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Review Article

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A systematic review on phytoremediation of indoor air pollution

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ABSTRACT

Degradation of Indoor Air Quality (IAQ) due to confined spaces and insufficient ventilation has become a serious concern to human health. Published literature has established phytoremediation as an efficient removal mechanism of indoor air pollutants such as formaldehyde, Benzene, Toluene, Ethyl benzene, Xylene (BTEX), Volatile Organic Compounds (VOCs), and Particulate Matter (PM) using potted plants. This review discusses both conventional and enhanced phytoremediation for removing air pollutants and the parameters influencing the removal efficiencies. A literature review was conducted following the PRISMA guidelines to identify published literature on indoor air phytoremediation. After eliminating duplicates and reviewing articles, the articles related to indoor air phytoremediation from 2011 to the present were selected. The database was managed using Mendeley reference manager. Indoor air pollutants can be removed efficiently through phytoremediation using potted plants. *Chlorophytum comosum* removed the broadest range of contaminants, whereas *Epipremnum aureum* is the frequently used plant species for pollutant removal. Adding enhancing factors to the plant enhances their ability to remove pollutants. Inoculation of plants with soil bacteria such as *Bacillus cereus* ERBP is the most common enhancement method reported. The present study highlighted advancements in phytoremediation and factors affecting the pollutant removal efficiencies of plants. The findings demonstrated that enhanced phytoremediation is more effective at removing pollutants than the conventional method. Depending on the plant species used, the removal of indoor air pollutants may vary. The findings suggested that a combination of various plant species could be used to remove indoor air pollutants more efficiently.

Review

Indoor Air Quality (IAQ) is a significant problem as the increased concentration in a confined space makes it more dangerous than the outside air [1]. The tightly sealed building constructions maximize thermal efficiency

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at the expense of fresh air circulation accumulating contaminants to toxic levels in enclosed spaces, posing significant health risks [2]. In industrialized countries, an individual spends about 80-90% of their time indoors, putting a risk of chronic exposure to lower levels of indoor pollutants [3, 4]. Chronic exposure to indoor air pollution can cause respiratory and cardiovascular diseases, which can result in Sick-Building Syndrome (SBS) and Building-Related Ilnesses (BRI) [5, 6]. Furthermore, indoor air pollution affects the work productivity and expenses associated with healthcare. World Health Organization (WHO) estimated that 4.3 million premature deaths occur annually due to individuals' exposure to Indoor Air Pollution (IAP) [7].

The primary indoor air pollutants are CO, CO_2, Volatile Organic Compounds (VOCs), oxides of nitrogen and sulphur, and Particulate Matter (PM) [8, 9]. Formaldehyde, toluene and xylene are the common VOCs released from a variety of indoor sources, including wood-based building materials, flooring, furniture, decorative accents, and other adhesives and resins [10, 11]. Other VOCs include benzene, ethylbenzene, and Polycyclic Aromatic Hydrocarbons (PAHs) [12, 13].

With the increase in IAP and time spent indoors, indoor air remediation is becoming more crucial. Various physicochemical approaches and science-based technologies have successfully mitigated indoor air pollution [14]. However, the existing air purification technologies cannot meet the criteria of World Health Organization (WHO) set for reducing pollutants to a safe level. These technologies have a high maintenance cost. Moreover, certain air purifiers release Ozone (O_3) hazardous to humans after its accumulation threshold level [15, 16]. Thus, the existing air remediation technologies can be replaced with cost-effective, environmentally friendly bioremediation strategies. Phytoremediation (a bioremediation technique) is a significantly more effective and natural method for reducing the concentration of various air pollutants in the ambient air [14]. Previous studies have shown evidence that the exposure of plants to pollutants leads to the most effective elimination of contaminants from indoor air [17, 18].

Phytoremediation by active means may include green walls, bio coverings, or green roofs, and passive methods like potted plants can efficiently remove indoor air pollutants [2, 19]. It is an eco-friendly and energy-efficient method of reducing IAP. Phytoremediation occurs in many ways, either by absorption, distribution, or transport of organic pollutants by phytoextraction (hyper-accumulation of contaminants through plant roots and storing them in the tissues of stems or leaves), rhizosphere biodegradation by microorganisms, phytodegradation (contaminants are metabolized and transformed in the tissues), stomatal uptake (gas extraction by plants), and phytovolatilization (pollutants are evaporated from leaves or transpired) [1, 15, 20, 21]. Recent research has investigated the use of specific plant species, such as Areca palm, to remove various contaminants [22, 23]. Additionally, the efficacy of peace lily in mitigating formaldehyde has been explored [18, 24]. Researchers from Asian countries have predominantly authored many research articles on phytoremediation, with Western nations following closely behind in terms of publication output. Several investigations have been conducted in European and African nations as well [17, 23, 25-28].

Although numerous studies have documented phytoremediation on indoor air by different types of plants, a comprehensive database containing integrated information on both conventional and enhanced phytoremediation methods is still lacking. As a result, the objective of this systematic review is to compile an exhaustive database regarding both conventional and enhanced phytoremediation methods using potted plants, based on research that has been examined and reported on the subject. Conventional methods discussed how factors such as light, leaf characteristics, and pollutant polarity affect plants' removal of indoor air pollutants. In addition, the enhanced methods provide insights into how different enhancing factors, such as gene modification, microbial inoculation, change in microenvironment, etc., contributed to removing indoor air pollutants. This review focused on providing a comprehensive analysis of both approaches and their respective efficacy in eliminating pollutants from indoor air.

Methods

Search strategy and information sources

A search for published papers on indoor air phytoremediation was conducted based on PRISMA guidelines [29, 30]. The keywords included phytoremediation, potted plants, enhancement method, and indoor air pollution. We employed Boolean searches with the "AND" operator, including indoor air and phytoremediation, phytoremediation, and enhanced phytoremediation. The online databases included to identify different literature that studied mitigation of IAP using phytoremediation and enhanced methods of phytoremediation were Google Scholar, PubMed, and Science Direct. The research publications' reference lists were used as the source for additional manual searches (simple forward snowball process). The reference manager Mendeley contained the database search results.

