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Chapter

Phytoremediation toward Air Pollutants: Latest Status and Current Developments

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Abstract

In recent years, air pollution has become one of the major environmental concerns that threaten health of the living organisms and its surroundings. Increasing urbanization, industrialization, and other anthropogenic activities impaired the air quality of indoor and outdoor environment. However, global organizations are focusing on ecological and biological means of solutions to reduce or eliminate dangerous contaminants from ecosystems in a sustainable manner. In this fact, plants are capable of improving or cleansing air quality and reduce the concentration of harmful pollutants from the environment through various remediation processes. Plants interact with air pollutants and fix them through various biological mechanisms in both associated and non-associated forms of microbes. In association forms, the mutualistic interaction of plant and microbes leads to higher growth efficiency of plants and results in enhanced pollutant degradation in rhizosphere as well as phyllosphere. In this background, the book chapter provides a comprehensive discussion of the existing literature and recent advances in phytoremediation process for the mitigation of harmful air pollutants. The role of indoor plants and aids for the enhancement of phytoremediation process towards air pollutants are also discussed.

Keywords: air pollution, phytoremediation, microbes, indoor gardens, biotechnological advancement

1. Introduction

Air pollution is one of the major threat to ecosystem services and imposes negative impacts on all living organisms [1]. The composition and type of air pollutants in a particular region majorly depends upon its sources, emission rate, and climate conditions. The pollutants that contribute to air pollution are as follows: carbon monoxide (CO), lead (Pb), nitrogen oxides (NO_x), ground-level ozone (O_3), sulfur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOCs), poly-aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) [2–4]. Ground-level ozone is a colorless secondary pollutant and is produced when NO_x and VOC_s react in sunlight and stagnant air [5]. On the other hand, particulate matter (PM) is comprised of carbonaceous particles with accompanying adsorbed organic substances and reactive metals [6]. Gaseous pollutants such as SO_x and NO_x also aid particle formation through complex atmospheric photochemical reactions involving ammonia released from agricultural fields [5]. Road traffic is a significant source of NO_2, particularly from diesel automobiles that contribute to the global air pollutants emission in large cities. However, the main sources of SO_2 are industrial emissions and maritime transportation.

Global organizations are concerned about the increasingly deteriorating air quality because it is believed to be one of the leading causes of approximately 3.1 million fatalities each year [7–10]. The average life expectancy of urban populations is decreasing as exposure to high levels of air pollutants over a longer period of time. Pollutants like fine particulate matter ($PM_{2.5}$) and ground-level ozone are unquestionably linked to an increase in mortality rate [11]. Particulate matter alone causes23% of total damage to human health despite representing only 6% of the total air pollutants [12]. Pollution-related illness has been estimated to cause as many as 9 million premature deaths during 2015, which was three times greater than the number of deaths from other illnesses such as malaria, AIDS, and tuberculosis altogether [13]. Alongside, the air quality of the indoor environment has become a global issue as people in urban areas spend more than 90 percent of their day in office spaces or residential areas [14]. Poor indoor microclimate adversely affects the health, happiness, and productivity of occupants [15]. Major indoor air pollutants such as PMs, VOCs, PAHs, PCBs, NH_3, SO_2, H_2O_2, HNO_3, HNCO, CO, and H_2S upon inhalation are linked to a range of health problems including asthma, heart disease, reproductive problems, neurological issues, irritate the eyes, and respiratory disorder [13].

Remediation of these pollutants for sustaining ecosystem and human health using either physical, chemical, or biological approaches is applicable but limited due to the cost, labor requirements, and safety hazards [16]. Here, phytoremediation can be effectively used as an alternative technique, and it is gaining popularity, acceptance, and implementation due to ease and an array of benefits. Phytoremediation is the use of plants and associated microorganisms to reduce or degrade the concentrations or toxicity of pollutants. Phyto-stabilization, rhizo-degradation, phyto-extraction, phyto-degradation, phyto-volatilization, and phyto-filtration are the fundamental mechanisms of the phytoremediation process. The efficiency of these processes can be improved by using synthetic and natural additives, suitable microbes and host, and genetic engineering/editing. Various modes of biological remediation include microbes-related remediation, enzyme-assisted remediation, vermi-remediation, phyto-remediation, and zoo-remediation exists in nature. However, microbial-assisted phytoremediation including plants and microbes is one the most effective, sustainable, and economical approach to reduce harmful pollutants from the environment [17, 18]. The bioremediation of air pollutants by the phyllosphere or microbes associated with the leaves, not just the microbes themselves, is known as phyllo-remediation. While rhizo-remediation is the process of degrading organic contaminants in the soil region around plant roots (the rhizosphere), typically as a consequence of enhanced catalytic activities of root associated microbes [19–21].

Various ornamental plant species have been used for the enhancement of air quality. Previously, *Chamaedorea elegans* and *Opuntia microdasys* plants have been shown to reduce the concentrations of formaldehyde and BTEX. Also, *Chlorophytum comosum* L. plants are able to accumulate indoor particulate matter pollutant (PM_{10}, $PM_{2.5}$, and $PM_{0.2}$). The rhizospheric microbes associated with the *Aloe vera, Tradescantia* *zebrina*, and *Vigna radiata* plant species have improved or enhanced the formaldehyde neutralization efficiency by 2–3 times [22]. The vertical gardens growing in soil-less system, the nutrient-enriched solution with activated carbon have reduced the level of VOCs in indoor environments [23]. Considering this, the book chapter discusses the existing literature and recent advances in the phytoremediation process and its potential against air pollutants.

2. Air pollutants: types, sources, and health issues

Gaseous pollutants and particulate matter are the two primary types of pollutants that are found in the atmosphere (**Figure 1**). There is a substantial difference between the levels of these pollutants found in outdoor and indoor environments which is primarily allocated to the sources from which they are derived.

