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Phytoremediation of indoor formaldehyde by plants and plant material

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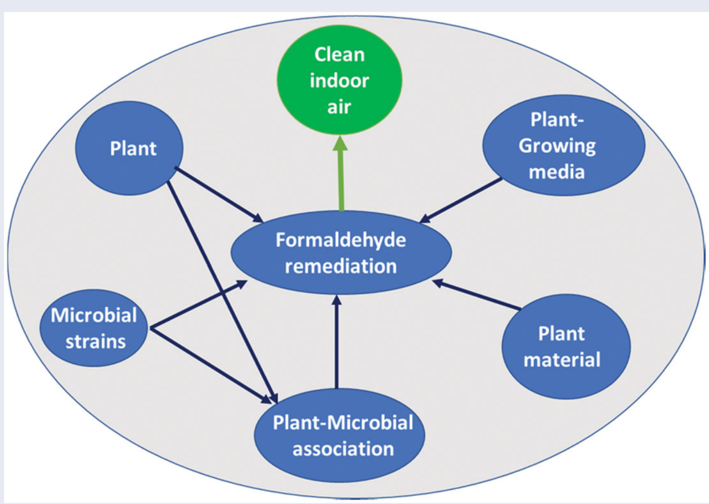
ABSTRACT

Formaldehyde evolves from various household items and is of environmental and public health concern. Removal of this contaminant from the indoor air is of utmost importance and currently, various practices are in the field. Among these practices, indoor plants are of particular importance because they help in controlling indoor temperature, moisture, and oxygen concentration. Plants and plant materials studied for the purpose have been reviewed hereunder. The main topics of the review are, mechanism of phytoremediation, plants and their benefits, plant material in formaldehyde remediation, and airtight environmental and health issues. Future research in the field is also highlighted which will help new researches to plan for the remediation of formaldehyde in indoor air. The remediation capacity of several plants has been tabulated and compared, which gives easy access to assess various plants for remediation of the target pollutant. Challenges and issues in the phytoremediation of formaldehyde are also discussed.

Novelty statement: Phytoremediation is a well-known technique to mitigate various organic and inorganic pollutants. The technique has been used by various researchers for maintaining indoor air quality but its efficiency under real-world conditions and human activities is still a question and is vastly affected relative to laboratory conditions. Several modifications in the field are in progress, here in this review article we have summarized and highlighted new directions in the field which could be a better solution to the problem in the future.

GRAPHICAL ABSTRACT



KEYWORDS
Formaldehyde; phytoremediation; plant-microorganisms association; indoor air pollution; plant material; air quality

Introduction

In recent years, the purification of atmospheric pollution becomes the focal point of scientific research. Humanity is surrounded by nearly 200 variety of airborne pollutants, which can seriously damage the respiratory and cardiovascular systems (Han *et al.* 2022). The presence of many of these pollutants is responsible for emergency visits or hospital admissions and eventually causes mortality (Orellano *et al.* 2020; Han *et al.* 2022). The global consideration is that air pollution (both outdoor and indoor) is a tremendous environmental health risk resulting in about one in every nine deaths annually (WHO 2016). As people tend to spend more than 80% of their time indoors, and as the indoor air pollutants are often 2–4 times higher than outdoor, people

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are seriously exposed to indoor air pollutants affecting their health, well-being, and productivity levels in working spaces (Pettit *et al.* 2018b; Mannan and Al-Ghamdi 2021a; Teiri *et al.* 2022). Among these pollutants formaldehyde (HCHO) is one of the most notorious pollutants present in the atmosphere. It is a volatile organic compound; toxic and chemically sensitive gas emitted from diverse indoor sources, such as wood-based construction materials, flooring, furniture, decoration elements, and other adhesives and resins (Wang *et al.* 2020; Zhang *et al.* 2020; Han *et al.* 2022; Huang *et al.* 2022), causing eyes and nose irritation and bodily discomfort. While long-term exposure may cause nervous system disorders and other carcinogenic effects (Zhu *et al.* 2019; Lee *et al.* 2021; Han *et al.* 2022).

On the other hand, formaldehyde is an economically essential chemical, endogenously produced in a living organism (Agathokleous and Calabrese 2021), annually producing $\sim 21 \times 10^6$ tones globally (Zhang 2018). It is manufactured as an aqueous solution known as formalin (which contains 37% of dissolved formaldehyde). It is widely used as an embalming agent or as a bactericide in medical laboratories (Bedino 2003). It is also mixed with other compounds to make casein formaldehyde, phenolic resins, urea formaldehyde, and melamine formaldehyde; which are used in the production of daily life products for domestic and industrial uses, such as resins, plastics, cups, saucers, lampshades, varnishes, laminates, adhesives; knitting needles, buttons, buckles, electrical automobile insulators, and other heavy industrial products. It is also widely used in glass and rock wool insulation, molding compounds, decorative laminate, and textile treatments (Zhang *et al.* 2009). Formaldehyde is emitted indoors from household elements including carpeting, plywood, particleboard, furniture, and items from the above-mentioned industries (Zhang *et al.* 2009). Based on serious health concerns, the safe concentration of this chemical has to be maintained particularly in places expected to have high concentration. The permissible exposure limit (PEL) approved by Occupational Safety and Health Administration (OSHA) is 0.75 ppm (8 h Time-Weight Average, TWA) and 2 ppm (15 min, Short-term Exposure Limit, STEL). The ACGH has set the Threshold Limit Value (TLV) to 0.3 ppm and the National Institute of Occupational Safety and Health (NIOSH) has approved 0.016 ppm (8 h, TWA) and 0.1 ppm (15 min, STEL) (Zhang *et al.* 2009).

Indoor air pollution may be controlled by eliminating the source of pollution, optimizing ventilation, and modifying users' behaviors (Bandehali *et al.* 2021). Various systems have been introduced to remove indoor air pollutants from air, i.e., filtration, ventilation, isolation, air cleaners, adsorption, and air stripping ozonation, ultraviolet (UV) photolysis, photocatalytic oxidation, cold plasma or non-thermal plasma (NTP), membrane separation, etc. (Teiri *et al.* 2018b; Yang *et al.* 2020).

