Beyond Aesthetics: Harnessing Indoor Plants to Combat Sick Building Syndrome and Indoor Air Pollution

Shubham

Department of Civil Engineering, National Institute of Technology Kurukshetra, Kurukshetra, India.

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Abstract

Indoor air pollution, characterised by elevated levels of volatile organic compounds (VOCs), particulate matter (PM), and inorganic gases, poses a serious threat to the well-being of individuals, contributing to sick building syndrome (SBS) and reduced cognitive function. This review paper explores the efficacy of indoor plants as a sustainable solution for improving indoor air quality (IAQ) through phytoremediation. The paper synthesises research demonstrating that plants, along with their root-zone microorganisms, act as a dynamic bio-filters, actively absorbing, degrading, and removing a wide spectrum of indoor air pollutants. The review also highlights the multi-faceted benefits of indoor plants, including their role in regulating humidity, reducing airborne microbes, enhancing psychological well-being, and enhancing cognitive performance of the individual in indoor spaces. Further, they can also be integrated with bio-systems and can act as enhanced bio-filters for indoor air pollution. While challenges and future research directions are acknowledged, the study concludes that integrating plants into indoor spaces offers a cost-effective, sustainable, and holistic strategy for creating healthier and more productive indoor environments.

Keywords: *Indoor air pollution; plants; phytoremediation; indoor air quality (IAQ); sick building syndrome (SBS); bio-filters*

INTRODUCTION

According to Wolverton *et al.* (1989), buildings are being designed to maximise energy efficiency and one of the major design considerations for this includes reduced fresh air exchange. Workers began to experience various health issues, such as itchy eyes, skin rashes, drowsiness, etc. It was found that the airtight sealing of buildings significantly contributed to workers' health issues, which are known to emit or "off-gas" various organic compounds linked to numerous health complaints. Building materials themselves off-gas a lot of various organic compounds. Humans themselves can contribute to indoor air pollution, especially in closed, poorly ventilated spaces. All of these factors collectively contribute to a phenomenon called "sick building syndrome" or SBS (Deswal, 2024). According to the World Health Organisation (WHO) estimate, about 30 percent of all or remodelled buildings have varying degrees of indoor air pollution (Wolverton *et al.*, 1989). Indoor air pollution has emerged as a major public health concern, with concentrations of pollutants often found to be 5-10 times higher than outdoor air levels (Li *et al.*, 2024). Rapid urbanisation and increased time spent indoors, over 80% of daily time for most people, necessitate solutions for maintaining healthy indoor air quality. Volatile organic compounds (VOCs), particulate matter (PM), carbon dioxide (CO_2), and microbial pathogens contribute to Sick Building Syndrome (SBS), respiratory disorders, and other health problems.

One of the cost-effective and effective solutions for this is the use of plants to curtail indoor air pollution (IAP) and enhance indoor air quality (IAQ). Research studies have shown that the installation of indoor plants significantly improves staff wellbeing, resulting in a reduction of sick leave by more than 60% (Fjeld, 2002; Berg, 2002). Yoneyama *et al.* (2002) examined the absorption and metabolism of NO_2 and NH_3 in 220 plant species, which included both sun-loving and shade-loving plants; the latter can be used indoors. In a study conducted in the United Kingdom on homes with flueless gas appliances, Coward *et al.* (1996) found that houses with six or more potted-plants experienced reductions of more than one-third in NO_2 levels. Lee and Sim (1999) conducted a study on Korean species and found that indoor plants can absorb and metabolise SO_2. In the USA, Lohr and Pearson-Mims (1996) demonstrated that indoor plants significantly reduce dust (particulate matter) levels. A study by Costa and James (1999) revealed that potted-plants also help in reducing indoor noise levels. The pioneering screening studies on indoor-air VOC removal by Wolverton *et al.* (1989) reported reductions in VOC levels across more than 50 plant species. Wolverton suggested that both plants and microorganisms in the potting-mix could play a role in this process. This project study also explored the potential use of plants in improving indoor air quality (IAQ), a concept known as phytoremediation, along with its advantages, challenges and possible future scope.

