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Review

Phytoremediation: The Sustainable Strategy for Improving Indoor and Outdoor Air Quality

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Abstract: Most of the world's population is exposed to highly polluted air conditions exceeding the WHO limits, causing various human diseases that lead towards increased morbidity as well as mortality. Expenditures on air purification and costs spent on the related health issues are rapidly increasing. To overcome this burden, plants are potential candidates to remove pollutants through diverse biological mechanisms involving accumulation, immobilization, volatilization, and degradation. This eco-friendly, cost-effective, and non-invasive method is considered as a complementary or alternative tool compared to engineering-based remediation techniques. Various plant species remove indoor and outdoor air pollutants, depending on their morphology, growth condition, and microbial communities. Hence, appropriate plant selection with optimized growth conditions can enhance the remediation capacity significantly. Furthermore, suitable supplementary treatments, or finding the best combination junction with other methods, can optimize the phytoremediation process.

Keywords: air pollution; air quality; air purification; phytoremediation; plants; botanical biofilter

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1. Introduction

Air is the most fundamental component for living organisms to survive, which is exceedingly polluted above the threshold limit due to the industrial revolution, global urbanization, burning fossil fuels, and other human activities [1]. In 2016, the World Health Organization (WHO) reported that more than 92% of the world's population is exposed to air pollutants exceeding the WHO limits. According to this report, air pollution is the largest environmental risk factor, which leads to increased morbidity and mortality [2]. Moreover, the Center for Research on Energy and Clean Air (CREA) calculated that the economic loss and health costs caused by air pollution from burning of fossil fuels was $2.9 trillion in 2018, representing 3.3% of global GDP [3]. Thus, the development of technologies to remove/reduce air contaminants has emerged as a challenge of major importance for the global community.

Plants are autotrophic organisms that carry out intensive gas exchange for performing cellular activities, whereby air pollutants can be absorbed or accumulated internally [1]. Phytoremediation defines the bioremediation of contaminated air, soil, and water using plants [4]. It has been considered a widely applicable and sustainable technique because plants eliminate the environmental contaminants in an eco-friendly, cost-effective, and noninvasive manner. Plants reduce the mobility, toxicity, and volume of the contaminants through varied mechanisms, such as accumulation, immobilization, volatilization, and degradation. These biological processes ultimately need solar-based energy, and therefore phytoremediation is a cheaper method than engineering-based remediation methods. Thus, phytoremediation is seen as an alternative or complementary technology for air purifiers [5–7]. The present review summarized the types of air pollutants and their impact on human diseases, phytoremediation mechanisms, and the recent status of developments of phytoremediation in the field of air purification.

2. Air Pollutants

Any gaseous or particulate matter present in high concentration, and which is not usually part of the air, can be defined as atmospheric air pollution. Accompanying industrialization, urbanization, and other human activities have generated a large number of hazardous pollutants that ultimately threaten human health and environment [8]. Among the types of pollutants, primary pollutants are released directly into the atmosphere, and secondary pollutants are formed through diverse chemical reactions in the presence of solar radiation [9]. Figure 1 illustrates the key air pollutants affecting the environment and human health, and their sources.

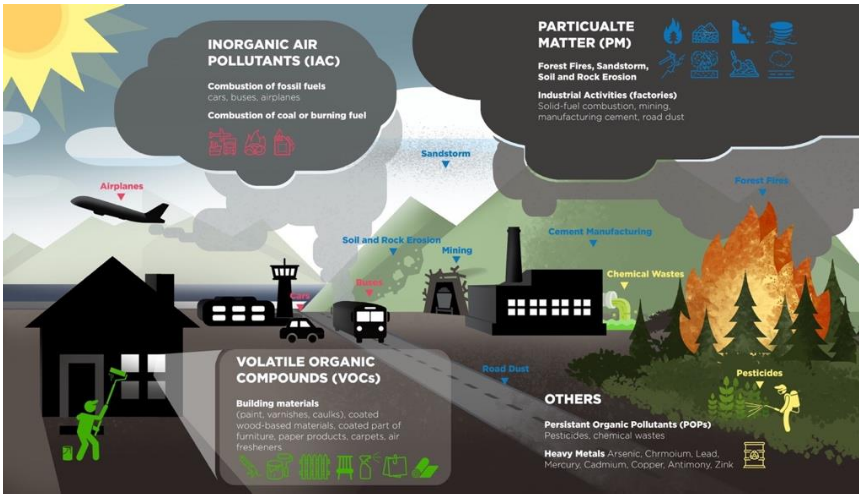

Figure 1. Schematic representation of air pollutants and their sources.

2.1. Particulate Matter (PM)

PM can be defined as a mixture of solid particles and liquid droplets with varied sizes, shapes, origins, and chemical compositions [10]. Outdoor PM is generated by both natural (e.g., forest fires, sandstorm, and soil and rock erosion) and anthropogenic sources (e.g., industrial activities, energies and solid-fuel combustion, mining, cement manufacturing, and road dust) [11]. Indoor PM is produced by human activities such as cooking or cleaning; however, the most indoor PM come from outdoor sources [12]. Based on the aerodynamic diameter, PM is classified in four fractions: PM_{10} (<10 µm), $PM_{2.5–10}$ (2.5 µm to 10 µm), $PM_{2.5}$ (<2.5 µm), and $PM_{0.1}$ (<0.1 µm) [13]. Depending on the time and regions, PM comprises varied chemical compositions, leading to different PM toxicity. Ions, organic compounds, reactive gas, minerals, transition metals, quinoid stable radicals of carbonaceous material, or materials of biological origin are the representative PM-containing components [2,14].

