlight (specifically UV-radiation) initiates complex photochemical reactions with NO*x*, CO, and VOCs (Zhong et al. 2017a). Inhaled ozone has the potential to absorb deeply into the lungs due to its low water solubility, which can cause throat irritation, coughing, breathing problems, asthma, emphysema, inflammation, and chronic pulmonary diseases (Koman and Mancuso 2017; Nuvolone et al. 2018).

Methods for phytoremediation of indoor air

Due to rapid urbanization globally, in the past few decades, staying in different indoor environments has become a common practice among the urban population (Mannan and Al-Ghamdi, 2021). However, staying in an indoor environment for a longer period of time with poor indoor air quality can pose a serious threat to human health (Tham et al. 2016). Generally, indoor air quality is determined by the variety of air pollutants, including VOCs and PM (Archibald et al. 2018). VOCs are the most abundant and harmful pollutants in indoor air and are known to be highly carcinogenic in nature (World Health Organization 2004). Emissions from paints, carpets, furniture, electronic appliances, and various indoor activities, including cooking, burning fuel, using heaters, and cooling, lead to increased VOCs in indoor air, making it an unsuitable environment for human health (Yu and Crump 1998; Torpy et al. 2018). Despite indoor activities, outdoor factors such as the entry of polluted air from outside also contribute to the increased VOC in the indoor environment. Furthermore, seasonal variations such as winters contribute to the increased indoor air VOC concentrations due to poor ventilation (Schlink et al. 2004). Therefore, for improving indoor air quality, the VOC level in the indoor air needs to be reduced, which can be done by improving ventilation, avoiding the use of sources of emission, reducing emissions, and purifying the pollutants. Pollutants can be purified by using adsorbent materials such as activated charcoal or silica gel and also through technologies like filtration (Yu et al. 2013). But, all these strategies are still ineffective in mitigating the effects of indoor air pollution. Thus, indoor potted plants and green walls serve as an eco-friendly as well as a cheaper alternative solution for remediating VOCs from the indoor air (Wolverton and Wolverton 1993; Wood et al. 2002b, 2006; Aydogan and Montoya 2011; Torpy et al. 2013). The approach where living plants are used for mitigating pollutants or contaminants from the air, water, and soil is generally known as phytoremediation (Cunningham et al. 1995). It involves the interaction of aerial parts of plants with microorganisms associated with both the phyllosphere and rhizosphere to remediate air pollutants. The combined action of plants and microorganisms is able to transform or remove gases by using them as an energy source (Guieysse et al. 2008). The removal of indoor pollutants can be achieved with the use of both passive (potted plants or an active green wall) and active systems (plant bio-filtration or an active green wall, respectively) (Xu et al. 2011). For improving air quality and possible green solutions, plants can be used in different ways, like potted plants or living green walls or green walls in hydroponic systems (Teiri et al. 2021).

Green walls

Green wall systems are an important development for the remediation of pollutants both indoors and outdoors. They are also referred to as "bio filters," "vertical gardens," or "living walls," which provide an aesthetic sense to the living spaces and are also suitable for the purification of air (Fig. 3). This is a system in which plants grow in ground, pots, or planter boxes. Generally, green walls are made up of continuous or modular, planted sections or covers that are fixed to walls or other building structures (Kiurski et al. 2013; Maslauskas 2015; Gunawardena and Steemers 2019). Such vegetation or plant-wall systems are manufactured in square or rectangular modular panels where plants are arranged in a vertical fashion along with their growing media to maximize the surface area for efficient pollutant removal. Many of the green walls have an integrated water delivery system and lead to temperature reduction, improved air quality, oxygen production, and social well-being. Depending upon the construction system and pollutant removal efficiency, green walls can be classified into two types: passive and active green walls (Modirrousta and Mohammadi 2015). A passive green wall is generally simpler in its design and known to be a cost-effective way to purify the air (Darlington et al., 2001; Prodanovic et al. 2019) (Fig. 3). The drawbacks associated with passive green wall systems are that they can remediate pollutants at the same rate as their diffusion rate in the functional zone of plants (phyllosphere) and rhizosphere of a potted plant or green wall (Soreanu 2016). Moreover, poor

