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Review

Phytoremediation of indoor air pollutants: Harnessing the potential of plants beyond aesthetics

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ABSTRACT

Indoor air pollution has emerged as a major threat to human health worldwide that needs to be dealt urgently. The present review is an effort to overview the different indoor air pollutants (CO₂, volatile organic compounds (VOCs) like formaldehyde, benzene, nitrous oxide, trichloroethylene, fluorine, ammonia, radon, aldehyde, hydrocarbons etc.) their hazardous effects on human health, potential of indoor plants in their remediation and their practical utility. Besides providing oxygen to breathe, multifaceted roles of indoor plants have been well documented. Plants were used since decades for indoor decorations based on their aesthetic value, but now studies are focused on screening plant species for their efficiency in absorption of indoor air pollutants. The basis for phytoremediation is the potent efficiency of some plants to assimilate, degrade, or modify toxic pollutants into non-toxic ones. Phytoremediation seems to be the key solution to improve indoor air quality as it has many potential advantages (simple, potentially cheap, and easily implemented) in comparison to other traditional or latest methods. Breathing walls, portable air filters for rooms or whole house filtration through heating, ventilation and air conditioning systems are some of the technologies developed, to reduce indoor air pollution and improve indoor air quality but all these are costly, resource consuming and still there is question on their efficiency. Detailed account of morphological, anatomical and molecular mechanisms underlying plant leaves and leaf associated microbes in reduction of pollutants have been reviewed that could help in developing cost effective and eco friendly remediation technologies. This review gives a brief discussion about air phytoremediation to improve effectiveness of this technology in practical use.

Keywords: Indoor air pollutants, herbs, phytoremediation and plants

INTRODUCTION

Degradation in air quality has become the biggest concern and awareness regarding its maintenance and protection is increasing all over the world. There are numerous anthropogenic causes of outdoor and indoor air quality degradation *viz.*, volcanic eruption, fossil fuel burning, forest fires, motor vehicle pollution, controlled burning in agriculture, fumes from paints or air sprays, waste deposits in landfills military resources such as nuclear weapons and toxic germ warfare, fertilizers, furnitures, coolants etc that leads to numerous respiratory, heart diseases and could even be carcinogenic.

Major air pollutants include particulate matters (PMs), carbon monoxide, oxides of sulphur and nitrogen,

ground-level ozone (O₃) and volatile organic compounds (VOCs) that can cause dozens of diseases and threaten human health (Archibald *et al.*, 2017; Burns *et al.*, 2020). According to a WHO report, nearly 91% of the world's population lives in areas where the level of airborne pollutants exceeds WHO permissible limits (Health Effects Institute, 2018).

The changing lifestyle is further adding to the problem as it has limited the activities of people to indoors which forces large percent of urban population to spend most of their times, indoors. Ventilation plays a crucial role in promoting the comfort and health of occupants (Rackes and Waring, 2014). The world has



experienced unprecedented urban growth during the last three decades. Urban population is expected to increase from 55% in 2018 to 68% by 2050. Projections show that urbanization, the gradual shift in residence of the human population from rural to urban areas, combined with the overall growth of the world's population could add another 2.5 billion people to urban areas by 2050, with close to 90% of this increase taking place in Asia and Africa, according to a new United Nations data set launched (Anon., 2018b). With increasing urbanization and rising migration of people from rural to urban areas, space is the major concern. Buildings generate almost 40% of global greenhouse gases (GHG's) annually as compared to transport (23%) and industries (32%). Closed working spaces and lack of ventilation leads to accumulation of pollutants - excess amounts. Human beings spend 80-90% of their time in enclosed spaces, such as houses, office buildings, and schools with restricted air circulation (Yrieix *et al.*, 2010). In closed buildings, besides pollutants, occupants themselves are a major source of indoor air contamination. The occupants are the major source of carbon dioxide (CO₂) that poses threat to health at higher concentrations (Siskos *et al.*, 2001). Therefore, indoor air quality (IAQ) may be worse than outdoor air quality (Watson, 2013). According to the studies conducted, indoor air has been reported to be 12 times more polluted than outdoor air (Zabiegala, 2006). So, urban IAQ has emerged as an important international health issue that needs to be reviewed and resolved at earliest possible. Further, it demands for greener indoors with good IAQ to cater the health issues of occupants.