This review study aims to synthesise existing research on the mechanisms of phytoremediation, evaluate the efficacy of indoor plants in mitigating various air pollutants, and discuss their holistic benefits and future application potential in built (indoor) environments. The review in this study commences from the study of Wolverton *et al.* (1989) carried out for the National Aeronautics and Space Administration's (NASA's) space project, and thereafter till date.

FUNDAMENTAL MECHANISMS OF PHYTOREMEDIATION

Basic Plant Physiology: Photosynthesis, Respiration, and Stomatal Uptake

At the most fundamental level, plants purify air through their inherent physiological processes of photosynthesis and respiration. During photosynthesis, plants absorb carbon dioxide (CO_2) from the atmosphere and release oxygen (O_2) as a byproduct. Conversely, during respiration, they absorb oxygen and release carbon dioxide. These vital gas exchanges occur primarily through tiny pores on their leaves called stomata, which are considered the main apparatus for both absorption and filtration mechanisms (El-Tanbouly *et al.*, 2021). The efficiency of CO_2 absorption and O_2 release is influenced by factors such as the quantity of natural or artificial light available and the size of the plant's leaves. Beyond these basic respiratory functions, plants also actively absorb various airborne pollutants through their stomata, a process known as stomatal uptake (plant-gas extraction). Additionally, lenticels, small pores on the branches and stems, can also facilitate the absorption of chemical pollutants. The fundamental gas exchange processes, photosynthesis and respiration, are intrinsically linked to the plants' capacity for pollutant removal. The same pathways that enable plants to perform essential gas exchange are utilised for the uptake of various airborne contaminants. This means that any factor optimising photosynthesis, such as providing adequate light and maintaining healthy leaves, will directly enhance the plant's ability to absorb pollutants. Consequently, plant vitality and proper care become integral to maximising their air purification efficiency.

The Pivotal Role of the Root-Soil Microcosm: Microbial Degradation and Symbiotic Relationships

While plant foliage plays a role in air purification, research consistently highlights the pivotal contribution of the root-soil microcosm. Phytoremediation, the process of using plants to reduce pollutants, involves both the leaf and root parts. However, the root-soil zone has been identified as the most effective area for removing volatile organic chemicals (Wolverton *et al.*, 1989). A critical discovery, made by retired NASA scientist Bill Wolverton, revealed that increasing air circulation to a plant's roots significantly enhances its ability to filter air. This observation underscored the importance of the rhizosphere - the area of soil directly influenced by root secretions and associated microorganisms. Rhizosphere biodegradation, carried out by these microorganisms, is a key mechanism in pollutant removal (Selvan *et al.*, 2023). Laboratory studies have unequivocally confirmed that soil microorganisms are the primary agents of VOC removal, actively breaking down soil organic matter (Tarran *et al.*, 2007). The plant's role in this symbiotic relationship is to nourish its species-specific root-zone microbial communities, creating a self-regulating biofilter and phytoremediation unit for indoor air (Tarran *et al.*, 2007). This was a groundbreaking finding, demonstrating for the first time the removal of gaseous-phase VOCs by in situ soil microorganisms (Tarran *et al.*, 2007). The understanding that the root-soil microcosm, rather than solely the plant foliage, serves as the primary engine for pollutant degradation, particularly for volatile organic compounds, fundamentally transforms the perception of "plant air purification." This means that the term "plant" in this context refers to a complex, biologically active system, emphasising the vital importance of healthy soil and root aeration. Therefore, strategies aimed at enhancing air purification should focus on optimising the root environment, including the selection of appropriate potting media and ensuring adequate aeration. Furthermore, the microbial communities within the soil exhibit a remarkable capacity for adaptation. Studies indicate that when plants and their potting soil are continuously exposed to toxic chemicals like benzene, their capacity to clean the air improves over time (Wolverton *et al.*, 1989). This phenomenon is attributed to the genetic adaptation of microorganisms, which allows them to increasingly utilise these toxic chemicals as a food source (Wolverton *et al.*, 1989). Common soil microorganisms, such *as Alcaligenes, Bacillus*, *Flavobacterium*, and *Pseudomonas*, are known to biodegrade toxic chemicals when activated by plant root growth (Wolverton *et al.*, 1989). This dynamic training effect means that, unlike mechanical filters that typically degrade in performance over time, plant-based biofilters can potentially become more robust and efficient. This suggests a paradigm shift from maintenance-heavy mechanical systems to self-optimising biological ones for long-term indoor air quality management. Researchers have also indicated that as the concentration of pollutants increases, the entire phytoremediation system adapts itself to counter the increased concentration (Li *et al.*, 2024).