2.2. Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) define any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions, except those designated by the EPA as having a negligible photochemical reactivity [15]. VOCs are emitted directly through transportation, industrial processes, and various outdoor sources. In an indoor environment, VOCs are emitted from almost every material, such as building materials, coated wood-based materials, coated different parts of the furniture, paper products, and carpets [16,17]. Among the hundreds of VOC species, benzene, toluene, ethylbenzene, and xylene (BTEX) and formaldehyde are most abundantly found in air [18]. Researchers have paid attention to VOCs because they are the significant contributors to the formation of ozone (O_3) in ambient conditions [19]. More so, discharge of VOCs into the environment result in ozone layer depletion in the stratosphere, urban smog, and the greenhouse effect.

2.3. Inorganic Air Pollutants (IAC)

Inorganic air pollutants (IAC) predominantly comprise of carbon dioxide (CO_2), carbon monoxide, O_3, nitrogen oxides (NOx), and sulfur dioxide (SO_2) [18]. While CO_2 is naturally present as part of the Earth's carbon cycle, it is more well known as the main greenhouse gas that is generated predominantly by the combustion of fossil fuels, construction of transport infrastructure, and energy production. The CO_2 emission by human activities has significantly contributed to its excess in the atmosphere, resulting in various problems such as global climate change, which threatens human health [20,21]. SO_2, a stinging gas, is well known as the main component of acid rain and is mainly generated by the combustion of coal or other fuels. Nowadays, low-sulfur-containing fuels and SO_2 scrubbers have been developed to decrease the SO_2 concentration [22,23]. Another major component of acid rain, NOx, is produced mainly by combustion processes, such as automobile traffic. NOx plays a critical role in the photochemical oxidant cycle, generating O_3, which might impact human health [18]. O_3 can be produced in the troposphere by complex photochemical reactions with VOCs, CO, or NOx [24].

2.4. Others

Other air pollutants showing a negative influence on human health include persistent organic pollutants (POPs), black carbon, and heavy metals. POPs including dioxins, furans, polyaromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) that can be accumulated in the body through the food chain, known as biomagnification [25]. Although the amount of POPs emission is not considerable, they are resistant to degradation in the environment; this increased bioaccumulation, leading to adverse impacts on human health, have raised serious concerns [1]. Heavy metals, such as arsenic, chromium, lead, mercury, cadmium, copper, antimony, and zinc, can be combined with particulate matter, which are bioavailable and thus easily accumulate in human cells [9]. Black carbon is a climate-modifying pollutant and one of the major components of PM [2].

3. Air Pollution and Human Diseases

According to the WHO, one out of every nine deaths in 2012 was correlated to air pollution-related conditions [2]. Studies have emphasized the close link between air contaminants and human diseases involving the upper airway, pulmonary, cardiovascular, liver, respiratory, renal, autoimmune, skin, eye diseases, and diabetes. For example, data on VOCs was reported to be positively correlated with emergency hospital visits for chronic obstructive pulmonary diseases [26]. Another report also demonstrated that exposure to VOCs increased the pulmonary health risk through alteration of the gas-liquid interface properties of pulmonary surfactants [27]. Short-term exposure to VOCs emitted from building materials can cause relatively mild symptoms, such as headache, dizziness, or irritation of the eyes or skin, while long-term exposure may result in life-threatening diseases, such as reduced pulmonary function, leukemia, and tumors [19].

Other reports on short-term exposure to NO_2 and SO_2 also showed positive correlation with hospitalization and mortality caused by respiratory diseases [28,29]. In Iran, where the yearly average SO_2 concentration was exceeded 8.62 times more than the WHO guidelines during the study period, a high hospitalization rate was observed for cases of acute respiratory diseases and asthmatic symptoms [30]. Compared to exposure to the first quartile of SO_2 (<3.38 ppb) and NOx (<23.4 ppb), exposure to those from the fourth quartile (SO_2 > 6.03 ppb, NOx > 38.6 ppb) increased the risk of chronic kidney diseases by 1.46- and 1.39-fold and end-stage renal diseases by 1.32- and 1.70-fold, respectively [31]. SO_2 predominantly irritates the upper airway, in turn inducing bronchoconstriction and mucus. Asthmatics, hyper-reactive airways, and other SO_2-related diseases are sensitive to acute exposure rather than chronic exposure because just a small amount of SO_2 deposits in the upper respiratory tract and penetrates into the lung. However, inhalation of excessive SO_2 can result in larynx, bronchi, trachea, and alveoli injury as SO_2 dissolves in the fluid, subsequently generating sulfites and bisulfites that oxidize to hydrogen peroxide and superoxide ion [8]. Inhaled NOx is converted into nitric and nitrous acids in lung fluids, injuring cell structure and function. Additionally, NO_2 with O_3 generates free radicals, which induces lipid peroxidation, in turn damaging the cell membrane [32].