The current article gives an overview of degrading IAQ and its effect on human health; criteria for selection of indoor plants with high phytoremediation efficacy and mechanism underlying their efficacy that could stimulate more research in this area and improve its effectiveness in practical use.

MAJOR INDOOR POLLUTANTS

Carbon dioxide is one of the major indoor pollutants that pose threat to human life. The average breath of an adult contains 35,000-50,000 ppm of CO₂ that gets accumulated in closed buildings (Prill, 2000). The outdoor CO₂ level is in a range of 350-450 ppm but the indoor CO₂ level is 100 times greater than outdoor CO₂ level, even in buildings where complaints with

regard to indoor air quality are few. The CO₂ concentration indicates air exchange rate in buildings as CO₂ levels more than 1000 ppm indicate inadequate ventilation and occupants have problems like headaches, nose and throat ailments, tiredness, lack of concentration and fatigue (Bulinska *et al.*, 2014). This does not mean that low CO₂ levels are indicators of good indoor air quality (IAQ) as IAQ is dependent upon several other pollutants.

Besides CO₂, the other indoor pollutants are volatile organic compounds (VOCs) like formaldehyde, benzene, nitrous oxide, trichloro-ethylene, fluorine, ammonia, radon, aldehyde, hydrocarbons *etc.* Exposure to such chemicals leads to severe diseases like multiple chemical sensitivity, sick building syndrome allergies, asthma, headache, stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer (Shinohara *et al.*, 2004). The effects of some of these air pollutants ranging from respiratory illness, cardiovascular disease to bladder and lung cancer affecting human health have been summarized by Kampa and Castanas (2008). Some indoor air pollutants, their source and health effects have been summarized in Table 1. According to the survey of World Health Organization (WHO) around 3.8 million people in a year die from the exposure to household air pollution (Anon., 2018a). Among various VOCs, formaldehyde is a main contaminant in terms of indoor air which originates from various paper products, curtains, adhesives, carpets, varnishes, permanent press-fabrics. Its concentration in new houses is often several times higher than that in older homes (Marco *et al.*, 1995).

The key solution to this problem is planting indoor plants that can survive under such adverse conditions with least maintenance and inputs. Besides acting as potential sinks of indoor pollutants, indoor plants add to the beauty and liveliness to our homes and offices and thus improve IAQ.

Indoor plants means the plants that can grow indoor i.e. their light, temperature and water requirements are low. They may be either flowering plants (Peace lily, Kalanchoe, Amaryllis, Hydrangeas, Poinsettia) or foliage plants (cactus, palm plants, fern and succulents). Besides oxygen producing ability another comprehensive research conducted by the National Aeronautics and Space Administration (NASA) has found that common household plants work as natural

air purifiers. Interestingly indoor plants can remove a notable amount of at least 87% of VOC's in 24 hours. VOC's are present in many household products, including paints, paint strippers and other solvents, wood preservatives, aerosol sprays, cleansers and disinfectants, moth repellents, hobby supplies, pesticides, dry-cleaned clothing, building materials and furnishing, office equipment including glues and adhesives, permanent markers and photographic solutions (Anon., 2021). Succulents and many indoor house plants are further advantageous as they are of small size and add continuous flush of fresh oxygen day and night. Studies have shown that people in buildings with plants like Money plant, Mother- In-Law's Tongue and Areca palm have 34% fewer respiratory problems, 54% less eye irritation and 24% fewer headaches (Anon., 2016).

ASSESSMENT OF UTILITY OF INDOOR PLANTS

Indoor plants absorb carbon dioxide, keep the oxygen flowing and remove harmful toxins like VOCs which help to deter the illness, lower the stress levels and create a relaxed and happy ambience. This further helps in improving concentration, enhancing creativity and increasing productivity that fulfills overall well-being. The air purifying qualities of indoor plants ultimately stimulate a happier and healthier environment.