ventilation and the availability of low concentrations and diffusivities of pollutants in the air make the process of pollutant removal by a passive green wall slow and inefficient. However, an active green wall is an upgraded version with the proper ventilation system and temperature control system that can regulate the heating and cooling of the building (Safikhani et al. 2014; Pandey et al. 2015; Pérez-Urrestarazu et al. 2016). Active green walls create an insulation effect by changing the ambient conditions of temperature and humidity in the air layers around them. Plants residing in active systems remove VOCs, CO, and CO_2 as well as PM from the air and create fresh air (Wolverton 2009; Modirrousta and Mohammadi 2015). The application of green walls (active and passive) depends upon various factors like location, cost, and infrastructure limitations. Active living walls with hydroponic plants (a botanical system) show a high rate of pollutant removal, especially of VOCs, with a high airflow rate. A preliminary study was conducted in Sydney, Australia, in suburban rooms to examine the removal of PM and TVOC. In this study, the authors conducted three sets of experiments on potted plants, active green walls and the combination of passive, and active green walls (Pettit et al. 2017). The result showed that the active green wall significantly removed the TVOC by 72.5% compared to the control experiment (Pettit et al. 2017). An active green wall can be effectively incorporated into the building without any support and potentially used for the phytoremediation of air in a short period of time (Franco et al. 2012; Pe'rez-Urrestarazu et al. 2016). Biofiltration is a kind of active living
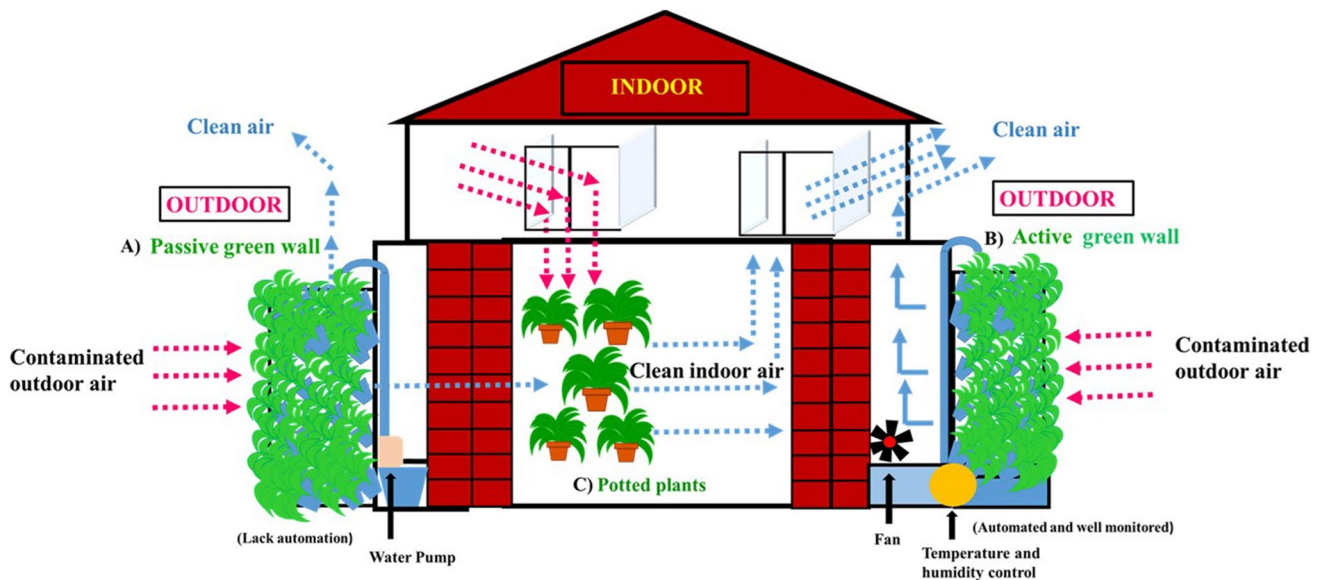

Fig. 3 Schematic representation of the purification of outdoor/indoor air through vertical green walls and potted plants. **A)** Active green walls with enhanced air circulation pulls polluted air mechanically through the plants and substrate. **B)** Passive green wall allows the fil-

tration of the polluted air naturally without any mechanical support and automation. **C)** In potted plant, polluted air diffuses through the plant foliage and substrate, where phyllospheric and rhizospheric microbes lead to VOCs removal

wall system that can be incorporated into any kind of building design; such systems can include hydroponic systems where air circulates through the nutrient-rich environment. The plant used in this system generally has denser roots, and microbe growth is supported by putting roots between synthetic fabric layers (Safikhani et al. 2014; Irga et al. 2018; Abdo et al. 2019). The combination of active living wall systems, i.e., biofiltration and phytoremediation, is called the bio-wall technique (Table 2) (Maslauskas 2015; Irga et al. 2018). Even if active biofilters can withstand high-pollutant environments and effectively filter the ambient air, long-term testing is required to assess potential decrease in filter efficiency due to substrate and microbial community changes.

Potted plants

Plants have the ability to absorb and catabolize toxic gases that exist in both indoor and outdoor environments. Potted plants significantly reduced indoor air pollutants via a variety of mechanisms, including pollutant transformation and localization by the external surfaces of leaves and the plant root-soil system (Pettit et al., 2018; Manisalidis et al. 2020; Moya et al. 2021). In previous studies, a number of plant species have been identified to absorb and metabolize VOCs like benzene, xylene, and formaldehyde. The mitigation of indoor air pollution is supported by the combination of plant metabolic activity, plant growth medium, and associated microorganisms (Aydogan and Montoya 2011). In the plant root zone below the ground, the microorganism decomposes the pollutant, and the root enhances the degradation process by secreting exudates (Xu et al. 2011). In a closed ecosystem (controlled chamber), potted plants are effective for the phytoremediation of VOCs and indoor air pollutants (Orwell et al. 2006). The in-house experiment was conducted at Suburban Rooms in Sydney, Australia, with passive and active green walls along with potted plants for the removal of PM and TVOCs in 2017 (Pettit et al. 2017). The results showed that an active green wall significantly reduced the TVOCs by around 72.5% compared to the control. It also helps in the purification of indoor air with the help of a purification system and successfully reduces the amount of PM and TVOC (Pettit et al., 2017). Hong-Bo et al. (2010) investigated the absorption of formaldehyde concentration per unit leaf area in 13 different potted plants. Out of 13 plants, *Asplenium nidus* per unit leaf area (5.13 mg/m^2) has the highest adsorption capacity; however, *Epipremnum aureum* (0.64 mg/m^3) has the lowest adsorption capacity for formaldehyde. Exposure to higher concentrations of formaldehyde for a long period of time produced subsequent growth retardation, leaf yellowing, and wilting (Su et al., 2019) (Table 3).

Plant-based mechanisms for indoor pollutant removal

The various strategies of plant-based remediation of pollutants are categorized on the basis of their mode of action and association between phyllosphere and rhizosphere: phytoextraction, phytodegradation, and phytovolatilization, phytostabilization, rhizodegradation, and rhizofiltration. The plants acts as a hyperaccumulators, absorb pollutants from the growing medium (rhizosphere) and transport them to the leaves and other aerial parts of the plant (phyllosphere); this phytoremediation strategy is known as "phytoextraction" (Pandey and Bajpai 2019). Plant aerial parts, such as leaves, branches, and stems, have the ability to absorb pollutants and metabolize them into non-toxic, degraded volatile components, which are then transpired into the atmosphere via the stomata of the leaves (Weyens et al. 2015). This process is known as phytovolatilization (Morikawa and Erkin 2003). In phyto-filtration, plants are used in a hydroponic system for the filtration of contaminants/pollutants from the water. However, a strategy named phytostabilization stabilizes pollutants in soil by avoiding erosion and also leads to the conversion of harmful pollutants into non-toxic ones. Besides this, degradation of pollutants and VOCs in the phyllosphere, i.e., within the aerial tissues of plants, by the action of plant enzymes and degradation of pollutants by microbes in the rhizosphere are referred to as phytodegradation and rhizodegradation, respectively (Fig. 4).