Eligibility criteria and data retrieval

Following a search for the keywords in particular databases, a total of 389 results were obtained. The removal of duplicates yielded 255 articles followed by evaluation based on their titles and abstracts. The exclusion criteria include:

- Case studies, review articles, and commentaries
- Articles that were not published in English
- Papers evaluating outdoor air pollution
- Papers based on an active system of phytoremediation
- Papers published before 2011

After removing irrelevant documents, 105 articles were appropriate for full-text examination. The screening procedure for the selected documents is depicted in Fig. 1. At the end, 50 articles were included in the review published from 2011 to the present. The key findings of these published works are presented in Table 1 and 2.

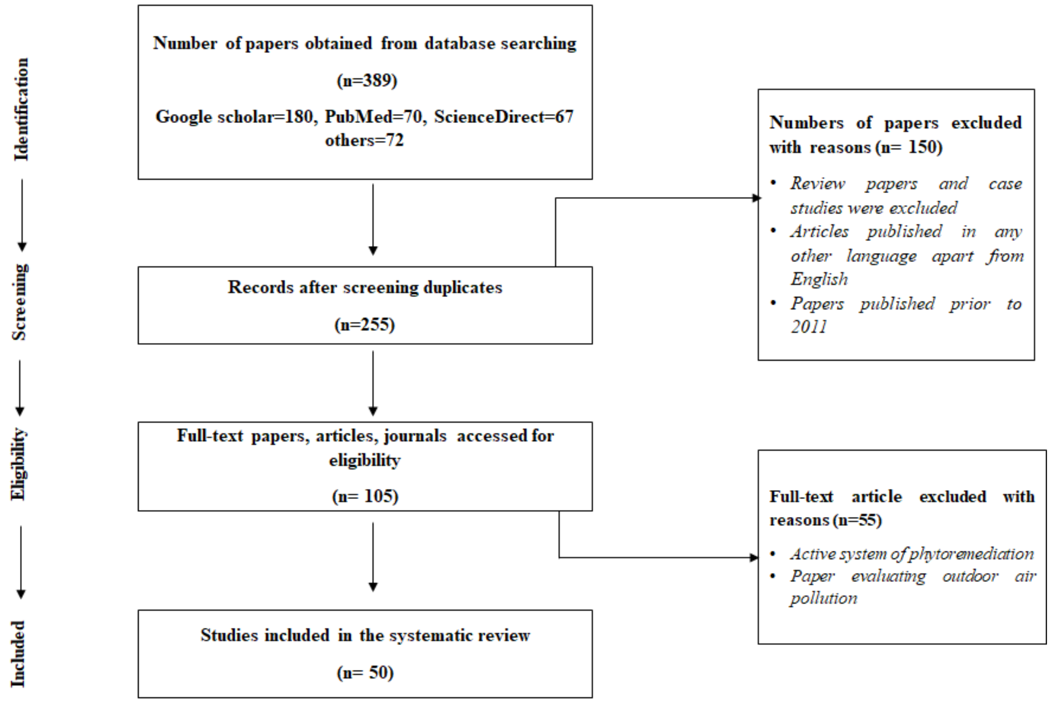

Fig. 1. The flow diagram for the review detailing the database searches the screening, and the inclusion of full text for reviewing (PRISMA method, adapted from Moher et al. [30])

Risk of biases in the selected studies

Most articles incorporated in this review employed chambered experimentation. In contrast to clinical research, no participants were involved in these studies. This prevents random selection of the studied plants. Since participants are not involved in the studies on phytoremediation of indoor air, it eliminates the necessity of considering risks associated with concealed allocation. Therefore, participant exclusion is not a possibility. However, there may be a risk of inadequate data outcomes due to the selected search procedure of literature considered for this review.

Results

The summary of the conventional phytoremediation experiments and their corresponding findings is presented in Table 1. Table 2 provides a comprehensive overview of the findings from various studies conducted on enhanced phytoremediation techniques. Among the 50 articles that were chosen, 34 focused on conventional passive methods and their impacts on different contaminants. The other 16 articles examined various approaches to augment potted plants' pollutant removal efficacy through enhancement methods. A total of 131 plant species belonging to 50 distinct families were studied in the selected literature. 115 plant species from 46 families were examined in the conventional phytoremediation approach (Table 1), whereas, only 28 plant species belonging to 17 families were examined in the enhanced phytoremediation approach (Table 2).

Table 1. Summary of the studies of potted plants and their results. Here, NM - not mentioned; LAI- Leaf area index; RE- Removal efficiency; CAM- Crassulacean acid metabolism

Sl. No.	Plant species	Pollutants	Key findings	References
1	C. *comosum*, A.*vera*, E. *aureum*	Formaldehyde	C. *comosum* had showed highest removal. Removal efficiency higher in day time compared to night time.	[31]
2	D. *maculata,* S. *wallisii,* A. *densiflorus*	Toluene, 2- ethyl hexanol	Influence of VOC was observed in the plants' species; effects varied based on light & darkness.	[26]
3	C. *comosum, Sansevieria,* S. *floribundum,* E. *aureum*, F. *elastica*, A. *vera*	$PM_{2.5}$	Plants with rough leaves & a high LAI had higher removal capacity. E. *aureum* showed highest removal rate which is very low in actual indoor environment than chambered experiment.	[32]
4	A. *triphylla*, M. *officinalis,* M. *piperita*, M. *suaveolens,* P. *tomentosus,* R. *officinalis,* S. *elegans*, *P. graveolens*, B. *maculate*, D. *mariesii*, F. *japonicum*, F. *verschaffeltii*, H. *helix,*	Toluene	Toluene removal rate decreased with increased exposure time. Woody & herbaceous foliage had highest & lowest toluene removal rate, respectively.	[33]
5	D. *picta,* E. *aureum,* S. *wallisii,* S. *podophyllum,* A. *pictum*, C. *variegatum*, C. *terminalis,* D. *marginata,* Y. *elephantipes,* S. *trifasciata*, R. *hypoglossum,* C. *comosum*, E. *japonicus*, S. *actinophylla*, F. *benjamina*	Formaldehyde, SO_2, & NO_2	C. *comosum* showed highest removal efficiency for SO_2 & formaldehyde. S. *walisii* had showed superior removal efficiency for NO_2. Density of stomata could be used as an indicator to measure the efficacy of removing pollutants HCHO, SO_2, & NO_2.	[25]
6	D. *deremensis*, D. *marginata*, *Spathiphyllum*	CO_2, CO, VOC, carbonyls, & PM_{10}	Concentration of all pollutants had decreased significantly in the presence of potted plants.	[27]
7	*Spathiphyllum*, *Dieffenbachia* spp., E. *aureum*, F. *Burgundy*, *Calathia* spp	O_3	O_3 deposition velocity had increased by1.7 times for *Dieffenbachia* & 4.7 times for *Spathiphyllum* when exposed to light similar to indoors. Ozone deposition velocities dropped by 50 to 66% at 2nd & 3rd exposures.	[34]
8	D. *lutescens*	VOC, CO_2, CO	D. *Lutescens* plants were efficient, inexpensive, self-regulating & sustainable for improving the quality of indoor air.	[23]