It may seem far-fetched and unconvincing that having greenery indoor can have such important effects but the scientific results and findings have proved it. Numerous indoor plants have huge capability of removing various categories of toxins from indoor air; hence foster the indoor air quality. Based on study conducted by NASA, toxins like benzene, formaldehyde, trichloroethylene, xylene, toluene and ammonia were considered and houseplants were selected to test their pollutant removal efficiency and it was found that they removed these pollutants in significant amounts (Table 2). Parallel to this, there are several other benefits of indoor plants which can be discussed under following headings:

Air purifiers: Succulents such as aloe vera and snake plant have excellent air purifying and toxins removal properties. The plants emit the water vapour and that in return generates the pumping action which pulls the contaminated air down to roots of plants. The succulents convert the contaminants to plant food and

thus purify the air. The studies showed that many common foliage plants reduced levels of some indoor pollutants, including formaldehyde and carbon monoxide, from small, sealed test chambers. The pollution reduction was largely due to bacteria growing on the plant roots (Wolverton *et al.*, 1989).

Plants grown in potting soil have been rated for their relative removal rate of toxins, such as formaldehyde. For this compound, Boston fern can remove 1863 µg/h, Bamboo palm 1350 µg/h, Janet Craig dracaena 1328 µg/h, English ivy 1120 µg/h, peace lily 939µg/h, areca palm and corn plant 938 µg/h. All the details of how plants clean such air, and how to use them, are in the classic paperback book "*How to Grow Fresh Air*" by the researcher B.C. Wolverton.

Living walls of plants have become more common in buildings, including modular units that one can even install in a home. A new technology of breathing walls introduces a method for improving the indoor air quality, and this technology is called breathing walls. The concept of a breathing wall is to purify the internal air flowing out through the walls and to reduce the concentration of indoor air pollutants. This draws a steady stream of filtered air through the walls and into the buildings all the times, providing exceptionally clean ventilation to occupants (Zhai, 2016). A company in Sydney (Australia) has partnered with the University of Technology to quantify the positive effects of what they term "breathing walls" to remove carbon dioxide and volatile organic compounds from interior air. The U.S. researchers Fisk and Rosenfeld of the Berkeley National Laboratory have quantified a \$58 billion annual savings from sick-building illness with the use of plants (Anon., 2007).

Improvement in indoor humidity level: The indoor plants regulate the humidity level which is an important factor influencing indoor weather. The studies conducted by Agricultural University in Norway revealed that indoor plants at home regulate the humidity levels inside the house as plants release moisture in form of vapour, and this increased moisture improves the sore throat, allergies, cold and dry cough and even some skin diseases (Fjeld, 2000).

The foliage plants can raise relative humidity to healthier and more comfortable levels in interior spaces. The relative humidity of the air inside buildings is often below the range of 30% to 60% recommended for human comfort, especially when buildings are

being heated. When the indoor relative humidity is too low, colds are more frequent and wood dries and cracks. In this study, when plants were present, less than 2% of the space was occupied by the plants, the relative humidity was raised from 25% without plants to 30% with plants. The enhancing effect of indoor plants on relative humidity raised the concern that indoor plants might result in too much increase in relative humidity. But this is unlikely to occur as when the relative humidity rises, the rate of water loss from the plant slows due to decreased concentration gradient between plant tissue and atmosphere (Lohr, 2010)

Continuous oxygen supply: Unlike most of the plants, succulents do not release carbon dioxide at night instead they have specialized built in mechanism which maintains the continuous supply of oxygen.

Improve our focus: Number of studies has been conducted on both students as well the workers which have proved that attentiveness, concentration and brain capabilities increase when plants were kept in their room. The University of Michigan conducted a study which found memory retention is improved as much as 20% when plants are present in room (Anon., 2008).

Increase pain tolerance: The plants in our vicinity have capability to decrease our sensitivity to pain. The Horticulture Therapy Research was conducted by University of Kansas which showed that patients needed less medication when they had plants in their room. One more study was conducted to examine people's ability of perception to pain in presence or absence of plants. About 71% of subjects in room with plants had their overall physical health above excellent whereas this per cent decline to 56% in the conditions when there were no plants around (Lohr and Pearson-Mims, 2000).

Increase working productivity: Mental fatigue has been shown to be reduced by plants. Indoor plants have potential to increase the productivity per working person. The studies conducted in Texas, Washington State and England revealed that the employees with plants in their environments were 12% more productive than those working in environment without exposure to interior plants.

Students in dorm room with the view of nature and plants had better and increased productivity than those without it, assuring the role of plants in increasing the potential of the subject for performance. (Lohr, 2010)

Improve memory: Another important aspect is memory which is influenced by plants. A study was conducted in the University of Michigan, which revealed that there are numerous benefits of interacting with nature. They reported that interaction for just an hour with nature could increase the memory retention (Berman *et al.*, 2008).