The presence of formaldehyde in surrounding air particularly indoor environments is required to be regularly monitored and regulated. There are various techniques in practice to cleanup formaldehyde, they can be on a laboratory scale using porous material (Hu *et al.* 2020; Tasbihi *et al.* 2015), fixed bed scrubber (Talaiekhozani *et al.* 2016), photocatalytic degradation (Mamaghani *et al.* 2018) and decomposition over nanomaterial (Cui *et al.* 2019; Luo *et al.* 2019), etc. These technologies are efficient but need considerable installation and replacement cost which make their use limited for an ordinary person. Phytoremediation is a better alternative in comparison to these technologies which are affordable for an ordinary person. Here in this review article, we have collected a list of plants efficient in formaldehyde remediation under ordinary conditions. Various phytoremediation strategies have been critically compared in terms of remediation efficiency, economic viability, and other demands. Various concepts associated with these concepts, strengths, and limitations (of some) are also discussed.

Recent reviews in the field

Enhanced concentration of various Volatile Organic Compounds (VOCs) in indoor air is of great public health concern and has frequently been reviewed (a brief list is presented in Table 1). Several hot spots have been identified where there is a need for extra cases and awareness among the technical staff related to their health and judicious use

Table 1. Some recent reviews published recently, aiming removal of formaldehyde from the ambient air.

S. No.	Title of review article	Publication year	References
1.	Plant-based remediation of air pollution: A review	2022	Han *et al.* 2022
2.	Key factors and primary modification methods of activated carbon and their application in adsorption of carbon-based gases: A review	2022	Wang *et al.* 2022
3.	Volatile organic compounds (Vocs) as environmental pollutants: Occurrence and mitigation using nanomaterials	2021	David and Niculescu 2021
4.	A review on recent advancements in photocatalytic remediation for harmful inorganic and organic gases	2021	Priya *et al.* 2021
5.	Rational design of catalysts toward energy-saving formaldehyde oxidation: A review	2021	Chen *et al.* 2021
6.	Autopsy, thanatopraxy, cemeteries and crematoria as hotspots of toxic organic contaminants in the funeral industry continuum	2021	Gwenzi 2021
7.	A review of different phytoremediation methods and critical factors for purification of common indoor air pollutants: an approach with sensitive analysis	2021	Teiri *et al.* 2022
8.	Active Botanical Biofiltration in Built Environment to Maintain Indoor Air Quality	2021	Mannan and Al-Ghamdi 2021b
9.	Biotechnology progress for removal of indoor gaseous formaldehyde	2020	Shao *et al.* 2020
10.	Effects of indoor plants on air quality: a systematic review	2020	Han and Ruan 2020
11.	Review on the effects of plants on indoor environments	2020	Aydogan and Cerone 2021

of the chemical (Gwenzi 2021). Catalytic deactivation and catalytic oxidation of formaldehyde by MnO_x (Vikrant *et al.* 2017; Irga *et al.* 2018; Kim *et al.* 2018; Pettit *et al.* 2018b) material have been described by applying various models, such as Mars-van-Krevelen, Eley-Rideal, and Langmuir-Hinshelwood. The removal capacity of the material suffers from some limitations and its practicality is therefore hindered for remediation of indoor formaldehyde (Zheng *et al.* 2022). Mitigation of this indoor air pollutant in an energy-saving manner may be achieved by tailoring the structure, morphology, and surface of the catalytic material (Chen *et al.* 2021). Various strategies for removal of formaldehyde are in practice where some are associated with secondary toxic products (Wu *et al.* 2022). The combination strategy relying on plants, bacteria, and physical adsorbents in the removal of formaldehyde is ecofriendly, economic, and safe (Shao *et al.* 2020). The activated carbon material is widely used for adsorption of toxic contaminants including formaldehyde based on their several intriguing properties like improved pore size, enough available surface area for adsorption, a variety of functional groups, reusability, low cost, and robust nature. There are some problems associated with this material, structural and chemical modification is a source of secondary pollutants, adsorption under humid conditions is affected and long-term gas removal capacity are some of the aspects to be addressed (Wang *et al.* 2022).

Nanomaterials seem to be efficient in the field of catalytic conversion of VOCs and some large molecules, they are comparatively new in the field and in most cases, the complex mechanism of decomposition is also unexplored (David and Niculescu 2021). These materials have several opportunities to play their role in the future, particularly as photocatalysts (Priya *et al.* 2021) and oxidation technologies (Chen *et al.* 2021).

The formaldehyde concentration in indoor air is always less and expensive materials and technology in normally not affordable. In this scenario, low-cost, efficient, and long-lasting technologies and materials are required. In this respect, plants are a viable and feasible solution to be grown or kept in side houses. Potted plants and green active walls are already in use to mitigate some pollutants. Still, some challenges are there to perform experiments on commercial bases to evaluate the technology for its cost and affordability. The uptake process during summer and winter and the temperature inside the building can also be a limiting factor that has to be evaluated in future studies (Han and Ruan 2020; Aydogan and Cerone 2021). It is evident from Table 1, that in literature potted plants and plant material for formaldehyde removal from the ambient air have not been reviewed.

Search and study selection

During searching literature in Scopus, the keywords, formaldehyde remediation, formaldehyde phytoremediation, indoor formaldehyde, and indoor air quality were included. The search was made limited to a specific period 2015–2022. Only journal articles were selected for this study and particularly those containing the keyword in their subject. The papers featuring quantitative data were critically studied and data therein were summarized and discussed. Special attention was paid to those articles that contained reliable experimental data, some of the papers were excluded during the study they were either based on theoretical calculations or the data were poorly presented.

Occurrence and chemistry of formaldehyde in the atmosphere

Formaldehyde is a colorless gas with a strong smell and is one of the common chemicals used in various building materials. Some of the materials where formaldehyde is used are, wood products processed in industries, paper products, coating, and insulating material, and as a reagent in the chemical industry. It is a reactive compound and lasts for a few hours in the air, it is highly soluble in water. The water solution of formaldehyde is called formalin which is used as a preservative in funeral homes, laboratories, as food preservatives (in some cases), as antiseptic, medicines, cosmetic products, and many more. It is also produced during the cooking of some foods and smoking in houses. Based on the toxicity of this chemical it has been declared a human carcinogen by the Environmental protection Agency (EPA), National cancer institute (NCI), International Agency for Research on Cancer (IARC), and National Toxicology Program (NTP) (Beane Freeman *et al.* 2009).

