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# Impact of Houseplants on Reducing Indoor Air Pollution

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## Abstract

Houseplants provide a natural and effective solution for improving indoor air quality and enhancing human health. They help purify the air by absorbing pollutants such as formaldehyde, benzene, and trichloroethylene, while increasing oxygen levels and humidity. The evapotranspiration process from plant leaves raises indoor humidity, which can alleviate respiratory issues, reduce skin dryness, and minimize static electricity. In addition, houseplants serve as natural filters, capturing airborne particles and volatile organic compounds (VOCs). Beyond their physical benefits, houseplants positively influence psychological well-being by reducing stress, improving mood, and boosting productivity. They create a calming, aesthetically pleasing environment that fosters a connection to nature. Effective houseplants for air purification include Aloe Vera, Sansevieria, Pothos, and Peace Lily, each with specific abilities to remove indoor pollutants. Overall, incorporating houseplants into indoor spaces provides a holistic approach to enhancing air quality, health, and well-being.

**Keywords:** Indoor Air Quality, Houseplants, Pollutant Removal, Psychological Benefits

## 1 Introduction

Houseplants are an effective and natural way to improve indoor air quality. These plants can absorb pollutants, increase oxygen levels, and raise humidity through different mechanisms. In addition to removing trichloroethylene, benzene, and formaldehyde, houseplants can help eliminate several other common indoor air pollutants Indoor air quality is vital for human health, especially in developed countries where people spend more than 90% of their time indoors (1). Studies show indoor air can be 2 to 50 times more polluted than outdoor air (2). Indoor pollutants typically come from building materials, human activities, and outdoor air entering the building (3). This problem has worsened in newer, energy-efficient buildings with lower ventilation rates. Common indoor pollutants include VOCs, particulate matter, ozone, radon, lead, and biological contaminants. Exposure to these pollutants can lead to short-term health issues like asthma and nausea, as well as long-term diseases, such as cancer, and various chronic conditions that affect the immune, neurological, reproductive, developmental, and respiratory systems (4). VOCs in indoor air are emitted from items like paints, varnishes, adhesives, furniture, clothing, solvents, construction materials, combustion appliances, and even potable water (5). VOCs harm indoor air quality (6). They are classified into four groups: aromatic hydrocarbons (e.g., benzene, toluene, ethylbenzene, xylene), aliphatic hydrocarbons (e.g., hexane, heptane, octane, decane), halogenated hydrocarbons (e.g., trichloroethylene, methylene chloride), and terpenes (e.g., alpha-pinene, d-limonene) (7). Due to their toxic effects, pollutants such as benzene, toluene, octane, trichloroethylene, and alpha-pinene are considered major indoor air pollutants (8).

Plants can remove VOCs from indoor air through processes like stomatal uptake, absorption, and adsorption on their surfaces (9). Some indoor plant species have been tested for their ability to remove benzene, with some able to eliminate 40 to 88 mg per cubic meter per day (10). These plants also reduce other VOCs like toluene, TCE, m-xylene, and hexane (9). The effectiveness of VOC removal varies greatly among plant species (Yoo et al., 2006) and depends on the molecular properties of each pollutant. Currently, only a few indoor plant species have been studied for their pollutant-removing abilities. Moreover, the range of pollutants tested remains limited. A more thorough study of different indoor plant species and their ability to purify a wider variety of pollutants would help improve our understanding of phytoremediation and its potential to enhance indoor air quality.

This paper provides a detailed analysis of the role of houseplants in improving indoor air quality by reducing pollution levels. It examines how plants absorb and break down harmful pollutants, such as VOCs and particulate matter, and their potential to reduce indoor air contaminants. The review also looks at recent studies on various plant species and their efficiency in

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absorbing specific toxins, highlighting which plants are most effective in different indoor settings. Additionally, the paper discusses the physiological processes in plants that contribute to pollutant removal, including stomatal uptake, adsorption on leaf surfaces, and microbial interactions in the soil.

## 2. Indoor Air Pollutants

Houseplants play a crucial role in improving indoor air quality by absorbing and removing various air pollutants through specialized structures in their leaves, stems, and roots. These plant structures help to capture, absorb, and break down harmful chemicals, such as VOCs, which are commonly found in indoor environments due to everyday activities and materials (11). The process occurs through a combination of physical absorption by the leaf surfaces, chemical breakdown in the roots, and uptake of pollutants through stomata. Some of the most important pollutants that plants can remove include formaldehyde, benzene, toluene, xylene, and ethylbenzene, among others. By utilizing their natural biological processes, houseplants not only reduce the concentration of these harmful substances but also contribute to healthier indoor spaces, offering a natural and cost-effective method for improving air quality in homes, offices, and other enclosed environments.

### *2.1 Formaldehyde*

Formaldehyde ($CH_2O$) is a colorless gas with a strong, sharp odor, used widely due to its unique properties (12). It acts as an adhesive in plywood, MDF, and particle board, and is commonly found in building materials, textiles, and household products that contribute to indoor air pollution. Additionally, it is used to make wrinkle-resistant fabrics for clothing, and in the chemical industry, formaldehyde is involved in producing resins, plastics, and polymers (13). It also functions as a disinfectant in labs and medical settings (14). Formaldehyde is present in household products like cleaners, paints, and cosmetics, including nail polish (15). Despite its utility, formaldehyde exposure has significant health risks. It can irritate the eyes, nose, and throat and cause respiratory issues at higher concentrations (16). Long-term exposure is linked to an increased risk of certain cancers, making it crucial to handle formaldehyde with care, especially in environments where it is frequently present. Sources of indoor formaldehyde are varied, making it a widespread air pollutant (17). Wood products, particularly furniture made from plywood and MDF, often contain urea-formaldehyde and phenol-formaldehyde resins (18). Other contributors include building materials like insulation, flooring, and wall coverings, which can release formaldehyde over time (19). Wrinkle-resistant clothing and certain cleaning products also emit this gas, as do cigarette smoke and indoor heaters or fireplaces (20). To reduce formaldehyde levels indoors, strategies include good ventilation, choosing low-formaldehyde materials, and introducing houseplants that can improve air quality naturally (21).

Formaldehyde concentrations indoors vary with the presence of emitting products and ventilation conditions (22). Indoor levels typically range from 0.1 to 0.5 ppm (100 to 500 $\mu g/m^3$), but in spaces with more formaldehyde-emitting products, such as certain furniture and flooring finishes, concentrations can be higher (23-25). These levels sometimes exceed 1 ppm (1,000 $\mu g/m^3$) soon after new installations (26, 27). OSHA sets the permissible exposure limit (PEL) for formaldehyde in workplaces at 0.75 ppm averaged over 8 hours and 2 ppm for short-term (15-minute) exposure (28). The ACGIH recommends a threshold of 0.3 ppm for 8-hour shifts, with a short-term limit of 1 ppm (29). For residential spaces, the EPA advises keeping formaldehyde below 0.1 ppm (100 $\mu g/m^3$) to minimize health risks, as higher levels can be particularly harmful for sensitive individuals (30).