Table 1 (continued)

9	S. *arboricola*, S. *wallisi*	Benzene	S. *arboricola* had a slightly higher RE than S. *wallisii* due to a higher leaf area. RE in both plants decreased with the increasing pollutant inlet concentration.	[35]
10	S. *actinophylla*, F. *benghalensis*	Toluene & Xylene	In S. *actinophylla* & F. *benghalensi*, the root region was a potential contributor to the removal of toluene & xylene, with stem transport playing an important role.	[36]
11	C. *elegans*	Formaldehyde	C. *elegans* could significantly remove formaldehyde depending on inlet concentration for a long exposure time. C. *elegans* were removed more effectively in light conditions compared to dark conditions.	[17]
12	C. *comosum*	Particulate matter (PM)	C. *comosum* had accumulated PM of all sizes, regardless of their position or the sort of activity in the inspected space. Fine PM was accumulated more as wax PM than suspended PM.	[12]
13	H. *helix*	VOCs	H. *helix* removed VOCs concentration efficiently in dynamic conditions.	[37]
14	D. *deremensis,* O. *microdasy*	Benzene, toluene, ethylbenzene, & xylene (BTEX)	O. *microdasys* had showed better results & efficiency in removing BTEX compared to D. *dermensis.*	[38]
15	D. *racemos*, R. *hyrcabus*	BTEX	R. *hyrcabus* had higher phytoremediation of air polluted with BTEX. Leaf tissue structures, stem & vascular bundles were seen to change after exposure to BTEX in both R. *hyrcabus* & D. *racemose.*	[39]
16	Z. *zamiifolia,* P. *martianum,* A. *commutatum,* A. *rotundum,* D. *botryoides,* A. *vera,* *C. comosum,* C. *fruticose,* S. *hyacinthoides,* F. *albiveni,* M. *platyclade,* T. *spathacea,* G. *lingulate,* C. *alternifolius*	Xylene	Z. *zamiifolia* had maximum xylene removal efficiency among the tested plants. Effect of photosynthetic types on xylene removal efficacy revealed that combination of Z. *zamiifolia*, S. *hyacinthoides*, & A. *commutatum* plants is the optimal system for xylene removal.	[40]
17	S. *wallisii*	Formaldehyde	S. *wallisii* had removed 4.998 ppm formaldehyde in 24 hours with the formaldehyde removal capacity ranging from 0.09-1.006 ppm/m^3 area.	[41]
18	A. *commutatum*, C. *austral*, C. *elegans,* D. *lutescens,* H. *forsteriana*, D. *deremensis*, F. *benjamina*	CO_2	D. *lutescens* had showed greatest CO_2 uptake rate of 657 mg CO_2/m^2 leaf area/h.	[42]

Table 1 (continued)

19	C. *seifrizii,* E. *aureum,* S. *aureus,* P. *domesticum,* M. *cuminate*, S. *trifasciata,* D. *sanderiana*, I. *ebarbatacraib*	Benzene	D. *sanderiana* had showed highest benzene removal efficiency. Benzene removal efficiency was higher in the light than in the dark.	[43]
20	*Opuntia* spp., C. *hexagonus*, D. *sanderina,* C. *comosum*, D. *camilla,* S. *aureus*, T. *spathacea*, P. *magnoliifolia*	Trimethylamine (TMA)	S. *aureus* had showed maximum TMA elimination efficacy in light conditions. C. *hexagonus* & Prickly pear cactus had highest efficiency in both light & dark conditions owing to CAM mechanisms.	[44]
21	S. *cymbifolium*	Suspended particulate matter (SPM)	S. *cymbifolium* had removed SPM efficiently in light compared to dark conditions & functions effectively in smoky conditions.	[45]
22	C. *comosum,* S. *trifasciata,* D. *fragrans*, S. *blandum*, P. *hederaceum,* A. *commutatum*	CO_2	S. *blandum* was most efficient in CO_2 removal. CO_2 absorption rates was directly related to light intensity. Pollutant removal efficiency can be increased by adding supplementary lights.	[46]
23	A. *vera*, S. *masoniana*, S. *trifasciata,* S. *hyacinthoides*, S. *ehrenbergii,* D. *deremensis,* D. *sanderiana,* C. *comosum*, K. *blossfeldiana,* C. *variegatum,* A. *commutatum*	Toluene, Ethylbenzene	The highest toluene & ethylbenzene removal was found in S. *trifasciata* & C. *comosum,* respectively. Hexadecenoic acid contributes to toluene & ethylbenzene absorption by plant cuticle wax.	[47]
24	H. *splendens*, C. *macrocarpa,* P. *orientalis*, A. *heterophylla,* P. *roebeleni*, E. *purpureum*, D. *reflexa,* S. *trifasciata*, E. *aureum*, F. *retusa,* C. *variegatum.*	PM	Average PM deposition rate was in order H. *splendens* > P. *roebelenii* > C. *variegatum*. Larger quantity of plants required to receive the same PM reduction as the increasing room size.	[48]
25	N. *obliterate*	Formaldehyde	N. *obliterata* had effectively eliminated formaldehyde from polluted air. Soil & roots eliminated 26% formaldehyde.	[49]
26	Z. *zamiifolia*, S. *trifasciata*	Formaldehyde, Toluene, CO_2	Individual plants were less efficient than mixture of Z. *zamiifolia* & S. *trifasciata* at removing mixed pollutants & reducing CO_2. Combination of Z. *zamiifolia* & S. *trifasciat*a can improve the elimination of VOCs.	[50]
27	Z. *zamiifolia,*	BTEX	Z. *zamiifolia* had decreased concentration of BTEX in indoor air. Removal of BTEX was mainly from stomatal & cuticle pathways.	[51]