Diverse Phytoremediation Pathways: Adsorption, Accumulation, Transformation, and Evapotranspiration

The utility of indoor plants in air purification stems from a diverse array of phytoremediation pathways, indicating a sophisticated, multi-faceted biological system rather than a single purification method. Pollutants can be absorbed, distributed, and/or transported by ornamental plants through various mechanisms. These include rhizosphere biodegradation by microorganisms, phytoextraction (plant-liquid extraction), stomatal uptake (plant-gas extraction), phytodegradation (via enzymatic catalysis inside plant tissues), and phytovolatilization (where pollutants are taken up from the soil and directly evaporated from leaves or indirectly through plant transpiration) (Selvan *et al.*, 2023). The overall process involves the adsorption, accumulation, decomposition, and transformation of air pollutants by plants to effectively achieve purification (Li *et al.*, 2024). Plants actively neutralise toxic pollutants into less harmful, non-toxic substances through redox processes (degradation), or they may accumulate and store these substances within their organs (Li *et al.*, 2024). The plant cuticle, the waxy outer layer of leaves, also serves as a channel for lipophilic contaminants, such as aromatic hydrocarbons (Selvan *et al.*, 2023). Once inside the leaf, xenobiotics (foreign chemical substances) can undergo various processes, including excretion, conjugation, compartmentalisation, or reduction to simple cell metabolites, all designed to protect the organism from contaminant toxicity (Selvan *et al.*, 2023). Beyond direct pollutant removal, plant evapotranspiration plays a crucial role in improving indoor environmental conditions (Selvan *et al.*, 2023). This process lowers the ambient temperature and controls relative humidity, which in turn reduces airborne pollution by promoting evaporation and transpiration (Selvan *et al.*, 2023). Plants can help maintain optimal relative humidity levels, which is important for overall air quality and occupant comfort (Selvan *et al.*, 2023). The diverse array of phytoremediation pathways - including absorption, degradation, accumulation, and volatilisation - demonstrates a sophisticated, multi-faceted biological system at work. This inherent complexity suggests a robust and adaptable capacity to address various pollutant types, making phytoremediation a highly versatile and resilient strategy for environmental engineering, capable of handling a broad spectrum of contaminants through multiple biochemical pathways (El-Tanbouly *et al.*, 2021).

KEY POLLUTANTS MITIGATED BY INDOOR PLANTS

Indoor plants have demonstrated a significant capacity to mitigate a wide range of airborne pollutants, encompassing volatile organic compounds, inorganic gases, particulate matter, and even biological contaminants.

Volatile Organic Compounds (VOCs)