Studies have shown that certain indoor plants significantly reduce formaldehyde levels in closed environments. For instance, research on Spider Plant (*Chlorophytum comosum*) indicates it can remove around 90% of airborne formaldehyde, making it a top choice for natural air purification (31). Similarly, Boston Fern (Nephrolepis *exaltata*) can reduce formaldehyde by about 60% under optimal conditions (32). The Peace Lily (*Spathiphyllum spp*.) can eliminate 60% to 70% of formaldehyde in well-ventilated areas, while the Areca Palm (*Dypsis lutescens*) reduces formaldehyde by 50% to 60% (9, 31, 33). The Rubber Plant (*Ficus elastica*), Dracaena species, and Snake Plant (*Sansevieria trifasciata*) also effectively absorb formaldehyde, although the Snake Plant is less effective, reducing levels by about 20% to 30% (9, 11). (34) examined ornamental plants and found that Ficus species achieved a 92.8% formaldehyde removal rate, with Hedera helix showing the lowest rate at 56.86%. This study also highlighted the role of stomatal density and conductance in formaldehyde removal, noting that thick cuticles and epidermis hinder this process. (35) demonstrated that inoculating plants with Ochrobactrum bacteria significantly increased formaldehyde removal, with treated Chlorophytum comosum removing 62.88% more formaldehyde at night than untreated plants. (36) reviewed plant-based formaldehyde remediation and emphasized the impact of plant physiology and environmental conditions, such as humidity, on removal efficiency, pointing out that real-world applications may differ from lab conditions. (37) explored plant metabolism and formaldehyde remediation, noting that rhizosphere activity, temperature, and humidity affect effectiveness, and stressed the importance of plant species in maintaining indoor air quality standards. (38) studied botanical biofilters, showing that low airflow (0.8 L/s) with formaldehyde concentrations of 0.3 $mg/m^3$ achieved a single-pass removal efficiency (SPRE) of 99.99%, though higher airflow rates reduced efficiency, indicating a need for improvement in real-world applications. (39) found that stems of *Epipremnum aureum* and Rohdea japonica removed formaldehyde effectively, with purification rates of 40.0% and 61.6%, respectively, and observed $CO_2$ increases correlating with formaldehyde decreases, indicating purification efficiency. Further research by (40) on *Chlorophytum comosum* showed recovery within 15 days after 7 days of formaldehyde exposure, although efficiency dropped by 35–50% with repeated fumigation, suggesting resilience but with limitations.

### *2.2. Benzene*

Benzene ($C_6H_6$) is a colorless and flammable compound with a sweet odor that is widely used in industry (41). It serves as a raw material for producing chemicals like styrene and toluene, essential in manufacturing plastics, synthetic fibers, cosmetics, paints, coatings, and pharmaceuticals (42). However, despite its industrial utility, benzene is harmful to human health. Classified as a carcinogen, prolonged exposure significantly increases the risk of leukemia, a type of blood cancer, and is linked to other health issues, including headaches, dizziness, and immune system weakening (43). Given these risks, it is crucial to manage benzene carefully in workplaces and industries to protect workers and surrounding communities. Regulatory agencies such as the OSHA have set permissible exposure limits for benzene in occupational settings, with OSHA's limit at 1 ppm, or about 3.2 mg/m³ averaged over an 8-hour workday (44). The ACGIH recommends a lower threshold of 0.5 ppm (45). Meanwhile, EPA suggests that residential indoor benzene levels be minimized as much as possible, ideally below 1 µg/m³ to protect sensitive populations (46-48).

Benzene is also a significant indoor air pollutant, with sources including vehicle exhaust, tobacco smoke, and household products such as cleaners and paints (49). Indoor concentrations vary widely depending on the presence of these benzene-containing products, indoor pollution sources, and ventilation levels, generally ranging from 0.1 to 10 µg/m³ (50). However, in homes with attached garages, industrial areas, or spaces with extensive tobacco use, benzene concentrations may reach several hundred micrograms per cubic meter (51). To address this indoor pollutant, recent research suggests that specific houseplants can help absorb benzene and improve indoor air quality. Plants remove pollutants through phytoremediation, a process where they absorb harmful substances through their leaves and roots, breaking down or storing these pollutants. In particular, plants can metabolize benzene through bioremediation, which involves enzymatic activity that converts benzene into less toxic compounds.

Research supports the effectiveness of various plants in absorbing benzene. For instance, (52) reviewed studies on indoor air phytoremediation, finding that *Chlorophytum comosum* (Spider Plant) demonstrated the broadest pollutant removal range, while *Epipremnum aureum* (Devil's Ivy) was especially effective for benzene removal. The review also highlighted that inoculating plants with *Bacillus cereus* increased their efficiency in pollutant absorption, suggesting that a combination of plant species might further enhance indoor air purification. Hu et al. (2023) conducted fumigation tests on *Tradescantia zebrina* and *Epipremnum aureum*, observing benzene removal rates that varied with plant transpiration levels, emphasizing the role of gas exchange in benzene uptake. Similarly, (53) studied the use of plants in a 74.7 m³ office space and found that 3 m² of greenery could reduce ventilation needs by up to 100% over seven hours, suggesting a potential reduction in ventilation costs for indoor environments with long-term plant use. Various plant species are particularly effective in absorbing benzene and other indoor pollutants. The Peace Lily (*Spathiphyllum spp.*) is known for its low-light suitability and ability to reduce pollutants while enhancing indoor aesthetics. The Spider Plant (*Chlorophytum comosum*), highlighted by (54), was effective in benzene removal even under microgravity, maintaining open stomata for gas exchange. This unique finding points to potential applications for plant-based air purification in space environments. The Bamboo Palm (*Chamaedorea seifrizii*) and the Rubber Plant (*Ficus elastica*) are other excellent choices for removing benzene and other pollutants, with the Bamboo Palm also adds beneficial humidity to indoor air, improving respiratory health. Additionally, *Dracaena* spp. and the Gerbera Daisy (*Gerbera jamesonii*) have proven effective at absorbing benzene, with the Gerbera Daisy adding vibrant color to indoor settings. Other benzene-absorbing plants include the Boston Fern (*Nephrolepis exaltata*), which also humidifies the air, the Areca Palm (*Dypsis lutescens*), and the Chinese Evergreen (*Aglaonema spp.*). The Devil's Ivy (*Epipremnum aureum*) is notable for its durability and ability to filter benzene in low-maintenance environments. (55) reviewed indoor phytoremediation techniques and noted that potted plants and green walls are cost-effective solutions for managing indoor air quality, especially for VOCs like benzene, highlighting how factors like light and temperature influence benzene removal efficiency. (56) compared benzene and formaldehyde removal by *Sansevieria trifasciata* to air purifiers. The study found that *Sansevieria* absorbed VOCs more effectively than purifiers. This result highlights plants' superior VOC removal potential over mechanical purifiers in indoor settings.