Recently, more studies have emphasized the association of PM exposure with a high risk of various human diseases. PM larger than 2.5 µm enters the nose, throat, larger upper branches, or bronchial tubes, depending on their size. From these locations, the particles can be eliminated by coughing, sitting, or swallowing. Whilst, particles smaller than 2.5 µm penetrate the deepest alveolar portions of the lung. Then, water-soluble particles pass directly into the blood in the alveolar capillaries, while water dissoluble particles remain in the lung causing inflammation, which releases bioactive substances into the bloodstream and lead to coagulation of the blood [8,14]. There is increasing evidence implying the association of $PM_{2.5}$ with lung inflammation and fibrosis, as a result in a series of chronic obstructive pulmonary diseases or asthma [33]. $PM_{2.5}$ could be internalized into cells through phagocytosis or pinocytosis, in turn activating the NLRP3 inflammasome, which led to lung fibrosis [34]. A recent study exposed $PM_{2.5}$ to RAW254 cells and observed that macrophages played a critical role in $PM_{2.5}$-induced respiratory inflammation by activating TLR4/NF-kB/COX signaling [35]. Meanwhile, acute exposure to PM_{10} and $PM_{2.5}$ particularly increased cardiovascular disease-related deaths [14]. Another study reported that an increase of 10 $\mu g/m^3$ $PM_{2.5}$ resulted in a 16% increased mortality due to ischemic heart disease and 14% increased mortality due to stroke [36]. An investigation of 65,893 postmenopausal women without previous cardiovascular diseases was conducted; among them, 1816 women suffered fatal or nonfatal cardiovascular events in response to $PM_{2.5}$ exposure. They demonstrated that an increase of 10 $\mu g/m^3$ $PM_{2.5}$ was associated with a 24% increase in the cardiovascular disease incident and a 76% increase in cardiovascular disease-related death [37]. Other studies that revealed a significant correlation between PM exposure and other human diseases are summarized in Table 1 [38–41].

Table 1. Human diseases associated with air pollutants.

Air Pollutants	Human Diseases	Observations/Health Impacts	References
VOCs	Chronic obstructive pulmonary diseases	The emergency hospital visits for chronic obstructive pulmonary diseases were positively linked to VOCs derived from household products, architectural paints, and gasoline emission showing excess risk (ER%) of 2.1%, 95% confidence interval (CI%): 0.9% to 3.4%; 1.5%, 95% CI: 0.2% to 2.9%; and 1.5%, 95% CI: 0.2% to 2.8%, respectively.	[26]
BTEX	Lung diseases	Exposure to BTEX may increase the risk of pulmonary diseases owing to the alteration of the gas-liquid interface properties of pulmonary surfactants.	[27]
SO_2, O_3, NO_2, PM_{10}, and $PM_{2.5}$	Respiratory diseases	The exposure to SO_2 and NO_2 were significantly linked to respiratory disease-related hospitalization. Females and the younger group were more vulnerable to air pollution than males and the older group.	[28]
SO_2 and NO_2	Respiratory diseases	An increment of 10 $\mu g/m^3$ in the SO_2 concentration led to respiratory disease-related mortality of 1.9% and 2.9% in the time-series and the case-crossover analyses in single pollutant models, respectively.	[29]
SO_2, O_3, and NO_2	Asthmatic diseases	The yearly average SO_2 concentration in the studied location was 8.62 times higher than the WHO guideline. Accordingly, the pollutants were closely linked to the high hospitalization rate by acute respiratory diseases and asthmatic symptoms.	[30]
SO_2, NO_x, and $PM_{2.5}$	Chronic kidney disease and end-stage renal disease	Compared to exposure to the first quartile of SO_2, NO_2, and $PM_{2.5}$, exposure to the fourth quartile exhibited an increased risk of developing CKD and ESRD at 1.46-fold and 1.32-fold, 1.39-fold and 1.70-fold, and 1.74-fold and 1.69-fold, respectively.	[31]

Table 1. *Cont.*

Air Pollutants	Human Diseases	Observations/Health Impacts	References
$PM_{2.5}$	Lung fibrosis	$PM_{2.5}$ could be internalized into cells and activate the NLRP3 inflammasome through multiple endocytosis processes involving phagocytosis and pinocytosis, leading to lung fibrosis.	[34]
$PM_{2.5}$	Respiratory diseases related inflammation	Respiratory disease-related inflammation might be induced by $PM_{2.5}$ exposure via activation of TLR4/NF-kB/COX signaling	[35]
$PM_{2.5}$	Cardiovascular diseases	Based on an average concentration of 13.5 μg/m^3 of $PM_{2.5}$, an increase of 10 μg/m^3 led to a 24% increase in cardiovascular diseases incidence and 76% increase in death by cardiovascular diseases.	[37]
PM_{10}, $PM_{2.5}$, and O_3	Dry eye diseases	Increased O_3 and $PM_{2.5}$ results in aggravated ocular discomfort. Increased PM_{10} irritated tear film stability in the DED group.	[38]
$PM_{2.5}$, and O_3	Renal dysfunction	After 1-year and 3-year exposure to $PM_{2.5}$ and O_3, 6.5% and 12.7% of participants showed a reduced eGFR level and elevated UACR level, respectively. These results indicated impaired renal function.	[39]
$PM_{2.5}$	Endocrine, digestive, urological, and dermatological diseases	A 10 μg/m^3 increase in $PM_{2.5}$ exhibited a significant connection with a 0.65%, 0.59%, 0.43%, and 0.36% increase in hospital visits for DERM, ENDO, DIGE, and UROL, respectively.	[40]
$PM_{2.5}$	Pediatric rheumatic diseases	Exposure to $PM_{2.5}$ during 11–40 weeks of pregnancy and 1–14 weeks after birth showed a significant association with the incidence of PRDs.	[41]
PM_{10} and $PM_{2.5}$	COVID-19	Air quality index and $PM_{2.5}$ and $PM_{1.0}$ concentration exhibited a significant association with the risk of COVID-19.	[42]
PM_{10} and $PM_{2.5}$	COVID-19	Italian northern regions showing an excess of PM_{10} and $PM_{2.5}$ levels from legislative standards (50 μg/m^3) have been seriously affected by COVID-19.	[43]

Note: BTEX, benzene, toluene, ethylbenzene, and xylene; ESRD, end-stage renal disease; DED, dry eye disease; AQI, air quality index; NO, nitrogen monoxide; NO_2, nitrogen dioxide; NO_x, nitrogen oxides; SO_2, sulfur dioxide; PM; particulate matter; CB, carbon black; O_3, ozone; CKD, chronic kidney disease; PRDs, pediatric rheumatic diseases; TLR4/NF-kB/COX, Toll-like receptor 4/Nuclear factor kappa-light-chain-enhancer of activated B cells/cyclooxygenase; eGFR, estimated glomerular filtration rate; UACR, urine albumin-to-creatinine ratio; ENDO, endocrine diseases; DIGE, digestive diseases; UROL, urological diseases; DERM, dermatological diseases; COVID-19, Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) diseases.