Volatile Organic Compounds (VOCs) represent a large group of airborne molecules originating from numerous common substances such as paints, stains, varnishes, solvents, pesticides, adhesives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, dry-cleaned clothing, building materials, and furniture (Selvan *et al.*, 2023). Exposure to VOCs can cause irritation to the eyes, nose, and throat, nausea, loss of coordination, and headaches, with some organics being carcinogenic or harmful to the liver, kidneys, and central nervous system (Selvan *et al.*, 2023). Formaldehyde, a colourless gas with a sharp and bitter odour, is one of the most common VOCs. It is found in various building materials like plywood, particleboard, and glues, and its secondary production can occur in the air from the oxidation of other VOCs (Selvan *et al.*, 2023). Formaldehyde has been classified as a group 1 carcinogen (Selvan *et al.*, 2023). High concentrations can lead to severe health issues, including nausea, vomiting, coughing, chest tightness, asthma, pneumonia, pulmonary oedema, and even mortality. Benzene, a significant VOC, is not only highly carcinogenic and teratogenic, but it is also persistent and resistant to degradation, posing a serious threat to human health and well-being (Li *et al.*, 2024). Potted plants have been shown to reliably reduce total VOC (TVOC) loads by 75%, bringing concentrations below 100 ppb (Tarran *et al.*, 2007). The NASA Clean Air Study by Wolverton *et al.* (1989) notably demonstrated that some plants could eliminate up to 87% of VOCs from the atmosphere in a single day. This quantitative evidence of a significant reduction in key indoor pollutants underscores the substantial environmental engineering impact of plant-based solutions, elevating them from a purely aesthetic role to a functional one.

Biological Contaminants: Airborne Microbes

Indoor plants also play a role in mitigating biological contaminants. Research has indicated that indoor houseplants can reduce airborne microbes by up to 50% compared to indoor spaces lacking plants. This suggests that volatile substances released by houseplants may contribute to controlling airborne microbe populations. More recent studies have provided evidence that plants can significantly decrease air microbiomes, fostering a healthier environment and reducing the risk of exposure to airborne diseases. Furthermore, a significant proposed role for indoor plants lies in mitigating viral transmission, such as that of SARS-CoV-2, particularly through the regulation of indoor humidity. Indoor relative humidity (RH) is a crucial factor influencing the viability and transmission of viruses. Recommended indoor humidity levels for human comfort typically range between 30% and 60%, with 40-60% specifically shown to prevent viral transmission. Studies have demonstrated that influenza virus transmission decreases at these humidity levels, as the virus becomes deactivated. The stability of viruses like SARS-CoV-2 has also been shown to decrease in high humidity conditions, likely by affecting the virus's lipid envelope. As plants can modulate indoor humidity to levels above 30%, their presence can help maintain intermediate humidity levels, which subsequently lowers the viability of SARS-CoV-2 in air particles and reduces its transmission rate. This positions indoor plants as a novel and highly relevant application in public health, suggesting a potential for them to serve as a passive, low-cost intervention in infectious disease control within confined spaces, complementing other mitigation measures. Beyond humidity regulation, plants release small quantities of secondary metabolites, such as polyphenols and alkaloids, into the air. These compounds, known as 'allelochemicals', have been reported to have antimicrobial activities and can interact with airborne microbes near the plant. While direct experimental evidence specifically linking plants to reduced viral transmission is still emerging, their established ability to reduce airborne microbes and regulate humidity suggests a promising avenue for further investigation in this area. (El-Tanbouly *et al.*, 2021).

Particulate Matter (PM)

Plants possess the capability to physically trap and filter particulate matter from the air (Kumari and Deswal, 2017), contributing to cleaner indoor environments.

Dust/Particulates: Indoor plants have been shown to significantly reduce general dust levels, acting as natural collectors of airborne particles (Tarran *et al.*, 2007).

PM 2.5 and PM 10: Specific studies highlight the effectiveness of Golden Pothos, which can lower concentrations of PM 2.5 by 75.2% and PM 10 by 71.9%, alongside an overall reduction of 85% in total suspended particles (Selvan *et al.*, 2023).

Beyond larger particles, plants are also capable of reducing ultrafine particles (El-Tanbouly *et al.*, 2021). Unlike gaseous pollutants that are absorbed, particulate matter primarily settles on the surface of leaves through either wet or dry deposition (Selvan *et al.*, 2023).

PLANTS AND THEIR POTENTIAL TO REMOVE SPECIFIC POLLUTANTS

Certain categories of plants have been reported to remove certain types of pollutants. Table 1, adopted from Soni and Gawri (2024), lists various plants and the potential pollutants they could remove, while Table 2 lists the percentage of CO_2 and formaldehyde that certain plants are capable of removing.