Other studies explore advanced techniques for enhancing benzene removal. For example, (57) experimented with titanium dioxide modified with copper oxide and graphene under LED lighting, achieving benzene degradation rates three times higher than standard titanium dioxide, indicating that innovative materials combined with plants could improve indoor air safety. (58) developed a predictive model for VOC removal using *Zamioculcas zamiifolia*, demonstrating that adequate leaf area could reduce pollutants like ethylbenzene and styrene by 0.23–4.14%, depending on ventilation, providing a basis for estimating plant coverage needed for indoor air improvements. The predictive model developed by (58) to estimate the VOC removal efficiency of *Zamioculcas zamiifolia* takes into account several key environmental factors. These factors include the plant's leaf area, which directly affects the plant's capacity to absorb VOCs, the ventilation rate of the indoor space, which influences the concentration of pollutants, and the plant's efficiency in absorbing specific VOCs. The model is designed to quantify how these factors interact and predict the plant's ability to reduce VOC concentrations such as ethylbenzene and styrene. The core equation for VOC removal is expressed as $R=(A{\cdot}E{\cdot}C)/(V+A)$, where $R$ represents the removal rate of VOCs (in %), $A$ is the leaf area of the plant ($m^2$), $E$ is the plant's absorption efficiency (in %), $C$ is the concentration of VOCs (in ppm or µg/m³), and $V$ is the ventilation rate (in m³/s or air changes per hour). This equation integrates these variables to estimate the VOC removal efficiency, showing that an increase in leaf area and plant efficiency enhances removal, while ventilation moderates this effect. The model offers a basis for estimating how much plant coverage is needed to improve indoor air quality effectively, depending on the specific conditions of the environment (58).

In an investigation of VOC interactions, (59) found that benzene presence decreased toluene removal by 50% in *Epipremnum aureum* and *Dracaena fragrans*, highlighting the complex nature of phytoremediation when multiple pollutants are present. (60) explored benzene removal by *Tradescantia zebrina* and *Epipremnum aureum* through fumigation tests. In air with benzene concentrations of 432.25–1314.75 $mg{\cdot}m^{-3}$, removal rates for *T. zebrina* ranged from 23.05 ± 3.07 to 57.42 ± 8.28 $mg{\cdot}kg^{-1}{\cdot}h^{-1}$ FW, and for *E. aureum* from 18.82 ± 3.73 to 101.58 ± 21.20 $mg{\cdot}kg^{-1}{\cdot}h^{-1}$ FW. Removal was linked to plant transpiration, highlighting its role in gas exchange for benzene uptake (60).

While valuable in industry, benzene poses significant health risks, especially as an indoor pollutant. Research indicates that certain houseplants, through phytoremediation and bioremediation processes, can effectively reduce indoor benzene levels, making them a promising, natural solution to improving air quality. By incorporating these plants into our homes and workspaces, we can enhance air quality, promote health, and reduce dependence on mechanical ventilation systems while creating a greener, more pleasant environment.

### *2.3 Trichloroethylene*

Trichloroethylene (TCE) is an industrial chemical with many applications in various sectors. It is commonly found in some household cleaners, paints, lacquers, and chemical solvents (61). Additionally, TCE can be present in cigarette smoke and may come from older equipment or industrial machinery (62). In older homes, residual trichloroethylene can gradually enter the indoor air due to outdated materials and chemicals. The typical concentration of TCE in indoor environments usually ranges from 0.1 to 10 µg/m³ of air (46). In some cases, particularly in areas where TCE-containing products are used or stored, concentrations can be significantly higher, sometimes reaching levels of 100 µg/m³ or more (63, 64). Certain industrial or commercial settings, such as dry cleaning facilities or factories that use TCE in manufacturing processes, may also present much higher indoor concentrations. The EPA and other health organizations classify TCE as a potential human carcinogen, underscoring the importance of reducing its levels in indoor air (65). Maintaining good ventilation and utilizing air-purifying strategies, such as incorporating certain houseplants, can help minimize exposure to TCE.

The maximum allowable level of exposure to TCE can vary based on guidelines set by different health and environmental agencies. According to the EPA, the recommended limits for TCE exposure in residential indoor air are generally around 2 to 10 µg/m³, although the agency does not establish a specific "safe" level (66). OSHA has set a permissible exposure limit for TCE in occupational settings at 100 parts per million (ppm), which is equivalent to approximately 540 milligrams per cubic meter (mg/m³) for an 8-hour workday (67). The ACGIH recommends a threshold limit value of 25 ppm for TCE in a workplace setting (67). Plants filter pollutants through bioremediation, a process in which they absorb air through their leaves, and filter out toxins. They take in TCE and carbon dioxide through tiny openings called stomata, and then specialized enzymes in the plant convert TCE into less harmful substances or store it in the plant tissue. This makes certain houseplants effective in combating indoor air pollution.

Recent studies highlight specific plants that efficiently remove TCE. For instance, certain plants significantly lower TCE levels indoors. The Peace Lily (*Spathiphyllum spp.*) can reduce TCE concentration by up to 60% in controlled environments and grows well in low light. The Spider Plant (*Chlorophytum comosum*) is effective too, with studies showing it can lower TCE by over 80% within 2-3 days in a closed setting. The Bamboo Palm (*Chamaedorea seifrizii*) has also demonstrated a 45% TCE reduction within 24 hours, while varieties of Dracaena (*Dracaena spp.*) can decrease TCE by 70% over several days. Other effective TCE-absorbing plants include the Rubber Plant (*Ficus elastica*), which reduces TCE by about 50%, the Boston Fern (*Nephrolepis exaltata*) with a reduction of around 35%, and the Areca Palm (*Dypsis lutescens*), which decreases TCE by approximately 30% in indoor spaces. The adaptable Chinese Evergreen (*Aglaonema spp.*) has also shown a 40% TCE removal rate. Adding these plants to indoor spaces can improve air quality and help reduce harmful TCE levels. Proper ventilation and choosing products with fewer chemical solvents are essential steps, but houseplants offer a natural solution for air purification. Several studies also focus on the factors affecting TCE levels in indoor environments and plant effectiveness. (68) found that TCE emissions from furniture can significantly raise indoor TCE levels, especially when vapor intrusion systems are ineffective, as observed in a condominium study. (69) investigated TCE uptake and transport in plants like wheat, corn, and tomatoes, finding wheat absorbed TCE most efficiently, with 2.39 ± 0.42 µg per gram of biomass after 24 hours of exposure. This study highlighted that the presence of other pollutants can reduce TCE uptake. Plasma-catalysis for TCE decomposition has also been researched. (70) demonstrated that plasma combined with catalytic reactions effectively breaks down TCE, overcoming the limitations of non-thermal plasma. Technologies like dielectric barrier discharge and corona discharge show promise for reducing TCE in indoor spaces. (7) tested 28 ornamental plants for VOC removal, finding high TCE removal rates in species like *Hemigraphis alternata*, *Hedera helix*, and *Hoya carnosa*, with removal rates up to 44.04 $mg \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$. (71) found *Chlorophytum comosum* notably efficient in removing TCE, while *Kalanchoe blossfeldiana* was more effective for benzene. This suggests that combining plant species could improve indoor air quality.

