

Systematic review of phytoremediation of airborne benzene and toluene

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ABSTRACT

Declining Indoor Air Quality (IAQ) in confined spaces and with insufficient ventilation poses serious health risks in industrial and office environments. The presence of volatile organic compounds in indoor air can cause human diseases, highlighting the need for effective and sustainable air quality improvement strategies. Phytoremediation offers an efficient, eco-friendly approach for removing contaminants from air, soil, and water, with plant species differing in their absorption capacities. This systematic review, conducted following Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, identifies plant species effective in the phytoremediation of airborne benzene and toluene and examines factors influencing their performance. Comprehensive searches of Scopus, Web of Science, Google Scholar, ProQuest, MagIran, and IranDoc databases retrieved relevant studies through a three-stage screening process (title, abstract, and full-text review). Findings highlight *Hedera helix* and *Epipremnum aureum* as the most frequently used and efficient species for benzene and toluene removal. Moreover, enhancing factors such as increasing plant exposure time to pollutants, repeated injection cycles, and modifications to plant characteristics or substrate can significantly improve phytoremediation efficiency. Comparative analysis of conventional and enhanced methods revealed that enhanced phytoremediation plants improve both the rate and extent of pollutant removal and can serve as cost-effective, sustainable, and eco-friendly strategies for controlling IAQ. Findings also suggest that selecting appropriate plant species and designing combined systems can maximize IAQ improvement and promote human health in industrial and office settings. Overall, phytoremediation, particularly using multiple plant species under optimized environmental conditions, can effectively enhance indoor air quality and guide the design of practical phytoremediation systems.

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Review

Air pollution caused by Volatile Organic Compounds (VOCs) is considered one of the most significant environmental and health challenges of the modern era. Among these compounds, benzene and toluene hold a particularly important position due to their widespread release in petrochemical industries, fuel production, paint manufacturing, and petroleum-derived products, which pose serious threats to human health and environmental sustainability [1]. Studies have shown that long-term exposure to benzene can lead to leukemia, bone marrow disorders, and weakened immunity, whereas toluene directly affects the central nervous system, causing symptoms such as headaches, fatigue, memory impairment, and, in severe cases, liver and kidney damage [2]. Considering the increasing concentration of these pollutants in enclosed industrial spaces as well as urban indoor environments, there is a growing need for sustainable approaches to manage and reduce their levels.

The sources of benzene and toluene in indoor environments are highly diverse, including fuel products, chemical solvents, paints, adhesives, tobacco products, and certain building materials [3]. In industrial settings, these compounds often enter the air as by-products of production or due to leaks and evaporation from processing lines, whereas in residential and office environments, sources such as wall painting, wooden flooring, and the use of chemical sprays significantly contribute to their concentration. Considering that individuals spend approximately 80–90% of their time indoors [4], chronic exposure to even low levels of these hazardous compounds poses a considerable risk. This risk is particularly pronounced in modern buildings, which are often tightly insulated to improve energy efficiency; reduced natural ventilation can lead to the accumulation of benzene and toluene to toxic

levels, exacerbating sick building syndrome and building-related illnesses [5].

Several approaches have been developed to reduce airborne pollutants in indoor environments, including mechanical filters, activated carbon, advanced ventilation systems, and photocatalytic oxidation. While these technologies have shown some success in removing volatile organic compounds, they face significant challenges such as high installation and maintenance costs, high energy consumption, and limited efficiency under real-world conditions [6]. Additionally, certain technologies, such as ozone-generating devices, can produce harmful secondary compounds, posing potential health risks [7]. Therefore, although these methods perform well in laboratory or short-term applications, they are not considered ideal for sustainable use in industrial or residential settings due to operational limitations and cost constraints. This underscores the need for natural, low-cost, and environmentally friendly approaches. Phytoremediation, as a nature-based solution, has attracted considerable attention from researchers in recent years. This approach utilizes the ability of plants, along with their symbiotic relationships with rhizospheric microorganisms, to absorb, degrade, stabilize, or transfer pollutants [8]. Various mechanisms contribute to this process, including phytoextraction (uptake of pollutants through roots and storage in plant tissues), phytodegradation (chemical breakdown and transformation of pollutants within plant tissues), phytovolatilization (release of transformed compounds through leaf transpiration), and stomatal uptake (direct absorption of gaseous pollutants through leaf stomata) [4]. A major advantage of phytoremediation over physical and chemical technologies lies in its low cost, minimal energy consumption, and ecological compatibility. Moreover, the use of plants in indoor environments also enhances aesthetics and promotes the psychological well-being of

occupants [9].

Numerous studies have investigated the ability of plant species to remove VOCs, particularly benzene and toluene. For instance, one study reported that *Epipremnum aureum* can significantly reduce benzene concentrations in enclosed environments [10]. Likewise, *Hedera helix* has demonstrated the capacity to absorb and degrade toluene through its roots and leaves [11]. Experimental research has shown that the presence of indoor plants can lead to a significant reduction in VOC concentrations within indoor spaces. Furthermore, other studies have highlighted the role of plant characteristics—such as leaf surface area, transpiration rate, and rhizospheric properties—in markedly enhancing phytoremediation efficiency [12, 13]. The use of green walls, green roofs, and the combination of plants with activated carbon substrates has also been proposed as enhanced strategies in recent research. Despite substantial evidence regarding the ability of plants to remove benzene and toluene, significant gaps remain in existing literature. Most studies have been conducted at laboratory or greenhouse scales, and field data on plant performance in real industrial environments—with complex airflow patterns, temperature fluctuations, and the simultaneous presence of multiple pollutants—are very limited [4]. Moreover, most of the research has focused on a single pollutant or a single plant species, whereas inter-species comparisons or studies on mixed plant systems could provide valuable insights for designing more efficient phytoremediation systems. The synergistic interactions between plants and rhizospheric microorganisms, as well as the potential for enhancing efficiency through genetic modification or microclimatic adjustments, are also topics that have received limited attention. These gaps indicate a clear need for interdisciplinary and larger-scale studies to enable practical and industrial applications of phytoremediation for benzene and toluene

removal.

This systematic review aims to collect and comprehensively analyze published studies on the phytoremediation of benzene and toluene. The primary focus is on identifying effective plant species, the biological mechanisms involved in pollutant removal, and the environmental conditions that influence the efficiency of the process. Additionally, the study seeks to highlight existing research gaps and propose directions for future investigations, providing a scientific foundation for the design and development of green and bio-Inspired systems in industrial and urban environments.

Search strategy and information sources

A systematic review is one of the most reliable secondary research methods used to collect, analyze, and synthesize findings from primary studies [14]. In this approach, after formulating a clear research question, a comprehensive and targeted search is conducted across relevant databases, and studies are selected or excluded based on predefined criteria. The quality and validity of the selected studies are then critically evaluated, and their findings are systematically compared and synthesized to provide a comprehensive and evidence-based understanding of the existing knowledge [15].

In this regard, the research keywords were first extracted and categorized as shown in Table 1, consisting of nine single keyword groups, seven paired combinations, and five three-word combinations. Examples of the search strings used include Phytoremediation and Benzene, Phytoremediation and Toluene and Phytoremediation and BTEX in both English and Persian. To enhance search precision, the Boolean operator and was applied between the keywords. In the next step, reputable databases were selected, including Web of Science, Scopus, ProQuest, and Google Scholar for English-language reference, and MagIran.com and Ganj.

irandoc.ac.ir for Persian-language reference. The defined keywords were entered in the Advanced Search section of each database, specifically in the Article Title field. Based on the search results obtained up to June 25, 2025, a total of 94 relevant articles were identified, which served as the foundation for subsequent screening stages.