Table 1 (continued)

28	E. *aureum,* C. *comosum,* H. *helix*, E. *tubiflora*	Benzene	CAM plants (E. *tubiflora*) had removed benzene more efficiently compared to C3 plants (E. *aureum,* C. *comosum,* H. *helix*).	[52]
29	E. *milii,* A. *andraeanum,* S. *cannifolium,* C. *papaya,* H. *rosa-sinensis,* I. *chinensis,* P. *atropurpureum*, S. *speciosa,* A. *obesum,* A. *nidus,* B. *spectabilis,* M. *alba*	Trimethylamine (TMA)	E. *milii* had exhibited maximum TMA removal efficiency among the plants tested.	[53]
30	E. *aureum*, R. *japonica*	Formaldehyde	E. *aureum* had removed more formaldehyde than R. *japonica*.	[54]
31	H. *helix*	Formaldehyde	Compared to natural dissipation, H. *helix* had reduced the time required to attain 0.5 ppm of gaseous formaldehyde by 70%. Residual formaldehyde can also be eliminated by potted H. *helix,* enhancing indoor air quality.	[55]
32	E. *aureum,* D. *seguine, Aglaonema* sp., C. *comosum,* S. *trifasciata*, N. *exaltata*, A. *vera*, T. *usneoides*	Formaldehyde	Plants with highest formaldehyde elimination effectiveness were in order: N. *exaltata* > T. *usneoides* > E. *aureum* > *C. comosum.* However, D. *seguine*, A. *vera*, & *Aglaonema* sp. were classified as lesser formaldehyde absorbers.	[56]
33	E. *aureum*, D. *trifasciata*	Benzene, acetone, methanol, ethanol	E. *aureum* had higher pollutant removal efficiency than D. *trifasciata*. E. *aureum* was more tolerant to contaminants since they suffer minimal tissue damage resulting from exposure.	[57]
34	*Aglaonema,* P. *aquatica,* F. *benjamiana*	Benzene, Toluene, Ethylbenzene, Xylene, Styrene, TVOC, Formaldehyde	*Aglaonema* & F. *benjamina* removed toluene efficiently. Formaldehyde removal was much more efficient in F. *benjamina*. An increase in no of plants’ increases the concentration of pollutant removal.	[58]

Table 2. Summary of the compiled study of potted plants, the enhancement factors, and their results. Here, ACC- 1-aminocyclopropane-1-carboxylic acid

Sl. No	Plant species	Pollutants	Enhancement Factor	Key findings	References
1	T. *zebrina*, A. *vera*, V. *radiata*	Formaldehyde	Soil Microorganisms	Formaldehyde elimination rates were higher in all three plant species inoculated with microbes. V. *radiata* showed the highest & A. *vera* showed lowest formaldehyde removal capacity.	[20]
2	*Z. zamiifolia*	Toluene Formaldehyde	Indole Acetic Acid (IAA)	Exogenous IAA at right concentrations could improve indoor plants' capacity to reduce airborne air contaminants. IAA exposure to roots decreases *Z. zamiifolia's* capacity for remediation.	[59]
3	A. *commutatum,* E. *aureum*, C. *comosum,* S. *trifasciata*	Formaldehyde	*Pseudomonas chlororaphis*	Formaldehyde absorption capacity of tested plants was increased with addition of P. *chlororaphis* in the soil. Tested plants could remove formaldehyde in the range of 0.0352 to 4.744 ppm. E. *aureum* removed formaldehyde more efficiently than other species.	[60]
4	S. *podophyllum*	Benzene & CO_2	Hydroculture (Soil-free growth techniques, such as passive hydroponic)	Plants in hydroculture had more CO_2 removal than potting mix & plants in potting mix had more benzene removal than hydroculture.	[61]
5	D. *sanderiana*	Benzene	*Staphylococcus* sp. B12 & *Pantoea*sp. B11	Benzene-tolerant epiphytic bacteria (*Pantoea* sp. B11 & *Staphylococcus* sp. B12) isolated from D. *sanderiana* could increase phytoremediation efficiency. D. *sanderiana* became more efficient when inoculated with a single strain of *Staphylococcus* sp. B12 than plants inoculated with a single strain of *Pantoea* sp. B11 or a co-culture of both inoculants.	[62]
6	S. *aureus, Z. zamiifolia,* D. *compacta,* A. *modestum,* P. *bipinnatifidum*, C. *comosum,* D. *sanderiana,* S. *trifasciata*, E. *milii,* C. *variegatium*, B. *spectabilis*, I. *chinensis*, S. *scutellarioides*, A. *nidus*, P. *obtosifolia* F. *verschaffeltii*, A. *comosus*	O_3	Bacillus cereus ERBP	Inoculating Z. *zamiifolia* with B. *cereus* ERBP increased O_3 elimination efficiency relative to non-inoculated plants.	[63]

Table 2 (continued)