Innovative air purification methods are also being explored. (72) created a biofilter system with moss, hydroponic plants, and a scrubber for the removal of TCE, toluene, and formaldehyde. This biofilter reduced TCE by 10% and toluene by 50%, though TCE accumulated in the aquatic system, showing slower breakdown than other VOCs. (51) examined TCE uptake in edible plants like spinach, carrots, and tomatoes. Spinach accumulated the most TCE, reaching levels of 580 ppb, and TCE transformed within the plant tissue, suggesting that it could be stored safely without high toxicity.

### *2.4 Xylene*

Xylene is a common indoor air pollutant found in many household products, such as paints, varnishes, and solvents (73). It can harm human health, causing symptoms like headaches, dizziness, and respiratory issues (74). The concentration of xylene in indoor environments varies widely, depending on factors like the presence of xylene-emitting products and ventilation quality. Generally, xylene levels in homes range from 0.1 to 10 µg/m³ of air (75). However, in spaces where xylene-containing products are heavily used or stored—such as garages, workshops, or recently painted rooms—concentrations can exceed 100 µg/m³. The maximum allowable level of xylene exposure varies according to health and safety guidelines. The OSHA has set a permissible exposure limit of 100 ppm for workplace environments, equal to approximately 435 mg/m³ for an 8-hour workday (75, 76). Similarly, the American Conference of Governmental and Industrial Hygienists (ACGIH) recommends a threshold limit value (TLV) of 100 ppm for xylene, which is generally considered safe for most workers during an 8-hour shift. For residential indoor air quality, the Environmental Protection Agency (EPA) does not set a specific maximum safe level for xylene but recommends minimizing exposure to volatile organic compounds (VOCs) overall to maintain healthy indoor air. Ideally, typical indoor xylene levels should stay below 10 µg/m³ to reduce health risks. It is important to note that prolonged exposure to high levels of xylene can lead to health problems. Maintaining good ventilation and using air-purifying plants can help mitigate xylene exposure. Many regulatory agencies advise minimizing xylene levels indoors to keep air quality safe for occupants.

Recent studies show that certain houseplants can effectively reduce xylene levels in indoor air, providing a natural method of air purification. These plants absorb xylene through their leaves and roots, helping to improve indoor air quality. Several studies highlight the ability of specific plants to remove xylene from indoor environments. For example, recent scientific research has shown that the Spider Plant (Chlorophytum comosum) has an exceptional ability to reduce xylene levels indoors. In controlled studies, the Spider Plant was able to lower xylene concentrations by up to 85% within a few days in closed environments, making it one of the most effective plants for air purification. This high efficiency is due to both the plant's biological mechanisms and its adaptability to various indoor conditions, including low light and variable humidity.

The Spider Plant absorbs xylene through its stomata, tiny openings on the leaf surface that regulate the intake of gases during the plant's natural breathing process. As xylene molecules come into contact with the plant, they enter through the stomata and diffuse into the mesophyll tissue, where further processing occurs. Xylene's lipophilic nature allows it to easily penetrate cell membranes, moving through the plant's cellular structure. Once inside, xylene is metabolized through a series of enzymatic reactions aimed at neutralizing harmful substances. Studies show that xylene breakdown in the Spider Plant occurs in two phases. In the first phase, oxidation, enzymes such as cytochrome P450 modify xylene by adding oxygen atoms, converting it into intermediate products like methylbenzyl alcohol or tolualdehyde. In the second phase, conjugation, these intermediate products combine with sugars or organic acids to form harmless, water-soluble compounds. The plant then either stores these in its vacuoles or further processes them into carbon dioxide and water for cellular respiration. Additionally, the Spider Plant's roots contribute to air purification. Research suggests that the roots release breakdown byproducts into the surrounding soil, where soil microorganisms further degrade them. This interaction with soil microbes completes the detoxification process. The combined actions of the Spider Plant's metabolic pathways and the microbial activity in the soil make it highly effective in removing xylene and other VOCs from the air. Due to its ease of care and adaptability, the Spider Plant is an ideal choice for home and office environments. It thrives in various light conditions, making it both practical and effective for improving indoor air quality.

Another effective plant for removing xylene is the Peace Lily (Spathiphyllum spp.). Research indicates that this plant can reduce xylene concentrations by about 60% within 24 hours. The Peace Lily filters indoor air pollutants through a process called phytoremediation, where pollutants are taken up and transformed into harmless compounds within the plant tissues. In addition to its air-purifying properties, the Peace Lily's flowers add beauty to indoor spaces.

The Bamboo Palm (Chamaedorea seifrizii) is also notable for its air-purifying abilities. Studies have shown that it can reduce xylene levels by approximately 50% within 48 hours. This plant thrives in low-light indoor environments, adding a tropical aesthetic while effectively removing pollutants. The Bamboo Palm absorbs xylene through its leaves and roots, processing it through metabolic pathways to detoxify the air.

The Areca Palm (Dypsis lutescens) is another plant with good xylene removal capabilities. In one study, it was shown to reduce xylene levels by about 40% within a few days. The Areca Palm works similarly to other plants by absorbing pollutants and breaking them down into less toxic forms. Additionally, the plant's high transpiration rate increases humidity, which can further contribute to its air-purifying qualities. When the Areca Palm absorbs xylene from the air, the pollutant undergoes several stages: uptake, transport, and metabolism. Xylene molecules enter the plant through stomata, then move deeper into the mesophyll tissue in the leaves. Due to its lipophilic nature, xylene crosses cell membranes and reaches various parts of the plant, including the stem and roots. Once inside, xylene is metabolized by enzymes like cytochrome P450, which convert it into less harmful compounds. These products then go through a process called conjugation, resulting in water-soluble compounds that the plant can safely store or release. The Areca Palm may also release some breakdown products through its roots, where soil microbes help degrade any remaining pollutants. This symbiotic relationship with soil microbes enhances the plant's ability to purify the air.

Lastly, the Rubber Plant (Ficus elastica) has shown the ability to reduce xylene concentrations by about 30% in enclosed spaces. This plant is relatively easy to maintain and can adapt to various light conditions. The Rubber Plant absorbs xylene and other VOCs through its broad leaves, utilizing metabolic processes to cleanse the air. Although the exact mechanisms are not fully understood, some scientists suggest that plants like the Rubber Plant may temporarily store xylene before breaking it down. However, more research is needed to understand the complete metabolic pathway of xylene in such plants. Nonetheless, the Rubber Plant is still valuable for improving indoor air quality, particularly when used alongside other air-purifying plants.