Help to prevent diseases: The positive effect of plants on health and disease prevention has been proved from several years. The presence of plants on working desk in office improved the health of subject as a study conducted in the University of Norway revealed that there was 60% decrease in sickness rates with plants in office (Fjeld, 2000).

Speed up the healing process: Researchers who have assessed the impact of nature/plants on human health have suggested that people-plant interactions provide physiological stress reduction within minutes along with faster physical recovery from stress that further improves emotional and cognitive health (Kaplan, 2001; Chang and Chen, 2005).

The healing process through plants was also supported by Texas A & M University. They recommended that patients who interacted with plants, engaged in gardening have faster recovery rate and less downtime in post-surgery patients. The soothing effects of ornamental flowers and plants are so great that simply having daily views of flowers and other ornamental plants in landscaped areas outside patient recovery room can also significantly speed up recovery time (Hall and Dickson, 2011).

Reduce stress: The study was conducted that stress reducing responses also occur when people are in a room with a few containerized interior plants, even when their attention is not drawn to the plants (Lohr *et al.*, 1996). A study revealed that people given a task on computer had higher systolic blood pressure in a room without any plant as compared to people doing same task in a room with plants (Lohr, 2010).

Reduce noise: The studies have shown that plants also reduce the indoor noise levels, making it a pleasant environment. For instance, a hedge of small indoor plant in workspace can reduce the noise levels up to five decibels. Plants absorb the sound and create a calming effect. A study from London South Bank University showed that there is a positive effect on noise reduction from large plants placed in corners of the rooms (Perry, 2018)

Table 1. Common indoor air pollutants and their effects on human health

Pollutant	Sources	Health Impact	References
Particulate Matter (PM)	Outdoor environment, cooking, combustion activities (burning of candles, use of fireplaces, heaters, stoves, fireplaces and chimneys, cigarette smoking), cleaning activities	Premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function	Hamanaka <i>et al.</i> (2018) Miller <i>et al.</i> (2012) Brook <i>et al.</i> (2010)
Volatile organic carbons (VOCs)	Paints, stains, varnishes, solvents, pesticides, adhesives, wood preservatives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plasites, printers, tobacco products, perfumes, dry-cleaned clothing, building materials	Eye, nose and throat irritation - Headaches, loss of coordination and nausea - Damage to liver, kidney and central nervous system - Some organics can cause cancer	Tang <i>et al.</i> (2015) Brickus <i>et al.</i> (1998) Weschler <i>et al.</i> (2012)
NitricOxide (NO ₂)	Gas-fueled cooking and heating appliances	Enhanced asthmatic reactions - Respiratory damage leading to respiratory symptom	Bernstein <i>et al.</i> (2008)
Ozone (O ₃)	Outdoor sources, photocopying, air purifying, disinfecting devices	DNA & lung damage, asthma, decreased respiratory functions	Salonen <i>et al.</i> (2018) Huang <i>et al.</i> (2019)
Sulphur di oxide (SO ₂)	Cooking stoves; fireplaces; outdoor air	Impairment of respiratory function - Asthma, chronic obstructive pulmonary disease (COPD), and cardiovascular diseases	Seow <i>et al.</i> (2016)
Carbon oxides (Cox)	Cooking stoves; tobacco smoking; fireplaces; generators and other gasoline powered equipment; outdoor air equipment	Outdoor air fatigue, chest pain, impaired vision, reduced brain function	Raub <i>et al.</i> (2000)
Heavy Metals	Outdoor sources, fuel-consumption products, incense burning, smoking and building materials	Cancers, brain damage, Mutagenic and carcinogenic effects: respiratory illnesses, cardiovascular deaths	Hamanaka <i>et al.</i> (2018) Rashed <i>et al.</i> (2008) Madany <i>et al.</i> (1994)
Aerosols	Tobacco smoke, building materials, consumer products, incense burning, cleaning and cooking	Cardiovascular diseases, respiratory diseases, allergies, lung cancer, irritation and discomfort	Koivisto <i>et al.</i> (2019) Oh <i>et al.</i> (2019) Kulmala <i>et al.</i> (1999)
Radon	Soil gas, building materials, and tap water Outdoor air	Lung cancer	Bruno <i>et al.</i> (1983)
Pesticides	Termiticides, insecticides, rodenticides, fungicides, disinfectants and herbicides - Building materials: carpet, textiles, and cushioned furniture - Outdoor environment	Irritation to eye, nose and throat; Damage to central nervous system and kidney; Increased risk of cancer	Halt <i>et al.</i> (2017) Colt <i>et al.</i> (2004) Hwang <i>et al.</i> (2008)
Biological allergens	House dust, pets, cockroaches, mold/dampness, pollens originating from animals, insects, mites, and plants	Asthma and allergies Respiratory infections, sensitization, respiratory allergic diseases and wheezing	Baldacci <i>et al.</i> (2015)
Micro-organism	Bacteria, viruses, and fungi are carried by people, animals, and soil and plants	Fever, digestive problems, infectious diseases, chronic respiratory illness	Anonymous <i>et al.</i> (1988)