7	H. *annuus*	O_3	Plant associated bacteria	H. *annuus* had decreased benzene concentrations in contaminated systems. *Enterobacter* EnL3, a plant-associated bacterium, could mitigate the phytotoxic effects of benzene on plants.	[28]
8	S. *trifasciata*, E. *milii*, C. *ternatea*, Z. *zamiifolia,* S. *podophyllum*	Formaldehyde	Endophytic *Bacillus cereus* ERBP—*Clitoria ternatea*	B. *cereus* ERBP had significantly increased seed germination & seedling growth in response to rising formaldehyde concentrations. Sterile *Clitoria ternatea* seedlings with endophytic B. *cereus* ERBP were much more efficient at removing gaseous formaldehyde than sterile seedlings without endophyte.	[64]
9	Z. *zamiifolia*	O_3	Catechin	Catechin had promoted O_3 elimination efficiently through a balanced redox state in plant cells, as catechin-quinone in Z. *zamiifolia* + catechin + O_3 conditions induce roughly 35-fold & 5-fold increases in glutathione concentration & ascorbate peroxidase gene expression, respectively.	[65]
10	A. *pusilla*	Toluene	Arabidopsis nucleoside diphosphate kinase 2 (AtNDPK2) gene	Higher toluene removal efficiency in Transgenic A. *pusilla* line NDPK2-12-4 (797.33 ± 59.41 g m^{-3} cm^{-2} leaf area) than the non-transgenic line (206.2 ± 31.19 g m^{-3} cm^{-2} leaf area).	[66]
11	P. *hybrida*	Formaldehyde	AtFALDH from *Arabidopsis thaliana*	AtFALDH-transgenic T2 plants had eliminated 49.0 $gm^{-3}cm^{-2}$ of formaldehyde, whereas non-transgenic plants only eliminated 38.9 gm^{-3} cm^{-2} (a difference of 25.9%).	[67]
12	C. *comosum*	Benzene	Microgravity system	In 3 days, C. *comosum* had removed over 80% benzene under microgravity (µG) in 24 h light & dark environments & 75% (in light) & 50% (in dark) of benzene under normal gravity conditions. Under µG, the auxin hormone may accumulate in the plant's shoot enhancing benzene phytoremediation.	[68]
13	C. *ternatea*	Ethylbenzene	*Bacillus cereus* ERBP	Compared to sterile inoculated C. *ternatea* seedlings (108 hr), the natural inoculation seedlings had removed the ethylbenzene pollutant with a 100% clearance efficiency within 84 hr. High expression of CYP83D1 & dehydrogenase occurred in naturally inoculated plant.	[69]

Table 2 (continued)

14	E. *milii*	Trimethylamine (TMA)	*Bacillus thuringiensis*, *Bacillus nealsonii,* white colony-soil bacteria (WCSB) & *Citrobacter amalonaticus* Y19	B. *thuringiensis* & C. *amalonaticus* Y19 were the most effective bacteria for enhancing plant's TMA elimination efficiency due to increase of IAA concentration in leaves resulting in increased stomatal opening improving the TMA elimination efficiency.	[70]
15	H. *helix*, C. *morifolium*, D. *compacta*, E. *aureum*	Formaldehyde	Hydrophonic growth media (grow stone, expanded clay, activated carbon)	Activated carbon had highest formaldehyde elimination rate of 98%. Elimination rates were identical for all examined plants. H. *helix* had slowest formaldehyde uptake, while C. *morifolium* had the fastest.	[71]
16	P. *hybrida*	Benzene, Toluene, Formaldehyde	CYP2E1 genes	Absorption capacity of benzene & toluene had significantly increased in P. *hybrida* with high CYP2E1 expression than wild type. Resistance to formaldehyde had significantly increased.	[72]

Araceae, Asparagaceae, Moraceae, Araliaceae, Asphodelaceae, Euphorbiaceae, and Arecaceae were the most commonly used plant families. The frequently used plant species were *Epipremnum aureum, Chlorophytum comosum, Sansevieria trifasciata, Zamioculcas zamiifolia, Aloe vera, Dracaena sanderiana, Hedera helix, Euphorbia milii, Aglaonema commutatum, Spatiphyllum wallisii, Ficus benjamiana, Schefflera actinophylla,* and *Chamoedorea elegans* (Fig. 2). These plant species were typically selected because of their widespread availability and notable resilience under harsh environmental conditions.

The frequently used plant species for phytoremediation along with the pollutants they remove are shown in Fig. 3. *Chlorophytum comosum* exhibited the most extensive capability for pollutant removal among the plant species studied, followed by *Sanseviera trifasciata, Zamioculcas zamifolia,* and *Epipremnum aurem*. In contrast, *Schefflera arboricola* and *Chamaedorea elegans* demonstrated the narrow range of effectiveness in removing pollutants.

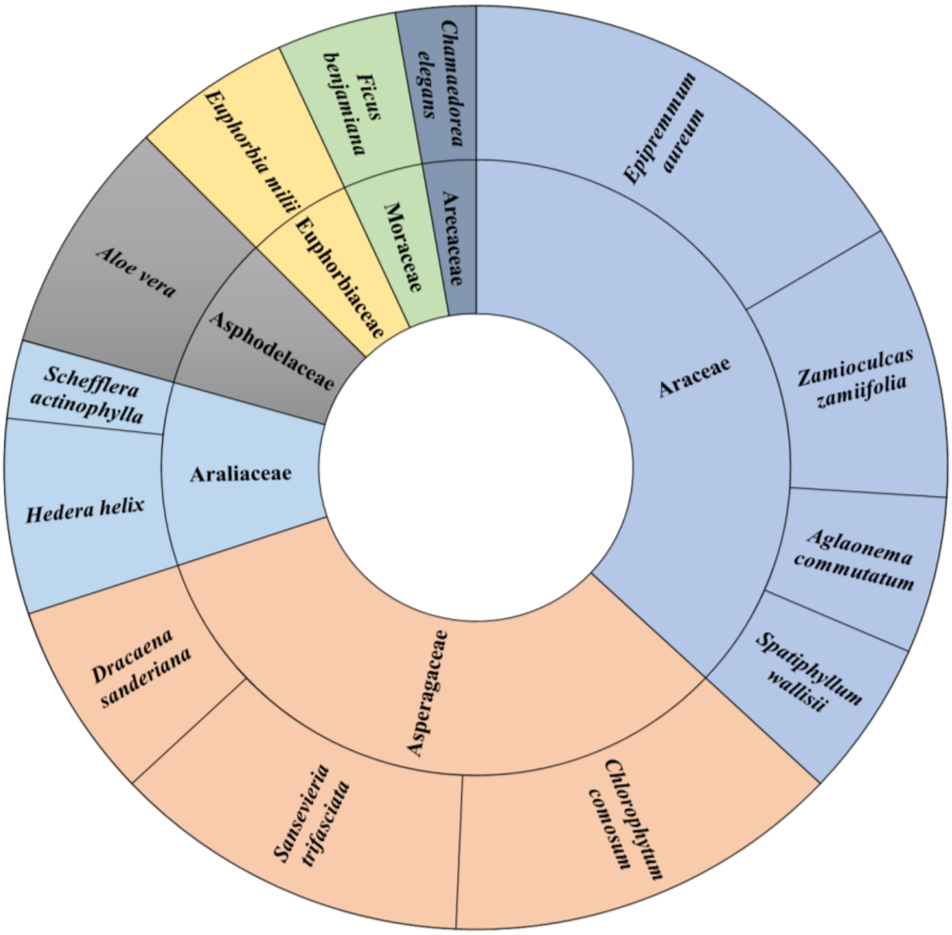

Fig. 2. Most commonly used plant family (inner circle) along with the plant species (outer circle)