Among the main advantages of a systematic review are the reduction of bias, transparency in the research process, and reproducibility of results [4]. Moreover, in the field of phytoremediation, systematic reviews play a crucial role in collecting and integrating fragmented studies, enabling the identification of efficient plant species for the remediation of air, soil, and water pollutants. This approach not only clarifies the current state of knowledge but also reveals existing research gaps and potential future directions [16].

Inclusion criteria and data extraction

Following the systematic search across the

selected databases, a total of 94 studies were identified. These records served as the input for the screening phase. The screening process was conducted in three stages-title, abstract, and full-text review-based on the PRISMA guidelines and standard procedures of systematic literature reviews [8].

In the first stage, the retrieved studies were limited to English and Persian journal and conference papers. Screening based on the article titles resulted in the selection of 28 studies, while 66 records were excluded due to duplication or irrelevance. In the second stage, the abstracts of the selected papers were reviewed, leading to the exclusion of 9 studies that were found to be unrelated to the research objectives. Consequently, 19 studies were retained. In the third stage, the full texts of the remaining papers were examined in detail. During this process, 6 studies were excluded due to low relevance to the study's main focus, leaving a total of 13 studies for the final analysis (Fig. 1)

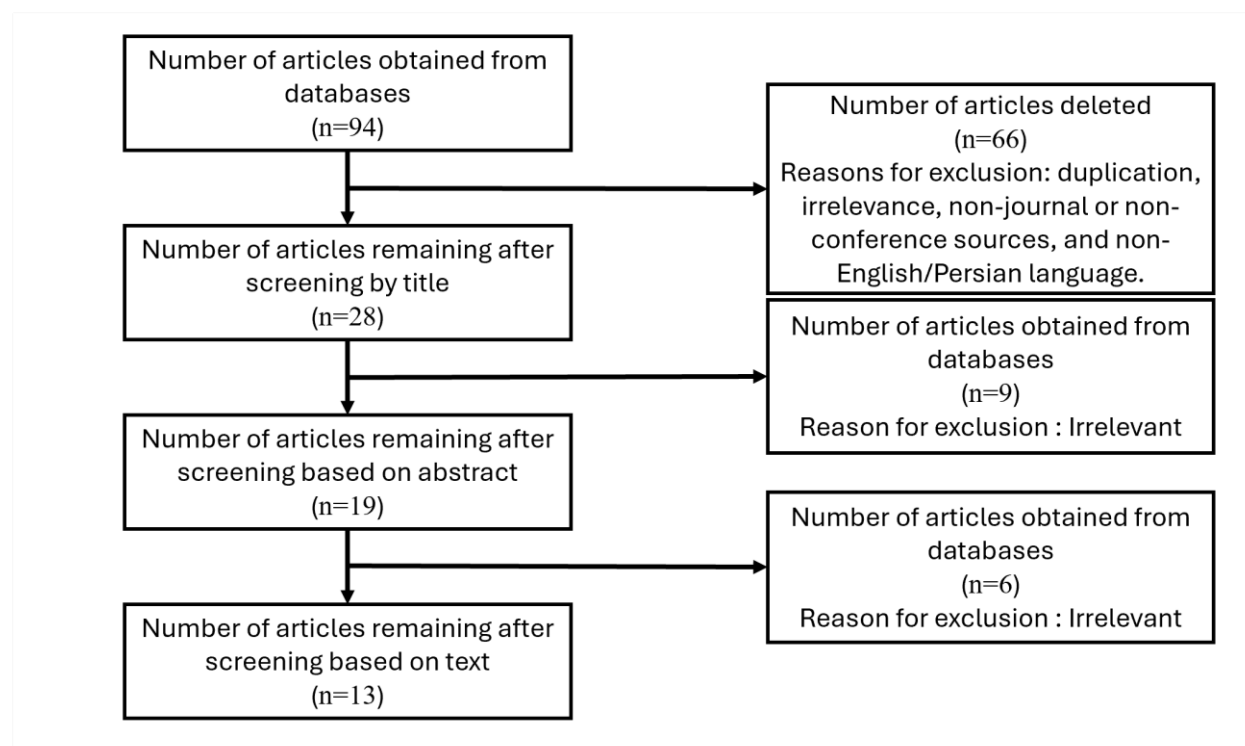


Fig. 1. PRISMA flow diagram illustrates the review process of benzene and toluene studies across selected databases (reference: Authors)

The process of identifying, screening, and selecting studies is illustrated in the PRISMA flow diagram (Fig. 1). As shown, a total of 94 records were initially retrieved. After completing the screening stages, 13 studies were included in the final data analysis and synthesis. Consequently, 81 records - including non-journal and non-conference papers, non-English or non-Persian references, duplicates, and irrelevant studies - were excluded from the review process.

Risk of bias assessment in the selected studies

Most of the studies included in this systematic review were conducted under controlled chamber or laboratory conditions. Unlike clinical research, where human participation requires strict randomization and controlled allocation procedures, studies on phytoremediation of airborne pollutants do not involve such requirements. Therefore, biases related to randomization or participant exclusion are not applicable in this context.

Nevertheless, certain types of bias may still occur. One of the most notable sources of potential bias arises from the limitations of the systematic search process and the inclusion/exclusion criteria, which may inadvertently lead to the omission of relevant data. Thus, while human-related biases are largely absent, selection bias, experimental constraints, and the limited scope of available studies remain potential factors affecting the external validity and generalizability of the results.

Results

Summary of the selected studies indicates that in the field of benzene and toluene phytoremediation, most research has focused on evaluating the ability of plants to remove each pollutant separately, while a smaller number have examined their simultaneous removal. Based on the present systematic review, 13 articles have investigated plants capable of removing benzene, in which various species from different plant families were tested and their performance in reducing benzene concentration in indoor environments was evaluated. Additionally, 10 articles have addressed toluene phytoremediation; although the species diversity in this group is lower than that of benzene, some species have shown notable efficiency in reducing toluene levels. Furthermore, 11 studies have examined the plants' ability to simultaneously remove both benzene and toluene. In this group, only a limited number of species were studied, most of which belong to well-known and widely used plant families in the field of phytoremediation. Overall, these studies encompass various indoor and ornamental plant species, reflecting a considerable diversity of plant families involved in the phytoremediation process. The findings also indicate that most research to date has been conducted under single-pollutant conditions, while studies on multi-pollutant remediation remain limited and in their early stages. The presented tables (Tables 1, 2, and 3) provide a comprehensive overview of the scope of existing studies as well as the distribution of plant species and families in each category.