(52) reviewed the use of plants for indoor air phytoremediation, showing that Chlorophytum comosum has a broad range of pollutant removal abilities, while Epipremnum aureum is effective at xylene removal. Inoculating plants with Bacillus cereus was found to improve pollutant removal, suggesting that combining different plant species could enhance xylene removal efficiency. (58) developed a model to predict VOC removal, focusing on Zamioculcas zamiifolia. This model demonstrated that plant leaf area and plant choice impact xylene removal, supporting customized phytoremediation designs. (59, 77) explored VOC interactions, finding that adding xylene reduced toluene removal by 39%, indicating that VOC interactions affect overall removal. (8) assessed mixed plant communities, finding that root zone bacteria like Microbacterium and Rhodococcus contributed to xylene breakdown. (78) tested green wall systems, showing high xylene removal efficiency with microbial support. (79) demonstrated xylene reduction using Sansevieria trifasciata, achieving a 72% reduction in plant-filled rooms. (80) found Bougainvillea buttiana achieved a 53.1% xylene removal rate with support from leaf microbes like Pseudomonas aeruginosa. Other studies, including work by (81) and (82), further support the effectiveness of biofilters, green walls, and optimized root zones for enhanced VOC phytoremediation.

### *2.5 Toluene*

Using houseplants to clean indoor air has gained attention in recent decades. A common indoor pollutant is toluene, a VOC found in many household products like paint, glue, and cleaning agents (5). Toluene can cause various health issues, including headaches, dizziness, and respiratory problems (83). Studies have shown that certain houseplants can absorb and help reduce toluene levels in indoor air, making them a valuable addition to homes and office spaces.

Several studies indicate that specific plants are particularly effective at removing toluene. For instance, the *Spatiphyllum* (peace lily) is often highlighted for its air-purifying qualities (55). Research demonstrates that this plant can significantly lower toluene concentrations in controlled environments. Another effective plant is the *Chlorophytum comosum* (spider plant). Studies show that it can thrive in low light and still purify air (84). Both of these plants are easy to care for, making them suitable for various indoor settings. Various factors affect how well these plants can remove toluene. The amount of light, temperature, and humidity in a room can all influence a plant's effectiveness. For example, plants generally perform better in bright, indirect sunlight. Certain studies suggest that more leaves on a plant can lead to better absorption rates of toluene and other VOCs. The surface area of the leaves is critical since more area means more space for absorption.

In terms of data, some articles provide specific measurements of toluene concentration before and after the placement of plants in a room. For example, one study might report an initial toluene level of 200 µg/m³, which could drop to 40 µg/m³ after a week with a peace lily present. These figures underscore the potential for household plants to create healthier indoor air. In (85), researchers tested twelve plant species for their ability to absorb toluene and ethylbenzene from the air. The study highlighted *Sansevieria trifasciata*, commonly known as snake plant, as particularly effective in removing toluene, while *Chlorophytum comosum*, or spider plant, excelled in ethylbenzene removal. Interestingly, the plants' absorption of these pollutants was not directly tied to stomatal density, suggesting that the wax layer on the leaves plays a significant role. Specifically, the wax in *Sansevieria trifasciata* species was rich in hexadecanoic acid, which may help in binding and absorbing these pollutants. (85) also studied how plants tolerate exposure to VOCs by measuring chlorophyll fluorescence. They found that some plant species were able to withstand pollution without harming their photosynthesis.

This data points to the potential of specific ornamental plants for improving indoor air quality in environments with low levels of VOCs (85). A method was proposed by (86) to enhance pollutant removal in *Myrtus communis*, or common myrtle, by incorporating titanium dioxide ($TiO_2$) into the growth media. The $TiO_2$-infused plants showed an increased capacity for breaking down a variety of pollutants, including toluene, formaldehyde, and benzene, when exposed in a controlled environment. This approach combines phytoremediation with photocatalysis, as $TiO_2$ enhances the degradation of VOCs under light exposure. Although this vombined method is not specific to home use, this method could be adapted for spaces that require both ornamental value and air-purifying functionality (86). (87) takes a different approach by focusing on toluene absorption via aqueous solutions with surfactants rather than plants. This study examined how adding surfactants like sodium dodecyl benzene sulfonate (SDBS) and sodium chloride to Tween-20 solution can improve toluene absorption. Although it is not directly related to ornamental plants, it offers insights into the chemical interactions that facilitate pollutant absorption. By understanding how surfactants capture VOCs in water-based systems, researchers may further explore how plant-based systems or soil moisture can similarly capture airborne pollutants. This study noted that adding specific chemicals to the solution enhanced toluene removal, reaching up to 77% efficiency with a ternary solution (87). It is also essential to recognize limitations. While plants can help reduce VOCs, they are not a complete solution for air quality issues. High levels of toluene from persistent sources still require ventilation or air purification technology for full remediation. Moreover, variations in plant growth and health could impact their efficiency over time. Research indicates that engaging with plants has additional health benefits. They can improve mood, reduce stress, and enhance overall well-being. Incorporating plants like the peace lily or spider plant into homes or workplaces can serve as both a functional and aesthetic improvement.

***2.6 Ammonia***

Ammonia ($NH_3$) is a colorless gas with a pungent odor, commonly found in indoor environments due to its widespread use in agriculture, cleaning products, and household items (88). It is primarily released from fertilizers, animal waste, cleaning agents, and even certain foods (89). In industrial and agricultural settings, ammonia is used to make fertilizers, which are often stored or transported, leading to its release into the air. It can also be present in household products such as cleaning agents, detergents, and air fresheners, contributing to indoor air pollution (90). Additionally, ammonia is emitted by cigarette smoke and human activity, such as cooking and exhalation (91). Despite its widespread presence, ammonia exposure can have harmful effects on human health, particularly at elevated concentrations. Short-term exposure can irritate the eyes, nose, and throat, while long-term exposure may lead to respiratory issues such as asthma and chronic bronchitis (92). High concentrations of ammonia in indoor air have been linked to reduced lung function and increased risk of chronic respiratory diseases (93). Sources of indoor ammonia are diverse, with pet waste, household cleaning products, and gas stoves being notable contributors (94).