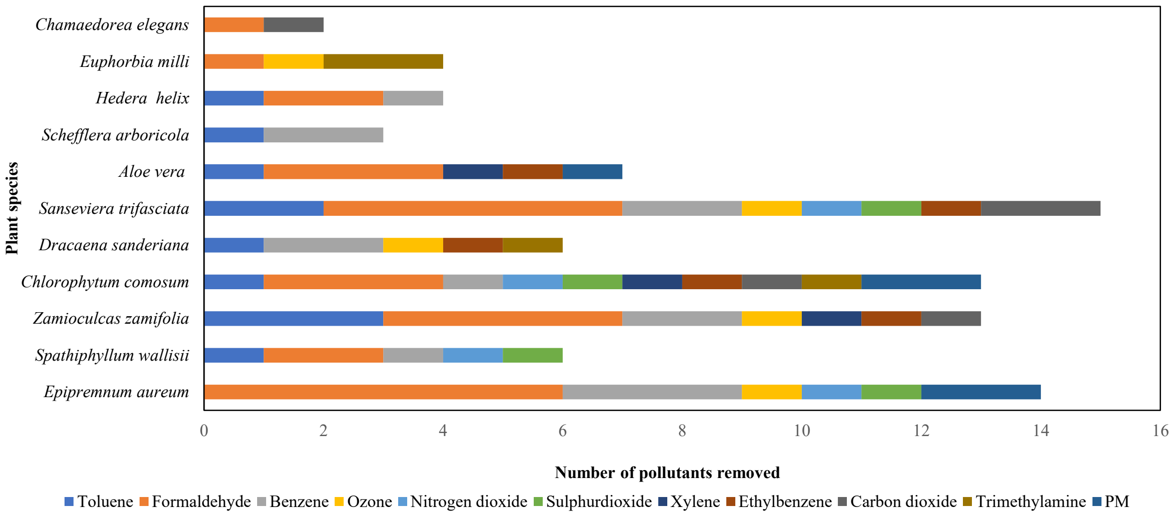

Fig. 3. Representation of the most common plant species used for phytoremediation and the pollutants they remove

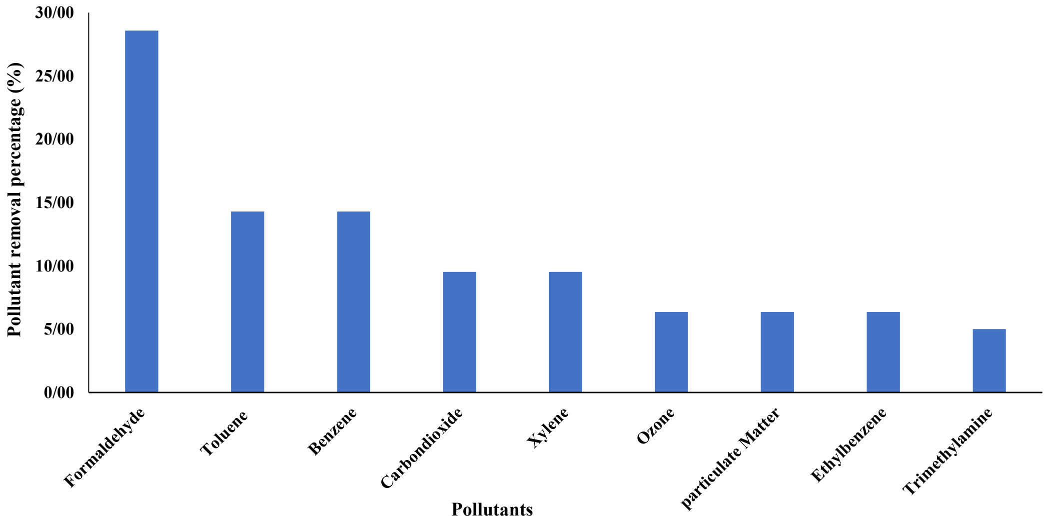

Fig. 4. Representation of the most commonly removed pollutants

Fig. 4 shows the commonly removed pollutants by phytoremediation technique. Formaldehyde (28.5%) is the most studied pollutant followed by toluene (14.2%), benzene (14.2%), carbon dioxide (9.5%), xylene (9.5%), ozone (6.3%) and other pollutants.

The various enhancement types and enhancement factors utilized in the studies are listed in Table 3. Inoculation with soil bacteria Bacillus cereus ERBP is the most common method of enhancement followed by alteration of genes, using chemicals, etc. Some studies used numerous microorganisms in a single experiment or similar microorganisms as boosting variables in two different experiments.

Table 3. Most common enhancement factors used in the phytoremediation experiment. Here, n denotes number of times used in the experiment

Enhancement type	Frequency (n)	Enhancement factor	Frequency (n)
Soil microorganisms	8	Soil micro-organisms (names not specified)	3
		Pseudomonas chlororaphis	1
		Staphylococcus sp. B12	1
		Pantoea sp. B11	1
		Bacillus cereus ERBP	3
		Bacillus thuringiensis	1
		Bacillus nealsonii	1
		Citrobacter amalonaticus Y19	1
Transgenic plant	3	AtNDPK2 gene	1
		AtFALDH gene	1
		CYP2E1 genes	1
Chemicals	2	Indole Acetic Acid	1
		Catechin	1
Change in Environment	1	Microgravity condition	1

Discussion

In recent times, phytoremediation of IAP has attracted considerable interest, and the number of studies has increased significantly. This shows the substantial importance of indoor air quality [73]. Accordingly, the purpose of this study was to conduct a review and summarise its main findings regarding the ability of various plant species to remove pollutants. The review of the 50 included publications revealed the multiple factors that influence and improve the efficiency of plant pollutant removal.