2.1 Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is a colorless and odorless gas, and it constitutes about 0.03% (300 parts per million) of the total atmospheric gases. It is heavier than other

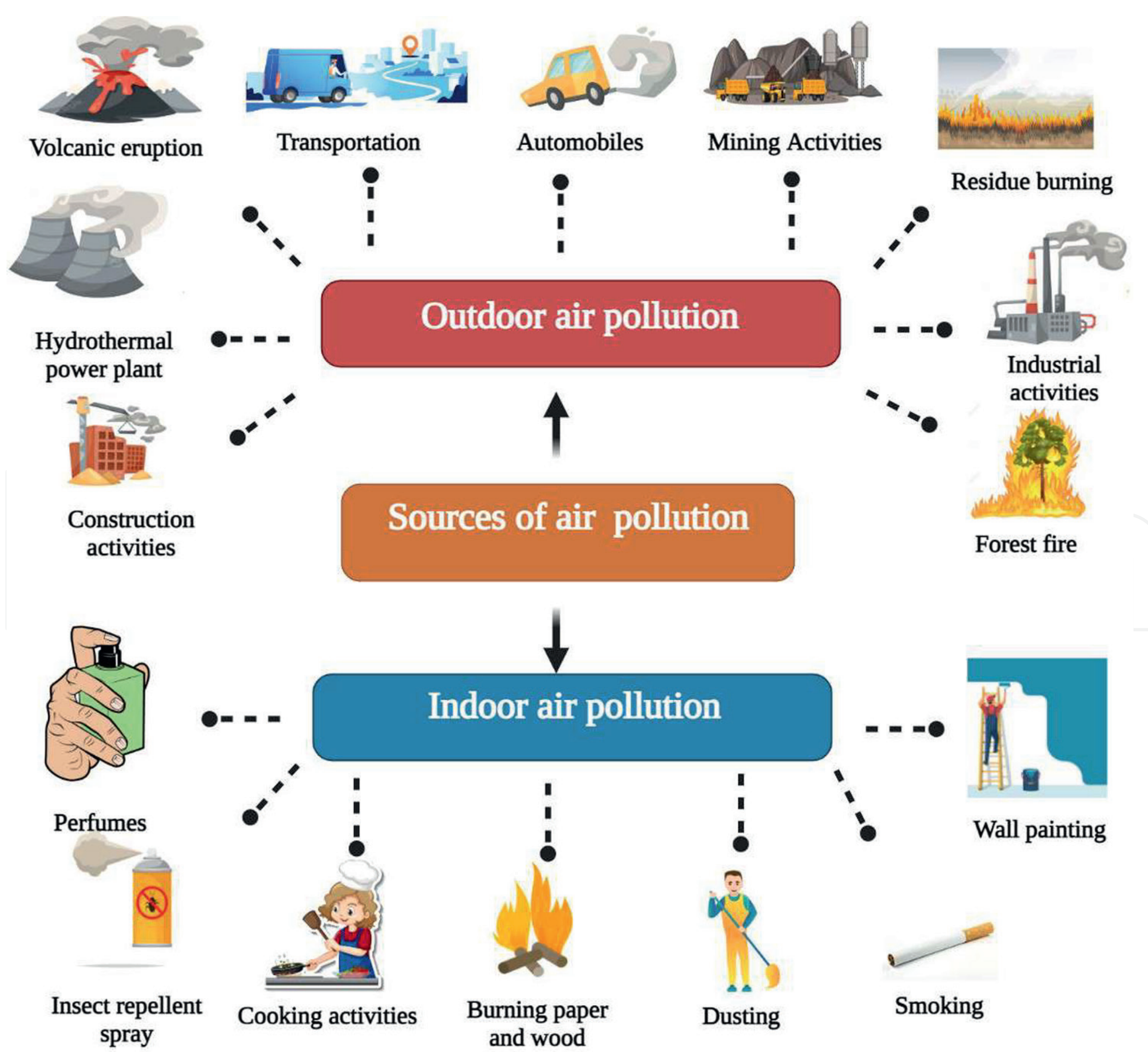

Figure 1.
Different sources of outdoor and indoor air pollutants.

non-combustible gas and can accumulate in the lower phase of the environment, resulting in an oxygen deficiency [24]. Carbon dioxide is majorly a by-product of biological respiration or fossil fuel combustion [25, 26]. Fossil fuel-fired power plants contribute about 33–40% of the total CO_2 emission globally, with coal-fired power plants being the key contributor [27]. Whereas, anthropogenic CO_2 emission is due to activities like forestry, deforestation, land clearing for agriculture [28]. Rising atmospheric CO_2 levels result in the greenhouse effect and speed up the global warming process [29]. The average ambient CO_2 concentration has been steadily rising and has reaches up to 410 ppm. A CO_2 level of 600 ppm is considered acceptable, but a CO_2 level above 1000 ppm is detrimental and leads to CO_2 toxicity-related side effects [30]. Excessive CO_2 concentration in the blood (hypercapnia) give rise to acidosis, which is characterized by a low blood pH (increased acidity). The respiratory, cardiovascular, and central nervous systems are all affected by the lower blood and tissue pH. Other commonly reported symptoms of CO_2 toxicity are headaches, lethargy, moodiness, mental slowness, emotional irritation, and sleep disruption [31].

2.2 Carbon monoxide (CO)

Carbon monoxide is colorless, combustible, and extremely deadly gas [32]. It is emitted from both natural and man-made sources. It is produced when carbonaceous materials are burned in an incomplete manner [33]. The two most common sources of emission of carbon monoxide in ambient air are smoke from fires and exhaust fumes from automobile engines (in the absence of a catalytic converter) [34]. Additionally, the combustion of charcoal and wood can also release carbon monoxide. The minimum exposure limit of carbon monoxide is around 100 mg/m^3 for 15 minutes, 60 mg/m^3 for 30 minutes, 30 mg/m^3 for 1 hour, and around 10 mg/m^3 for 8 hours [35]. In most cases, carbon monoxide poisoning causes from inhalation of gases coming out from common household areas such as garages, kitchens, basements, or workrooms and fuel burning. Carbon monoxide toxicity leads to dizziness, headache, weakness, nausea, vomiting, and loss of consciousness [36]. Further, the inability of a cell to use oxygen (e.g., effective oxygen deprivation) leads to chemical asphyxiation and hypoxia, which is the most significant harmful effect of carbon monoxide.