Interestingly, the high spread of the newly emerged Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) disease (COVID-19) may be also related to air pollution. According to a recent report, the air quality index and the levels of $PM_{2.5}$ and $PM_{1.0}$ are positively associated with COVID-19 infection [42]. As the atmospheric PM has a sub-layer, the virus could survive in airflows for hours or days [43]. In the northern regions of Italy, one of the most affected regions by COVID-19, showed a great amount of atmospheric particulate matter going above the legislative standards in February 2020. In response to exposure to air pollution, angiotensin-converting enzyme 2, the receptor for SARS-CoV-2, was upregulated, which might increase the efficiency of viral infection. Moreover, air pollution could accelerate SARS-CoV-2 spread and survival by facilitating their transmission and attachment to a pollutant [44].

Several potential mechanisms have been suggested that can be activated in the human body by air pollutants. There is an increasing scientific consensus that the inhaled air pollutants generate reactive oxygen species (ROS) that, in turn, induces a systemic inflammatory state and autonomic nervous system imbalance [8,45–47]. Meanwhile, air pollutants contain byproducts of oxidative stress that trigger or exacerbate the inflammatory reaction by damaging mitochondrial function [48–50]. The interaction between the byproducts and certain genes may also induce specific chronic diseases. The accumulated data indicate that inhaled PM can cause an increase in the white blood cell count, blood pressure, fibrinogen levels, plasma viscosity, inflammatory responses, insulin resistance, and endothelial dysfunction, as well as a decrease in NO excretion and impaired sodium excretion. All these alterations are correlated with vascular damage, intraglomerular hypertension, glomerulosclerosis, or tubulointerstitial damage, which cause various diseases [45,51].

4. Mechanisms of Phytoremediation

Understanding the basic phytoremediation processes is vital to advance the applicability of plants for air purification. The gas exchange to obtain CO_2 is well known as a primary process of plants [1]. During this process, the phyllosphere of plants absorbs the air contaminants and transferred them into the soil and rhizosphere, consequently, metabolized, isolated, or excreted into the substances showing lower toxicity and promoting plant growth [18]. Figure 2 illustrates various phytoremediation processes.

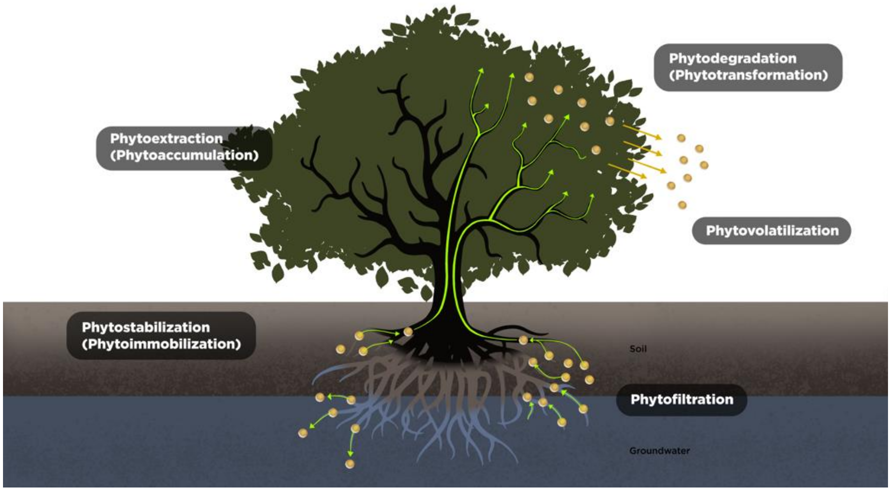

Figure 2. Schematic representation of phytoremediation processes.

4.1. Phytoextraction (Phytoaccumulation)

Phytoextraction or phytoaccumulation defines the uptake of contaminants, primarily metals, from the soil [52]. In general, the uptake of contaminants into plants is performed by the root via an aqueous phase. The soil contaminants resulting from air pollution penetrate through the plasma membrane into the cytoplasm of the root cells via transpiration, diffusive transport, and microbial-facilitated transport [53].

4.2. Phytostabilization (Phytoimmobilization)

Phytostabilization describes the immobilization of contaminants that occurs in the rhizosphere area. Lignin in the cell wall of plant roots or humus absorbs and converts contaminants into insoluble compounds, in turn accumulating them in the rhizosphere [25]. In general, this technique is useful for soil remediation to reduce metal contaminants such as arsenic, cadmium, chromium, copper, lead, and zinc. The phytostabilization process prevents the migration of contaminants into the groundwater by reducing their mobility, diminishing the bioavailability of metal into the food chain. Moreover, this process can reconstruct the vegetation cover where natural vegetation is difficult due to high metal concentrations in the soil or physical disturbances by surface materials [54].

4.3. Phytovolatilization

In phytovolatilization, the inorganic and organic contaminants captured by plants are degraded and subsequently volatilized into the atmosphere through stomata [55]. The transpired contaminants may be degraded by hydroxyl radicals into the atmosphere and can stay as air pollutants but with a lower toxicity than before [56].