To mitigate ammonia levels in indoor environments, strategies such as increasing ventilation, using ammonia-free cleaning agents, and employing air purifiers are recommended (95). Plant-based approaches have also been studied for their potential to reduce ammonia concentrations indoors. Some studies have shown that certain houseplants can absorb ammonia, improving indoor air quality. For instance, the Spider Plant (Chlorophytum comosum) has demonstrated some ability to remove ammonia, along with formaldehyde and other volatile organic compounds (96). Similarly, the Peace Lily (Spathiphyllum spp.) is noted for its ability to purify ammonia, along with other pollutants. Studies have shown that the Rubber Plant (Ficus elastica), Aloe Vera (Aloe barbadensis), and Bamboo Palm (Chamaedorea seifrizii) are effective in reducing ammonia levels in closed environments under controlled conditions (97). Furthermore, various factors influence the effectiveness of plants in ammonia removal, including light, humidity, and temperature (98). 86 plant species was screened by (99) to evaluate their ability to remove ammonia from indoor air in concentration of 7.0 mg/m³. Some plants such as *Nephrolepis exaltata* 'Bostonniensis' and *Plectranthus oertendahlii* showed significant potential for ammonia removal (99).

Plants with higher stomatal density and efficient rhizosphere activity can enhance ammonia absorption rates. In lab conditions, some plants have been shown to remove up to 70% of ammonia in controlled environments. However, real-world effectiveness may vary, and it is often necessary to combine plant-based solutions with other methods, such as ventilation, for optimal indoor air quality management. In summary, ammonia is a common indoor air pollutant with potential health risks, and efforts to reduce its concentration through proper ventilation, careful selection of household products, and natural purification methods like houseplants can significantly improve air quality in indoor spaces.

### *2.7 Carbon Monoxide*

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas that poses severe health risks due to its insidious nature (100). As it cannot be detected without specialized equipment, it remains one of the most dangerous indoor air pollutants. CO is primarily produced by the incomplete combustion of carbon-based fuels such as natural gas, oil, wood, and coal (101). Common indoor sources include stoves, fireplaces, water heaters, and automobiles left idling in attached garages. Additionally, CO can emanate from tobacco smoke, industrial emissions, and malfunctioning or poorly ventilated heating systems. Inadequate ventilation allows CO to accumulate, reaching dangerous concentrations that threaten human health. When inhaled, CO binds irreversibly to hemoglobin in red blood cells, forming carboxyhemoglobin (102). This reduces the blood's capacity to transport oxygen to vital organs and tissues. Prolonged exposure to even low levels of CO can lead to symptoms such as headaches, dizziness, nausea, fatigue, and confusion (103). Severe exposure, particularly in enclosed spaces, can result in unconsciousness, permanent neurological damage, or death. Vulnerable populations, including children, the elderly, and individuals with pre-existing heart or respiratory conditions, are particularly susceptible to the adverse effects of CO exposure. Chronic exposure to low levels can exacerbate existing health conditions, leading to long-term cardiovascular and respiratory complications.

The concentration of CO indoors depends on various factors, including the number and type of combustion sources, ventilation quality, and the building's design and materials. Generally, indoor CO concentrations range between 1 to 10 parts per million (ppm) under normal conditions (104-106). However, levels can spike dramatically in poorly ventilated areas such as basements or garages, especially when combustion appliances or engines are continuously used. Regulatory authorities have established exposure limits to mitigate health risks. For instance, the OSHA prescribes a permissible exposure limit (PEL) of 50 ppm over an 8-hour workday (107). The EPA recommends maintaining indoor CO levels below 9 ppm to safeguard health, particularly for sensitive populations (105). Any concentration above these thresholds is considered hazardous and requires immediate remediation.

Traditional methods for controlling CO levels include ensuring proper ventilation, regular maintenance of combustion appliances, and installing CO detectors. While these strategies are effective, they do not directly reduce CO concentrations. As a result, researchers have explored innovative approaches, including the use of houseplants for natural air purification. Although plants do not utilize CO in photosynthesis, they can absorb and process the gas through other mechanisms. CO enters the plant through stomata, which are microscopic pores on the surface of leaves and stems (108). Once inside, CO can be stored in the plant's tissues or metabolized into less harmful compounds. Specialized enzymes, such as carbon monoxide dehydrogenase, facilitate the breakdown of CO into organic molecules, which are then incorporated into plant tissues (109). Healthy roots and high stomatal conductance enhance this process, as do certain soil microorganisms that degrade CO into inert compounds. The interaction between plants and beneficial soil bacteria in the root zone significantly increases CO removal efficiency (110).

Research has identified specific plant species with exceptional abilities to reduce indoor CO levels. The Spider Plant (*Chlorophytum comosum*) is particularly effective, capable of absorbing CO and other volatile organic compounds even in low-light conditions (111). Peace Lilies (*Spathiphyllum spp.*) are also well-suited for indoor environments, thanks to their large leaf surface area, high transpiration rates, and ability to absorb pollutants such as CO, formaldehyde, and benzene (112). Similarly, the Areca Palm (*Dypsis lutescens*) efficiently removes CO from indoor air through its broad fronds, which facilitate gas exchange (113). Aloe Vera (*Aloe barbadensis*) and Bamboo Palm (*Chamaedorea seifrizii*) are also noteworthy, especially in environments with high light and humidity. Integrating these plants into indoor spaces not only enhances air quality but also offers aesthetic and psychological benefits (114).

Environmental factors such as humidity, light, and temperature significantly influence the effectiveness of plant-based CO mitigation. Plants with higher stomatal density and larger leaf surfaces are generally more efficient at absorbing gases, as they provide a greater area for gas exchange (115). Root health is equally critical, as it supports the transport and processing of absorbed CO (116). Inoculating plants with beneficial soil bacteria, such as *Pseudomonas* species, has been shown to enhance their ability to metabolize CO (117). These bacteria break down CO in the root zone, further increasing the overall purification efficiency of the plant system (118).

The potential of plants to mitigate CO levels has been extensively studied. (115) were among the first to quantify CO absorption in plants, identifying species-specific differences in uptake rates. Recent advancements have built on this foundation, incorporating plants into dynamic air purification systems. (113) developed the Dynamic Botanical Air Purifier (DBAP), which combines plants, activated carbon, and blue light to enhance pollutant absorption. Their system achieved a 40% reduction in CO levels, with additional improvements through active filtration. (119) highlighted the benefits of orthogonal lighting strategies, demonstrating how tailored light environments can optimize plant growth and pollutant uptake. (114) used wavelet analysis to monitor CO pollution trends, providing valuable insights for deploying plant-based systems in high-risk areas.

On a larger scale, (117) modeled the impact of urban vegetation on CO levels in Makassar, Indonesia. Their simulation predicted an 8.93% reduction in annual CO emissions through strategic planting of trees and shrubs, emphasizing the importance of vegetation density and diversity. (118) and (120) explored CO's role as a signaling molecule in plants, revealing its importance in stress response and growth regulation. These findings suggest that manipulating CO signaling pathways could further enhance plant resilience and pollutant processing capabilities. Complementary approaches integrate biological and mechanical systems to maximize air purification. (121) described a hybrid system combining activated carbon with plants for efficient filtration in industrial settings. While these advancements are promising, (122) underscored the need for systemic policies and incentives to encourage the adoption of CO reduction technologies in both residential and occupational environments.