2.3 Volatile organic compounds (VOCs)

VOCs are categorized as harmful air pollutants because of their relation with carcinogenic, impairing blood production and weakening nervous system in humans [34]. Commonly found VOCs in atmosphere are aromatic hydrocarbons BTEX (benzene, toluene, ethyl benzene, and xylene) and halogenated hydrocarbon like chloroethylene and trichloroethylene [37]. The major sources of BTEX are vehicle/aircraft, processing of petroleum products, paints, thinner, ink, cosmetics, and pharmacy. Benzene/toluene ratio is used more often to know the source of emission. If the ratio is >0.5 shows that the source is other than transport and if the ratio is <0.5, vehicular emission is the major source. Among the six compounds of BTEX, toluene is the one that is most easily degraded due to the presence of a side chain that provides different attack routes for the microbial enzymes to act upon. Isoprene, a naturally occurring biological component, is one of the most significant contributors to emissions of VOC [38]. Anthropologically, VOCs are generated from both domestic and industrial processes including textile cleaning, fertilizers and pesticide application, septic system, traffic, fumigation, building materials, and pharmaceutical industries [39]. In indoor environments, VOCs are released by combustion, newly constructed or refurbished structures and building materials such as paints, carpets, solvents, various plastics, and wooden furniture [40]. The acceptable level of VOCs concentration in an indoor environment is ranged from 0 to 400 ppb [41, 42]. Short-term exposure of VOCs may induce like nausea, vomiting, and fatigue. However, long-term exposure may cause lung cancer, leukemia, and other forms of malignancy [43, 44].

2.4 Particulate matters (PMs)

Carbon-containing particles along with reactive metals and adsorbed organic compounds belong to the particulate matter components of air pollution [7]. It is a mixture of solid and liquid particles in the air that can be breathed in and may cause serious health problems. According to particle size, PM is further divided into three groups: coarse particles (PM_{10}, diameter less than 10 μm), fine particles ($PM_{2.5}$, diameter less than 2.5 μm), and ultra-fine particles ($PM_{0.1}$, diameter less than 0.1 μm) [7]. It can be originating either from natural or anthropogenic activities. Eruptions of volcanoes, dust and wind storms, forest fires, salt spray, rock debris, chemical reactions between gaseous emissions, and soil erosion are some examples of natural sources. PM is also produced by human activities such as burning fuel, making steel, processing petroleum, making cement, making glass, mining, smelting, power plant emissions, burning coal, and disposing of agricultural waste [45]. There is a clear relationship between PM concentrations and seasonal variations [46, 47]. According to the recent air quality guidelines 2021 by WHO, exposure to $PM_{2.5}$ and PM_{10} concentration up to 65 $\mu g/m^3$ for the 24-hour is safe. Black carbon is a carbonaceous component released because of incomplete combustion of fossil fuels (particularly diesel, wood, and coal) (PM 2.5) [10, 48]. Higher exposure to black carbon is a major health issue that can induce heart attacks and strokes. The regulations governing air pollution focus on $PM_{2.5}$ as the primary concern. PM_{10} mostly affects the upper respiratory system, whereas ultra-fine particles detrimental to the lower respiratory tract, lungs, and alveoli.

2.5 Polycyclic aromatic hydrocarbons (PAHs)

These are the vast categories of chemical compounds that include two or more bound benzene rings as diverse arrangements [49]. PAHs are a type of pollutant that can be found almost everywhere in the environment including soil, water, and air. PAHs are the by-product of the incomplete burning of organic substances such as wood, coal, petrol, and oil [44]. Forest fires, garbage incineration, volcanic eruptions, and hydrothermal processes are natural sources of PAHs. Whereas, combustion of timber, waste, and fossil fuels are some examples of anthropogenic activities which are responsible for the emission of PAHs [45, 48]. PAHs have cancer causing and mutation inducing properties in living organisms [47, 50]. The most common ways for people to be exposed to PAHs are through smoking cigarettes or cigars and breathing smoke from open fires or other sources of combustion [46]. Health issues such as skin-related diseases, lungs and gastrointestinal malignancies, and damages in liver and loss of immunity have been resulting in long-term exposure. The National Institute for Occupational Safety and Health (NIOSH) recommends that exposure to PAHs in the workplace should be limited at or below the minimum reliable detectable concentration of 1 $\mu g/m^3$.

2.6 Ozone (O_3)

Ground-level ozone is produced by a chemical interaction between oxides of nitrogen and originating from natural sources and/or as a result of human activities. Ozone damages the uppermost skin layers and tear ducts. Short-term exposure is resulted in malondialdehyde production in the epidermis as well as vitamin C and E depletion in mice model [1]. Due of ozone's limited solubility in water, it can enter deep into the lungs when inhaled. During the warm season, an increase in ozone concentration was related to an increase in the daily number of fatalities (0.33%), respiratory deaths (1.13%), and cardiovascular deaths (0.45%). During the winter, no such effect was noticed [51].

2.7 Nitrogen and sulfur oxides

Nitrogen oxides (NOx) are the gases that are released by natural sources, automobiles, and other fuel-burning actions [1]. NO_2 is an odorous, acidic, and extremely corrosive gas that have negative impact on human health and the environment. They are responsible for the yellowish-brown hue of the smog. It causes pulmonary disorders such as obstructive lung disease, asthma, chronic obstructive pulmonary disease, and in rare circumstances acute aggravation of COPD as well as fatalities [52]. High concentrations of NO_2 are also detrimental to vegetation causing damage to leaves, stunting growth and diminishing crop yields. The suggested NO_2 air quality criteria are 0.12 ppm for a 1-hour exposure duration and 0.03 ppm for a yearly exposure period. These regulations are intended to safeguard vulnerable individuals such as children and asthmatics [53, 54]. Sulfur oxides (SOx) composed of molecules of sulfur and oxygen is an odorless gas detectable by taste and smell at concentrations between 1000 and 3000 micrograms per cubic meter [55, 56]. The majority of SO_2 is produced by the combustion of sulfur-containing fuels and metal sulfide ores. Volcanoes are natural sources of SO_2 (35–65%) among others. After industrial boilers and nonferrous metal smelters thermal power plants that burn high-sulfur coal or heating oil are generally the largest producers of anthropogenic SO_2 emissions on a global scale. The accumulation of SO_2 and smoke which reached 1500 mg/m^3 resulted in increased number of fatalities [55, 57].