Table 1. Plants identified as effective in benzene phytoremediation extracted from the systematic review (reference: Author)

	Botanical name	Plant family	Reference
1	Hedera helix	Araliaceae	[17]
	Epipremnum aureum	Araceae	
	Spathiphyllum mauna loa	Araceae	

Table 1. Continued

	Botanical name	Plant family	Reference	
1	Dracaena reflexa	Asparagaceae	[17]	
	Gerbera jamesonii	Asteraceae		
	Chrysanthemum morifolium	Asteraceae		
2	Aloe vera	Asphodelaceae	[18]	
	Hedera helix	Araliaceae		
	Chrysanthemum	Asteraceae		
3	Chrysanthemum morifolium	Asteraceae	[19]	
	Chamaedorea seifrizii	Arecaceae		
	Gerbera jamesonii	Asteraceae		
	Spathiphyllum wallisii	Araceae		
	<u>Ficus benjamina</u>	Moraceae		
	Nephrolepis exaltata	Nephrolepidaceae		
	Dracaena fragrans	Asparagaceae		
	Hedera helix	Araliaceae		
	Hedera helix	Araliaceae		[20]
	Dracaena marginata	Asparagaceae		
4	Dracaena deremensis	Araceae	[21]	
	Chrysanthemum	Asteraceae		
	Gerbera daisy	Asteraceae		
	Dracaena warneckii	Araceae		
5	Peace lily	Araceae	[22]	
	Hedera helix	Araliaceae		
6	Epipremnum aureum	Araceae	[22]	
	Orchid	Orchidaceae		
	Spathiphyllum	Araceae		
	Azalea	Ericaceae		
	Aloe vera	Asphodelaceae		
	Spathiphyllum	Araceae		
	Hedera helix	Araliaceae		
	Epipremnum aureum	Araceae		

Table 1. Continued

	Botanical name	Plant family	Reference
6	Chrysanthemum	Asteraceae	[22]
	Dracaena	Asparagaceae	
	Pachira aquatica	Malvaceae	
	Gerbera	Asteraceae	
	Zantedeschia aethiopica	Araceae	
	Sword fern	Nephrolepidaceae	
	Schefflera	Araliaceae	
	Ficus	Moraceae	
	Ficus benjamina	Moraceae	
	Croton	Euphorbiaceae	
	Bamboo palm	Arecaceae	
	Butterfly palm	Arecaceae	
	Zamioculcas zamiifolia	Araceae	
	Acer campestre	Sapindaceae	
	Epipremnum aureum	Araceae	
	Phoenix roebelenii	Arecaceae	
	Syngonium podphyllum	Araceae	
Azalea	Ericaceae		
7	Aloe Vera	Asphodelaceae	[23]
	Sansevieria masoniana	Asparagaceae	
	Sansevieria trifasciata	Asparagaceae	
	Sansevieria hyacinthoides	Asparagaceae	
	Sansevieria ehrenbergii	Asparagaceae	
	kalanchoe blossfeldiana	Crassulaceae	
	Dracaena deremensis	Asparagaceae	
	Codiaeum variegatum	Araceae	
	Chlorophytum compositum	Asparagaceae	
	Dracaena sanderiana	Asparagaceae	
	Cordyline frutescens	Asparagaceae	
	Aglaonema commutatum	Araceae	
	Clitoria ternatea	Fabaceae	
	Z. Zamiifolia	Araceae	

Table 1. Continued

	Botanical name	Plant family	Reference
7	S. Trifasciata	Asparagaceae	[23]
	S. Kirkii	Asparagaceae	
	O. Microdasys	Cactaceae	
	Canna	Cannaceae	
	Poplar trees	Salicaceae	
	Leek	Amaryllidaceae	
	Ruscun hyrcanus	Asparagaceae	
	Danae racemosa	Asparagaceae	
8	Epipremnum aureum	Araceae	[5]
	Spathiphyllum wallisii	Araceae	
	Chlorophytum comosum	Asparagaceae	
	Echinopsis	Cactaceae	
	Tubiflora	Cactaceae	
	Ruscus hyrcanus	Asparagaceae	
9	Syngonium podpphyllum	Araceae	[24]
	Sansevieria trifasciata	Asparagaceae	
	Euphorbia milii	Euphorbiaceae	
	Chlorophytum comsum	Asparagaceae	
	Epipremnum aureum	Araceae	
	Dracaena sanderiana	Asparagaceae	
	Hedera helix	Araliaceae	
	Clitoria ternatea	Fabaceae	
	Ficus	Moraceae	
	Golden pothos	Araceae	
	Spider Plant	Nephrolepidaceae	
	Christmas cactus	Cactaceae	
	Schefflera	Araliaceae	
	Howea forsteriana	Arecaceae	
	Dracaena marginata	Asparagaceae	
	Spathiphyllum	Araceae	
Aglaomena	Araceae		

Table 1. Continued

	Botanical name	Plant family	Reference
10	S. podophyllum	Araceae	[5]
	S. trifasciata	Asparagaceae	
	E. milli	Euphorbiaceae	
	C. comosum	Asparagaceae	
	E. arueam	Araceae	
	D. snderiana	Asparagaceae	
	H, helix	Araliaceae	
	C. tematea	Fabaceae	
11	Schefflera arboricola	Araliaceae	[25]
	Spathiphyllum willisii	Araceae	
12	Epipremnum aureum	Araceae	[26]
	Chlorophytum comosum	Asparagaceae	
	Hedera helix	Araliaceae	
	Echinopsis tubiflora	Cactaceae	
13	S. arboricola	Araliaceae	[4]
	S. wallisi	Araceae	
	C. seifrizii	Arecaceae	
	E. aureum	Araceae	
	S. aureus	Asparagaceae	
	P. domesticum	Araceae	
	M. cuminata	Marantaceae	
	S. trifasciata	Asparagaceae	
	D. sanderiana	Asparagaceae	
	I. ebarbatacraib	Amaranthaceae	
	E. aureum	Araceae	
	C. comosum	Asparagaceae	
	H. helix	Araliaceae	
	E. tubiflora	Cactaceae	
	D. trifasciata	Asparagaceae	
	S. podophyllum	Araceae	
	C. comosum	Asparagaceae	

According to Table 1, all plants identified as effective in benzene phytoremediation were included in the analysis, regardless of their

growth form - whether potted or non-potted, tree, shrub, herbaceous, or climbing species.

Table 2. Plants identified as effective in toluene phytoremediation extracted from the systematic review (reference: Author)

	Botanical name	Plant family	Reference
1	Danae racemosa	Asparagaceae	[27]
	Hedera helix	Araliaceae	
	Dracaena deremensis	Asparagaceae	
	Pittosporum tobira	Pittosporaceae	
2	Alternanthera	Amaranthaceae	[28]
	Hedera helix	Araliaceae	
	Tradescantia zebrina	Commelinaceae	
	Hosta	Asparagaceae	
	Ficus benjamina	Moraceae	
	Fittonia albivenis	Acanthaceae	
	Peperomia	Piperaceae	
	Schefflera	Araliaceae	
	Ficus elastica	Moraceae	
Dieffenbachia seguine	Araceae		
3	Orchid	Orchidaceae	[22]
	Spathiphyllum wallisii	Araceae	
	Azalea	Ericaceae	
	Aloe vera	Asphodelaceae	
	Anthurium andraeanum	Araceae	
	Euphorbia pulcherrima	Euphorbiaceae	
	Hedera helix	Araliaceae	
Epipremnum aureum	Araceae		
Chrysanthemum morifolium	Asteraceae		