FACTORS INFLUENCING PLANT'S POLLUTANT REMOVAL EFFICACY

Beyond the inherent capabilities of specific plant species, several environmental and physiological factors significantly influence their air purification efficacy:

- Pollutant Concentration (Li *et al.*, 2024): The effectiveness of plants in pollutant removal is directly correlated with the concentration of the contaminant. Studies on benzene purification show that while the

Table 1: Indoor plant effective in removal of air pollutants (*Source: Soni and Gawri, 2024*).

Indoor Plant			Effective in the Removal of Air Pollutants										
			VOCs							GHGs			
Common Name(s)	Botanical Name	Family	Formaldehyde	Benzene	Xylene	Toluene	Styrene	Trichloro-ethylene	Ammonia	Carbon monoxide	Carbon dioxide	CFCs	Methane
Peace Lily, White Sails	*Spathiphyllum wallisii*	*Araceae*	√	√	√								
Money Plant, Devil's Ivy	*Epipremnumaureum*		√	√	√	√		√					
Arrowhead	*Syngonium podophyllum*		√	√	√	√							
Elephant's Ear	*Colocasia esculenta*		√	√		√	√	√	√	√			
Chinese Evergreen, Silver Evergreen, Painted Drop-Tongue	*Aglaonema commutatum*		√	√									
Dumb cane	*DieffenbachiaCamille*		√		√								
King of hearts, Homalomena	*Adelonemawallisii*										√		
English ivy	*Hedera helix*	*Araliaceae*	√	√				√					
Ground Rattan, Bamboo Palm, Lady Palm, Miniature Fan Palm	*Rhapis 97xcels*	*Arecaceae*	√		√				√				
Golden cane palm, Areca palm, yellow palm, Butterfly palm	*Dypsis lutescens*		√		√	√							
Ground Rattan, Bamboo Palm, Lady Palm, Fern Rhapis	*Rhapis excelsa*		√		√				√		√		
Airplane/ Ribbon plant, Spider Ivy	*Chlorophytum comosum*	*Asparagaceae*	√		√	√				√			
Dragon plant, Madagascar dragon	*Dracaena marginata*		√	√									
Corn plant	*Dracaena fragrans*		√	√				√					
Mother-in-law's Tongue, Snake Plant, Spear Plant	*Dracaena trifasciata*		√	√	√	√		√					
Mahogany	*Swietenia mahagoni*	*Meliaceae*								√		√	√
Indian Rubber Tree	*Ficus elastica*	*Moraceae*	√	√						√	√		
Bodhi / Sacred Fig / Pipul Tree	*Ficus religiosa*	*Moraceae*								√			
Moon orchid, moth orchid, or mariposa orchid	*Phalaenopsis amabilis*	*Orchidaceae*	√	√				√					

Table 2: Effectivity of indoor plants in eliminating formaldehyde (HCOH) and CO_2.

Plant's Name	CO_2	CHOH	Reference
Areca Palm	88.5 %	88.16 %	Bhargava *et al.*, 2020; Hashim *et al.*, 2019
Peace Lily	83.8 %	-	Hormann *et al.*, 2017
Dumb Cane	90.2 %	81-96 %	Sarker *et al.*, 2022
Aloe Vera	78 %	90-95 %	Sarker *et al.*, 2022
English Ivy	26.7 %	100 %	Hashim *et al.*, 2019; Liu *et al.*, 2007
Bird Nest Fern	60 %	95 %	Su and Lin., 2015
Snake Plant	81 %	99.75 %	Sarker *et al.*, 2022; Ullah *et al.*, 2021
Golden Pothos	93.76 %	81-96 %	Tan *et al.* 2022; Aydogan *et al.*, 2011

overall purification rate of plants tends to decrease with increasing benzene concentration, the total purification amount per unit leaf area actually increases. This suggests that plants absorb more of the pollutant when exposed to higher levels, even if their percentage removal efficiency drops. This also implies a saturation point and critical tolerance levels for plants, beyond which their capacity may be overwhelmed.