3. Absorption of air pollutants in plants

3.1 Stomata

The primary entry site for air pollutants in the plants is likely to be stomatal pores, either through exchange of gases or penetration of a liquid layers into the sub-stomatal cavity. By altering the aperture between the guard cells, plants regulates absorption of air pollutants with a diverse range of molecular masses. The movement of guard cells is regulated by the K^+ concentration in the cell sap. However, the mechanism of stomatal response to external environmental stimuli involves cellular sodium potassium pump and calcium homeostasis of guard cells as well as K^+ ion and its counter-ions, malate, chloride, and nitrate [49, 58]. Several environmental factors (temperature, light, and relative humidity) and cell internal factors (partial pressure of CO_2, sucrose concentration, turgidity of guard cells and the presence or absence growth inhibitors) also affect stomatal opening. Absorption of oxides of sulfur (SOx) and nitrogen (NOx) is regulated by light intensity and heavy metals with airborne particulates will directly enter through the stomatal pores, while lipophilic substance enters through cuticular wax [59].

3.2 Cuticle

When stomata are closed, the cuticle acts as the entry point for the pollutants. Lipophilic substances enter through cuticles of the plants, whereas hydrophilic compounds such as gaseous and liquid contaminants can be absorbed by cuticle to some extent. The morphology and composition of cuticles vary with species age, and location of the cuticle in plant as well as some climatic factors such as temperature and relative humidity. Organic compounds such as PAHs, PCBs, dioxins, and charged particulates may alter chemical constituent of cuticle that increase permeability of the cuticle. Once these pollutants enter through cuticle, they infiltrate slowly by diffusion process or get deposited on cell wall or the vacuoles [60].

4. Phytoremediation and its mechanism

In phytoremediation, plants absorb contaminants from the surrounding atmosphere and then degrade or detoxify them using a variety of mechanisms [61, 62]. It is currently unclear how specific air pollutants are captured by plants for subsequent degradation, metabolization, or sequestration. Additionally, phytoremediation has been studied for plant propensity to filter ambient air and exchange gases with their surroundings [63]. The large biologically active surface areas of plants have added advantage in capturing different air pollutants through absorption, transport, and deposition of organic pollutants in the rhizosphere and phyllosphere [64]. For the elimination of air pollutants, the photosynthetic systems of C3, C4, crassulacean acid metabolism (CAM), and facultative CAM plants have been studied under various circumstances [65]. C4 plants posses high intensity in exchange of gases as compared to C3 plants and may exchange more CO_2, especially during the day. CAM plants exchanges the gases during the night which makes them highly efficient in phytoremediation specially when they are placed in indoors [66]. Microorganisms that make up a phyllo-microbiome colonize on leaf surfaces and have potential to degrade a variety of organic contaminants [67]. Even soil microorganisms have ability to eliminate gaseous air pollutants when they are associated with plants [68]. Various mechanisms in phytoremediation are discussed below (**Figure 2**).

Phytoextraction refers to the process of taking up of pollutants from soil and transporting them to above ground plant parts for further degradation. Thus, in phytoextraction both phyllosphere and rhizosphere are involved [69]. Efficacy of phytoextraction process is dependent upon mobility and availability of heavy metals in the root zone [70–72]. Phytovolatilization is transport of contaminants into the phyllosphere of plants through the epidermis by diffusion across the cuticle and also through open stomata. These contaminants are further degraded into volatile components which are further released in the atmosphere through transpiration from the stomata [73]. Transpired volatile components either stay in the atmosphere as an air pollutant or they may break down by the action of hydroxyl radicals [74]. Phytovolatilization process is observed for number of contaminants both inorganic and organic forms. In phytovolatilization, pollutants are absorbed by plants through phyllosphere and transformed into volatile compounds. Eventually, these degraded volatile substances transpired into the atmosphere via stomata [75].

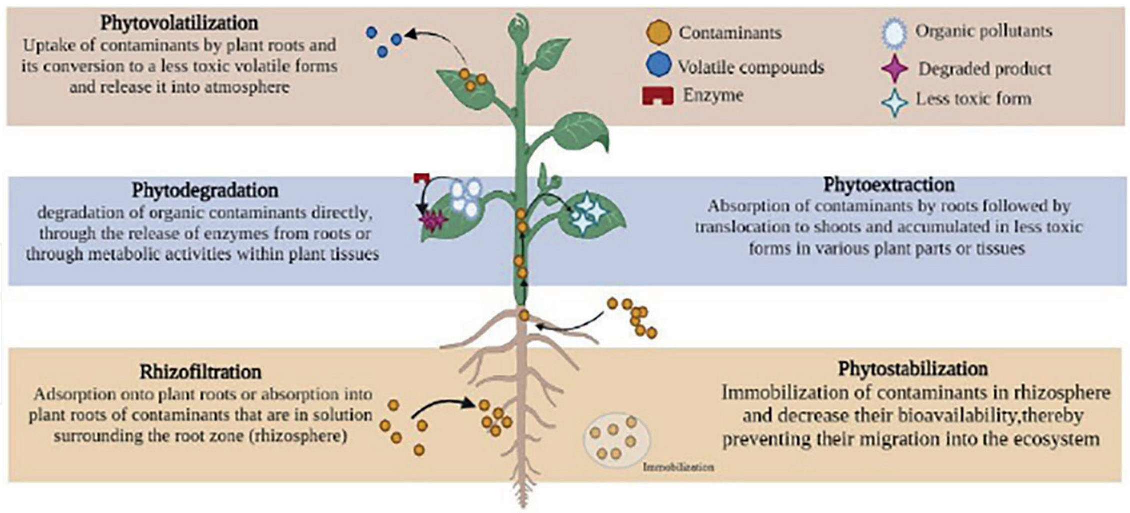

Figure 2.
Mechanisms of phytoremediation.