Formaldehyde is an oxidation intermediate of most VOCs present in the air. Photochemical reactions of long-lived VOCs at high altitude is also a source of formaldehyde and the concentration varies with overhead sunlight (Hong *et al.* 2022). Photochemical conversion of HCHO into H_2 and CO at 324 nm, is reported in the literature. Formaldehyde readily reacts with OH and NO_2 in the troposphere. The calculated lifetime of formaldehyde for OH radical reaction is 1.2 d, NO_2 is 83 d and ozone is longer than 4.5 years. It means tropospheric OH has a greater influence on the lifetime of formaldehyde (Atkinson and Arey 2003). Formaldehyde is an atmospheric trace gas and its concentration in addition to some chemicals in the air (methane, methanol, isoprene, formaldehyde, and OH), depends upon the daylight (Nussbaumer *et al.* 2021). The production of formaldehyde from the reaction between OH radical and the mentioned chemical is almost equal to its loss. Loss of this chemical is achieved by photolysis and oxidation during daytime and by deposition during nighttime. If not inhaled, the concentration of this chemical is naturally kept balanced. The indoor concentration of formaldehyde is dependent on various factors, such as the use of various wood products rich in formaldehyde, paper, and polymeric material. These materials are sources of indoor formaldehyde which need to be monitored and controlled in a timely manner, various sources, degradation/photolysis, and remediation of formaldehyde are represented in Figure 1.

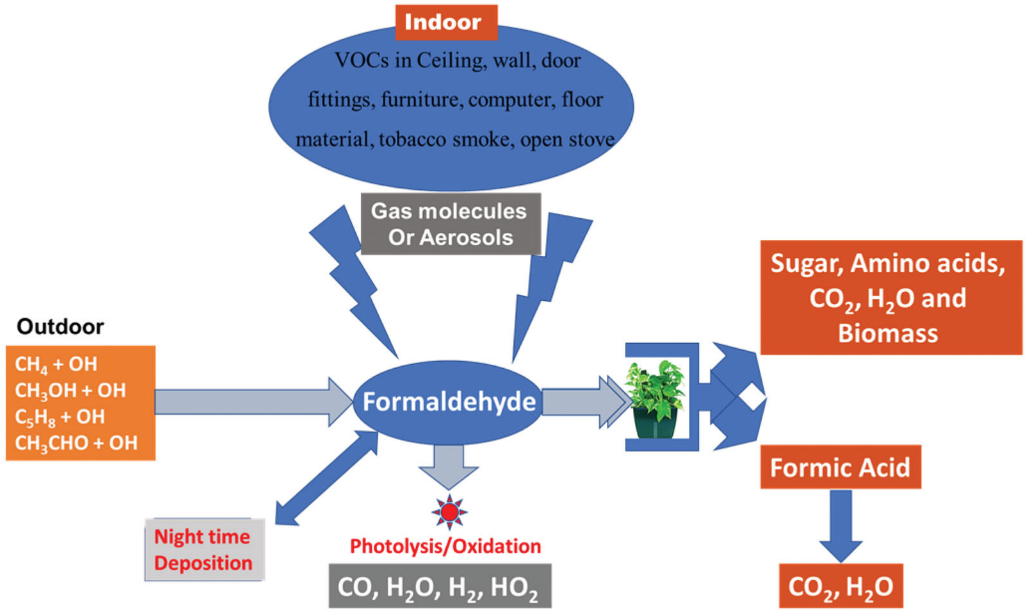

Figure 1. Common in-/outdoor sources of formaldehyde and its remediation/decomposition.

Mechanism of phytoremediation

Plant microorganisms play a pivotal role in the remediation, they use VOCs as a source of energy or degrade them with the help of certain enzymes. The remediation or degradation depends upon the nature of pollutants (hydrophobicity, toxicity, and solubility) and certain factors (i.e., type of microorganisms, composition of pollutants, and intensity of light). The uptake of formaldehyde by selected plant species in a specific experiment was more under dark conditions in comparison to light (Aydogan and Montoya 2011). Root and aerial zones of plants have different efficiency in remediation of formaldehyde and other VOCs, rhizosphere degradation of these pollutants is the prominent rout in the plant system (Soreanu *et al.* 2013). Some of the plant species are reported to absorb formaldehyde from the air, part of it is translocated to the rhizosphere, and part is volatilized. Plant leaves adapt naturally to become more efficient in absorption and showed higher absorption capacity in comparison to young leaves (Su and Liang 2015). Photosynthesis is a well-known process in which plants take up CO_2 and produce O_2 thus improving indoor air quality if present inside the building. Plants also enhance humidity inside the building through the process of transpiration. Plants absorb gaseous pollutants, bioaerosols, and particulate matter are absorbed on the surface of leaves or absorbed by stomata and are accumulated in the internal structure of the plant (Lee 2013).

Phytoremediation of VOCs and its types

Phytoremediation is an effective, eco-friendly and cost-effective, and sustainable method to improve Indoor Air Quality (IAQ) and decrease air pollution and heavy metal concentration in soil segments (Ali *et al.* 2013). Absorption and degradation of atmospheric pollutants are the main processes during phytoremediation which depends on the metabolic activities of plants (Lee *et al.* 2021; Han *et al.* 2022). Indoor plants are mainly herbs and small shrubs and the adsorption ability of pollutants can be measured via air-tight experimental containers. On the other hand, outdoor plants are mainly trees or big shrubs and their purification impact can be directly evaluated by the adsorption ability of their foliar surfaces and roots (Han *et al.* 2022).