4.4. Phytodegradation (Phytotransformation)

Phytodegradation describes the breakdown of complex organic pollutants to simple compounds or metabolization of pollutants in the phyllosphere and rhizosphere [57]. The transformation in the rhizosphere, also termed as rhizodegradation (or considered as phytostimulation), is carried out by soil organisms such as bacteria, fungi, or enzymes released from plants or microorganisms [56]. The contaminants are degraded in the rhizosphere, as well as within the plants by specific plant enzymes such as nitroreductases, dehalogenases, and laccases [25]. The compounds released from plants, such as sugars, amino acids, or enzymes, can stimulate bacterial growth in the soil and reversely stimulate microbial and fungal degradation by releasing exudates/enzymes into the rhizosphere. That is why rhizodegradation is also called plant-assisted bioremediation [54,58].

4.5. Phytofiltration

This technique is dominantly used for remediation of groundwater, wastewater, or surface water contaminated by metals or organic and inorganic compounds [59]. When plants exceed the saturation limit of contaminants, they act similarly to phytoextraction. The rhizosphere of plants ab/adsorb and precipitate contaminants into the biomass, which is why this process is generally called rhizofiltration. To use this technique effectively, tolerance for contaminants, high surface area, root biomass, and accumulation capacity are the most important criteria for selecting the appropriate plant species [25].

5. Phytoremediation Mechanisms of Main Air Pollutants

5.1. Removal of Gaseous Pollutants

During photosynthesis, plants absorb the VOCs through the stomata and cuticle wax, subsequently converting them into amino acids through the Calvin cycle [60,61]. In the intercellular spaces of plants, the absorbed pollutants are stored or react with the inner-leaf surfaces and water film, then are degraded or excreted into the atmosphere [18,25]. Other common gaseous air pollutants, such as SO_2, CO_2, NOx, and O_3, are also accumulated in plant cells and tissues mainly through the stomata, wax, and cuticles. Photosynthesis is a basic plant mechanism in which plants absorb carbon dioxide (CO_2) and changes it into oxygen. Stomata located on the epidermis of leaves and plant stems are the primary area where the gas exchange process occurred [62]. SO_2 is predominantly accumulated through the stomata, then utilized in a reductive sulfur cycle. NO_2 accumulates in plant cells directly through foliar deposition or indirectly through soil deposition or rainwater. The leaf penetration of NO_2 occurs via stomata opening and is governed by various factors, including the plant species, plant age, and atmospheric concentration of NO_2. NO_2 may also be accumulated in plants in the form of nitrate and nitrite, subsequently being reduced by nitrate and nitrite reductases, generating NH_4, which is then assimilated to glutamate through the GS-GOGAT pathway [63,64].

5.2. Removal of Aerosol Pollutants (Prticulate Matter)

PM removal depends on plant-morphology, climatic circumstances, such as rain and wind, and composition of PMs. Plants remove PM predominantly via two mechanisms. First, they adsorb PM through their shoots or foliage or shoots, in turn accumulating them in the phyllosphere [25]. The removal capacity via this mechanism is significantly correlated with the leaf structure, size, and surface roughness. Meanwhile, plants can stabilize PM in their wax layers, which is influenced by the wax thickness and composition [65].

Some plant-associated microbes play a role in pollutants removal by degrading organic pollutants or reducing the phytotoxicity of the contaminants [64]. In addition, they contribute to plant growth and development by producing plant growth hormones and organic acids to cope with biotic and abiotic stress, such as pollution. These released products lead to increased plants biomass, subsequently improving the PM removal capacity [66,67]. In general, PM toxicity is induced by ROS generation on its surface, which is related to surface-associated EPFRs (environmentally persistent free radicals). Some plant-associated microbes reduce the EPFR concentration on the PM surface, also neutralizing the ROS formed by the EPFRs. However, the detoxification mechanism of the contaminants on the surface of leaves by microorganisms has not been well determined [18].