In phytodegradation, organic contaminants including polycyclic aromatic hydrocarbons (PAHs), total petroleum hydrocarbons (TPHs), polychlorinated biphenyls (PCBs), and inorganic contaminants like atmospheric nitrogen oxides and sulfur oxides are taken up and transformed by plants into simpler less toxic forms [9]. The obtained products of phytotransformation are incorporated into phyllosphere and rhizosphere. Specific plant enzymes such as nitroreductases, dehalogenases, laccases, and peroxidase play vital role in the phytotransformation process [73]. The immobilization of contaminants takes place in the rhizosphere during phytostabilization and is known as phytoimmobilization. Lignin, which is found in the cell wall of plant roots, is able to adsorb pollutants which then precipitates into insoluble compounds and stores them in the root zone [71]. Rhizodegradation refers to the biodegradation of contaminants in the soil by edaphic microbes enhanced by the inherent character of the rhizosphere itself. The roots of plants offer an additional surface area which allows for the transmission of oxygen and the growth of microorganisms. Plants emit biodegradable enzymes and metabolites into the rhizosphere, where microbes can use them to develop and break down contaminants [76]. Root exudates have many potential uses such as enhancing plant defense mechanism, boosting nutrient availability in the root zone, and even phytoextraction of heavy metals. The ability of bacteria to degrade pollutants is *Bacillus*, *Acinetobacter*, *Arthrobacter*, *Diaphorobacter*, *Enterobacter*, *Flavobacterium*, *Phanerochaete chrysosporium*, *Polysporus*, *Pseudomonas*, *Pseudoxanthomonas*, *Rhodococcus wratislaviensis*, *Sphingomonas*, and *Stenotrophomonas*.

5. Phytoremediation of major pollutants

5.1 Airborne particulates

By adsorbing particles leaf surface or fixing them in waxes, plants effectively remove substantial amounts of airborne particulates from the atmosphere, particularly in metropolitan areas [77]. Urban areas with trees can significantly reduce PM_{10} level [73]. In order to decrease the spread of air pollution from industrial areas, an

8 m wide green belt may be installed which could able to minimize dust fall over two to three times [78]. The trees such as *Ficus* spp., *Mangifera* spp., and *Azadirachta* spp. in urban roadsides can effectively control particulate matter emitted from vehicles. C_3 and C_4 plants intake several gaseous pollutants at larger quantity during daytime and CAM plants intake gases at night time through stomatal openings [79]. PCBs enter into plants through the cuticle and metabolized through cytochrome P-450 in some of the plant species such as pine and eucalyptus [80]. Generally, metals such as Cr, V, Ni, Pb, and Fe accumulated in plants from soil, but they are not translocated to aerial plant parts. Therefore, accumulation of such metals in aerial parts of the plants is majorly absorbed from atmospheric air [81]. High density organic compounds and metals can penetrate wax layer and enter into epidermis of the cell through the process of diffusion and sequestered in vacuoles or cell wall [82]. The ability of some bacteria to convert reactive oxygen species into less harmful forms through their anti-oxidant properties. This ability of bacteria in turn contributes to the bio-remediation of PM by plants as PM have shown to develop ROS which is harmful to plants [83–86].

5.2 Volatile organic compounds

Phytoremediation can effectively remove VOCs like formaldehyde, xylene, toluene, benzene, and ethylbenzene from the environment [87]. In order to protect from pathogens, animals and other environmental stresses plants used low molecular weight VOCs [84]. Generally, plant uptake VOCs via leaf stomata, while few plants uptake VOCs through cuticle [88], and their further translocation is done by phloem to designated plant organs [89]. In plants system, VOCs are degraded, stored or removed through various process, and get volatilized into atmosphere through diffusion from trunks, stems, roots, and leaves of plants [90, 91]. Phytoremediation efficiency of plants is determined by properties of VOCs, as lipophilic VOCs are absorbed through cuticle, whereas hydrophilic VOCs are absorbed through leaf stomata [13]. VOCs also get deposited in soil and plant rhizosphere due to leaf fall and runoff. Microbes present in plants aid metabolization of these organic compounds into less toxic forms such as carbon dioxide, water, and cellular biomass [13]. Spider plant (*Chlorophytum comosum* L.) detoxifies low concentrations of formaldehyde into amino acid, sugars lipids, and cell wall components. Soybean plant (*Glycine max* L.) converts formaldehyde into serine and phosphatidylcholine. Additionally, microbes can modify plant VOC emissions by activate an immunological response [92]. An experiment was conducted using the green wall system for degradation of VOCs and showed proteobacteria as the dominant species. *Nevskiaceae* and *Patuli bacteraceae* were VOC utilizing bacteria in the irrigation water of the green wall system. *Burkholderiales* were part of bio-wall root bacterial communities where VOC degradation was also reported [93]. Bacteria associated with the rhizosphere of the plants also play a crucial role in the degradation of these air pollutants, and one such bacteria *Rhodococcus erhythopolis* U23A isolated from the roots of *Arabidopsis thaliana* was able to break down polychlorinated biphenyls [94]. The flavanones were found to be the inducers of the polychlorinated biphenyls pathway. According to Barac et al. [94], the introduction of a plasmid expressing a toluene-degrading enzyme reduced phytotoxicity and toluene evapotranspiration by 50–70% through the leaves. Sandhu et al. [95] provided direct evidence that endophytic bacteria in the phyllosphere degrade volatile organic compounds. De Kempeneer et al. [96] proved that phyllosphere micro-biota undertakes toluene cleanup via toluene-degrading bacteria. Kempeneer et al. [96] demonstrated that phyllosphere micro-biota significantly degrades the toluene compound. As per the reports, formaldehyde has varied from 0.14 to 0.61 mg/m^3 in remodeled residences; however, benzene, toluene, and xylenes were found in 124, 258, and 189.7 g/m^3 concentrations, respectively [97]. Sriprapat et al. [98] highlighted that *Helianthus annuus* associated with EnL3 strain significantly removed benzene from the environment. The study also reported that a total of sixty-two proteins was up and down-regulated in leaves, while thirty-five proteins were up or down-regulated in roots of *H. annuus*. Additionally, toluene has been removed by the association of *F. verschaffeltii* and *H. carnosa* indoor foliage plants with rhizospheric bacteria [99, 100]. To summarize these, it is clear that the above ground and below ground plant-associated microorganisms play a crucial role in the mineralization of VOCs through their degradation potential.