Table 2. Continued

	Botanical name	Plant family	Reference
	Dracaena	Asparagaceae	
	Codiaeum variegatum	Euphorbiaceae	
	Bamboo palm	Arecaceae	
	Lady palm	Arecaceae	
	Phoenix palm	Arecaceae	
	Japanese maple	Sapindaceae	
4	Begonia maculata	Begoniaceae	
	Ardisia crenata	Primulaceae	[29]
	Anguilla japonica	Araceae	
	Dieffenbachia amoena	Araceae	
	Dracaena deremensis	Asparagaceae	
5	Spathiphyllum wallisii	Araceae	[30]
	Sansevieria trifasciata	Asparagaceae	
	Zamioculcas zamiifolia	Araceae	
6	Epipremnum aureum	Araceae	[31]
	Dracaena fragrans	Asparagaceae	
	Aloysia triphylla	Verbenaceae	
	Melissa officinalis	Lamiaceae	
	Mentha piperita	Lamiaceae	
	Mentha piperita	Lamiaceae	
	Mentha suaveolens	Lamiaceae	
	Mentha suaveolens	Lamiaceae	
	Pelargonium graveolens	Geraniaceae	
	Plectranthus tomentosus	Lamiaceae	
7	Rosmarinus officinalis	Lamiaceae	[32]
	Salvia elegans	Lamiaceae	
	Begonia maculata	Begoniaceae	

Table 2. Continued

	Botanical name	Plant family	Reference
	<i>Davallia mariesii</i>	Davalliaceae	
	<i>Farfugium japonicum</i>	Asteraceae	
	<i>Fittonia verschaffeltii</i>	Acanthaceae	
	<i>Hedera helix</i>	Araliaceae	
	<i>Philodendron sunlight</i>	Araceae	
	<i>Soleirolia soleirolii</i>	Urticaceae	
	<i>Ardisia crenata</i>	Primulaceae	
	<i>Ardisia japonica</i>	Primulaceae	
7	<i>Ardisia pusilla</i>	Primulaceae	[32]
	<i>Cinnamomum camphora</i>	Lauraceae	
	<i>Schefflera elegantissima</i>	Araliaceae	
	<i>Eurya emarginata</i>	Pentaphylacaceae	
	<i>Ilex cornuta</i>	Aquifoliaceae	
	<i>Ligustrum japonicum</i>	Oleaceae	
	<i>Pinus densiflora</i>	Pinaceae	
	<i>Pittosporum tobira</i>	Pittosporaceae	
	<i>Rhododendron fauriei</i>	Ericaceae	
8	<i>Vigna radiata</i>	Fabaceae	[33]
9	Yellow lupine	Fabaceae	[34]
	<i>D. maculata</i>	Araceae	
	<i>S. wallisii</i>	Araceae	
	<i>A. densiflorus</i>	Asparagaceae	
10	<i>A. triphylla</i>	Verbenaceae	[4]
	<i>M. officinalis</i>	Lamiaceae	
	<i>M. piperita</i>	Lamiaceae	
	<i>M. suaveolens</i>	Lamiaceae	

Table 2. Continued

	Botanical name	Plant family	Reference
	P. tomentosus	Lamiaceae	
	R. officinalis	Lamiaceae	
	S. elegans	Lamiaceae	
	P. graveolens	Geraniaceae	
	B. maculate	Begoniaceae	
	D. mariesii	Davalliaceae	
	F. japonicum	Asteraceae	
	F. verschaffeltii	Acanthaceae	
	H. helix	Araliaceae	
	S. actinophylla	Araliaceae	
	F. benghalensis	Moraceae	
10	A. vera	Asphodelaceae	[4]
	S. masoniana	Asparagaceae	
	S. trifasciata	Asparagaceae	
	S. hyacinthoides	Asparagaceae	
	S. ehrenbergii	Asparagaceae	
	D. deremensis	Asparagaceae	
	D. sanderiana	Asparagaceae	
	C. comosum	Asparagaceae	
	K. blossfeldiana	Crassulaceae	
	C. variegatum	Euphorbiaceae	
	A. commutatum	Araceae	
	Z. zamiifolia	Araceae	
	A. pusilla	Primulaceae	

According to Table 2, all plant species capable of phytoremediating airborne toluene were

included in the analysis, regardless of their type.

Table 3. Plants identified as effective in the phytoremediation of benzene and toluene extracted from the systematic review (reference: Author)

	Botanical name	Plant family	Reference
1	<i>Dracaena deremensis</i>	Asparagaceae	[27]
	<i>Epiremnum aureum</i>	Araceae	
	<i>Dracaena maraginata</i>	Asparagaceae	
	<i>Schefflera actinophylla</i>	Araliaceae	
	<i>Syngonium podophyllum</i>	Araceae	
	<i>Kalanchoe blossfeldiana</i>	Crassulaceae	
	<i>Crassula portulaca</i>	Crassulaceae	
	<i>Spathiphyllum wallisii</i>	Araceae	
	<i>Syngonium podophyllum</i>	Araceae	
	<i>Hedera helix</i>	Araliaceae	
	<i>Cissus rhombifolia</i>	Vitaceae	
2	<i>Aglaonema commutatum</i>	Araceae	[28]
	<i>Fittonia verschaffeltii</i>	Acanthaceae	
	<i>Alternanthera</i> spp.	Amaranthaceae	
	<i>Hedera helix</i>	Araliaceae	
	<i>Syngonium podophyllum</i>	Araceae	
	<i>Ficus benjamina</i>	Moraceae	
	<i>Peperomia</i> spp.	Piperaceae	
	<i>Schefflera</i> spp.	Araliaceae	
	<i>Aloe vera</i>	Asphodelaceae	[22]
	<i>Sanseveria masonina</i>	Asparagaceae	
	<i>Sanseveria trifasciata</i>	Asparagaceae	
	<i>Sanseveria ehrenbergii</i>	Asparagaceae	
3	<i>Kalanchoe blossfeldiana</i>	Crassulaceae	
	<i>Dracaena deremensis</i>	Asparagaceae	
	<i>Dracaena sanderiana</i>	Asparagaceae	

Table 3. Continued

	Botanical name	Plant family	Reference
3	Codiaeum variegatum	Euphorbiaceae	[22]
	Chlorophytum comosum	Asparagaceae	
	Cordyline fruticosa	Asparagaceae	
	Aglaonema commutatum	Araceae	
4	Daracaena sanderiana	Asparagaceae	[35]
	Opuntia microdasys	Cactaceae	[36]
5	Dracaena deremensis	Asparagaceae	
6	Ruscus hyrcanus Woronow	Asparagaceae	[37]
	Danae racemosa	Asparagaceae	
7	Zamioculcas zamiifolia	Araceae	[38]
8	Tradescantia pallida	Commelinaceae	[30]
	Hedera helix	Araliaceae	
	Hemigraphis alternata	Acanthaceae	
	Hoya carnosa	Apocynaceae	
	Asparagus densiflorus	Asparagaceae	
	Fittonia argyroneura	Acanthaceae	
9	Danae racemosa	Asparagaceae	[27]
	Hedera helix	Araliaceae	
10	Zamioculcas zamiifolia	Araceae	[38]
11	P. hybrida	Solanaceae	[4]
	Aglaonema	Araceae	
	P. aquatica	Malvaceae	
	F. benjamina	Moraceae	
	Z. zamiifolia	Araceae	
	D. racemos	Asparagaceae	