Improves perception: Plants improve the rate of perception as revealed in a study of Opryland Hotel in Nashville. The occupancy rate of that hotel was higher than national average. A scientific study was conducted and the main factor accounting for this was their high investment over \$1 million on interior plants, as a matter of fact it was the largest investment on indoor plants in country (Perry, 2018).

AMELIORATIVE POTENTIAL OF INDOOR PLANTS TO IMPROVE INDOOR AIR QUALITY

The studies conducted by NASA back in 1980s, demonstrated that plants have potential to ameliorate airborne pollutants. Susanto *et al.* (2021) provided evidence-based insight into usefulness of indoor plants as an alternative way for indoor air remediation. Several studies demonstrated efficient phytoremediation of specific indoor air pollutants through the use of specific plants. The plants *Osmunda japonica*, *Davalliamariesii*, *Selaginella tamariscina*, *Polypodium formosanum*, *Lavandula* spp., *Pteris dispar*, *Pteris multifida*, *Pelargonium* spp., *Aloe vera*, and *Epipremnum aureum* were reported to be efficient in removing formaldehyde from indoor air (Kim *et al.*, 2010). Liu *et al.* (2007) reported that *Crassula portulacaea*, *Hydrangea macrophylla*, *Cymbidium* “Golden elf”, *Syngonium podophyllum*, *Euphorbia milii*, *Sansevieria trifasciata*, *Chlorophytum comosum*, *Dracenas anderiana*, *Hedera helix*, and *Clitori aternatea*, with *Chlorophytum comosum* have high benzene removal efficiency. Phytoremediation of toluene may be achieved through *Schefflera elegantissima*, *Philodendron* spp. “Sunlight,” and *Hedera helix* (Kim *et al.*, 2011). *Zamioculcas zamiifolia* was potent in remediating xylene (Sriprapat *et al.*, 2013) and ethylbenzene to some extent (Toabaita *et al.*, 2016). *Hoya carnososa*, *Hemigraphis alternata*, *Fittonia argyroneura* and *Asparagus densiflorus* efficiently remove VOCs like benzene, toluene, octane, TCE, and a-pinene and *Ficus benjamina* octane and a-pinene. Wood *et al.* (2006) documented that the popular indoor pot plant *Dracena deremensis* “Janet Craig” as an excellent species for the removal of VOCs. Similar results for removal of VOCs *viz.*, benzene, ethylbenzene, xylene, styrene, formaldehyde, acetaldehyde, and toluene was recorded for *Ficus* spp. (Hong *et al.*, 2017). The efficiency of *Nephrolepis obliterate* in reducing indoor

formaldehyde levels was found up to 100% (Teiri *et al.*, 2018). Aydogan and Montoya (2011) revealed the efficacy of plants such as *Hedera helix*, *Chrysanthemum morifolium*, *Dieffenbachia compacta*, and *Epipremnum aureum* in reducing formaldehyde levels up to 90% within 24 hours. Indoor plants are not only potent to reduce VOCs, CO and CO₂ levels but also particulate matter (Panyametheekul *et al.*, 2018).

Several other studies also have shown the use of potted plants as a mechanical system for phytoremediation of several indoor air pollutants. Latest technologies have provided biofiltration walls or green walls or large filtration systems but potted plants are most effective in terms of phytoremediation capacity, maintenance and cost (Agarwal *et al.*, 2019). Recent advancements in indoor air phytoremediation technologies, botanical biofiltration systems could more efficiently reduce the concentrations of indoor air pollutants through action of active airflow in plant growing medium, along with vertically aligned plants that leads to higher leaf area density per unit of floor space. Despite of clear potential of these latest systems, still research needs to be focused on potential and cost effectiveness for proper selection of plants and their functional integration in buildings (Petit *et al.*, 2018). The use of indoor plants as phytoremediation technology in comparison to latest technologies is slow but environment friendly air-purification strategy i.e. financially affordable with minimal energy consumption (Susanto *et al.*, 2021).