6. Applications of the Phytoremediation for Improving Air Quality

6.1. Indoor Air Quality

The initial study that used the phytoremediation technique for air pollution mitigation was conducted by the National Aeronautics and Space Administration (NASA). This study achieved a reduction of more than 300 VOCs in the interior atmosphere of their station (Skylab), which triggered the investigation for improving indoor air quality using potted plants [68]. Ornamentally potted *Chamaedorea elegans* plants were used to remove formaldehyde in the experimental chamber; subsequently, *C. elegans* eliminated formaldehyde with a maximum capacity of 1.47 mg/m^2 h at an inlet concentration of 14.6 mg/m^3 [69]. A study revealed that *Opuntia microdasys* removed 2 ppm of BTEX in the experimental chambers completely after 47, 48, 55, and 57 h at the removal rates of 1.64, 1.18, 0.54, and 1.35 mg/m^2d^1, respectively. The study suggested that 2.5 ppm of BTEX in a 30 m^3 room can be removed completely by ten *O. microdasys* pots after 36, 40, 30, and 39 h, respectively [70]. Another study demonstrated that potted *Chlorophytum comosum* L. accumulated indoor PM_{10}, $PM_{2.5}$, and $PM_{0.2.}$ in their wax to facilitate the attachment of PM to leaves tightly, and it was effectively stabilized [71]. Usage of microorganisms can improve the remediation capacity of potted plants. Addition of cultured microorganisms into the rhizosphere of plant species improved the formaldehyde removal efficiency: removal rates for fresh weight *Aloe vera* 23.1 $\pm$ 0.1 µg/h with microbes versus 18.5 $\pm$ 0.21 µg/h/g without microbes; *Tradescantia zebrine* 86.4 $\pm$ 0.7 with microbes versus 59.3 $\pm$ 0.2 µg/h/g without microbes; and *Vigna radiata* 97.6 $\pm$ 0.9 with microbes versus 25.1 $\pm$ 4.2 µg/h/g without microbes [72]. In addition, a hydroponic system was designed that was composed of *Ophiopogon japonicus* and phenol-degrading bacteria, *Staphylococus epidermis* and *Pseudomonas* spp., which was combined with an air compressor. This system showed the high phenol-degrading capacity of about 1000 g/L daily [73]. Although potted plants revealed the ability to reduce air contaminants, their capacity is deficient to control complex air pollutants or indoor air conditions. For example, indoor spaces have low light intensity conditions that lead plants to emit a significant amount of CO_2 into the atmosphere during their respiration [74]. This problem was resolved using a botanical biofilter composed of CAM and C3 plant species [75,76]. CAM plant species are capable of fixing CO_2 during the nighttime, and C3 plant species fix CO_2 during the daytime and emit it during the night [77]. Hence, the mixture of CAM and C3 plants in a botanical biofilter can minimize the total CO_2 emission accompanying high VOCs and $PM_{2.5}$ removal efficiency, compared to the biofilter composed of individual plant species [76]. As mentioned above, the botanical biofilter (green wall) is gaining more attention because generally plants in green walls are vertically aligned, and this alignment can provide a space-efficient means of exposing greater plant biomass to the polluted air [68]. The authors in [78] emphasized the importance of plant selection on the plant wall, since the green walls composed of different plant species showed different PM single-pass removal efficiencies (SPRE). In this study, fern species removed all measured particle sizes with the highest removal efficiencies ($PM_{0.3–0.5}$ = 45.78% and $PM_{5–10}$ = 92.46%), and plants with fibrous roots revealed a higher removal efficiency than those having tap roots. Meanwhile, various studies demonstrated that the airflow through the plant wall and the optimization of the growing medium in the plant wall system can maximize the capacity of the biofiltration. A recent study suggested the prototype of a botanical biofilter, which comprises of a botanical biofilter containing the horizontally grown plants in growth media, an evaporative medium, and a mechanical ventilation system. This biofilter revealed $PM_{2.5}$, PM_{10}, and VOCs removal efficiencies of 54.5%, 65.42%, and 46%, respectively [79]. Another recent study reported that a botanical biofilter using a large-scale indoor species by connecting it to an air handling unit (AHU). Consequently, this system removed 3826.4 ppbv of isobutylene with an initial concentration of 5000 ppm, recording an average of 2% single-pass efficiency [80]. A study also suggested that a fan located at a central opening on the green wall's back side can drive air through the plant medium, then onward to the plant's canopy, which can increase the rate of air purification. Moreover, the wet plant wall modules led to much more air through the modules as the water coalesced the medium particles that generated larger pores for air to pass through [81]. For optimizing the biowall capacity, the selection of a plant medium was emphasized; the organic-rich growing medium of vermicompost along with perlite and cocopeat was suggested as an optimized internal green wall medium, especially when this is combined with *Aptenia cordifolia* [82]. By adding granular activated carbon into the differently sized coconut husk-based substrates could improve the VOC removal capacity of the biowall, and it was suggested that a 50:50 composite medium presented the best VOC deposition [83]. Plant walls containing a soil-less growing medium with activated carbon, which was connected to the forced-air system, reduced the VOCs significantly, recording a 57% single-pass removal efficiency [84].

To understand the plant wall mechanism compared to the plant in the soil, a study investigated the change in bacterial communities surrounding plant roots in the botanical biofilter in response to VOC exposure. Consequently, they observed differences in bacterial communities between the biowall-grown and soil-grown plants as well as between bacterial communities surrounding plant roots exposed to clean air and those from VOC-exposed plant roots. As an enriched level of *Hyphomicrobium*, well known as a degrader of halogenated and aromatic compounds, was observed from VOC-exposed and biowall-grown roots, this bacterial genus was suggested as the key microorganism in the plant wall mechanism [85]. Another study monitored the microbial dynamics in the plant walls, subsequently establishing that airborne VOCs formed microbial communities, enriching the VOCs utilizing bacteria species in the irrigation water, where most of the VOC degradation in the biowall occurs [86]. Though microbial communities surrounding the wall-grown plants play a critical role in phytoremediation, most studies have focused on VOC-related microorganisms. Therefore, future investigations of microbial communities in response to exposure to other pollutants is needed for understanding the biowall mechanism. Further investigation of the toxicity of the biodegradation products also is needed to develop an appropriate usage of microorganisms in the phytoremediation process. More details about the phytoremediation for improving indoor air quality are listed in Table 2.

Table 2. Phytoremediation for improving indoor air quality.