Table 3. Continued

	Botanical name	Plant family	Reference
	<i>R. hircabus</i>	Asparagaceae	
	<i>D. deremensis</i>	Asparagaceae	
	<i>O. microdasy</i>	Cactaceae	
11	<i>H. helix</i>	Araliaceae	[4]
	<i>D. lutescens</i>	Arecaceae	
	<i>D. marginata</i>	Asparagaceae	
	<i>Spathiphyllum</i>	Araceae	

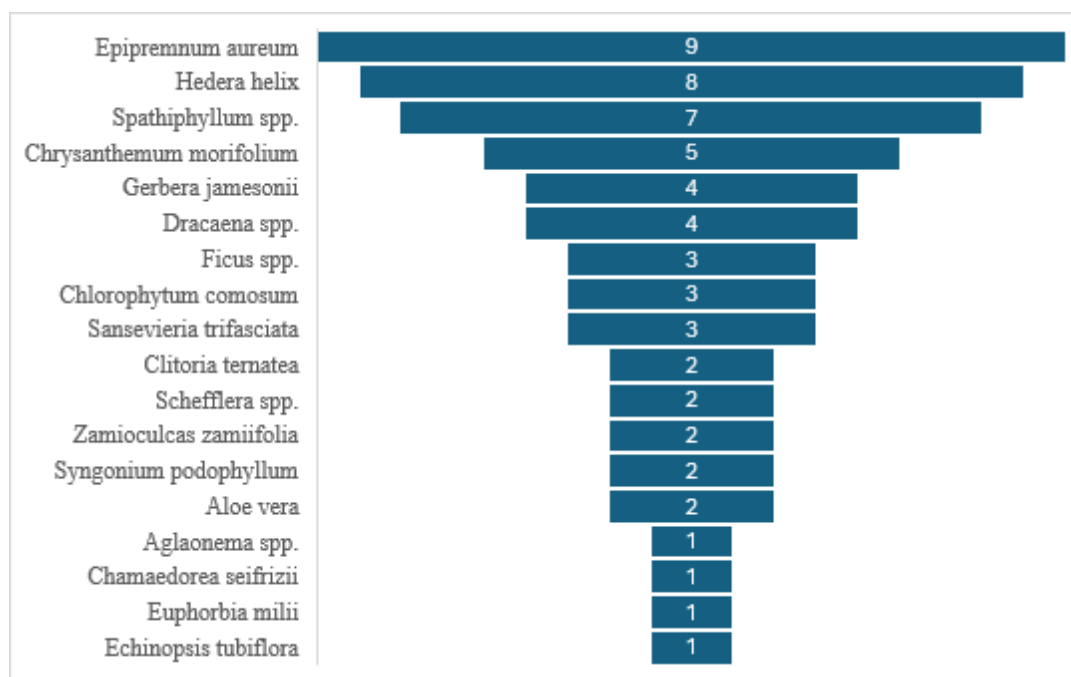


Fig. 2. Plants with the highest frequency of Benzene phytoremediation reported in the systematic review (reference: Author)

According to Table 3, all plants capable of phytoremediating airborne benzene and toluene pollutants, regardless of their type, were identified.

Following the review of the screened articles and extraction of relevant data, the phytoremediating plants for benzene and toluene were determined.

These plants were categorized into three main groups: benzene phytoremediators, toluene phytoremediators, and those effective for both pollutants. The frequency of each plant's occurrence for the remediation of each pollutant was extracted separately and ranked in the following tables (Fig. 2).

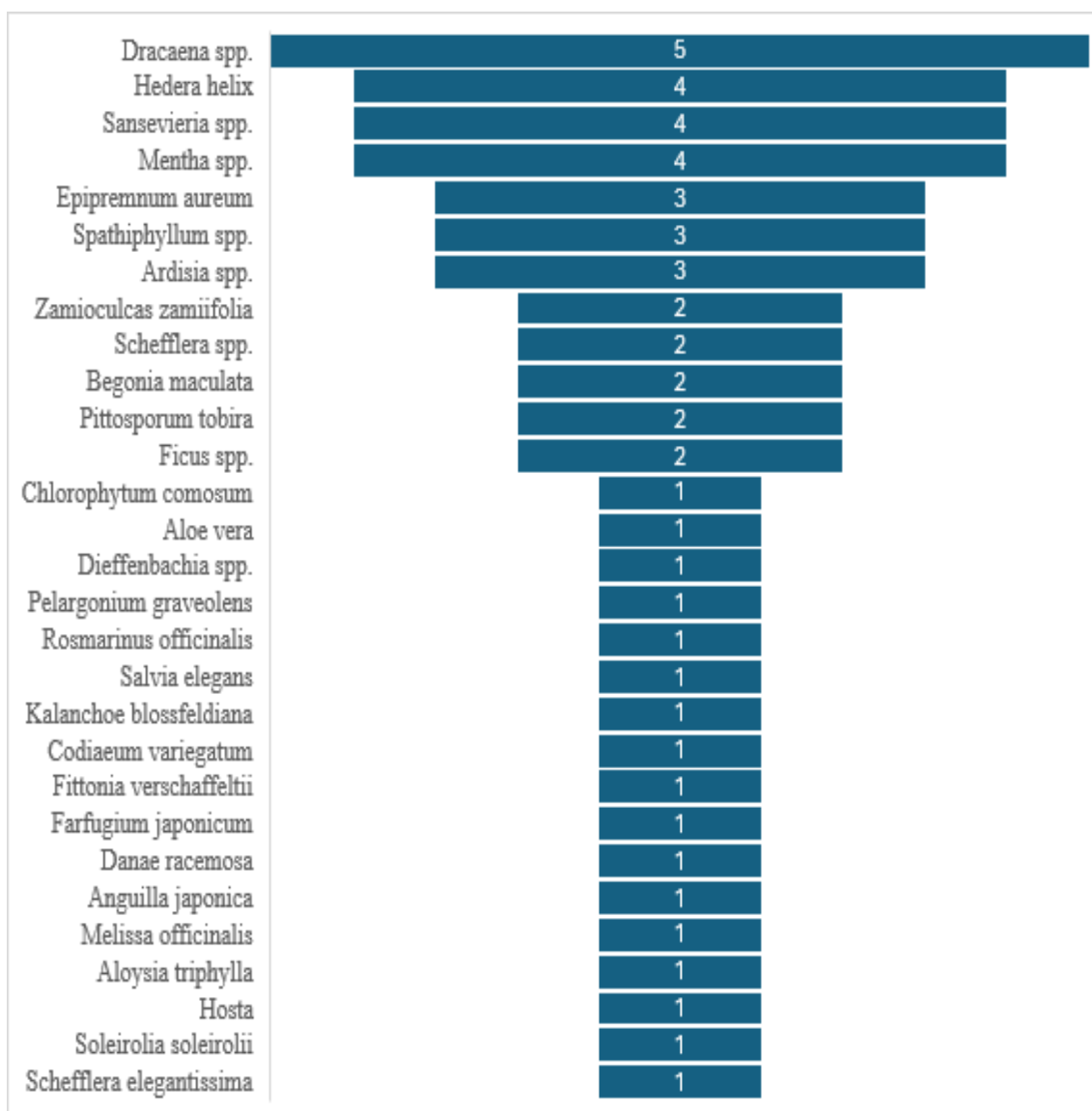


Fig. 3. Plants with the highest frequency of Toluene phytoremediation reported in the systematic review (reference: Author)

Among the plants capable of phytoremediating airborne benzene pollution, *Epipremnum aureum* was the most frequently reported species, appearing in nine studies (Fig. 2).