- Leaf Characteristics (Li *et al.*, 2024): The morphological and physiological characteristics of plant leaves play a crucial role in their absorption capacity. Differences in leaf texture, total leaf area, stomatal density, and the arrangement of mesophyll cells can all influence purification efficiency. Furthermore, the composition and content of keratin and waxes on the leaf epidermis are more strongly related to pollutant absorption than stomatal density or cuticle thickness. Succulent and leathery-leaved plants, often rich in keratin and waxes (e.g. palmitic acid), frequently exhibit stronger purification capabilities.
- Air Circulation (Wolverton *et al.*, 1989): As highlighted by NASA research, increasing air circulation to a plant's roots significantly enhances its air filtering capabilities. This emphasises the importance of proper ventilation around the root-soil zone to maximise microbial activity and pollutant degradation.
- Light Levels (Selvan *et al.* 2023): The quantity of natural or artificial light directly affects a plant's photosynthetic rate, which in turn influences its CO_2 absorption and O_2 release. Higher light levels can generally improve CO_2 absorption and potentially enhance the removal of other gaseous pollutants by increasing overall metabolic activity.
- Plant Size and Biomass (Li *et al.*, 2024): The overall size and biomass of a plant, particularly its leaf area, are directly related to its purification capacity. Larger plants with more leaf surface area generally have a greater potential for pollutant uptake.
- Humidity (El-Tanbouly *et al.*, 2021): Plants contribute to maintaining optimal indoor relative humidity (RH) levels, ideally between 40-60%, which is crucial for human comfort and has been shown to reduce the viability and transmission of airborne viruses.
- Microbial Activity in the Soil (Tarran *et al.*, 2007; Wolverton *et al.*, 1989): The symbiotic relationship between plant roots and soil microorganisms is paramount. These microorganisms are the primary agents for degrading many pollutants, and their activity can be enhanced or "induced" by continuous exposure to contaminants.
- Potting Medium (Tarran *et al.*, 2007): The composition and water-holding matrix of the potting mix are important for the optimal functioning of the soil microorganisms involved in VOC removal.

ADVANCED APPLICATIONS AND FUTURE SCOPE

The utility of indoor plants in air purification extends beyond their standalone capabilities, offering promising avenues for advanced applications and future research.

Combining Plants with Engineered Systems: Biofilters and Living Walls

Phytoremediation is recognised as a highly effective method for eradicating indoor air pollution, not only through potted plants but also via more integrated solutions such as green roofs, living walls, and bio coverings (Selvan *et al.*, 2023). These "green systems" have demonstrated positive effects on improving overall interior comfort (Selvan *et al.*, 2023). The integration of living plant systems, such as living walls and botanical biofilters, with conventional engineering solutions represents a synergistic approach that maximises efficiency. For instance, NASA designed an innovative air filter system that combines plants with an activated carbon filter and a fan. This system is specifically engineered to remove high concentrations of pollutants, including cigarette smoke and organic solvents. The fan rapidly moves large volumes of polluted air through the activated carbon filter, which adsorbs the contaminants (Wolverton *et al.*, 1989). Crucially, the plant roots and their associated microorganisms then utilise these adsorbed pollutants as a food source, effectively bio-regenerating the carbon filter (Wolverton *et al.*, 1989). This concept of bio-regenerating activated carbon filters using biological components is a significant innovation. It not only extends the lifespan of filtration media but also reduces waste and operational costs, aligning with principles of the circular economy and long-term environmental sustainability. Furthermore, analysis of the exhaust air from these biofilter systems has confirmed the absence of pathogenic microorganisms, ensuring their safety for indoor environments (Wolverton *et al.*, 1989). This hybrid model leverages the strengths of both biological and mechanical systems, offering a more comprehensive and sustainable solution for complex indoor air quality challenges.