Phytoremediation is divided into passive and active biofiltration systems. The passive system is defined as a plant-soil system where the plant is grown in different pots and watered regularly as needed (potted plant) or vertically planted in hanging lightweight pots with growing media (green wall and vertical garden). This system is slow in purifying low concentrations of indoor air pollutants because it relies on the diffusion of the gaseous indoor pollutants (González-Martín *et al.* 2021; Mannan and Al-Ghamdi 2021b, p. 672102; Han *et al.* 2022; Teiri *et al.* 2022). Due to the limitation of the passive phytoremediation system, recent researches are focused on creating an active green wall-based system (vertical hydroponic system). Which integrates the use of mechanical devices (low power fans—active fan-assisted hydroponic technology) to create an airflow of the polluted indoor air forcing it to flow toward the whole plant getting intimately in contact with its aerial (leaves and stems) and rhizosphere parts (roots and microorganisms). Thus, phytoremediation will be significantly higher (Pettit *et al.* 2018b; Moya *et al.* 2019; Bandehali *et al.* 2021; González-Martín *et al.* 2021; Teiri *et al.* 2022). Another reason for maximizing phytoremediation is the plant's high density as a large number of plants grown compared to the limited floor area being utilized (vertical alignment) with the aid of mechanical ventilation (Pettit *et al.* 2018b). In the active system, the air is actively forced through the aerial plant and rhizosphere microorganisms, while passive system plant and microorganisms act as a sink for air pollutants that produce clean air by capturing pollutants or converting them into less toxic molecules (Soreanu *et al.* 2013).

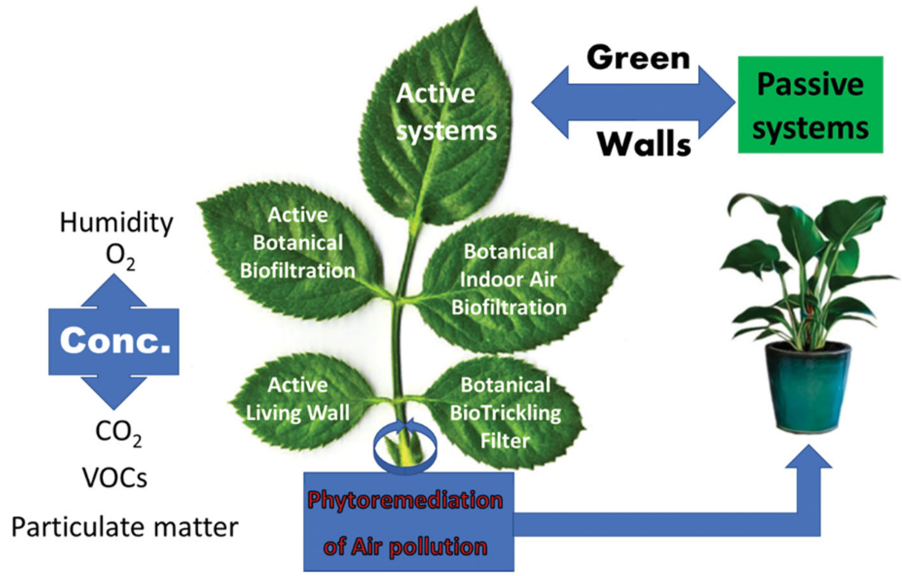

Figure 2. Passive and active modes of phytoremediation of organic volatile pollutants.

There are various terminologies referred to as phytoremediation, such as active botanical biofiltration (ABB), botanical indoor air biofilters (BIAB) (Ibrahim *et al.* 2018; Pettit *et al.* 2018b), active living wall (ALW), active green wall (Pettit *et al.* 2018b, 2019; Mannan and Al-Ghamdi 2021c), and Plant-assisted bio-trickling filter (PBTF) (Soreanu *et al.* 2013), summarized in Figure 2. These remediation techniques are briefly explained under.

Potted plants (PP)

The PPs has been a focus of researcher for the purification of indoor air from organic pollutants (Irga *et al.* 2018; Kim *et al.* 2018). They are passive removers of pollutants from the air and have a much slower rate than other techniques/systems. They can be used for relatively less polluted air, their efficiency and decontaminating efficiency cannot be controlled. Still, PPs play their role in controlling air pollution and some plants have been found very proficient in eliminating VOCs, such as formaldehyde (Xu *et al.* 2011; Teiri *et al.* 2018a), toluene (Kim *et al.* 2011), benzene, ethylbenzene, xylene (Sriprapat and Thiravetyan 2013), and inorganic gaseous pollutants like CO_2 (Torpy *et al.* 2017) and ammonia (Ortakci *et al.* 2019), etc. They suffer from certain limitations in addition to the abovementioned, i.e., they need soil which is not least desired in some houses and their maintenance is somehow a challenge.

A more efficient and controlled system is a plant-assisted bio-trickling filtration active system, which is discussed below.

Active botanical biofiltration (ABB)

Limitations of potted plants were seriously taken, and the research was directed to wall-based air purification. The air was brought in contact with microorganisms present in the rhizosphere of plants and air flow was created through certain mechanical devices for enhanced phytoremediation. This system is called ABB or BIAB (Mannan and Al-Ghamdi 2021b). This system has been studied for its efficiency under various conditions, such as plant type, temperature, rate of air flow, temperature, nutrition, and type of light however, its applicability in a realistic indoor environment is still poorly understood. Multiple factors influence the efficiency of the ABB, such as quantity and types of plants, type of growing media, temperature, lighting intensity, and plant nutrition (Mannan and Al-Ghamdi 2021b, p. 672102).

Green walls/living walls/vertical gardens (GW, LW, VG)

They are also called living walls or vertical gardens, structurally can be wall-climbing or hanging. As described by Samaneh *et al.* Green Walls are pre-vegetated planted covers or frame upright modules installed on a wall or attached to other structures (Bandehali *et al.* 2021). These vegetated flat walls are square or rectangular in shape, fixed either indoor or outdoor, and partly or entirely covered with plants. They contain directly growing media and are usually made up of lightweight material. The green wall system cleans up indoor air and also acts as a thermal regulator. They are further divided into two types, passive and active green walls. Active green walls have received significant research attention for improving indoor and outdoor air quality. These systems have been tested in an indoor environment for the mitigation of CO_2 and have effectively been used in the reduction of roadside pollutants (Dominici *et al.* 2021; Pettit *et al.* 2021). Active green walls allow air free of particulate matter (PM), CO, CO_2, and most VOCs into the indoor space. Active walls with hydroponic plants are efficient in gaseous air pollutants removal at a high air flow rate (Wolverton 2012). Passive living walls are economically viable and simple in structure but less efficient in pollutants removal. Some authors also classify green walls based on types of plants, growing media, and structure of the wall.