Table 2 Different plant species involved in phytoremediation of PM

S. No.	Plant	Common name	Removal efficiencies		Reference
			PM 2.5	PM 10	
1	*Epipremnum aureum*	Pothos, money plant	-	-	Nakazato and Inagaki 2012
	Epipremnum aureum	Pothos, money plant	0.2–0.36%	0.24–0.39%	Peng et al. 2020
	Epipremnum aureum	Pothos, money plant	30%	-	Cao et al. 2019
2	*Chlorophytum comosum*	Spider plant	56.04%	10.74%	Gawrońska and Bakera 2015
3	*Aloe vera* L.	Aloe vera	5.2%	-	Cao et al. 2019
4	*Nephropelis exaltata bostoniensis*	Boston fern	-	92.46%	Pettit et al. 2017

Table 3 Phytoremediation of air pollutants by plant species in active green wall system

S. No.	Plant species	Type of plant-based system	Growing media	Pollutant	Pollutant concentrations ($\mu g/m^3$)	Type of exposure	Removal rate	References
1	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	Chlorophytum (20%) and Epipremnum (8%)	Torpy et al. 2017
2	Chlorophytum comosum	Active green wall	Soil	Total suspended particles PM10, PM2.5	700	Batch	48.21–53.35%	Irga et al. 2017
3	Philodendron scandens, Philodendron scandens 'Brazil', Asplenium antiquum, Syngonium podophyllum	Active green wall	Inorganic growing media, activated carbon	Methyl ethyl ketone; MEK C_4H_8O (MEK)	101.63	Batch	$56.6 \pm 0.86\%$ in 8 h	Torpy et al. 2018
4	Nephrolepis exaltata	Green wall	Coconut fiber and peat	TVOCs	3900–6600	Batch	12.8–77.3% in 3 h	Suárez-Cáceres GP et al. 2021
5	Epipremnum aureum	Hydroponic systems	Growstone expanded clay and activated carbon	CH_2O	2000	Batch	81–96% in 24 h	Aydogan and Montoya 2011
6	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 al. 2021

Areca palm
Dypsis lutescens

Filters pollutants like xylene, carbon monoxide, formaldehyde, trichloroethylene, toluene from the air

Spider plant
Chlorophytum comosum

Filters formaldehyde, xylene, toluene, benzene, and carbon monoxide in from the air homes or offices.

Golden pothos
Epipremnum aureum

Filters formaldehyde, trichloroethylene, toluene, xylene, and benzene from the air

Gerbera daisy
Gerbera jamesonii

Filters benzene, formaldehyde, and trichloroethylene from the air

Rubber plant
Ficus elastica
Filters formaldehyde from the air

Boston fern
Nephrolepsis exaltata

Filters formaldehyde, xylene and toluene from the air

Weeping fig
Ficus benjamina

Filters xylene, formaldehyde, toluene from the air

Peace lilly
Spathyphylum wallisii

Filters formaldehyde, xylene, benzene, ammonia and trichloroethylene from the air

Chrysanthemum
Chrysanthemum morifolium

Filters benzene, xylene, toluene, formaldehyde, trichloroethylene from the air

Snake plant
Sansevieria trifasciata Prain,

Filters formaldehyde, trichloroethylene, toluene, xylene, ammonia, benzene and carbon dioxide from the air

Aloe vera
Aloe vera L.

Filters benzene, formaldehyde from the air

Fig. 4 List of recommended plants for indoor air pollutants (VOC and other pollutants) removal

Pathways for VOC and PM removal

Various studies have shown that indoor potted plants have the potential to reduce VOCs concentrations in the indoor environment (Wolverton et al. 1989; Orwell et al. 2006; Irga et al. 2013; Cruz et al. 2019; Moya et al. 2021). VOCs removal by plants is not solely dependent on the aerial parts of plants; other factors, such as the quality and quantity of microflora in the soil, the microflora associated with the roots of the potted plant, and the type of plant-growing medium, all play role in VOCs removal. The present review focuses on the role of plants in VOC removal by different pathways. Here, we have presented different pathways that are involved in VOCs elimination or removal by plants: (1) elimination by aerial parts of plants; (2) elimination by the soil micro-flora; (3) elimination by the rhizosphere, which include the roots and growing media.

VOC and PM elimination by aerial parts of plant

Among various aerial parts, stomata located on the abaxial side of the leaves act as the gateway for air pollutants, including VOCs, during the normal gaseous exchange. The two guard cells in the stomata usually regulate the uptake of VOCs of different kinds with varying molecular weights through the aperture between the guard cells (Fig. 4). Once VOCs come in contact with a leaf, they get adsorbed through

the stomata and get degraded, stored, and excreted after conversion into the least harmful components. All of these VOC phytoremediation processes occur either at the site of uptake or after being translocated to other parts of the plant, such as the roots. The ability of VOC removal by the leaves of plants was confirmed by conducting experiments on VOC removal with aboveground plant parts after isolating and separating them from the roots and growing media using some physical obstructions (Tani and Hewitt 2009; Treesubsuntorn and Thiravetyan 2012; Sriprapat et al. 2014). The stomatal conductance determines VOC uptake by leaves. Previous studies have shown that the rate of VOC removal by the leaf stomata is directly proportional to its conductance (Tani et al. 2007). The stomatal conductance can be measured by measuring the transpiration rate. Therefore, by monitoring the rate of transpiration, VOC concentration in intercellular spaces can be predicted, which indirectly suggests the contribution of stomatal regulation on VOC uptake (Tani et al. 2007). Studies performed with the aerial parts of plants under light conditions reported efficient removal of VOCs like formaldehyde, benzene, and toluene from the indoor air. As a result, the role of stomata in VOC uptake was demonstrated, as stomata remain open under light conditions (Yoo et al. 2006). However, it was observed that despite the darkness and aerial parts, the elimination of VOCs was continuous. This continued VOC removal under dark conditions was attributed to the absorption of