5.3 Gaseous pollutants

Gaseous air pollutants include oxides of sulfur, carbon, and nitrogen as well as ozone [101]. Plants metabolize CO by oxidation into CO_2 or get reduced into amino acids. The tendency of plant canopy to act as NO_2 sinks and assimilation of NO_2 has also been demonstrated. Plants can assimilate ammonia (NH_4) from the air and soil [102]. Abatement of pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O3) can be accomplished by the implementation of phytoremediation. Through the process of photosynthesis, plants remove carbon dioxide from the atmosphere and store it for any given period of time or convert it to humus [13]. This process of storing carbon dioxide in plants for an extended period of time is known as carbon sequestration [103]. The "reductive sulfur cycle" is the process by which sulfur dioxide is broken down after it is diffused through the stomata of plants. Plant's root uptake by-products of the sulfur cycle including sulfur containing amino acids necessary for their growth. The adsorption of nitrogen dioxide through stomata, leaf, and root surfaces is the first step in the nitrogen toxicity abatement process. Nitrogen dioxide has the potential to be used as an alternative fertilizer and to supply essential nutrients to plants but, prolonged exposure to high concentrations of nitrogen within the plants could be toxic [13]. Ozone reacts with the waxes of cuticle, ions, salts, and biogenic and anthropogenic volatile organic compounds. Stomata are the means through which plants take in ozone into their systems. In another study, plant and microbially-assisted bio-remediation systems accrued the air pollutant by 0.24 to 9.53 folds than individual plant systems [104]. Moreover, ozone was efficaciously reduced or removed in an uninterrupted system of *Z. zamiifolia* combined with *B. cereus* ERBP. This endophytic bacterium has the potential to protect the plant against ozone stress [105] and has been developed an effective microbially-assisted bio-remediation strategy against formaldehyde pollutants by adhering rhizosphere microbes with *T. zebrina*, *A. vera*, and *V. radiata*. As per the report [49], the phenolic pollutant has been eliminated by vetiver grass by using *A. xylosoxidans*. The association of F3B has the potential to endure plants against toluene stress and enhanced the chlorophyll content of leaves. As per the report [106], chloromethane (volatile halo-carbon pollutant) was removed/degraded by *Hyphomicrobium* sp. (isolated from the leaf of *A. thaliana*). NO_2 may also be accumulated in plants in the form of nitrate and nitrite. Later, it can be reduced by nitrate and nitrite reductase enzyme for the generation of ammonia, which is further assimilated to glutamate through the ammonium assimilation pathway (GS- GOGAT) [107, 108]. As per the recent report by Lee et al. [16], the absorbed pollutants are stored in the inter-cellular spaces of leaves. Further, it can react with the inner-leaf membranes or water film and after that it can be degraded or excreted into the environment [16].

5.4 Removal of polyaromatic hydrocarbons (PAHs)

Various bacterial groups like *Haemophilus* spp., *Paenibacillus* spp., *Pseudomonas* spp., *Mycobacterium* spp., *and Rhodococcus* spp. are reported to degrade and utilize PAHs as a sole source of energy and carbon [109]. Yutthammo et al. [110] reported that about 1–10% of phyllosphere bacteria have potential to degrade PAHs (acenaphthylene, acenaphthene, phenanthrene, and fluorine) from the environment. However, the removal of PAH was achieved by the mutualistic association between microbes and *Epipremnum aureum* plant [111]. A lot of changes take place in the soil around the roots which leads to more aeration that supports the growth of autochthonous PAH degrading microbial communities, which allows the efficient mineralization of the PAH present in the rhizosphere soil [112]. Thus, even deeper layers support the process of aerobic degradation [113]. Myco-augmentation, phytoremediation and natural attenuation can be used individually for the bioremediation process. However, using these techniques in combination can increase bioremediation efficiency to several folds. Thus, the synergism between the microbes and plants can be exploited for the bioremediation not only for PAH but also other compounds as it is more effective than simple phytoremediation [114]. There have been few studies that has used the combination of bacteria and plants for the bioremediation of PAH [49], but rarely there has been a combination of plant and white-rot fungi used for the process of PAH bioremediation. The maize plant was associated with *Crucibulumleave* (fungi) in a comparative study where phytoremediation process was enhanced. This combination was highly effective in PAH degradation to 5–6 folds compared to phytoremediation alone. This could be possible due to the increased surface area of fungal hyphae which could assist bacterial transport through the soil and alteration of root exudates possibly increasing the bioavailability of the compounds and increasing the degradation of the PAH [115]. For the removal of hydrocarbons from soils, the most researched plants are prairie grasses because of their vast fibrous root systems [116].