Plant-assisted bio-trickling filtration

This technology was developed in Canada and is currently being commercialized for the removal of VOCs from the air. Bio-trickling filters are equipped with packing material for root support and hydroponic plants. They make an active biofiltration system and are continuously fed with contaminated air, trickled with nutrient solution. During this process uptake and degradation of pollutants take place leading to pollutant-free air which is allowed into the building. This system is superior in terms of using no soil and avoiding maintenance difficulties as in the case of potted plants. This system is more suited for improving indoor air quality and is efficient in terms of enhanced gas exchange and higher pollutants removal performance (Soreanu *et al.* 2013). This technology is supported by theoretical models for the removal of hydrophilic VOCs (ethanol, ethyl acetate, and 1-ethoxy-2-propanol) (San-Valero *et al.* 2015) and ammonia (Melse *et al.* 2012), etc. The system supports the biodegradation of highly lipophilic compounds due to the higher bioavailability of more hydrophilic intermediates. Benzaldehyde, the transformation product of styrene, is highly water soluble and can be degraded efficiently by this technology (Dobslaw *et al.* 2017).

Benefits of phytoremediation

Phytoremediation is counted as one of the promising depollution technologies with the benefit of high efficiency, cost-effectiveness, effortless operation, and the avoidance of forming secondary pollution (Yang *et al.* 2020). On the other hand, elevating the ventilation rate indoors to dilute the indoor air pollutants is often complex and cost-effective. Thus, phytoremediation becomes a significant alternative because of its vast benefits to the environmental, social, and economic sectors with its potential contribution to zero emissions (Teiri *et al.* 2022). In addition, it can reduce the dependency on costly and energy-consuming mechanical ventilation and the installation of filters to purify indoor air and improve indoor air quality (IAQ) (Teiri *et al.* 2018a, 2018b; Han *et al.* 2022). Green systems inside an indoor environment have many benefits that have positive effects on the space users as their satisfaction, comfort, and happiness levels increase (Moya *et al.* 2019). Plants reduce the indoor temperature and act as passive acoustic insulation by reducing levels of indoor sound. Surprisingly, the active system has several other benefits, such as minimizing indoor temperature, enhancing relative humidity, and enhancing sound insulation (Moya *et al.* 2019; González-Martín *et al.* 2021). Quantitatively, a decrease in temperature by 1 °C, an increase in humidity by about 9–13%, and save 20% of fresh air instead of outdoor air (Wang and Zhang 2011). An additional benefit is to reduce the indoor temperature, which reduces the energy needed for cooling the indoor environment, additionally, it adds esthetic benefits for the space users. Added to this, the environmental, economic, and social benefits of this system are worth mentioning (Ghazalli *et al.* 2018; González-Martín *et al.* 2021; Mannan and Al-Ghamdi 2021c). As a result, during plants' natural life cycle and growing habits, it can purify atmospheric pollutants, such as hazardous compounds (organic compounds and metals), greenhouse gases, etc. (Han *et al.* 2022). Additional benefits of growing plants decrease airborne pollutants, reducing soil and sand deterioration, initiating windbreaks, capturing air microbes, and cleaning up indoor spaces contaminated with formaldehyde, benzene, and other volatile contaminants (Han *et al.* 2022). Indoor plants decrease physical tiredness, improve mental health, positively change the health status of space users specifically asthmatic patients, and reduce the level of indoor volatile organic compounds (VOCs) (Kim *et al.* 2014). Ornamental indoor plants are capable of minimizing energy consumption and can emerge in the recent trend of sustainable green buildings (Soreanu *et al.* 2013).

How do plants absorb formaldehyde?

Readers are referred to a detailed study on the plant-microbe association in mitigating formaldehyde from the air (Weyens *et al.* 2015). Many researches showed that formaldehyde is absorbed by plants not only through stomata and cuticles of leaves but also by the root system and soil microorganisms. Formaldehyde is degraded, detoxified, or sequestrated by promoting plant growth (Weyens *et al.* 2015; Teiri *et al.* 2018a). Stomata on plant leaves are responsible for the absorption of the air pollutants and purifying HCHO via conversion into non-toxic substances and discharging it either by the root system or by concentrating it inside the branches. While enzymes in the plant metabolism are responsible for the decomposition and degradation of multiple air pollutants (Rachmadiarti *et al.* 2019; Wang *et al.* 2020; Han *et al.* 2022). Studies confirmed that the growing media not only supports the plant by holding the roots but also simplifies the primary pollutant removal process. Using different growing media resulted in different removal rates and adding activated carbon may significantly increase the purification rates of gaseous pollutants (Pettit *et al.* 2018a). In the plant leaves, the absorbed formaldehyde is converted into carbon dioxide (via oxidization) or other combinations inside the plant body, for example, organic acids, amino acids, sugars, and water in the Calvin cycle (Teiri *et al.* 2018b).

HCHO metabolism in plant

In an absorption experiment utilizing *Chlorophytum comosum*, ^{14}C was used to label formaldehyde, results revealed the presence of HCHO in the cell tissue of the plant. This experiment emphasizes the C present in the molecule of formaldehyde. The *comosum's* ability in converting formaldehyde into organic acids, amino acids, and sugars by the metabolic reaction was explored. Thus, it is evidenced that plants can purify pollutants *via* self-metabolism (Schmitz *et al.* 2000). The aerial part of the plant and the root zone both compete in adsorbing formaldehyde while the rhizosphere plays an essential role in VOCs degradation (Bandehali *et al.* 2021; Lee *et al.* 2021). Potted plants can remove formaldehyde from air as it dehydrogenases in plant tissue with the help of the microorganisms in the roots and substrate to enhance the removal ability. Enzymes in plants are responsible for purifying formaldehyde from polluted air (Zhao *et al.* 2019).

Inside the plant, formaldehyde is enzymatically transformed by particular dehydrogenases to either formic acid and eventually to CO_2 and H_2O or into amino acids, sugars, CO_2, H_2O, and biomass (Soreanu *et al.* 2013) (see Figure 1).

HCHO damage to indoor plants

Plants can survive breathing ambient air polluted with formaldehyde. Nevertheless, when exposed to enormous amounts of HCHO for a lengthy period, it will be negatively impacted by turning yellow, getting flaccid and loosen, growing slowly, and eventually dying (Su *et al.* 2019). Two formaldehyde fumigation studies showed that exposing *N. obliterate* potted plant up to 11 mg/m^3, and exposing *C. elegans,* another potted plant up to 16 mg/m^3 could not stop the growing nature of the plant due to the high resistance of the plant and high tolerance toward HCHO (Teiri *et al.* 2018a, 2018b). In this study, 30 indoor potted plants from three distinct species were exposed to air contaminated with 15 mg/m^3 of formaldehyde for 7 days for testing their HCHO removal ability inside a sealed glass box (1 × 1 × 0.8 m). After 7 days, the plants were classified into five grades (0–4) according to the damage response caused by formaldehyde. Grade 0 was normal with no damage and grade 4 with deterioration in the stem region and half of the leaves were rotten or dried (Zhou *et al.* 2011).