VOCs by the cuticle (Treesubsuntorn and Thiravetyan 2012). Thus, among the aerial parts of plants besides stomata, the cuticle also offers an efficient means of VOC removal by adsorbing or diffusing VOCs (Treesubsuntorn et al. 2013). Few researchers have suggested the role of cuticle wax quantity and its chemical structure in the elimination of VOCs (Treesubsuntorn et al. 2013). The removal of benzene, toluene, ethylbenzene, and xylene has been reported in *Dracaena sanderiana* and *Z. zamiifolia* (Treesubsuntorn and Thiravetyan 2012; Sriprapat and Thiravetyan 2013). The chemical properties of VOCs also determine the rate of VOC removal by plants. Earlier, it was observed that a cuticle consisting of lipids helped in the removal of lipophilic VOCs like benzene instead of hydrophilic VOCs like formaldehyde. Apart from stomata and cuticles, physical structures such as leaf morphology, leaf shape, leaf size, trichrome, and leaf size, as well as other factors such as epicuticular waxes, aid in the pollutants' filtration process (Saebo et al. 2012). Plants having broad leaves with rough surfaces capture more VOCs as compared to smoother leaves.

The upper part of the plant also helps with the removal of PM in significant amounts, particularly in urban areas. When PM are absorbed on the foliage or shoot, they accumulate on the leaf surface, where they are stabilized by the wax (Saebo et al. 2012). The absorption and filtration of the PM can be influenced by the morphological characteristics of plants like leaf size, leaf structure, surface roughness, thickness, pubescence, and wax content. Climate conditions such as temperature, wind, precipitation, and the quantity and composition of PMs also play a significant role in scavenging PMs (Weyens et al. 2015). It is estimated that Beijing (China) removes 772 tonnes of PM10 on an annual basis through a plantation of trees in the city center (Yang et al. 2005). Another study in Shanghai (China) found that around the forest area, PM levels were reduced by 9.1% (Yin et al. 2011). The planting of trees in the West Midlands (UK) reduced the PM10 concentration by about 26%, resulting in an annual reduction of approximately 200 tonnes (McDonald et al. 2007). In Chicago, the yearly reduction of PM10 is 234 tonnes (Nowak 1994). Plants are involved in phytoremediation through a biofilter, which can adsorb PM on the leaf surface and whose accumulation ability depends on the plant species (Popek et al. 2013). The plants used for PM removal are listed in Table 4.

VOC elimination by microorganisms

Phytoremediation, or the removal of pollutants through microbial degradation, has been confirmed by previous studies (Wenzel 2009). Microbial communities in both the phyllosphere and rhizosphere have a significant role in aiding indoor plants in removing VOCs from the indoor environment (McGuinness and Dowling 2009) (Fig. 4). Most VOCs that penetrate plant aerial parts must be degraded to harmless constituents, but phototrophic plants are incapable of degradation and cannot use them as carbon or energy sources (Ma and Burken 2003). In such cases, storage and excretion/volatilization of VOCs are mandatory. However, excessive VOC storage can be lethal to plants and have a negative impact on their health. However, VOCs usually get excreted by the roots and degraded by microorganisms present in the soil. Generally, due to the falling of leaves on the soil surface, VOCs tend to accumulate in the soil and rhizosphere of plants. Such VOCs deposited in the soil need to undergo rhizodegradation for efficient VOC removal. Microbial populations that exist in the soil of indoor potted plants break down VOCs into carbon dioxide, water, and cellular biomass. Therefore, microbes are crucial in the removal of VOCs (Randazzo et al. 2020). Characteristics of microbes, like biofilm formation, production of extracellular polymeric substances, and biosurfactants, led to an increase in VOCs in bioavailable form. Also, few studies have hypothesized that the microorganisms (epiphytic and endophytic) present in the phyllosphere are capable of removing VOCs (Khaksar et al. 2016). But it has been found that the information about the phyllospheric microbes is not sufficient. As compared to the rhizosphere, the phyllosphere is a relatively harsh environment for microbial growth, which, therefore, results in a less dense and less diverse population of microbes (Wei et al. 2017a). The VOC removal by microorganisms is substrate-dependent, and instead of plants, the bacterial population associated with the growth substrate facilitates efficient VOC removal (Kim et al. 2008). The bacterial population isolated from the pots of the plant *Howea forsteriana* could effectively remove VOCs (benzene and n-hexane) without the presence of plants (Wood et al. 2002b). Furthermore, it was found that the inoculation of VOC-degrading bacteria in the soil mixture of potted plants augments the efficiency of phytoremediation without interfering with the activity of existing rhizosphere microbes. A higher rate of toluene removal was observed after inoculating *Azalea indica* with the toluene-degrading bacteria *Pseudomonas putida* (De Kempeneer et al. 2004) (Fig. 4). Among microbes, gram-negative bacteria, particularly *Pseudomonas* spp., have been reported to be more efficient in VOC removal in the potting mixture as compared to gram-positive bacteria (Zhang et al. 2013). Behind the degradation of different VOCs such as benzene, ethylbenzene, toluene, and xylene in the environment, enzymatic systems such as monooxygenases and dioxygenases of bacteria are known to be responsible (Jindrova et al. 2002). The enzymatic degradation of VOCs was further confirmed upon the identification of rhizospheric bacteria with the toluene monooxygenase gene (Zhang et al. 2013). Apart from bacteria, mycorrhizal fungi also accelerate the phytoremediation process (Bouwer and

Table 4 Phytoremediation of air pollutants using different potted plant species under a control system