5.5 Indoor air pollution

Green houseplants can act as a biological filter to purify the indoor air [76]. Plants considerably deplete CO_2, VOCs, PMs, organic carbon, nitrate, sulphate, ammonia, and carbonate levels in indoor environments [117]. It was reported that *Dracaena deremensis*, *Dracaena marginata*, and *Spathiphyllum* spp. efficiently remove benzene, toluene, ethylbenzene, and xylenes in indoor environment [118]. Eight ornamental indoor plants namely *Chlorophytum comosum*, *Clitoria ternatea*, *Dracaena sanderiana*, *Euphorbia milli*, *Epipremnum aureum*, *Hedera helix*, *Syngonium podophyllum and Sansevieria trifasciata* were studied for the removal efficiency of benzene in indoor air pollutants. It was found that *C. Comosum* was most efficient in removing benzene from air and water pollutants. Green walls are recent innovation, formed of a pre-vegetated frame that are attached to a wall or other interior structure [87, 117]. An updated version called active living wall integrates the building heating, cooling, and ventilation systems [119]. A green wall system regulates temperature and also filters the air inside buildings [120]. The plants remove CO and CO_2 and assist in removing particulate matter from air [121, 122]. Using urban indoor vegetation is one strategies for accomplishing this since it can be drastically reducing air pollution. Green walls are either partially or entirely covered with greenery, incorporating a growing medium. It is well-known that the incorporation of green walls and other forms of living infrastructure into an indoor environment has the potential to contribute to an improvement in air quality, through the reduction in amount of volatile organic compounds (VOC), inorganic gaseous compounds, and carbon dioxide (CO_2), as well as the retention of particulate matter (PM) [123]. Study revealed that potted plants are capable of removing significant levels of gaseous VOCs in sealed chambers, lowering VOCs by 10–90% in 24 hours [124]. It was demonstrated that the removal of organic contaminants is accomplished more effectively in areas of the root soil that are in contact with air [125]. The *Chamaedorea elegans* and *Opuntia microdasys* plants have significantly reduced the concentrations of formaldehyde and BTEX in controlled environmental chambers, respectively. In another study, the *Chlorophytum comosum* L. plants have significantly accumulated indoor PM10, PM2.5, and PM0.2. The researchers also observed that the plant wax is helpful in the accumulation or attachment of PM on their leaf's surfaces [126]. As per the literature, associated microorganisms can significantly enhance the remediation properties of plants. In one experiment, the rhizosphere microbes associated with the *Aloe vera*, *Tradescantia zebrine*, and *Vigna radiata* plant species have improved or enhanced the indoor formaldehyde neutralization efficiency by 2–3 times. In addition, the combined system of the *Ophiopogon japonicus* plant associated with *Staphylococcus epidermidis* and *Pseudomonas spp.,* bacterium has been degrading the phenol pollutants with 1000 g/L per day capacity [118]. In commercial buildings and urban areas, vertical gardens are gaining more attention because vertical alignment can offer a space-efficient method of exposing more plant biomass to contaminated air [127]. In these gardens, the significance of plant selection on the green walls demonstrated the varying capacity of pollutant degradation. As per the report, the especially fern species have high removal efficiency toward the particulate matter of size range $PM_{0.3–0.5}$; 45.78% and $PM_{5–10}$; 92.46%. Whereas, the plant species with fibrous roots have greater degradation efficacy toward air pollutants compared to plants with tap root systems. Moreover, for vertical gardens and green walls, the growing medium, vermicompost, perlite, coco-peat, and so forth significantly influence the plant microbe's associations and pollutant degradation mechanism. In *Apteniacordifoli*, the addition of granular activated carbon into coconut husk-based substrates could increase the VOC removal ability of the green walls [128]. Mikkonen et al. [129] investigated the filtration efficiencies for seven volatile organic chemicals as well as the microbial dynamics in simulated green wall systems. The results highlighted that Golden pothos plants had a minor effect on VOCs filtration and bacterial diversity. In another report by Gonzalez-Martin [92], indoor green walls contributed significantly to the ambient fungal load, but concentrations remained well below WHO safety standards. In this sense, the botanical air filtration approach is a promising way for reducing indoor air pollution, but a greater knowledge of the underlying mechanics is still required.

6. Biotechnological advances

Generally, biotechnological tools provide researchers the ability to change the gene expression regulation at certain specified sites which speeds up the discovery of new information regarding the functional genomics of plants [128]. In *Noccaeac aerulescens*, *Arabidopsis spp.* (hyperaccumulator of Cd and Zn*), Hirschfeld spp.* (tolerant to Pb toxicity), *Pterisvittata*, and *Brassicaspp* have genomes sequenced for model phytoremediators [129]. These phytoremediators have been found to be effective at removing heavy metals from the environment. Similarly expressing the *MerC* gene in *Arabidopsis* and Tobacco plants led to an increase in the accumulation of the Hg metal, but it also rendered the plant hypersensitive to the effects of mercury (Hg). Several additional types of organic contaminants such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls are also include in this method [92]. Editing the genes in rice and *Arabidopsis* for the production of naphthalene dioxygenase resulted in the recent development of genes that express tolerance against naphthalene and phenanthrene [130]. Some of the genetically modified plants for phytoremediation of organic pollutants include tobacco (gene *hCYP2E1*) for benzene, *Atropa belladonna* (gene *rCYP2E1*), and Poplar (gene *rCYP2E1*) for TCE [131]. An experiment was carried out on the *tou* cluster, which encodes for the enzyme Tolueneo-Xylene Monooxygenase (ToMO) which can degrade the aromatic hydrocarbons from *Pseudomonas stutzeri*. It was cloned and expressed in Antarctic *Pseudoalteromonas* algae [88]. Genetically modified plants like *P. angustifolia*, *N. tabacum*, and *S. cucubalis* have been shown to accumulate more heavy metals pollutants than their wild counterparts by over expressing-glutamylcysteine-synthetase [132]. The γ-ECS *B. juncea* transgenic seedlings (*E. coli* gshl gene insertion) showed greater tolerance toward cadmium, phytochelatins, glutathione, and non-protein thiols than wild type [132]. The expression of genes including *AtNramps*, *AtPcrs*, *CAD1* (*A. thaliana*), *gshI*, *gshII* (*D. innoxia*), *CAX-2*, *NtCBP4* (*N. tabacum*; *A. thaliana*), *Ferretin* (*soybean*), *merA* (bacteria), and *PCS* cDNA clone (*B. juncea*) has been shown enhanced heavy metal tolerance and accumulation [133, 134]. However, in transgenic *A. thaliana*, the combined expression of SRSIp/ArsC and ACT 2p/γ-ECS presented increased tolerance to arsenic (Ar). Additionally, plants accrued 4 to 17-fold shoot biomass and accumulated 2 to 3-fold more AR compared to wild plants [135, 136]. For enhanced phytoremediation, metabolic pathways have been expressed by introducing *MerA, MerB, ars C,* and *γ-ECS* genes in *Arabidopsis* plants and resulted in enhanced accumulation of mercury, arsenate, and arsenite pollutants [137]. The over-expression of 1- amino cyclopropane-1-carboxylic acid deaminase in plants resulted in a higher accumulation of pollutants [75, 137]. Presently, the researchers aim to work on the genetic modification of common ornamental and houseplants for the improvement of indoor air quality. In this context, pothos ivy or devil's ivy has been modified by genetic engineering approach for the removal of chloroform and benzene by the expression of the Mammalian Cytochrome P450 *2e1* gene [138].