Location	Pollutants	Observations/Suggested Measures	References
Chamaedorea elegans	Formaldehyde	Potted *C. elegans* removed 65–100% of formaldehyde in the chamber. The removal capacity depends on the inlet concentration, and the light condition was more efficient than the dark condition.	[69]
Opuntia microdasy	BTEX	*O. microdays* removed BTEX in the chambers with the removal rates 1.35, 1.18, 0.54, and 1.64 $mg/m^2\ d^1$, respectively. For complete removing 2.5 ppm of BTEX in a 30 m^3 room, ten pots of *O. microdasys* were suggested.	[70]
Chlorophytum comosum L.	PM	*C. comosum* accumulated indoor PM_{10}, $PM_{2.5}$, and $PM_{0.2}$ in their waxes. The accumulation occurred more in wax than on the surface to facilitate the attachment tightly to leaves and phytostabilize effectively. The accumulation amount depends on the kind of activity taking place in the room.	[71]
Aloe vera (Haw.) Ber, Tradescantia zebrina Bosse, and Vigna radiata (Linn.) Wilczek (V. radiata)	Formaldehyde	Adding microbes to hydro-cultured plants system improved the formaldehyde removal efficiency by 6.7–90.5%. While the remediation process in plant-only systems occurred through redox and enzymatic reactions, that in the plant-microbe systems occurred mainly via microbial degradation mechanisms.	[72]

Table 2. *Cont.*

Location	Pollutants	Observations/Suggested Measures	References
Ophiopogon japonicus	Phenol and PM	A hydroponic system composed of *Ophiopogon japonicus* and phenol-degrading bacteria, *Staphylocoсus epidermis* and *Pseudomonas* spp., was combined with an air compressor that sucks air and injected it into the bioreactors to circulate in the plant pots. This system showed a high phenol-degrading capacity of about 1000 g/L daily. Additionally, this system absorbed PM and produced oxygen, improving air quality.	[73]
Chlorophytum comosum and *Sansevieria trifasciata*	CO_2	The biofilter containing a combination of *C. comosum* and *S. trifasciata* removed 3.9–4.7 mg/m^3 toluene within 2–3 h, showing low CO_2 emission under both light and dark conditions.	[75]
Sansevieria trifasciata and *Chlorophytum comosum*	$PM_{2.5}$, VOCs, and CO_2	A biofilter composed of a CAM and C3 plants combination minimized the total CO_2 emission accompanying high $PM_{2.5}$ and COCs removal efficiency, compared to a biofilter composed of individual plant species.	[76]
Ficus lyrate, *Chlorophytum orchidastrum*, *Nephrolepis cordifolia duffii*, *Nephropelis exaltata bostoniensis*, *Nematanthus glabra*, *Schefflera amate*, *Schefflera arboricola*	PMs	Plants having fibrous roots revealed higher removal efficiency than those having tap roots, and fern species presented the highest single-pass removal efficiencies ($PM_{03–0.5}$ = 45.78% and $PM_{5–10}$ = 92.46%).	[78]
Epipremnum aureum	PM_{10}, $PM_{2.5}$, and VOCs	A botanical biofilter comprising horizontally grown plants in growth media, an evaporative medium, and a mechanical ventilation system showed $PM_{2.5}$, PM_{10}, and VOCs removal efficiencies of 54.5%, 65.42%, and 46%, respectively.	[79]
Schefflera arboricola	VOCs	An air handling unit connected to a biowall removed 3826.4 ppbv of isobutylene, recording an average of 20% single-pass efficiency.	[80]
Schefflera arboricola and *Chlorophytum comosum* 'variegatum'	PM_{10}, $PM_{2.5}$, and VOCs	A fan located at a central opening on the green wall's back space can drive air through the medium-plant-roots mix, then onward to the plant's canopy. This enabled more air to pass through the green wall substrate with greater remedy efficacy. Additionally, the wet plant wall modules led to much more air through the modules.	[81]
Aptenia cordifolia, *Carpobrotus edulis*, *Peperomia magnoliiaefolia*, and *Kalanchoe blossfeldiana*	[1] n.g.	The organic-rich growing medium of vermicompost along with perlite and cocopeat was suggested as an optimal medium for designing a sustainable internal green wall, especially when this is combined with *Aptenia cordifolia*.	[82]
Nephrolepis exaltata bostoniensis	PM, benzene, and VOCs	Adding granular activated carbon (GAC) into the coconut husk-based substrates, improved the VOCs and benzene deposition rate, while PM removal rate was reduced.	[83]
Asplenium antiquum, *Philodendron scandens*, *Philodendron scandens* 'Brazil', and *Syngonium podophyllum*.	Methyl ethyl ketone	The plant wall with a soil-less growing medium containing activated carbon was combined with a forced-air system, which draws the polluted air through the biowall and reduced the VOCs significantly, recording a 57% single-pass removal efficiency.	[84]
Ficus elastica and *Schefflera arboricola* "Gold Capella"	VOCs	Compared to clean-air exposed and soil-grown plants, VOC-exposed and biowall-grown plants exhibited an enriched level of *Hyphomicrobium*, a degrader of halogenated and aromatic compounds, surrounding the roots area.	[85]
Epipremnum pinnatum cv. Aureum and *Davallia fejeensis* Hook	VOCs	VOCs formed the microbial communities, enriching the VOCs utilizing bacteria species in the irrigation water, where most of the VOC degradation in the biowall occurs.	[86]

[1] n.g., not given.