S. No.	Plant species	Type of plant-based system	Growing media	Pollutant	Pollutant concentrations ($\mu g/m^3$)	Type of exposure	Removal rate	References
1	Nephrolepis exaltata, Chrysanthemum morifolium, Phoenix roebelenii	Potted plant	Soil	CH_2O	6140	Batch	Nephrolepis exaltata 1863 (μg plant^{-1} h^{-1}), Chrysanthemum morifolium 1450, Phoenix roebelenii 1385	Wolverton and Wolverton 1993
2	Howea forsteriana	Potted plant	Composted hardwood sawdust, composted bark fines, coarse river sand with Macracote "Green plus" 9-month fertilizer	C_6H_{14}	353,000	Batch	4032 mg/m³/day/m²	Wood et al. 2002b
		Potted plant	Soil	C_6H_{14}	80,000–353,000	Batch	367–4032 mg/m³/day/m²	Wood et al. 2002b
3	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 fertilizer	C_6H_6	80,000	Batch	40 to 88 mg m^{-3} day^{-1} per pot	Orwell et al. 2004
4	Azalea indica	Potted plant	Soil	C_7H_8	339,000	Batch	7–76 h to remove 95% of the initial dose	De Kempeneer et al. 2004
5	Hedera helix, Spathiphyllum wallisii, Sygonium podophyllum, Cissus rhombifolia	Potted plant	Hydroball cley pellets	C_6H_6	3195	Batch	S. wallisii 174.5 ± 3.8, S. podophyllum 103.4 ± 6.9, C. rhombifolia 50.3± 7, H. helix 102.8 ± 8.3	Yoo et al. 2006
6	Hedera helix, Spathiphyllum wallisii, Sygonium podophyllum, Cissus rhombifolia	Potted plant	Hydroball cley pellets	C_7H_8	3769	Batch	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
7	Syngonium podophyllum	Potted plant	Soil	C_6H_6	3204–3779	Batch	18.8–220.2 ng/m³/cm²/h	Yoo et al. 2006
8	Epipremnum aureum	NA	NA	C_3H_6O	307–3071	Batch	0.8–2.4 nmol/m²/s	Tani et al. 2007

Table 4 (continued)

S. No.	Plant species	Type of plant-based system	Growing media	Pollutant	Pollutant concentrations (µg/m³)	Type of exposure	Removal rate	References
9	*Fatsia japonica Decne.*	Potted plant	Sun Gro Horticulture Bark humus and sand, sphagnum peat moss, perlite, dolomitic lime, gypsum, and a wetting agent	CH_2O	2456	Batch	*F. japonica* 39% (day) and 98% (night)	Kim et al. 2008
10	*Planch. Ficus benjamina* L.	Potted plant	Sun Gro Horticulture Bark humus and sand, sphagnum peat moss, perlite, dolomitic lime, gypsum, and a wetting agent	CH_2O	2456	Batch	*F. benjamina* 57% (day) and 94% (night) in 5 h	Kim et al. 2008
11	*Ficus benjamina*	Potted plant	NA	CH_2O	2472	Batch	0.14–1.36 mg/m³/cm² in 5 h	Kim and Lee 2008
12	*Ardisia japonica*	Potted plant	NA	CH_2O	2488	Batch	0.14–0.88µg/m³/cm² in 5 h	Kim and Lee 2008
13	*Fatsia japonica*	Potted plant	bark, sand, and growth media	CH_2O	2400	Batch	700 µg/m³ in 5 h	Lim et al. 2009
14	*Ficus elastica*	Potted plant	Hydroball	C_6H_6	15,116	NA	28–91% in 12 h	Chun et al. 2010
15	*Hedera helix, Chrysanthemum morifolium, Dieffenbachia compacta, Epipremnum aureum*	Potted plant	Grown stone (99% recycled glass bottles) expanded clay-activated carbon	CH_2O	2000	Batch	88%, 84%, 96%, 94% in 24 h	Aydogan and Montoya 2011
16	*Agave potatorum*	Potted plant	NA	CH_2O	15,000	Batch	2.21–4.60 mg/m³ in 7 days	Zhou et al. 2011
17	*Dracaena sanderiana*	Potted plant	Soil	C_6H_6	63,894	Batch	46% by wax, 54% by stomata in 72 h	Treesubsuntorn and Thiravetyan (2012)
18	*Scindapsus aureus*		Soil	C_6H_6	62,392		43–50% in 72 h	Treesubsuntorn and Thiravetyan 2012
19	*D. sanderiana*	NA	NA	C_6H_6	62,392 ( )	Batch	60–77% in 72 h	Treesubsuntorn and Thiravetyan 2012
20	*Begonia maculata, Ardisia crenata, Ardisia japonica*	Potted plant	Bark-humus, sand, sphagnum peatmoss, perlite, dolomitic lime and gypsum	C_7H_8	4896–13,181	Batch	358%, 318%, 252%,	Kim et al. 2012
21	*Melissa officinalis, Hedera helix*	Potted plant	NA	CH_2O	2500	Batch	25.06 mg/m²/h, 2.22 mg/m²/h	Jin et al. 2013
22	*Sansevieria trifasciata*	Potted plant	Soil	C_7H_8	78,800–81,670	Batch	10.17µmol in 72 h	Sriprapat et al. 2014

Table 4 (continued)

S. No.	Plant species	Type of plant-based system	Growing media	Pollutant	Pollutant concentrations ($\mu g/m^3$)	Type of exposure	Removal rate	References
23	*Hedera helix*	Potted plant	Sterilized media	CH_2O	6,140,000	Batch	99.99% in 67.6 hours	Chen et al. (2017)
24	*Fenbachia maculata, Spathiphyllum wallisii*	Potted plant	Soil	C_7H_8	146,000–20,000	Batch	1–9.5 mg/m³ over 48 h	Hormann et al. 2017
25	*Epipremnum aureum, Chlorophytum comosum, Hedera heli, Echinopsis tubiflora*	Potted plant	Soil	C_6H_6	319,470 benzene (100 ppm, Weichuang Inc., Shenzhen, China) was injected into the chamber at 200 mL·min⁻¹ for 120s	Batch	72% in 72 h	Gong et al. 2019
26	*Ruscus hyrcanus, Danae racemosa*	Potted plant	Soil	C_6H_6, C_7H_8, $C_6H_5CH_2CH_3$ C_8H_{10}	31,947–217,097	Batch	8.5075–86.66 mg/m³/h cm²	Fooladi et al. 2019
27	*Epipremnum aureum, Rohdea japonica*	Potted plant	Soil	CH_2O		Batch	0.089 mg•m⁻³•h⁻¹, 0.137 mg•m⁻³•h⁻¹	Zuo et al. 2022