STRATEGIES FOR SELECTION OF INDOOR PLANTS

Selection of plants for indoors is based on criteria such as aesthetic features, good survival and low maintenance. Generally evergreen plant species with broad leaves and inhabitants of understory of large canopies of tropical and sub-tropical climates have been selected as indoor foliage plants as they have been adapted to photosynthesize under low light intensities and grow profusely (Anderson *et al.*, 1987). The plants that are adapted to shade have large leaf area and reduced stomatal aperture leading to removal of pollutants through adsorption rather than absorption (Gommer *et al.*, 2013). This selection criteria of shade adaption for indoor plants need to be supplemented with morphological (i.e.,) leaf shape, size, and hairiness), anatomical (i.e.,) composition of epidermis

Table 2. Indoor Plants and their indoor pollutant removal efficacy

Indoor Plant	Indoor pollutants					
	Benzene	Formaldehyde	Trichloroethylene	Xylene	Toluene	Ammonia
Peace Lilly						
Parlour Palm						
Lady's Palm						
Florist's chrysanthemum						
English Ivy						×
Bamboo palm						×
Variegated Snake palm						×
Red-edged dracaena						×
Cornstalk dracaena						×
Janet Craig						×
Warneckei						×
Flamingo lily	×		×			
Dwarf Date palm	×		×			×
Areca palm	×		×			×
Boston fern	×		×			×
Kimberly queen fern	×		×			×
Spider plant	×		×			×
Weeping fig	×		×			×
<i>Dendrobium</i> orchid	×		×			×
King of Hearts	×		×			×
Moth orchids	×		×			×
Chinese evergreen			×	×	×	×
Aloe vera			×	×	×	×
Heartleaf philodendron	×		×	×	×	×
Selloum philodendron,	×		×	×	×	×
Elephant ear philodendron	×		×	×	×	×
Rubber plant	×		×	×	×	×

(Source: NASA Clean Air Study)

and mesophyll layers, and stomatal density and size) and physiological (CO₂ assimilation rate and activity of detoxifying enzymes) properties that determine their air phytoremediation potential. Advanced omics technologies (genomics, proteomics, and metabolomics) could be used to understand the biochemical mechanism of indoor air pollutant degradation. The detailed unraveling of metabolic pathways, genes and enzymes involved in catabolism of pollutants will enable the determination of biomarkers for phenotyping appropriate plant species for improving IAQ.

The selection of plants for indoor should be done very carefully with scientific approach as some plants may have negative impact on human health too. Some ornamental plants produce allergic pollens and/or release harmful VOCs; their surfaces may harbor pathogenic microbes and/or pests (Carinanos and Casares-Porcel, 2011). Thus, ornamental shade-loving plants with more foliage (leafy part), less pollen, and short blooming period could be selected to reduce indoor air pollution. Low grade plastic pots used for planting can also produce VOCs; hence, alternatives to plastic pots for indoor planting besides appropriate plants have to be considered.

One of the best tools for selecting plants for indoor is the Air Pollution Tolerance Index (APTI). APTI considers biochemical properties of leaves such as ascorbic acid; relative water content, total chlorophyll and leaf extract pH. These properties affect the value of the plant's tolerance to air pollutants. For example, under water stress, the content of chlorophyll induces reactive oxygen species in the chloroplast. The high value of ascorbic acid is one of the strategies to prevent oxidative damage to the thylakoid membranes under water stress conditions (Bandehali *et al.*, 2021).