The results listed the best 10 plants having high purification ability toward formaldehyde with the least damage (Zhou *et al.* 2011). In another study, the morphological response of the plant toward formaldehyde by testing 15 hydroponic plant species in an automatic fumigation chamber was studied. Plants were exposed to 10, 50, and 100 mg/m^3 formaldehyde for 1 h a day, for 6 days. Symptoms of plant damage were classified into four groups. Plant withered, leaf tips withered, Foliar injury and leaf withered but stem upright. These results listed the best five tolerating and performing plants that came out to be: *S. floribundum*, *A. cucullata*, *D. bullata*, *S. podophyllum*, and *S. octophylla* (Wang *et al.* 2020).

Summary of formaldehyde phytoremediation studies

Summarized information for selected plant species is given in Table 2 below. The National Aeronautics and Space Administration (NASA) research in the 1980s was the first in studying the efficiency of plant-based remediation for purifying indoor polluted air and improving IAQ (Wolverton *et al.* 1984; Moya *et al.* 2019; Lee *et al.* 2021). Since Wolverton's studies, diverse ornamental potted plants have attracted researchers' attention to be nominated for air-tight experiments to test formaldehyde and other gaseous pollutants removal rate and purification capacity. Indoor ornamental potted *C. elegans* plant (plant-soil system) was chosen to measure the removal capacity of formaldehyde in an air-tight Plexiglas chamber using a fumigation method at various HCHO concentrations (0.66–11.7 mg/m^3). As a result, the plant effectively removed 65–100% of formaldehyde vapors from polluted air in the experiment during

Table 2. Summary of passive, potted plant systems toward pollutants removal.

No.	Plant species (treatment/system)	Experimental				References
		Conditions	Sampling methods/tools	Time	Removal capacity per plant in mg/m^3	
1	*Spathiphallum wallissii Regal*	Sealed glass chamber	Advanced formaldehyde detector	24 h	4998	Ghate 2020
2	*T. zebrine, A. vera, V. radiata*	Clear glass container	UV Spectrophotometry and automatic formaldehyde detector	24 h	1.95	Yang *et al.* 2020
3	*E. aureum* (Golden pothos)	Airtight stainless-steel chamber	A proton transfer reaction mass spectrometer (PTR-Ms)	12 h	8.6	Wang *et al.* 2014
4	*C. comosum* *A. vera* *E. aureum*	Dynamic chamber, cylindrical Plexiglas.	Formaldehyde analyzer (4160, Interscan Co.)	3 d	4.27 2.38 3.78	Xu *et al.* 2011
5	*N. exaltata, C. morifolium, P. roebelenii*	Airtight cubical plastic chamber	Sensidyne-Gastec air sampling pump and gas detector tubes.	1 h	1.86 1.45 1.38	Wolverton and Wolverton 1993
6	*H. helix*	Acrylic quasi-closed box	Combo air quality sensor (AQM-100 and APM-200, AIGO TECH Co.)	21 h	0.5	Chen *et al.* 2017
7	*H. helix* *C. morifolium* *D. compacta* *E. aureum*	Clear glass chamber, cover made from Lexan	Formaldehyde monitor (HFX 105, Hal Technology)	24 h	1.73 1.67 1.91 1.84	Aydogan and Montoya 2011
8	*C. comosum green* (GC) Green and white (CC) Purple (PC)	Dynamic fumigation system made from Tedlar bags	Formaldehyde detector Remediation calculated for 1 ppm.	7 d	0.71 0.84 0.46	Li *et al.* 2019
9	*E. aureum*	Sealed fumigation box	Removal by stem	1 h	0.089	Zuo *et al.* 2022
10	*Rohdea japonica*	Sealed fumigation box	Removal by stem	1 h	0.137	
11	*Z. zamiifolia*	Plant-microbial cooperation in closed class chamber	DNA extraction method	24 h	20,000	Khaksar *et al.* 2016a

Results are summarized from laboratory-based experiments.

long time exposure (Teiri *et al.* 2018a). Same experimental procedures were conducted on *N. obliterata* indoor potted plant which effectively removed 90–100% of formaldehyde vapors from the contaminated air in the sealed chamber at a concentration (0.63–9.73 mg/m^3) (Teiri *et al.* 2018b). The studies in sealed chamber reveal that the plant exhibit excellent efficiency and can be useful in cleaning indoor new or renovated spaces from formaldehyde. Another crop of three indoor ornamental plants was investigated using the fumigation method to evaluate their ability to clean off indoor formaldehyde. During 24 h exposure, the formaldehyde level was decreased from 1.65 to 1.22 mg/m^3. The results revealed that *C. comosum* (0.63 mg/m^3) and A. Americana (0.62 mg/m^3) had more superior power to eliminate HCHO than *A. modestum* (0.13 mg/m^3) (Zhao *et al.* 2010). The results of a formaldehyde fumigation experiment (in sealed stainless steel, and glass chamber, 1 m^3) involving two indoor potted plants *Epipremnum aureum* and *R. japonica* showed that stems and leaves as main aerial parts could both effectively purify formaldehyde present in the air. The stem's purification rate of formaldehyde was 40% and 61.6%, respectively. While, the leaves' purification rate was 74.4% and 71.8%, respectively (Zuo *et al.* 2022).