Zehnder 1993). The uptake of PAHs and VOCs by the roots of *Lolium multiflorum* by arbuscular mycorrhizal fungal hyphae has been reported (Gao et al. 2010). Similarly, a plant named *Polygonum aviculare* in association with its rhizospheric fungi was far more efficient in phytoremediation of petroleum-polluted soil than the remediation done by the plant or fungi alone (Mohsenzadeh et al. 2010). All the above findings confirmed the importance of the rhizosphere microbial community in augmenting the VOC removal efficiency of indoor plants (Fig. 4).

With the phytoremediation of PM, plant-associated microbial communities increase their own biomass to absorb pollutants on the surface. In general, direct and indirect plant-associated microbes help the growth and development of plants by increasing nutrient availability, producing plant growth hormones, and helping the plant toward biotic and abiotic factors (Weyens et al. 2009; Bulgarelli et al. 2013). The detoxification of the PM is carried out by the reactive oxygen species (ROS), and some microorganisms have higher antioxidant properties and release ROS on their surfaces (Wu et al. 2014). When PM adheres to the surface, ROS production begins, resulting in the formation of an ultrafine particle related to surface-associated EPFRs (Kiruri et al. 2014). The microorganisms associated with plants are capable of degrading organic and inorganic pollutants and reducing phyto-toxicity (Weyens et al. 2009; Kumar et al. 2020). However, leaf-associated microorganisms might also support plants to manage abiotic stress, which is caused by contaminants bound to PM, and enhance phytoremediation. But phytoremediation and detoxification on leaves' surfaces with the help of microorganisms are still poorly understood.

VOC and PM elimination by growing media and roots

Instead of the aerial parts of plants, the VOC removal efficiency is also determined by the underground parts, root zone, and growing medium of the plant. VOCs are generally adsorbed by aerial parts such as leaves and then finally translocated to the root zone via the stem or directly from the air into the growing medium through diffusion. The root zone has a major contribution to the degradation or removal of gaseous toluene and benzene, upon their transportation from air to the root zones of *Schefflera actinophylla* and *Ficus benghalensis* via stem (Kim et al. 2016). The gaseous formaldehyde removal rate of different commonly used indoor plants such as *Hedera helix* (English ivy), *Chrysanthemum morifolium* (pot mum), *Dieffenbachia compacta* (dumb cane), and *Epipremnum aureum* (golden pathos) growing in grow stone hydroponic medium was higher than aerial parts of plants (Tables 4 and 5) (Aydogan and Montoya 2011).

Table 5 Phytoremediation of air pollutants using different potted plant species in real-time settings

S. No.	Plant species	Type of plant-based system	Growing media	Pollutant	Pollutant concentrations ($\mu g/m^3$)	Type of exposure	Removal rate	References
1	*Chlorphytum-comosum*, *Aloe vera*, *Epipremnum aureum*	Potted plant	Fluvo-aquic soil	CH_2O	4000	Continuous	95%, 53%, 84%	Xu et al. 2011
2	*Chlorophytum comosum*	Potted plant	Horticultural media	PM	PM available in the room environment (real life)	Continuous	13.62 to 19.79 $\mu g \cdot m^{-2}$ leaf blade in 2 months	Gawrońska and Bakera 2015
3	*Schefflera actinophylla*	Potted plant	Sun Gro Horticulture Bark humus and sand, sphagnum peat moss, perlite, dolomitic lime, gypsum, and a wetting agent	C_7H_8 total C_8H_{10}	43.0, 62.3	Continuous	Toluene and xylene 13.3 and 7.0 $\mu g \cdot m^{-3} \cdot m^{-2}$ leaf area	Kim et al. (2016)
	Ficus benghalensis	Potted plant	Sun Gro Horticulture Bark humus and sand, sphagnum peat moss, perlite, dolomitic lime, gypsum, and a wetting agent	C_7H_8 total C_8H_{10}	43.0, 62.3	Continuous	13.0 and 7.3 $\mu g \cdot m^{-3} \cdot m^{-2}$ leaf area	Kim et al. 2016
4	*Schefflera arboricola*, *Spathiphyllum wallisii*	Potted plant	Loamy soil: 30% sand, 30% silt, 15% clay, 25% humus	C_6H_6	3.6–29.5	Continuous	91–97% in 48 h	Parseh et al. 2018
5	*Nephrolepis obliterata*	Potted plant	Loamy soil: 30% sand, 30% silt, 15% clay, 25% humus	CH_2O	600–11,000	Continuous	81–100% in 48 h	Teiri et al. 2018
6	*Chamaedorea elegans*	Potted plant	Loamy soil: 30% sand, 30% silt, 15% clay, 25% humus	CH_2O	660–16,400	Continuous	65–100% in 48 h	Teiri et al. 2018
7	*Laurus nobilis*	Potted plant	garden soil, slow-releasing fertilizer	CO_2	684,003–1,800,009	Continuous	360,002 $\mu g/m^3$/day/m^2	Salvatori E et al. 2020
8	*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 al. 2021