HOW PLANTS REMEDIATE INDOOR AIR POLLUTANTS

The plants during photosynthesis simultaneously take up CO₂ and release O₂ and during transpiration, release water vapour through stomata on their leaf surface (Smith and Pitt, 2011). Thus, the potential of plants to improve IAQ depends upon the capacity of leaves to exchange gases and pollutants from indoor air through stomata. Schreck *et al.* (2012) also reported that the points of entry of metal-enriched particles after their deposition on the leaf surface, could be the cuticle

and stomata. This capacity is further limited by physical constraints pertaining to stomatal and mesophyll resistance. The size of stomatal pore varies with variation in environmental conditions *viz.*, light, temperature, humidity -and cascades of signaling through plant hormones especially abscisic acid. Besides stomatal absorption, pollutants can get adsorbed on the external surfaces of plants or soil-root interface and thus get removed. The process of absorbing lipophilic semi volatile compounds is achieved through leaf surface adsorption, where atmospheric resistance serves as a major limiting factor (Wei *et al.*, 2017). This type of removal depends upon the total surface area and anatomical, morphological and chemical features of the plant surface along with characteristics of the soil substrate (Irga *et al.*, 2013). The adsorption of pollutants especially lipophilic VOCs, such as benzene, on plant surface is dependent upon type and density of trichomes (Li *et al.*, 2018), cuticular wax deposition and lipid composition of epidermal membrane (Gawronska and Bakera, 2015). The potential of plants to ameliorate indoor pollutants was earlier based on simplistic approaches but more accurate experimentation through simulation of foliage to indoor air pollutants not only confirmed the earlier reports (Fares *et al.*, 2015) but also revealed that the amount of pollutants absorbed through stomata is 30-100 times more than adsorbed on the plant surface or non-stomatal deposition (Tani *et al.*, 2009). After entering into plant leaf either through absorption or adsorption, pollutants are translocated to shoots and roots for metabolic degradation through oxidases or hydrolases and then conjugation with different metabolic compounds (sugars, amino acid, organic acids, and peptides) to form bioproducts. These products are either re expelled (into air or as root exudates into soil) or used as carbon and energy sources (Oikawa and Lerda, 2013).

In addition to air phytoremediation through absorption and adsorption of pollutants by plant surface, another least explored aspect is phylloremediation *i.e.* remediation through habituated microbes either on leaf surface or endophytes by biodegrading or transforming pollutants into less or nontoxic molecules (Sandhu *et al.*, 2007). Leaves are the primary photosynthetic organs with dorsiventral symmetry and play pivotal roles in supporting phyllosphere microbes (Bringel and Couee, 2015). Several reports documented that both

plant leaves and leaf-associated microbes mitigated air pollutants, such as azalea leaves and the leaf-associated *Pseudomonas putida* in reducing VOCs (De Kempeneer *et al.*, 2004) and poplar leaves and the leaf-associated *Methylobacterium* sp. decreased xenobiotic compounds (Van Aken *et al.*, 2004).

Thus, the different mechanisms underlying the phytoremediation potential of plants for indoor pollutants are microbial degradation through rhizospheric microorganisms, phytoextraction i.e. plant-liquid extraction, plant-gas extraction i.e. stomatal uptake, enzymatic catalysis inside tissues and plant transpiration & evaporation from leaves (Sharma *et al.*, 2019)

CONCLUSIONS AND FUTURE PERSPECTIVE

The complexities in the source, chemical nature, effects and stability of air pollutants pose a great challenge for standardizing technologies for their remediation. Further, different pollutants are prevailing at different rates in different microenvironments which demands for location specific remediation for pollutants individually or in groups. The selection of plants suitable for indoor phytoremediation should follow unambiguous scientific criteria that reflect their capacity to sequester air borne pollutants, instead of only taking into consideration their aesthetic features.

The plant-soil-microbe system through metabolizing, sequestering or degrading air pollutants improve indoor air quality. Limited information on number and group of plant species indicating their potential and suitability for removing air pollutants entails uncertainties. The studies should be planned to concentrate on developing plant by editing genomes through DNA modifications to over express or insert genes coding for detoxifying enzymes. The integration of smart sensor networks and computerized technologies with highly performing indoor plant species could provide great opportunities to improve IAQ through eco-sustainable and cost-effective techniques. Recent advancements in indoor air phytoremediation technologies, botanical biofiltration systems could more efficiently filter indoor air but still research needs to be focused on potential and cost effectiveness for their functional integration in buildings. Further research is needed to develop, test and confirm their effectiveness and safety before they can be.

Studies on indoor air phytoremediation technologies is a multidisciplinary approach that demands collaboration among researchers from different fields at regional, national, and international levels so that there is a paradigm shift in the way in which plants will become functional entity instead of just a decorative tool.

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