Holistic Health Benefits Beyond Air Purification

The benefits of integrating indoor plants into living and working spaces extend far beyond their capacity for air purification, establishing a compelling multi-dimensional value proposition. Plants play a fundamental role in human well-being, directly providing oxygen and food, and their extracts are widely used in the pharmaceutical industry for disease prevention and treatment (El-Tanbouly *et al.*, 2021). Indirectly, by purifying the air, they enhance the overall environment, contributing to healthier living conditions (El-Tanbouly *et al.*, 2021). Indoor plants have been shown to enhance thermal comfort, creating more pleasant indoor climates (Selvan *et al.*, 2023). They can also function as passive acoustic insulation, helping to lower noise levels in indoor environments (Tarran *et al.* 2007; Selvan *et al.*, 2023). Beyond these physical comforts, their presence significantly impacts psychological well-being. Working in biophilic environments and interacting with plants has been linked to increased productivity and mental happiness (Selvan *et al.*, 2023). Plants provide a positive physiological effect and enhance the visual and psychological atmosphere, fostering a sense of serenity and connectedness to nature (Selvan *et al.*, 2023). Studies have demonstrated tangible cognitive and emotional benefits: indoor plants like rubber trees, English ivy, and spider plants have been shown to increase student performance in classrooms (El-Tanbouly *et al.*, 2021). The presence of both scented and unscented plants, such as lavender, poinsettia, alocasia rhizome, and apple geranium, has been found to enhance human comfort (El-Tanbouly *et al.*, 2021). Furthermore, plant photosynthesis contributes to improved air quality by producing negative air ions. Some plants even offer traditional home remedies for common ailments like cold and flu symptoms (El-Tanbouly *et al.*, 2021). These diverse benefits, ranging from thermal and acoustic comfort to psychological well-being and potential direct health remedies, position plants not merely as air purifiers but as integral components of a holistic approach to creating healthier, more productive, and more pleasant indoor environments.

Challenges and Future Research Directions

Despite the known benefits of indoor plants for air purification, challenges remain in fully understanding their potential, particularly regarding their role in reducing viral transmission, such as for SARS-CoV-2. While it's established that plants can reduce airborne bacteria and fungi, direct evidence on their impact on virus survival is lacking. This gap presents an opportunity for rigorous research to explore the broader health benefits of indoor plants, especially in pathogen control.

Current studies often face limitations due to experimental site choices, setup complexities, and high costs, leading to inconsistent results. Future research should focus on developing standardised protocols for controlled experiments, potentially using AI to monitor key factors. Key research questions include:

- The minimum amount of potted plants needed for effective VOC removal in different indoor environments.
- Factors influencing CO2 reduction by plants, such as light conditions and species differences.
- The roles of plants versus potting-mix microorganisms in removing pollutants like carbon monoxide.

Addressing these challenges will clarify the utility of indoor plants, promoting their integration into healthier indoor environments.

CONCLUSIONS

Indoor air pollution presents a profound and widespread challenge to global health, significantly affecting human well-being and productivity due to extended indoor exposure. Modern building designs, prioritising energy efficiency through airtight construction, inadvertently worsen this issue by trapping a complex mixture of chemical (VOCs, inorganic gases, particulate matter) and biological contaminants. Indoor plants, utilising the natural process of phytoremediation, provide a highly effective, sustainable, and cost-efficient solution to this problem. Their benefits are multifaceted:

- Pollutant Removal: Plants actively absorb and break down a broad range of chemical pollutants, including carcinogenic VOCs such as formaldehyde and benzene, as well as inorganic gases like CO2, CO, NO2, and SO2. They also effectively reduce particulate matter through deposition and absorption.
- Biological Control: Plants help decrease airborne microbes, and their ability to regulate indoor humidity levels (maintaining optimal levels between 40-60%) offers significant potential for reducing viral transmission, including SARS-CoV-2.
- Holistic Benefits: Beyond air purification, indoor plants improve thermal comfort, provide passive sound insulation, and greatly enhance psychological well-being, productivity, and mental happiness, fostering a biophilic connection essential for human flourishing. The vital role of the root-soil microcosm, where symbiotic microorganisms actively break down pollutants, highlights that the plant in air purification is a complex biological system. This system shows remarkable adaptability, with its effectiveness possibly improving over time with continuous pollutant exposure.

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Conflict of Interest

The author declares that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the author.

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