Among the plants capable of phytoremediating

airborne toluene pollution, *Dracaena* species appeared most frequently (5 occurrences), followed by *Hedera helix*, *Sansevieria trifasciata* (snake plant), and *Mentha spicata* (mint), each reported in four studies (Fig. 3).

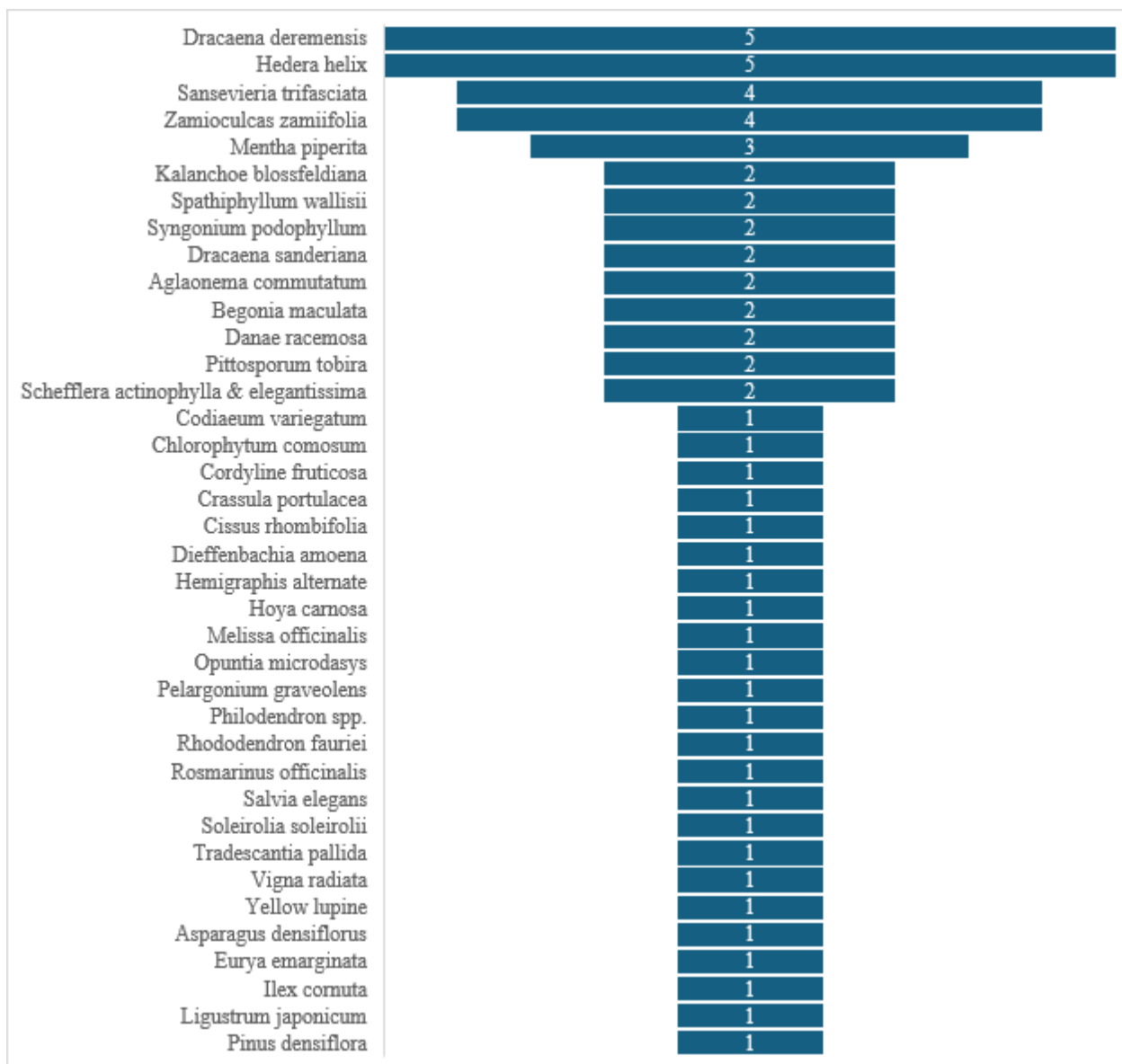


Fig. 4. Plants with the highest frequency of both Benzene and Toluene phytoremediation reported in the systematic review (reference: Author)

Among the plants capable of phytoremediating airborne benzene and toluene pollutants, *Dracaena* and *Hedera helix* were the most frequently reported species, each appearing in five studies (Fig. 4).

In the next step, the phytoremediation rates of benzene and toluene for all identified plants were extracted from the reviewed articles and are presented in the following tables (Table 4).

Table 4. Phytoremediation rates of plants for airborne benzene and toluene pollutants (Reference: Author)

Row	Plant Species	Phytoremediation rate			Reference
		Benzene	Toluene	Unit	
1	Ruscus hyrcanus	8.5075	22.567	mg m ⁻³ h ⁻¹	[37]
2	D. racemosa	2.1418	10.11		
3	H. helix	14.1	-	mg m ⁻³ h ⁻¹ m ⁻²	[39]
4	D. deremensis	2.4	-		
5	D. racemosa	13	-		
6	Hedera helix	233.02	329.85	mg m ⁻³ h ⁻¹ m ⁻²	[27]
7	Danae racemosa	76.39	90.11		
8	Daracaena sanderiana	348	-	mg m ⁻³	[35]
9	Pinus densiflora	-	919.7 ± 89.9		
10	Ilex cornuta	-	429.7 ± 104.5		
11	Pelargonium graveolens	-	510.3 ± 78.1		
12	Ardisia japonica	-	500.1 ± 47.2		
13	Mentha xpiperita	-	440.6 ± 20.4		
14	Mentha suaveolens	-	733.7 ± 55.7		
15	Pineapple mint	-	422.9 ± 13.6		
16	Rhododendron fauriei	-	928.3 ± 135.5	mg m ⁻³ h ⁻¹ m ⁻²	[32]
17	Eurya emarginata	-	213.7 ± 24.4		
18	Ligustrum japonicum	-	250.9 ± 4.6		
19	Fittonia verschaffeltii	-	449.8 ± 31.9		
20	Cinnamomum camphora	-	244.1 ± 45.7		
21	Aloysia triphylla	-	761.4 ± 3.6		
22	Mentha xpiperita	-	209.9 ± 10.4		
23	Davallia mariesii	-	190.7 ± 21.1		
24	Farfugium japonicum	-	245.5 ± 23.5		