Five indoor potted plants were chosen to analyze their formaldehyde adsorption capability using the airtight fumigation and steaming method. The results revealed that the decrease in formaldehyde concentration was 0.33 mg/m^3 after 12 h exposure to 37% formaldehyde solution. The order of the plants according to their effectiveness in purifying formaldehyde was observed to *S. trifascita* (1.90 mg/m^3), *E. aureum* (1.87 mg/m^3), *C. comosum* (1.78 mg/m^3), *F. elastic* (1.27 mg/m^3), *Aloe vera* (0.64 mg/m^3) (Xiong and Su 2009). Following the same experimental procedure 3 plants were tested in airtight bins for efficiency against the same pollutant. Leaves and root-basin soil were sealed, after 12 h exposure to 40% formaldehyde solution, the leaves' absorption capability was found in the order: *S. kochii* > *C. makoyana* > *E. eureum*. While the roots-basin soil adsorption capacity was found in a different order *C. makoyana* > *S. kochii* > *E. eureum* (Lan 2010). The leaves were the dominant part in absorbing formaldehyde among the three tested plants, while *S. kochii* presented the highest 12 h HCHO adsorption capacity (the mass of absorbed formaldehyde per leaf area per hour) at 0.086 mg/m^2/h The tolerance level of a plant is a direct measure of formaldehyde remediation from the ambient air. If a plant has a more powerful tolerance to formaldehyde, it will have a powerful ability to purify formaldehyde pollution (Han *et al.* 2022). In fact, the chlorophyll amount inside plants is directly influenced (degraded) by air pollutants. It has also been proved that chlorophyll degradation in plants could be used to calculate roughly its anti-pollution capability (Rabe and Kreeb 1979). The result of the formaldehyde press experiment on three potted indoor plants in relation to their chlorophyll contents revealed that the plants performed in order of *C. comosum* > *A. modestum* > *A. American* (Zhao *et al.* 2010). In another enclosed experiment against formaldehyde contents, 13 indoor decorative plants were able to decrease the concentration of formaldehyde ranging from 46.7 to 92.8% during 24 h exposure. The plant with optimum adsorbing capability per unit leaf area was *S. podophyllum* (3.32 mg/m^2), while the poor performance was shown by *A. vera* (0.19 mg/m^2). Taking the efficiency of a plant based on leaf area, a group of 13 indoor ornamental plants was considered for the same function. The compiled results revealed that *E. aureum* had the most HCHO purification and similarly *Asplenium. nidus* had the most HCHO adsorption capability per unit leaf area (Han and Ruan 2020). The most efficient plants in formaldehyde remediation are summarized in Table 2.

The current study of *E. aureum* and *Rohdea japonica* with 41 and 61% formaldehyde removal was conducted and the enhanced efficiency of plant species was linked to the increased concentration of CO_2 during the experiment in a sealed environment. An increase in the concentration of CO_2 after efficient uptake of formaldehyde by the plant indicates its phytodegradation capability against HCHO. Roots and leaves of plants were found to be active in remediation while the role of the stem is still unclear (Zuo *et al.* 2022). The plant, *Spathiphallum wallissii* was tested in a 1 m^3 static glass chamber for its capacity in removing indoor HCHO (Ghate 2020). Readings were collected twice at the beginning of the experiment and after 24 h. Results showed that *S. wallissii* can remediate HCHO to improve IAQ as the HCHO level was reduced from 40,998 to 0 ppm. Another study was aimed to study formaldehyde removal using three hydroponic plants *T. zebrine*, *A. vera*, and *V. radiate* with the addition of cultured microorganisms to the rhizosphere (Yang *et al.* 2020). The experiment was conducted in a laboratory using a clear glass container (50 × 30 × 35 cm) for 24 h. The results showed that using a plant with a microbial system, formaldehyde removal was increased by 6.7–90.5%. The *A. vera* has the lowest removal capacity $18.8 \pm 0.21\ \mu g\ h^{-1}\ g^{-1}$ without microbes *vs.* $23.1 \pm 4.2\ \mu g\ h^{-1}\ g^{-1}$ in the presence of microbes. While *T. zebrine* and *V. radiate* showed more removal capacity of 59.3 ± 0.2 *vs.* 86.4 ± 0.7 and 25.1 ± 4.2 *vs.* $97.6 \pm 0.9\ \mu g\ h^{-1}\ g^{-1}$, respectively. Cooperativity studies of plants and microorganisms indicate that degradation >90% can be achieved efficiently. Among six selected plants, two *L. esculentum* and *H. annuus* were very efficient in the removal of formaldehyde (Zhao *et al.* 2019). Such studies clarify a new direction in the field to get information about cooperation between plants and microorganisms in rhizosphere solutions (microbe-plant system). The same strategy (*Bacillus cereus ERBP-Clitoria ternatea* and *Zamioculcas zamiifolia*) has also been proved to have better efficiency toward seed germination under formaldehyde stress with increased gaseous formaldehyde removal (Khaksar *et al.* 2016a, 2016b).

Plant material and other strategies to control indoor air formaldehyde

Besides potted plants, dead plant materials are also active in the field of formaldehyde remediation. There are several studies addressing the issue in a wonderful way. These studies are somehow reliable and efficient as compared to the natural plants in terms of remediation. The material can be designed/modified in the lab, structural and surface studies are carried out with the help of several modern techniques and material can be fabricated in a suitable shape to cope with removal efficiency. A composite of MnO_x/natural loofah was prepared via *in-situ* reduction under ambient conditions. The MnO_x nanoparticles were loaded on the fibrous structure, which efficiently exhibited catalytic decomposition and adsorption of formaldehyde at room temperature. The study further indicated that the final decomposition product was CO_2. The material is effective in the removal of the target contaminants up to 97.5% under ordinary conditions, in a relatively short time, and in a cost-effective way (Feng *et al.* 2020).

To reduce VOCs and other indoor air pollutants levels below the threshold limit, several methods have been adopted, such as source prevention (formation emission) and ventilation (dilution) by replacing polluted indoor air with fresh outdoor air, which is not sustainable because of the cost related to filtered and conditioned air. Other methods involve technologies, such as filtration, adsorption, photocatalytic oxidation, plasma technology, and UV photolysis (Luengas *et al.* 2015; González-Martín *et al.* 2021; Masi *et al.* 2022). Despite the fact, that recent diverse methods available for removing HCHO from indoor air (photocatalytic oxidation, activated carbon, fibers adsorption, biological methods, and biofiltration), no one of the previous methods is 100% efficient because of low concentrations and the volatile characteristics of this pollutant (Teiri *et al.* 2018b). Nanotechnology as an evergreen technology is at the forefront to remediate VOCs and other pollutants from the air, water, soil, etc. This technology is prominent always in the aspect of its multidimensionality, a recent study established a composite nanofiber membrane (ZIF-8@SiO_2) that showed a combined effect, high dust, and formaldehyde removal efficiency (Zhu *et al.* 2019; Masi *et al.* 2022). Hereunder, the discussion will be confined to plant material as a component of nanocomposites in fighting formaldehyde pollution in the air.