Plants offer a sustainable, cost-effective, and aesthetically pleasing solution for reducing indoor CO levels. Their ability to absorb and process CO, coupled with the support of soil microorganisms and innovative hybrid systems, makes them an attractive option for improving indoor air quality. Future research should focus on optimizing plant selection, refining hybrid technologies, and expanding their application to diverse environments. By integrating plants into air quality management strategies, we can create healthier indoor spaces and mitigate the health risks associated with CO exposure.

### *2.8 Microbial germs removal*

Certain plants, in addition to their ability to absorb chemical pollutants, also contribute to indoor environmental health by reducing microbial contamination. While VOCs like toluene present significant health risks, biological pollutants such as bacteria also impact indoor air quality and can lead to respiratory and other health issues (123). One notable bacterium, *Pseudomonas aeruginosa*, commonly thrives in damp indoor spaces such as bathrooms, kitchens, and poorly ventilated areas (124). This bacterium is known for its resistance to many antibiotics and can cause serious infections, especially in individuals with weakened immune systems (125). Its presence indoors, therefore, can be a hidden but significant health hazard.

Plants like the Boston fern (*Nephrolepis exaltata*) have been studied for their antibacterial properties, which may help mitigate bacterial pollution, including that from *Pseudomonas aeruginosa* (10). While plants are primarily known for their capacity to absorb VOCs and purify air, certain species produce bioactive compounds in their leaves and roots that can act as natural antibacterial agents. These bioactive compounds are part of the plants' defense systems, protecting them against soil and air-borne pathogens, and in some cases, they can benefit surrounding indoor environments by reducing bacterial loads (10). The Boston fern, in particular, is rich in compounds that may exhibit inhibitory effects against certain bacteria. These properties could reduce bacterial levels in indoor air and surfaces around the plant, creating a healthier environment.

The exact mechanisms by which plants like the Boston fern inhibit bacterial growth are complex and likely involve several biochemical processes. Studies suggest that certain plants release VOCs of their own—distinct from harmful VOCs like toluene—that have antimicrobial properties. In the Boston fern, these plant-derived VOCs and other secondary metabolites may interfere with bacterial cell walls, disrupt bacterial growth, or inhibit replication (126). The antimicrobial action could also stem from root exudates, substances secreted by plant roots into the surrounding soil, which can alter the microbial community (127). In hydroponic or damp environments, these exudates might influence bacterial populations, potentially suppressing harmful species like *Pseudomonas aeruginosa* while promoting beneficial microorganisms (10).

The combined effect of these antibacterial and air-purifying properties points to a significant potential for certain plants in holistic indoor air purification systems. While plants like Sansevieria and Chlorophytum excel at removing chemical pollutants such as toluene (85), species like the Boston fern offer an additional layer of protection by helping control microbial contaminants (10). Integrating a variety of plant species that address both chemical and biological pollutants could optimize indoor air quality and health benefits. For environments particularly prone to dampness and bacterial growth, such as bathrooms or poorly ventilated spaces, combining traditional air-cleaning plants with those known for antibacterial properties could create a balanced approach to maintaining indoor hygiene.

This multi-functional approach to plant-based air purification not only offers a natural and sustainable solution but also underscores the potential of plants as low-maintenance biofilters capable of tackling a range of indoor contaminants. These findings suggest that plant choice should be tailored to the specific needs of each indoor environment, considering both the types of chemical pollutants and the risk of microbial contamination.

## 3 Oxygen Production

Houseplants improve indoor air quality primarily by absorbing carbon dioxide and releasing oxygen through photosynthesis. During this process, plants take in carbon dioxide ($CO_2$) through tiny pores on their leaves, called stomata, and absorb sunlight using chlorophyll, the green pigment in their cells. In the presence of water, which plants draw up through their roots, the energy from sunlight enables plants to convert $CO_2$ and water into glucose and oxygen. Oxygen is then released into the air, while the glucose is used as energy for the plant's growth and maintenance. This natural oxygen production helps create a healthier, more comfortable environment for occupants by boosting indoor oxygen levels.

Higher oxygen indoors has various positive effects on human health. Enhanced brain function is one benefit, as the brain requires a significant amount of oxygen to operate efficiently. With increased oxygen, people may experience better concentration, improved memory, and reduced mental fatigue, leading to heightened focus and alertness throughout the day. Increased oxygen levels also boost physical energy and reduce fatigue. Sufficient oxygen allows body cells to perform metabolic processes more efficiently, resulting in greater energy levels for daily activities. Another benefit is improved sleep quality, as breathing oxygen-rich air promotes better rest by aiding the body's repair processes during sleep. Individuals may experience relief from sleep problems like insomnia, and waking up feeling refreshed and more energetic.

Higher oxygen levels can also help reduce stress and anxiety, creating a sense of calm. The central nervous system functions optimally with adequate oxygen, leading to a positive impact on mood and mental well-being. Additionally, an oxygen-rich environment strengthens the immune system, allowing immune cells to combat infections more effectively, which means greater resilience against illnesses. Both lung and heart function improve with more available oxygen, enhancing respiratory capacity and cardiac efficiency. This boost supports the overall health of the circulatory and respiratory systems, contributing to better physical well-being. To maintain high oxygen levels indoors, there are a few effective methods. Specific houseplants, such as Aloe Vera, Snake Plant, Pothos, and Ficus Benjamina, naturally increase oxygen production and create a more soothing, pleasant atmosphere. Proper ventilation, such as opening windows to allow fresh air exchange, also raises oxygen levels by bringing in outdoor air and removing carbon dioxide. Alternatively, oxygen generators or air purifiers with oxygen-boosting capabilities can further improve indoor air quality for an overall healthier environment.

## 4 Increasing Air Humidity

Houseplants can increase indoor air humidity through a natural process known as transpiration, where moisture is released from the plants' leaves into the surrounding environment. This added humidity can benefit indoor air quality and support health, particularly during colder seasons when indoor air tends to become dry. By increasing moisture levels, houseplants can help reduce dryness in the respiratory tract, which often leads to discomforts like sore throats and coughing. The added humidity can also be advantageous for skin, helping to retain moisture and prevent issues like dryness and cracking. Another benefit of increased indoor humidity from houseplants is the reduction of static electricity, which is common in dry environments. Reduced static electricity can make interactions with clothing and objects more comfortable and can also enhance sleep quality by reducing potential irritants in the air. However, increasing indoor humidity with houseplants also has potential drawbacks. Excessive humidity can create conditions favorable for mold and mildew growth, which may lead to respiratory issues and trigger allergies in sensitive individuals. High humidity can also cause damage to indoor materials like walls, floors, and wooden furniture, which may begin to rot or deform over time. Additionally, an increase in moisture may attract pests, adding another layer of concern.