Table 4. Continued

Row	Plant Species	Phytoremediation rate			Reference
		Benzene	Toluene	Unit	
25	<i>Schefflera elegantissima</i>	-	174.6 ± 19.9		
26	<i>Ardisia crenata</i>	-	114.1 ± 5.0		
27	<i>Rosmarinus officinalis</i>	-	558.7 ± 84.7		
28	<i>Soleirolia soleirolii</i>	-	254.0 ± 12.0		
29	<i>Philodendron</i> spp.	-	183.8 ± 2.8		
30	<i>Ardisia pusilla</i>	-	88.6 ± 5.2	mg m ⁻³ h ⁻¹ m ⁻²	[32]
31	<i>Hedera helix</i>	-	401.0 ± 33.5		
32	<i>Melissa officinalis</i>	-	218.7 ± 18.8		
33	<i>Plectranthus tomentosus</i>	-	108.6 ± 22.3		
34	<i>Pittosporum tobira</i>	-	22.1 ± 5.3		
35	<i>Begonia maculata</i>	-	55.9 ± 1.8		
36	<i>Salvia elegans</i>	-	188.4 ± 1.8		
37	<i>Dracaena deremensis</i>	10.6	4.86	mg m ⁻³ m ⁻² day ⁻¹	[36]
38	<i>Opuntia microdasys</i>	23.2	10.7		
39	<i>Schefflera arboricola</i>	91-97%	-	μg m ⁻³	[25]
40	<i>Spathiphyllum wallisii</i>	91-97%	-		
41	<i>Vigna radiata</i>	7.9-10.8%	-	Percent day ⁻¹	[33]
42	<i>Zamioculcas zamiifolia</i>	0.96±0.01	0.93 ± 0.02	mmol m ⁻²	[38]
43	<i>Ardisia pusilla</i>	-	206.2 ± 31.19	g m ⁻³ cm ⁻²	[4]
44	<i>Ardisia pusilla</i>	-	797.33 ± 59.41		
45	<i>Epipremnum aureum</i>	1.1	-		
46	<i>Hedera helix</i>	0.85	-	g m ⁻³ cm ⁻²	[26]
47	<i>Chlorophytum comosum</i>	0..27	-		

In the next step, the factors influencing the enhancement of phytoremediation efficiency and rate were extracted from the reviewed articles and are presented in the table below (Table 5).

Table 5. Factors influencing the increase in phytoremediation efficiency of plant species for benzene and toluene pollutants (Reference: Author)

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
1	Hedera helix	Benzene and Toluene	Injection stages + exposure time in the contaminated environment	With an increase in the number of injection stages and the exposure time in the contaminated environment, an enhancement in phytoremediation is observed due to the adaptability of the species.	[27]
2	Danae racemosa	Benzene and Toluene	Injection stages + exposure time in the contaminated environment		
3	Dracaena sanderiana	Benzene	Benzene-resistant microorganisms: <i>Staphylococcus</i> sp. B12	Enhancement of benzene phytoremediation capacity through IAA production and ACC deaminase activity, improving plant health by supporting photosynthetic activity and maintaining chlorophyll under high benzene concentrations.	[35]
4	Dracaena sanderiana	Benzene	Benzene-resistant microorganisms: <i>Epacian</i> a. B11	Decrease in benzene phytoremediation rate.	
5	Ardisia crenata	Toluene	Injection stages + exposure time in the contaminated environment	A 358% increase in phytoremediation rate over three injection stages and exposure to the contaminated environment, due to genetic changes in plants or alterations in the microorganisms present in the growth medium.	[29]

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
6	Begonia maculata	Toluene	Injection stages + exposure time in the contaminated environment	A 318% increase in phytoremediation rate over three injection stages and exposure to the contaminated environment, attributed to genetic changes in the plants or alterations in the microorganisms present in the growth medium.	[29]
7	Ardisia japonica	Toluene	Injection stages + exposure time in the contaminated environment	A 252% increase in phytoremediation rate over three injection stages and exposure to the contaminated environment, due to genetic changes in the plants or alterations in the microorganisms present in the growth medium.	
8	Pinus densiflora	Toluene	Injection stages	A 69.8% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
9	Ilex cornuta	Toluene	Injection stages	A 589.0% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
10	<i>Pelargonium graveolens</i>	Toluene	Injection stages	A 147.1% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
11	<i>Ardisia japonica</i>	Toluene	Injection stages	A 116.3% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
12	<i>Mentha x piperita</i>	Toluene	Injection stages	A 70.5% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]
13	<i>Mentha suaveolens</i>	Toluene	Injection stages	A 29.9% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
14	<i>Cepacian suaveolens</i>	Toluene	Injection stages	A 63.7% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
15	Rhododendron fauriei	Toluene	Injection stages	A 21.0% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
16	Eurya emarginata	Toluene	Injection stages	A 256.3% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
17	Ligustrum japonicum	Toluene	Injection stages	A 125.9% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]
18	Fittonia albivenis	Toluene	Injection stages	A 42.0% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
19	Cinnamomum camphora	Toluene	Injection stages	A 97.2% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
20	Aloysia triphylla	Toluene	Injection stages	phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
21	<u>Mentha x piperita f. citrata</u>	Toluene	Injection stages	A 119.3% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
22	Davallia mariesii	Toluene	Injection stages	A 111.6% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]
23	Farfugium japonicum	Toluene	Injection stages	A 66.6% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
24	Schefflera elegantissima	Toluene	Injection stages	A 101.1% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
25	<i>Ardisia crenata</i>	Toluene	Injection stages	A 202.7% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
26	<i>Rosmarinus officinalis</i>	Toluene	Injection stages	A 15.6% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
27	<i>Soleirolia soleirolii</i>	Toluene	Injection stages	A 40.2% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]
28	<i>Philodendron</i> spp.	Toluene	Injection stages	A 39.4% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
29	<i>Ardisia pusilla</i>	Toluene	Injection stages	A 113.5% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
30	Hedera helix	Toluene	Injection stages	An 8.9% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
31	Melissa officinalis	Toluene	Injection stages	A 16.4% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
32	Plectranthus tomentosus	Toluene	Injection stages	A 39.1% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]
33	Pittosporum tobira	Toluene	Injection stages	A 613.8% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	
34	Begonia maculate	Toluene	Injection stages	A 17.1% increase in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
35	Salviael egans	Toluene	Injection stages	An 8.1% decrease in phytoremediation due to gene expression in the plant and/or changes in certain soil microbes or in the population of toluene-metabolizing microorganisms.	[32]
36	Epipremnum aureum	Toluene	Presence of VOCs (xylene and benzene) / (xylene only)	The presence of xylene and benzene reduced the toluene removal rate by 58%, while the presence of xylene alone caused a 39% decrease in the toluene removal rate.	[31]
37	Dracaena fragrans	Toluene			
38	Vigna radiata	Toluene	Microgravity conditions	The toluene removal rates at 24, 72, and 120 hours under microgravity conditions were reported as 10.8%, 18.2%, and 25.8%, respectively, while under normal gravity conditions they were 7.9%, 13.3%, and 16.4%. This increase under microgravity was attributed to faster water uptake, increased leaf surface area, maintenance of hormone levels, and stomatal opening.	[33]
39	Zamioculcas zamiifolia	Benzene and Toluene	Molecular size	Smaller molecular size of gaseous pollutants leads to higher phytoremediation efficiency. Therefore, the phytoremediation rate of benzene is higher than that of toluene.	[38]

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
40	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	Leaf stomata	Increased stomatal aperture or density enhances gas uptake, leading to higher phytoremediation efficiency.	
41	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	Cuticular wax compounds on the leaf surface	An increase in the amount or effective compounds of cuticular wax on the leaf surface enhances pollutant absorption, thereby improving phytoremediation efficiency.	
42	BTEX-phytoremediating plants	Benzene, toluene,	Molecular size	Smaller molecular size of pollutants, such as benzene, increased phytoremediation efficiency.	
43	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	Plant Species	Plant species also play a role; those with larger leaf area, strong photosynthetic capacity, or high metabolic activity exhibit higher phytoremediation efficiency.	[40]
44	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	Plant tolerance to toxicity	Plant tolerance to BTEX toxicity helps maintain normal physiological functions and enhances uptake, whereas sensitivity leads to decreased phytoremediation efficiency.	
45	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	Growth conditions	Favorable growth conditions, such as adequate light and proper humidity, enhance photosynthesis and stomatal opening, thereby improving pollutant uptake.	