Micro-organisms present in the potting mixture or within the root zone of indoor potted plants are the necessary agents that determine the VOC removal rate (Wood et al., 2002b; Burchett et al. 2010). *Fatsia japonica* (Decne, Planch, and L.) and *Ficus benjamina* L. root zones were found to be more effective in formaldehyde removal. The root zone's capacity for VOC removal is largely determined by the structure of its microbial populations (90%); however, only a very small fraction (10%) of VOC removal can be attributed to adsorption by the growing medium. The soil microflora plays a considerable role in the removal of gasoline VOCs (Cruz et al. 2019). This microbe-assisted VOC removal is indirectly assisted by plants by nourishing the root zone–associated microbial population (Wood et al., 2002b; Kang and Freeman 2007; Torphy et al. 2013; Kim et al. 2021). This indicates that the root zone microflora plays a crucial role in enhancing the phytoremediation efficiency of indoor plants by reducing VOCs and other pollutants (Kim et al. 2008). Among growing media, potting mixture or soil type, used or unused potting mixture, hydroponic plant system (liquid media), and the microbiome associated with it, the former actually determine the latter's VOC removal rate (Wood et al., 2002a; Moya et al., 2021). The type of soil mixture used and the type of VOC to be removed both had an influence on the effective removal of VOC by *Epipremnum aureum*. Upon using four different potting mixtures such as Ecodo-Hydro, Japanese charcoal, hummus, three-layered clay, and Hydro, the three-layered clay was found to be most efficient for formaldehyde removal. However, for acetone removal, both Ecodo-Hydro and clay (three-layered) were found to be more efficient as compared to other soil types (Oyabu et al. 2003). When pot soil was used instead of tap water and growing water, *Epipremnum aureum* had a high capacity for VOC (formaldehyde, xylene, and toluene) removal (Sawada and Oyabu 2008). The removal of benzene and toluene in a hydroponic system by *Howea forsteriana*, *Spathiphyllum wallisii*, and *Dracaena deremensis* was less efficient when compared with soil. Instead of the hydroponic medium, the soil was found more effective as a growing medium for benzene removal by *Syngonium podophyllum* (Table 4) (Irga et al. 2013). The VOC removal rate of plants in a hydroponic medium or without a potting mixture is dependent upon the microorganisms associated with their roots after washing with water. The acclimatization of plants in hydroponics for a 2-day or longer period, before exposure to VOCs, can lead to a better VOC removal rate due to the increased number of microorganisms in the water (Wood et al., 2002a). The rate of removal of airborne VOCs usually showed a decline upon the removal of plants from the potting mixture or growing medium (Godish and Guindon 1989; Wood et al., 2002a; Irga et al. 2013). Compared to the potting mixture

with plant roots, sterilized potting mixture or soil showed a sharp decline in the formaldehyde removal rate, which summarized the importance of the microflora associated with plant roots for VOC removal, before soil sterilization (Kim et al. 2008).

Recommended plants for VOC removal

The role of green plants in improving indoor air pollution has been well established (Wood et al. 2006; Weyens et al. 2015; Han et al. 2020; Liu et al. 2022). Various species of ornamental plants have been found efficient in pollutant elimination for indoor air (Yang et al. 2009; Cruz et al. 2019; Wang et al., 2020b). The type and selection of plants also have a great influence on the VOC removal rate (Kim and Paulos, 2010). Among two species of plants (peace lily and Boston fern), Boston ferns using soil as substrate showed better depletion of formaldehyde in a glass chamber (Moya et al., 2021). Upon evaluation of its xylene removal capacity, *Zamioculcas zamiifolia* performed best among a range of other test-potted plant species, including *Aloe vera*, *Cordyline fruticosa*, *Philodendron martianum*, *Sansevieria hyacinthoides*, *Aglaonema rotundum*, *Muehlenbeckia platyclada*, *Tradescantia spathacea*, *Guzmania lingulata*, and *Cyperus alternifolius*. *Areca palms* have already proven themselves as an efficient, economical, and workable solution for improving indoor air quality through the removal of indoor air pollutants. The elimination efficiency of *Areca palm* TVOCs was about 90% (Bhargava et al. 2021). Few tropical plants, including *Dracaena fragrans*, *Nephrolepis exaltata*, and *Rhapis excelsa*, have demonstrated their ability to remove indoor air pollutants, particularly gases (Bhargava et al. 2021). For the removal of formaldehyde from the indoor air, the spider plant (*Chlorphytum comosum*) and soybean (*Glycine max* L.) have also shown satisfactory results (Pandey and Bajpai 2019) (Fig. 4). Indoor plant species have been assessed for the removal of a range of VOCs such as benzene, toluene, m-xylene, and hexane (Orwell et al. 2006; Wood et al. 2002b; Yoo et al. 2006) (Fig. 5). *Dracaena deremensis* 'Janet Craig' showed a 75% reduction in VOCs in naturally ventilated offices (Wood et al. 2006). Two plant species, *Dieffenbachia maculata* and *Spathiphyllum wallisii*, have also demonstrated their phytoremediation potential by eliminating toluene and 2-ethylhexanol from indoor air using their aerial parts. Without these plants, the potting soil depletes VOCs (Hormann et al. 2017, 2018). Various ornamental species in the interiors have been screened for their pollutant and VOC removal efficiency. Plants such as *Hemigraphis alternata*, *Hedera helix*, *Hoya carnosa*, and *Asparagus densiflorus* were found efficient
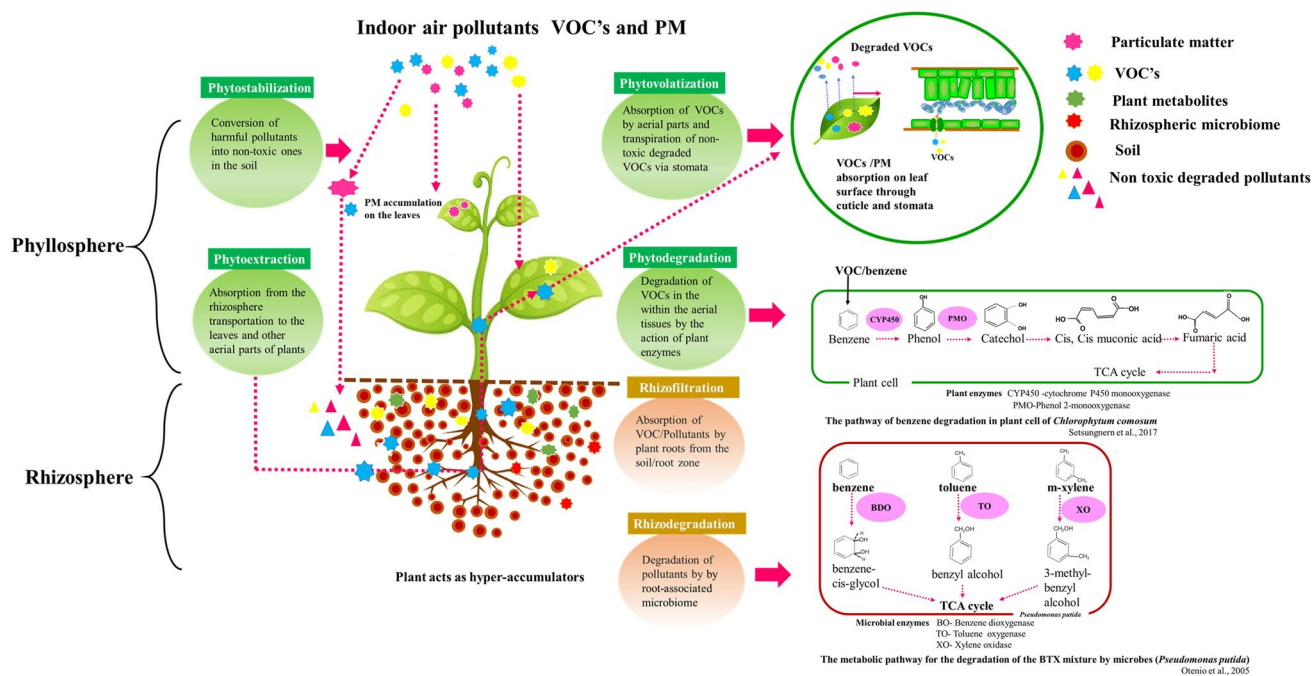
Fig. 5 Mechanisms of phytoremediation/plant-based approach for mitigation of indoor air pollution