The care and maintenance required for houseplants present another challenge. Regular watering, pruning, and other upkeep can be time-consuming and costly, which may not be feasible for all individuals. To gain the benefits of increased humidity from houseplants while minimizing the potential downsides, it is important to monitor and control indoor humidity levels. Using humidity meters can help maintain an optimal balance, ensuring that the humidity level remains within a healthy range. Overall, while houseplants can be an effective way to improve indoor humidity, careful management is essential to prevent problems associated with excessive moisture.

## 5 Particle Capture

The leaves of houseplants can act as natural filters, capturing airborne particles. This natural ability of plants is particularly useful in indoor environments where air pollution may be an issue. Airborne particles can include dust, smoke, chemicals, and other pollutants that can degrade air quality and lead to respiratory and allergy problems. Houseplants with large leaves and broad surfaces can effectively capture these particles. As air passes through the leaves of the plants, airborne particles adhere to the leaf surfaces, thus removing them from the surrounding air. This process helps reduce air pollution levels and provides cleaner and healthier air. In addition to capturing airborne particles, some houseplants can also absorb and break down VOCs. These compounds are typically released from household chemicals like paints, cleaning agents, and building materials, and can lead to various health issues. Plants such as Ficus, Sansevieria, and Aloe Vera can be effective in absorbing and breaking down these compounds. Using houseplants as natural air filters can improve indoor air quality and reduce the risks associated with air pollution. This method not only helps clean the air but also adds beauty and freshness to the indoor environment, providing a better atmosphere for residents. Therefore, incorporating houseplants into interior decor can be a simple and effective way to enhance indoor air quality and increase the health and comfort of individuals.

## 6 Psychological and Physiological Effects

Houseplants not only help improve indoor air quality but can also have positive effects on individuals' psychological and physiological health. By evaporating water through their leaves and capturing airborne particles and pollutants, houseplants clean and humidify indoor air. Beyond these benefits, houseplants can also enhance individuals' mental and physical well-being. Studies have shown that having plants in work and home environments can reduce stress. When people are in an environment with plants, their blood pressure and heart rate decrease, and they experience a greater sense of calm. These positive effects on mental health include improved mood and reduced anxiety. Plants create a natural and serene space, which can provide individuals with a better sense of well-being and help alleviate daily stress and tension. In addition to reducing stress, the presence of plants can also enhance focus and productivity. Work environments with plants are generally more attractive and pleasant, which can boost employee motivation and concentration. Plants create a lively and dynamic atmosphere, making the workspace more enjoyable and potentially increasing individuals' efficiency and productivity. Another benefit of having houseplants is the improved connection to nature. In today's world, where many people spend most of their time indoors, having plants in the home or workplace can enhance the feeling of connection to nature. This sense of connection can have positive effects on mood and mental health, providing greater feelings of relaxation and satisfaction. Overall, having houseplants in indoor spaces can improve air quality, reduce stress, increase focus and productivity, and create a sense of calm and connection to nature. These benefits can positively impact physical and mental health, making living and working environments more pleasant and healthier.

## 7 Effective Houseplants

Table 1 provides an overview of the efficiency of various houseplants in removing specific indoor air pollutants, including benzene, toluene, TCE, xylene, and α-pinene. Among the plants, Peace Lily (Spathiphyllum wallisii) and Pothos (Epipremnum aureum) demonstrate high removal efficiencies across most pollutants, making them particularly effective for improving indoor air quality. Similarly, Spider Plant (Chlorophytum comosum) and English Ivy (Hedera helix) also perform well, especially in benzene, toluene, and xylene removal. In contrast, some plants, such as the Guzmania bromeliad and Cast Iron Plant (Aspidistra elatior), show minimal pollutant removal efficiency. Overall, the findings suggest that while certain plants are highly effective air purifiers, others may have limited impact, emphasizing the need for selective choices based on specific air quality goals.

## 8 Conclusion

In conclusion, houseplants offer a multifaceted approach to improving indoor air quality and enhancing overall health and well-being. Their ability to absorb harmful pollutants, such as carbon monoxide, volatile organic compounds, and particulate matter, while simultaneously producing oxygen and increasing humidity, underscores their value as natural air purifiers. Furthermore, specific plant species have shown promise in mitigating microbial contamination, providing both chemical and biological purification. Beyond their environmental benefits, houseplants contribute to psychological and physiological health by reducing stress, enhancing productivity, and fostering a sense of connection to nature. Integrating houseplants into indoor spaces presents a sustainable, cost-effective, and aesthetically pleasing solution for creating healthier and more comfortable environments. Future research and advancements in hybrid systems combining plants with innovative technologies could further optimize their efficacy and broaden their applicability across diverse settings.

Table 1: Effectiveness of Various Indoor Plants in Removing Common Air Pollutants: Comparison of Species by Family, Leaf Area, and Efficiency in Absorbing Benzene, Toluene, TCE, Xylene, and α-Pinene

| Family | Latin Name | Common Name | Benzene Removal Efficiency | Toluene Removal Efficiency | TCE Removal Efficiency | Xylene Removal Efficiency | α-Pinene Removal Efficiency | Citations |
|---|---|---|---|---|---|---|---|---|
| Euphorbiaceae | *Codiaeum variegatum* (L.) Blume | Croton | Moderate | Low | Low | Low | Low | (52) |
| Araceae | *Chlorophytum comosum* (Thunb.) Jacq. | Spider plant | High | High | Moderate | High | Low | (52) |
| Acanthaceae | *Fittonia argyroneura* Coem. | Silver-net leaf | Moderate | Low | Low | Low | Low | (79) |
| Bromeliaceae | *Guzmania sp.* | Guzmania bromeliad | Low | Low | Low | Low | Low | (79) |
| Araceae | *Spathiphyllum wallisii* Regel | Peace lily | High | High | High | High | Moderate | (128) |
| Araceae | *Anthurium andraeanum* Linden | Flamingo flower | Moderate | Moderate | Low | Low | Low | (129) |
| Asclepiadaceae | *Hoya carnosa* (L.f.) 'Variegata' | Variegated wax plant | Moderate | Low | Low | Moderate | Low | (79) |
| Araliaceae | *Schefflera elegantissima* Lowry & Frodin | False aralia | Moderate | Moderate | Low | Low | Low | (128) |
| Palmaceae | *Howea belmoreana* Becc. | Sentry palm | Low | Low | Low | Low | Low | (129) |
| Araliaceae | *Schefflera arboricola* Merr. 'Variegata' | Variegated schefflera | Moderate | Low | Low | Moderate | Low | (79) |
| Araceae | *Epipremnum aureum* | Pothos | High | High | High | High | Moderate | (52) |
| Araceae | *Philodendron scandens* ssp. oxycardium | Heart leaf philodendron | High | Moderate | Moderate | Moderate | Moderate | (128) |

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## Ethical issue

Authors are aware of, and comply with, best practice in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language.

## Competing interests

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

## Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses and manuscript writing.

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