Phytoremediation through conventional methods

Effects of compounds polarity on pollutant removal

VOCs are emitted from a vast array of indoor sources by combustion and evaporation, such as cigarette smoking, solvent-related emissions and paints, cosmetics, building and furnishing materials, cleaning agents, and air fresheners, etc. [74, 75]. Numerous VOCs are categorized as potential carcinogens, particularly benzene (human carcinogen primarily associated with leukemia risk), formaldehyde, and BTEX [76, 77]. Therefore, these contaminants have been subject to extensive experimentation. Among these substances, there exist both polar and nonpolar compounds. According to Ullah et al. the efficacy of plants in removing nonpolar contaminants is inversely related to their efficiency in eliminating polar pollutants. Similarly, there is a reduced efficacy in removing nonpolar contaminants by plants that can eliminate polar pollutants [59]. For instance, *Zamioculcas zamifolia* removed toluene (nonpolar) concentration efficiently, while *Sansevieria trifasciata* removed both formaldehyde (polar) and toluene (nonpolar) concentration efficiently. The efficient removal of the polar pollutants over the nonpolar pollutants might be due to the polar nature of the composition of the cuticular waxes, which might favor the adsorption of polar pollutants [47,50]. Combinations of such plant species can effectively remove polar and nonpolar indoor air contaminants.

Effects of leaf area index (LAI) and leaf characteristics on pollutant removal

The LAI and the leaf surface characteristics play a vital role in pollutant removal. The structural characteristics of a leaf have a crucial role in influencing the deposition of PM. Particulate matter with a diameter of 2.5 µm or less ($PM_{2.5}$) possessed a greater specific surface area and a better adsorption capacity. Deposition of atmospheric particulates in to the surface of plant leaf is crucial in removing PM from the air. Studies have shown a positive correlation between LAI and leaf surface roughness with the capacity to remove $PM_{2.5}$ pollutants [32]. This could be due to the presence of finely grooved tissues, fluffy, sticky, waxy substances, and textured surfaces, which may contribute to the adsorption of PM [78, 79]. It is also observed that surfaces with a coarser texture exhibit more resilient folds and patterns, resulting in a higher capacity to retain dust. On the other hand, leaves with smoother surfaces and shallower, less concentrated grooves display weaker characteristics in terms of dust retention [80, 81]. In contrast, *Aloe vera* with a higher LAI demonstrated a lower $PM_{2.5}$ removal capacity than Sansieveria with a lower LAI. Possible reason could be the smoother and flattened leaf surface of *Aloe vera*. Cao et al. suggested that the LAI is not always positively correlated with the plant's ability to eliminate pollutants [32]. The toluene removal capacity was higher in the woody, herbaceous plants with higher leaf area than the foliage herbaceous plants with lower leaf area. Likewise, woody foliage plants have the broadest range of toluene elimination, whereas herbaceous foliage plants have the narrowest spectrum [33]. However, no proper reasons for this trend were provided.

Effects of light on pollutant removal

The presence, absence, and intensity of light also influence the effectiveness of plants in removing pollutants. An LED lamp is a suitable light source, similar to sunlight due to its similar wavelength [44]. Among fluorescent, LED, and incandescent lamps, LED lamps are the most optimal light source for growing plants. Long-term use of an incandescent lamp needs more electricity and becomes excessively hot [82]. Most plants are capable and have high efficiency to remove pollutants in the presence of light. *Chlorophytum comosum, Dieffenbachia camilla, Peperromia magnoliifolia,* and *Scindapsus aureus* had a higher Trimethylamine (TMA) removal rate in the presence of light than its absence [44]. The rate of formaldehyde and CO_2 removal in *Tradescantia zebrina* and *Vigna radiata* increased with the increasing light intensity [20, 61]. *Sphagnum* is also seen to remove Suspended Particulate Matter (SPM) more efficiently in light conditions [45]. However, some plant species such as the Prickly pear cactus and *Cereus hexagonus* are capable and have high efficiency to remove pollutants in both presence and absence of light [44].

Effects of stomata and cuticle wax on pollutant removal

Stomata and cuticle wax also influence plants' pollutant removal efficiency. Several studies have found that the opening and the closure of stomata influence the pollutant removal rate of the plants since the pollutants are absorbed through the stomata or the cuticle [43, 51]. *Dieffenbachia maculata* and *Spathiphyllum wallisii* have higher 2-ethyl hexanol removal rates during open stomata than in closed stomata. However, the toluene removal rate was almost constant during the opening and closing of the stomatal pore suggesting that the uptake of toluene was with cuticle sorption rather than gaseous diffusion through stomata [26].

Phytoremediation through enhancement factors

Effect of microbial inoculation on pollutant removal

Introducing diverse microorganisms into plant is widely used to enhance plants' ability to eliminate pollutants. Inoculation involves applying microorganisms to the plant's foliage, roots, and potting soil. Due to inoculation, the chemical potential difference between the internal environment of the root solution and the surrounding air in the shoot increased, resulting in substantial rises in the rates of absorption through the foliage and subsequent transport of pollutants to the roots of plants [20]. The formaldehyde elimination efficiency of the plants under investigation, namely *Aglaonema commutatum, Epipremnum aureum, Chlorophytum comosum,* and *Sansevieria trifasciata,* exhibited an increase when the potting mix was inoculated with bacterium *Pseudomonas chlororaphis* [60]. The inoculation of *Bacillus cereus* ERBP (an endophytic bacteria isolated from the root of *Clitoria ternatea*) into *Zamioculcas zamiifolia* increased the catalase (CAT), Ascorbate Peroxidase (APX), and flavonoid contents, thereby increasing the O_3 detoxification in the plant [63]. Similarly, the inoculation of *Staphylococcus* sp. B12 to *Dracaena sanderiana* increased the plant's capacity to remove benzene. This enhancement can be attributed to plant growth stimulation through indole-3-acetic acid (IAA) production and 1-aminocyclopropane-1-carboxylic acid (ACC) regulation. Moreover, it was observed that this phenomenon significantly enhanced the plant's ability to withstand and adapt to adverse environmental conditions, as demonstrated by Jindachot et al. [62].