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
46	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	P450 enzyme and dioxygenase	The activity of P450 and dioxygenase enzymes accelerates the degradation of BTEX into harmless compounds, thereby enhancing phytoremediation efficiency.	[40]
47	BTEX-phytoremediating plants	Benzene, toluene, ethylbenzene, and xylene	Epiphytic bacteria	Epiphytic bacteria on the leaf surface assist in the degradation of organic compounds, and their presence increases removal efficiency.	
48	Yellow lupine	Toluene	Inoculation with engineered endophyte (<i>Burkholderia epacian</i> VM1468)	Increased toluene uptake, reduced release from leaves, and decreased root antioxidant enzyme activity resulting from reduced toxicity due to inoculation with an engineered endophyte led to an increased toluene phytoremediation rate.	[34]
49	Epipremnum aureum, Chlorophytum comosum,	Benzene	Plant transpiration rate	Plants with higher transpiration rates have greater ability to absorb benzene.	
50	Hedera helix, Echinopsis tubiflora	Benzene	Chlorophyll concentration	Plants with higher chlorophyll content exhibit more active photosynthesis, which contributes to greater benzene uptake.	[26]

Table 5. Continued

Row	Plant Species	Pollutant	Variable	Change in phytoremediation rate	Source
51	Epipremnum aureum, Chlorophytum comosum,	Benzene	Plant photosynthetic metabolism type (C3 vs. CAM)	CAM plants, such as Echinopsis tubiflora, can absorb benzene even in the dark.	[26]
52	Hedera helix, Echinopsis tubiflora	Benzene	Light conditions	In CAM plants, stomata remain open at night, allowing benzene uptake to continue, whereas in C3 plants, uptake decreases during nighttime	
53		Benzene	Initial benzene concentration in air	In Echinopsis tubiflora, high removal efficiency (50–80%) was maintained even at high concentrations	
54		Benzene	Leaf stomatal characteristic	This enables continuous pollutant absorption at night and increases overall phytoremediation efficiency.	

Overall, according to Table 4, by understanding the characteristics of plants that directly influence their phytoremediation performance (such as metabolism, transpiration, chlorophyll content, growth conditions, stomatal density, and wax layer), it is possible to introduce positive modifications to enhance their efficiency in removing airborne benzene and toluene pollutants.

Discussion

The results of this systematic review indicate that indoor and ornamental plants play a significant role in reducing airborne

benzene and toluene pollutants. Data analysis revealed that most studies have been conducted under single-pollutant conditions, focusing primarily on the ability of plants to remove either benzene or toluene individually, while research on simultaneous multi-pollutant phytoremediation remains limited. Nevertheless, certain species such as *Epipremnum aureum* and *Hedera helix* demonstrated considerable efficiency in removing both pollutants, suggesting their potential use in developing multi-pollutant phytoremediation systems.

In the case of benzene-remediating plants,

Epipremnum aureum (9 occurrences) and *Hedera helix* (8 occurrences) were identified as the most frequently reported species. This finding aligns with previous studies showing that *Epipremnum aureum* and *Hedera helix* possess extensive leaf surface areas and favorable physiological activities for the absorption and metabolism of benzene. Additionally, other species such as *Spathiphyllum* spp., *Chrysanthemum morifolium*, and *Gerbera jamesonii* also demonstrated notable performance, reflecting the wide phytoremediation potential across different plant families.

For toluene pollutants, the most frequently reported species included *Dracaena* spp., *Hedera helix*, *Sansevieria* spp., and *Mentha* spp. The phytoremediation rates of these plants indicated that certain *Mentha* and *Dracaena* species could increase toluene removal efficiency by several hundred percent. This enhancement is not only attributed to the plants' physiological characteristics but is also strongly influenced by environmental factors and microbial interactions-particularly in studies where the exposure duration and pollutant injection cycles were extended.

Analysis of plants capable of simultaneously remediating benzene and toluene revealed that *Dracaena deremensis* and *Hedera helix* were the most frequently cited species, both demonstrating remarkable efficiency in the concurrent removal of the two pollutants. This finding underscores the importance of selecting multi-pollutant species for the design of phytoremediation systems applicable to industrial and domestic environments. The extracted phytoremediation rates further showed that species such as *Dracaena sanderiana* and *Hedera helix*, through the synergistic action of pollutant-resistant microorganisms and elevated physiological activity, can achieve high removal efficiencies

in indoor-scale environments.

The factors influencing the enhancement of phytoremediation efficiency included pollutant injection stages, duration of plant exposure in the contaminated environment, interactions with microorganisms, and genetic or gene expression modifications in the plant. For instance, increasing the number of injection stages and extending exposure time significantly improved phytoremediation rates due to species adaptation and enhanced physiological activity. Moreover, the simultaneous presence of multiple VOCs (such as benzene and xylene) could exert a competitive effect, reducing toluene removal efficiency. This highlights the importance of carefully designing experimental environments and developing multi-pollutant phytoremediation systems for more realistic and effective applications.

Conclusion

This systematic review comprehensively evaluated the effectiveness of plants in the phytoremediation of benzene and toluene, highlighting their significant role in reducing airborne pollutants. The findings indicate that species such as *Epipremnum aureum* and *Hedera helix* exhibit the highest pollutant removal capacities under laboratory and controlled conditions. Pollutant absorption rates were found to be influenced by environmental factors, exposure duration, pollutant concentration, and interactions with microorganisms-emphasizing the importance of optimizing growth conditions and plant combinations. Furthermore, the simultaneous removal of multiple pollutants has been less explored, and long-term assessments of plant performance are needed to understand potential declines or adaptations over time. The review suggests that employing multi-

pollutant systems, selecting resilient species, and optimizing environmental parameters can substantially enhance phytoremediation efficiency. This study serves as a valuable guide for future research on multi-pollutant phytoremediation, field-scale validation, and environmental optimization, demonstrating the need for further development and refinement of plant-based strategies for effective indoor air pollution reduction.

Indoor plant species with broad leaf surfaces, climbing or resilient growth habits, and symbiotic interactions with pollutant-resistant microorganisms demonstrate higher efficiency in the phytoremediation of benzene and toluene. The phytoremediation rate is highly dependent on environmental and management conditions (including plant exposure time and pollutant injection stages) which should be considered in the design of intelligent phytoremediation systems.

Overall, the findings of this systematic review indicate that indoor and ornamental plants, beyond their aesthetic and psychological benefits, can serve as effective tools for mitigating airborne pollutants in both industrial and domestic environments.

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Competing interests

The authors declare no competing financial or non-financial interests related to this work.

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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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