Airtight interior environment issues and health issues

Airtight and insulated buildings globally are results of the energy-saving strategy that was introduced during the energy crisis in the 1970s. It was aimed at saving more energy by reducing the fresh air rate indoors. However, this strategy accumulates more indoor air pollutants with the improved lifestyle, using more chemical and synthetic materials for indoor finishing and decorating materials, using cleaning products, air fresheners, and other appliances (Mannan and Al-Ghamdi 2021a). Reduce fresh air exchange and well-insulated (sealed) are claimed to be widely applied design strategies to improve energy efficiency. Moreover, the emerging status of airtight building design, which is increasingly applied in diverse buildings, such as homes, schools, hospitals, and offices to meet high rates of energy efficiency (González-Martín *et al.* 2021) resulted in insufficient fresh air to be introduced to the space users. Thus, the indoor air becomes stagnant while odors and pollutants accumulate and deteriorate the indoor air quality causing the sick building syndromes (SBS) (Suhaimi *et al.* 2016; Teiri *et al.* 2022). The relationship between environmental conservation, energy conservation, and human health is an overly complex phenomenon (Suhaimi *et al.* 2016). In airtight buildings, that indoor air pollutants concentrations are greatly higher than outdoors due to limited air exchange of indoor and outdoor air (low ventilation rate) (Zhang *et al.* 2020; González-Martín *et al.* 2021). This is always accompanied by several health complications in space users, such as asthma, nausea, eye irritation, headache, cough, lung cancer, etc. (Mannan and Al-Ghamdi 2021b). Nasopharyngeal cancer and leukemia are considered symptoms or health impacts of elevated levels of exposure to formaldehyde (Yang *et al.* 2020). While chronic exposure to HCHO by inhalation is connected with eyes, nose, and throat irritation, sinus infections, and respiratory problems (Zhang *et al.* 2009).

Future advances and research

The issue of volatile contaminants is strongly expected to exponentially increase with future technological advances. To keep the environment clean, plant materials with the efficiency of simultaneous remediation of more than one contaminant are highly needed. Some of the research work done in the field is recently reviewed, and the association between plants and microorganisms seems to improve the remediation of air pollutants in a synergistic way (Gunasinghe *et al.* 2021; Supreeth 2022). There are some researches that have already addressed these challenges, such as the application of exogenous indole-3-acetic acid on shoots of *Z. zamiifolia* for enhancing toluene and formaldehyde removal (Ullah *et al.* 2020). This line of research is still unexplored and needs further exploration to come up with an optimum solution. Plants accommodate several bacterial strains which help in the degradation and absorption of pollutants present in the air (Wei *et al.* 2017). Plant-microbial cooperation toward formaldehyde remediation is promising and is expected to be continued with exciting results. Moreover, remediation of formaldehyde in highly polluted air plants have some limitations and must be used in combination with other available techniques/material. The field of phytoremediation is scientifically unexplored, in the future a combined application of advanced “omics” technologies (genomics, proteomics, and metabolomics) is needed in the field. Plant omics profiling will allow to quantify and characterize the pool of molecules. The exact understanding of major metabolic pathways, genes, and enzymes involved in the remediation process will enable to screen plant species to improve indoor air quality. Such studies can also explore the selectivity of plant species against specific pollutants. Hopes are associated with precise and targeted DNA modification for inserting genes encoding detoxification enzymes for better efficiency (Brilli *et al.* 2018). Moreover, non-stomatal adsorption followed by removal of VOCs by rhizosphere and/or phyllosphere microorganisms needs in-depth study to be explored (Figure 3).

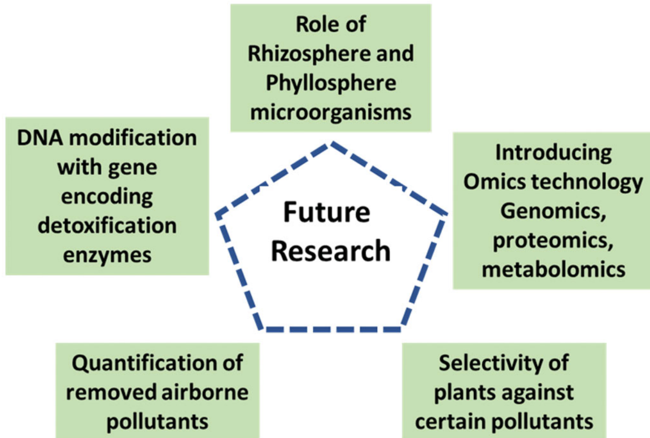

Figure 3. Future research advances in the field of phytoremediation.

Conclusion and recommendations

Plant materials are continually active in the remediation of various pollutants present in ambient air ranging from volatile organics to particulate matters. At the domestic level, there are several plants that can effectively clean the ambient air for space users. For huge buildings, either the plant population has to be increased which is not feasible sometimes, or to use phytoremediation in combination with other techniques. Plants are a natural material, and their growth and efficiency cannot be controlled easily, the efficiency of potted plants has been tremendously enhanced by green walls where the intensity of plants is increased in combination with some mechanical operations. The selectivity and efficiency of plants are required to be determined because volatile pollutants are not uniform everywhere. Plants with the efficiency of simultaneous remediation of more than one compound are the focus of future research and are expected to come up with interesting results. It is further recommended that the research may be promoted in all regions throughout the globe on native plants because the natural habitat for plants varies with altitude and other environmental conditions. It is also expected that the same plant can show different remediation efficiency toward a contaminant.

Among the so far tested plants, *Hedera helix, Dracaena compacta, Sansevieria trifasciata, E. aureum, C. comosum, N. obliterata, C. morifolium, A. vera*, and *C. elegans* have shown remediation efficacy in the range above 80% and they are regarded top candidates in formaldehyde remediation tools. The research will still continue in search of increasingly efficient, pollutant-resistant plants with economic viability and availability under prevailing.

Author contributions

AK and EK contributed equally in conceptualization, literature collections, draft writing, and reviewing and MSA contributed toward draft revising and editing.

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