Effects of gene alteration on pollutant removal

Genetic transformation can be an effective strategy and a potent measure for improving the phytoremediation potential of plants [14]. For instance, *Petunia hybrida* plants encoded with CYP2E1 transgene using *Agrobacterium* rhizogenes K599 exhibited significantly greater benzene elimination capacity than their natural counterparts. Zhang et al. had described that specific electron transfer enzymes are produced in *Petunia* to facilitate CYP2E1's role in decomposing organic pollutants [72].

However, additional research is necessary to fully comprehend how the CYP2E1 transgene enhances the plant's ability to remove pollutants.

Similarly, encoding the AtFALDH gene into *Petunia hybrida* isolated from *Arabidopsis thaliana* increased the plant's capacity to remove formaldehyde [67]. Transgenic *petunia* plants expressing AtNDPK2 had also improved sulphur dioxide (SO_2) gas resistance. Additionally, the transgenic Ardisia pusilla encoded with the AtNDPK2 gene removed substantially more toluene than non-transgenic Ardisia pusilla [66]. This gene regulates the cellular redox and promotes tolerance to various plant stresses. To fully understand how AtNDPK2-transgenic *Ardisia pusilla* plants remove toluene from the air through toxic deactivation and detoxification metabolic pathways, further research is required.

Effects of Hydroponic system on pollutant removal

Plants are cultivated using various growing media, excluding soil in hydroponic systems. The critical characteristics of hydroponic growth media essential for the development of roots include water-holding capacity and air-filled porosity of the media. Greater efficacy of CO_2 removal was reported through hydroponics than conventional potting mix. Irga et al. had provided evidences of the capacity of hydroculture plants to remove VOCs in *Syngonium podophyllum* [61]. However, VOC removal rate was comparatively slower in this system than in typical potting mix plants. Aydogan et al. also demonstrated that *Hedera helix, Chrysanthemum morifolium, Dieffenbachia compacta* and *Epipremnum aureum* exhibited greater efficacy in removing formaldehyde when grown hydroponically using growstone as the hydroponic growing media [71]. Thus, by improving the flexibility, the hydroculture system can be viable for indoor plants, replacing the conventional potting mix.

Effects of the microenvironment and chemicals on pollutant removal

Environmental changes and the addition of certain chemical compounds enhance the pollutant removal rate [65, 68]. Treesubsuntorn et al. found that the rate of benzene elimination in *Chlorophytum comosum* increased substantially in light and dark microgravity environments. This improvement was attributed to the significant increase in the hormone Indole-3-Acetic Acid (IAA), which played a crucial role in keeping the stomata of plants open [68]. Consequently, it facilitated benzene absorption, enhancing its efficacy in phytoremediation processes. According to Khaksar et al. introducing exogenous plant growth hormones can ameliorate stress caused by salt, heavy metals, and air pollutants [64]. Appropriate concentrations of exogenous IAA facilitated the opening of stomatal apertures. Similarly, Ullah et al. had reported that applying exogenous IAA at adequate concentrations increases *Zamioculcas zamiifolia*'s ability to remove pollutants [59]. Adding catechin to *Zamioculcas zamiifolia* increased the efficacy of O_3 removal. This improvement can be explained by the catechin's ability to produce a quinone metabolite that increases the efficiency of O_3 removal in plant cells [65].

Limitations and future recommendations

IAQ has risen to current priorities as people spend most of their time indoors. Therefore, our immediate attention is to create a sustainable green environment and increase the use of inexpensive remedial techniques. This review advances our knowledge of the conventional and enhanced phytoremediation techniques for eliminating numerous indoor air pollutants. The review examines the phytoremediation of indoor air pollutants using various plant species and enhancing factors. The outcomes are contingent on the search specifications, keywords, and selection criteria. This may have excluded some scientific publications released at the same time that may not have appeared in our search engines. Moreover, the studies included in the review did not generalize the method for selecting indoor plant species based on their morphology, anatomy, and physiological qualities that can remediate air since the researchers had yet to define and specify plant selection standards.

The efficiency of the various plant species is examined in this study. However, uniform experimental methodologies and measurement units are necessary to compare plant efficacy in pollutant removal. The removal capacity of indoor air pollutants is needed to be quantified in realistic scenarios. Thus, conducting these experiments in indoor settings rather than chamber experiments is necessary to determine the feasibility of pollutant removal in indoor settings. It is crucial to explain the metabolic detoxifying pathways governing the processes of enhancement methods.

Future studies must emphasize on-

1. Evaluating the practicality and efficacy of phytoremediation on a larger scale, especially in indoor environments like office buildings, residential spaces, and commercial establishments.
2. Conducting long-term studies to ascertain the sustained impact of phytoremediation on indoor air quality, considering factors like plant lifespan, maintenance requirements, and microenvironmental conditions.
3. Exploring the potential synergies between phytoremediation and other indoor air purification technologies, aiming for integrated strategies that maximize pollutant removal in indoor environments.
4. Evaluate the economic feasibility of large-scale phytoremediation of indoor air pollution.

By focusing on these areas, future research and initiatives can contribute to the continued development and practical application of phytoremediation techniques for improving indoor air quality.

Conclusion

Phytoremediation has been demonstrated to be an efficient technique for removing indoor air pollutants. Plant parameters such as LAI, stomata, surface texture, cuticle wax thickness, and light intensity influence the efficiency of pollutant removal. In particular, LAI and surface roughness were found to be directly linked to plants' $PM_{2.5}$ removal rate. As pollutants are absorbed through the stomata or cuticle, the opening and closing of the stomata influence the pace at which plants eliminate airborne pollutants. Toluene, formaldehyde, benzene, and CO_2 are often eliminated through phytoremediation. Moreover, the addition of enhancing factors boosted the plants' ability to remove pollutants. Microorganism-inoculated plants were substantially more effective than uninoculated plants. Along with this, transgenic plants with altered genes demonstrated a higher capability for detoxification than their wild counterparts. Furthermore, incorporating hydroculture and microgravity systems into the conventional plant potting medium could also increase its pollutant removal efficiency. Most of the studies included in this review were conducted under simulated environments (closed chamber) rather than actual indoor air settings. Additional research is required to explore the potential impacts of potted plant systems and enhancement methods, as the effect of remediation might not be as significant in indoor environments as in the test chambers.

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Competing interests

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc) have been completely observed by the authors.

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