in the removal of all indoor pollutants, but *Tradescantia pallida* has shown its better efficiency, particularly in VOC elimination, including benzene, toluene, TCE, and a-pinene. Among ferns, Nephrolepis obliterate has demonstrated its ability to reduce indoor pollutants by removing formaldehyde from the air (Yoo et al. 2006). A study conducted by Zhao et al. (2019) showed efficient formaldehyde removal from the air by wild *Taraxacum mongolicum Hand.-Mazz.* and *Plantago asiatica* L., thus recommending them as good candidate species for developing phyto-microbial technologies. *Ledebouria socialis*, *Eugenia* sp., *Piper porphyrophyllum*, and *Peperomia* sp. had the highest and most significant VOC absorption among the various potted indoor plant species studied by Noor and Ahmad, (2020). Several common green wall plants are also known to have a tolerance against indoor air pollutants at high concentrations (Paull et al. 2018). In a study conducted in a controlled environment, the ability to remove formaldehyde and carbon dioxide from the air was evaluated using two plant species (peace lily and Boston fern) and three substrates (expanded clay, soil, and activated carbon). The soil substrate performed the best, while the Boston ferns were the top performers among plant species (Moya et al. 2021). The discrepancy in pollutant removal efficiency among plant species indicates that for a better understanding and improvement of indoor air quality parameters, more plant species still need to be screened out. Moreover, the number and type of plants should be customized according to the

type of VOCs present in the indoor air for a more efficient cleansing of air pollutants.

Conclusions and future prospects

Since the COVID-19 epidemic, improving indoor air quality (IAQ) has become a pressing global concern, making it the foremost task facing the scientific community today. Consequently, the creation of a sustainable green environment and the increased usage of inexpensive indoor plants urgently need our attention. Depending on the species, different indoor plants may decrease or moderate the negative effects of air pollution to varying degrees. Plants in different forms, such as potted plants or green walls, are viewed as potentially green solutions for enhancing indoor air quality and inhabitants' health. As a result, the purpose of this study is to look at how indoor plants' aerial parts, growth medium, roots, and microbes improve indoor air quality. In light of all of these considerations, phytoremediation seems to be a potentially beneficial technique of remediation since it is a low-cost, plant-based, environmentally friendly, low-maintenance, soil stabilizing, cost-effective, and esthetically pleasing solution. This review improved our understanding of the plant-based mechanisms responsible for the elimination of numerous indoor pollutants. To develop and comprehend the true indoor pollution removal process, the removal capability of indoor plants must be defined in depth. Additional study is required on plant characteristics such as the

size of the leaf, the thickness of the leaf, the surface area of the leaf, the effectiveness of certain species, and the plant components that are involved with the process of eliminating air pollutants. Furthermore, to improve the implementation of this plant-based method, a comprehensive understanding of the underlying physiology and biochemistry of the many phytoremediation processes is essential. Likewise, the influence and complexity of the plant microbiome must yet be thoroughly understood. So further research based on OMICS approaches is required for identifying microorganisms that can be helpful for the removal of indoor air pollutants. More experiments in real-time settings are needed to evaluate the efficacy of plant-based methods for removing air pollutants. Hence, the following topics are recommended as a priority basis for future research to address the common questions related to indoor air pollution removal and avoiding pollutant-related potential health risks. As in the current scenario, the health systems of various nations face several obstacles and strains. Thus, switching to indoor plants and adopting a sustainable and green environment may help to alleviate the burden on the health sector while maintaining improved public health.

Limitations of the study

Although this review primarily used a systematic approach, our goal was to offer a deep insight into the indoor air pollutants, types of indoor plants (potted plants/green walls), and mechanisms behind plant-based indoor air pollutant removal. However, in order to better understand how plants and their associated microbes can be used to mitigate the effects of indoor air pollution on human health, meta-analyses detailing the underlying physiological, biochemical, and genetic basis of the phytoremediation processes need to be done. The effectiveness of using green plants could be explained in detail concerning learning or productive efficiency, post-operative healing, and the emotional state of the patient.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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