6.2. Outdoor Air Quality

While most phytoremediation technologies have been developed at the lab-scale, the potential of various plant species to reduce outdoor air pollution has been well established. In 2015, shrubs and trees in Tabriz removed 238.4 t of air pollutants, and they are expecting an increase of the elimination level up to 814.46 t over the next 20 years [87]. In another study, vines, shrubs, and coniferous trees were demonstrated as suitable species for phytoremediation. Among them, *Parthenocissus quiquefolia* and *Betula pendula* 'Youngii' showed the highest capacity to remove PMs by collecting them on the wax [88]. By sampling leaves from in situ plant walls, the authors in [89] examined that *Nematanthus glabra*, *Chlorophytum comosum variegatum*, *Philodendron Xanadu*, and *Spathiphyllum wallisii* showed the highest PM accumulating capacity. They found no specific correlation between leaf traits and PM deposition, while other indoor-based studies have considered that leaf characteristics play a critical role in performing PM removal in green walls. In contrast to this study, most outdoor-based studies discovered a close correlation between remediation capacity and leaf characteristics. *Wedelia trilobata*, having wider leaves, have been reported to absorb more heavy metals than *Syzigium oleina* showing a smaller leaf surface area [90]. Moreover, plants presenting the acicular needle shape in their leaves accumulated $PM_{2.5}$ more efficiently than plants having broad leaves [91]. Plant species with a low leaf area, hydrophilic leave traits, and a high abaxial stomatal density entrapped significantly more ambient PM; accordingly, *Muntingia calabura* removed the highest amount of PM among 49 screened plant species [92]. *Hebe albicans Cockayne*, *Hebe x youngii Metcalf*, *Buxus sempervirens* L., and *Thymus vulgaris* L., having smaller leaves, entrapped a significant amount of PM_1, $PM_{2.5}$, and PM_{10} [93]. In addition, the leaves with adaxial surfaces revealed significantly higher PM densities compared to the leaves with abaxial surfaces [93]. Meanwhile, the pollutant removal capacity varies from spaces having different degrees of pollution. For example, *Cinnamomum japonicum*, *Loropetalum chinense*, and *Osmanthus fragrans* possessed high efficiency for PM accumulation in traffic and university campus areas, also showing moderate removal efficacy in an industrial area [94]. A recent study evaluated Air Pollution Tolerance Indices (APTI) from sixty-seven plant species in terms of chlorophyll and ascorbic acid levels, leaf pH, and relative water content. They suggested that the plants with the highest APTI (greater than 10.83) for planting near areas showing heavy vehicular air pollution, and the species showing the next highest APTI (10.83 to 8.77) for greenbelts [95]. Although, the potential of plants to improve the outdoor air condition has been well established, while their functional value at the in situ scale is yet to be assessed adequately [96]. More details about the phytoremediation for improving outdoor air quality are listed in Table 3.

Table 3. Phytoremediation for improving outdoor air quality.

Location	Pollutants	Observations/Suggested Measures	References
Tabriz, Iran	O_3, SO_2, NO_2, CO, $PM_{2.5}$	In 2015, shrubs and trees removed 238.4 t of air contaminants, and an increase of the elimination up to 814.46 t over the next 20 years is expected if appropriate, feasible urban forest management is performed.	[87]
North Katowice, Poland	PM	Among vines, shrubs, and coniferous trees, *Parthenocissus quiquefolia* and *Betula pendula* 'Youngii' accumulated the highest amounts of PM in their wax. The accumulated PM contained carbon, oxygen, silicon, iron, and heavy metals.	[88]
Fifteen different urbanized areas in Sydney, Australia	PM	The leaf traits were not the specific factor to determine the deposition capacities of plants. Among investigated plants, *N. glabra, C. comosum variegatum, P. Xanadu,* and *S. wallisii* entrapped the most amount of PM.	[89]
Surabaya town, Indonesia	Lead (Pb)	*Wedelia trilobata* and *Syzigium olein* are grown on the main roads and exposed to heavy metals. *Wedelia trilobata*, having wider leaves, absorbed more heavy metals than *Syzigium oleina* showing a smaller leaf surface area.	[90]

Table 3. *Cont.*

Location	Pollutants	Observations/Suggested Measures	References
Beijing Forestry University, Beijing, China	$PM_{2.5}$	Compared to broadleaved plant species, needle-leaved coniferous species accumulated higher amounts of $PM_{2.5}$. The $PM_{2.5}$ removal capacity of broadleaved species was correlated to the number of grooves and trichomes.	[91]
Hanoi, Vietnam	PM	Leaves with a lower area, hydrophilic traits, and a high abaxial stomatal density entrapped more PM; accordingly, *Muntingia calabura* showed the highest PM removal capacity among 49 screened plant species.	[92]
Birmingham New Street railway, United Kingdom	PM_1, $PM_{2.5}$, and PM_{10}	*Hebe albicans Cockayne*, *Hebe x youngii Metcalf*, *Buxus sempervirens* L., and *Thymus vulgaris* L., which have small leaves, revealed the highest PM removal capacity. Leaves with adaxial surfaces showed higher PM densities compared to those with abaxial surfaces.	[93]
Kunming City, Southwest China	PM	*Platanus acerifolia* and *Magnolia grandiflora* showed the highest PM removal among deciduous and evergreen trees, respectively. PM entrap capacity depends not only on the leaf characteristics, but also on the pollution grade; *Loropetalum chinense, Osmanthus fragrans, and Cinnamomum japonicum* exhibited significant accumulation of PM in traffic and university campus areas, whereas showing moderate removal efficacy in an industrial area.	[94]
Trivandrum City, Kerala, India	Air Pollution Tolerance Indices (APTI)	Based on APTI, plants showing the highest APTI, *Agave americana*, *Anacardium occidentale*, *Cassia fistula*, *Cassia roxburghii*, *Mangifera indica*, and *Saraca asoca*, were suggested for near areas presenting heavy vehicular air pollution, and plants showing the next highest APTI for greenbelts.	[95]

7. Conclusions

Phytoremediation is an emerging potential tool to improve in situ air conditions due to its significant advantages, such as being eco-friendly, cost-effective, and having publicly applicable methods. However, plant growth mainly depends on the growing conditions, while the remedy mechanisms are relatively slower than other mechanical air-purifying processes. The applicability of the phytoremediation technique in highly polluted air has not been clearly revealed. To become a complementary or alternative tool for engineering-based remediation methods, optimizing the remedy process by supplementary treatments or finding the best combination junction with other methods is necessary. Moreover, investigation of the toxicity of the biodegradation products is needed for high public acceptance.

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