7. Conclusions

The removal or degradation of harmful pollutants from the air is far more challenging than water and soil pollution. As per the literature, phytoremediation has way more potential for eradication of harmful pollutants from the indoor and outdoor air environment in a sustainable manner. This way of phytoremediation is more sustainable, green, cost-effective, and easy to handle. In phytoremediation, the plants and microbes eradicate the pollutants through the following mechanisms, such as phyto-extraction, phyto-stabilization, rhizo-filtration, phyto-volatilization, phyto-degradation, and phyto-desalination. However, the selection of plant species and microbe's assistance for particular pollutant, their site, and condition are very crucial. As per the literature surveyed, in sustainability, the phytoremediation methods are 5–13 times more economical, higher success rate, good acceptance, and indeed an ecological way than the other remediation strategies. In the urban context, indoor plants serve as solution for phytoremediation against harmful air pollutants and also add esthetic value to the indoor space. Furthermore, the utilization of biotechnology will revolutionize and enhance the phytoremediation process against variety of pollutants.

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References

[1] Manisalidis I, Stavropoulou E, Stavropoulos A, Bezirtzoglou E. Environmental and health impacts of air pollution: A review. Frontiers in public health. 2020;**8**:14

[2] Newby DE, Mannucci PM, Tell GS, Baccarelli AA, Brook RD, Donaldson K, et al. Expert position paper on air pollution and cardiovascular disease. European Heart Journal. 2015;**36**:83-93b

[3] Brook RD, Rajagopalan S, Pope CA III, Brook JR, Bhatnagar A, Diez-RouxAV, et al. Particulate matter air pollution and cardiovascular disease: Anupdate to the scientific statement from the American Heart Association.Circulation 2010;121:2331-2378.

[4] Chin MT. Basic mechanisms for adverse cardiovascularevents associated with air pollution. Heart. 2015;**101**:253-256. DOI: 10.1136/heartjnl-2014-306379

[5] Hamanaka RB, Mutlu GM. Particulate matter air pollution: Effects on the cardiovascular system. Frontiers in Endocrinology. 2018;**9**:680

[6] Bourdrel T, Bind MA, Béjot Y, Morel O, Argacha JF. Cardiovascular effects of air pollution. Archives of Cardiovascular Diseases. 2017;**110**(11): 634-642

[7] Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A. The contributionof outdoor air pollution sources to premature mortality on a global scale. Nature. 2015;**525**:367-371

[8] Brook RD, Newby DE, Rajagopalan S. The global threat of outdoor ambientair pollution to cardiovascular health: Time for intervention. JAMA Cardiology. 2017;**2**:353-354

[9] Zhang Y, Beggs PJ, McGushin A, Bambrick H, Trueck S, Hanigan IC, et al. The 2020 special report of the MJA–lancet countdown on health and climate change: Lessons learnt from Australia's "black summer". Medical Journal of Australia. 2020;**213**(11):490-492

[10] Weyens N, Thijs S, Popek R, Witters N, Przybysz A, Espenshade J, et al. The role of plant–microbe interactions and their exploitation for phytoremediation of air pollutants. International Journal of Molecular Sciences. 2015;**16**(10):25576-25604

[11] Landrigan PJ. Air pollution and health. The Lancet Public Health. 2017;**2**(1):4-5

[12] Bhargava B, Malhotra S, Chandel A, Rakwal A, Kashwap RR, Kumar S. Mitigation of indoor air pollutants using areca palm potted plants in real-life settings. Environmental Science and Pollution Research 2021. 2021;**28**(7):8898-8906

[13] Frontczak M, Andersen RV, Wargocki P. Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. Building and Environment. 2012;**50**:56-64

[14] Turner MC, Andersen ZJ, Baccarelli A, Diver WR, Gapstur SM, Pope CA III, et al. Outdoor air pollution and cancer: An overview of the current evidence and public health recommendations. CA: a Cancer Journal for Clinicians. 2020;**70**(6):460-479

[15] Ali H, Khan E, Sajad MA. Phytoremediation of heavy metals—Concepts and applications. Chemosphere. 2013;**91**(7):869-881

[16] Haritash AK, Kaushik CP. Biodegradation aspects of polycyclic aromatic hydrocarbons (PAHs): A review. Journal of Hazardous Materials. 2009;**169**(1-3):1-15

[17] Alagić SČ, Maluckov BS, Radojičić VB. How can plants manage polycyclic aromatic hydrocarbons? May these effects represent a useful tool for an effective soil remediation? A review. Clean Technologies and Environmental Policy. 2015;**17**:597-614

[18] Yang Y, Su Y, Zhao S. An efficient plant–microbe phytoremediation method to remove formaldehyde from air. Environmental Chemistry Letters. 2020;**18**(1):197-206

[19] Torpy F, Clements N, Pollinger M, Dengel A, Mulvihill I, He C, et al. Testing the single-pass VOC removal efficiency of an active green wall using methyl ethyl ketone (MEK). Air Quality, Atmosphere & Health. 2018;**11**(2):163-170

[20] Sly PD. Environmental pollutants and postnatal growth. In: Victor R, editor. Handbook of growth and growth monitoring in health and disease. Preedy. New York, USA: Springer; 2012. pp. 757-768. DOI: 10.1007/978-1-4419-1795-9_44

[21] Van Groenigen KJ, Osenberg CW, Hungate BA. Increased soil emissions of potent greenhouse gases under increased atmospheric CO_2. Nature. 2011;**475**(7355):214-216

[22] Tian ZH, Yang ZL. Scenarios of carbon emissions from the power sector in Guangdong province. Sustainability. 2016;**8**(9):863

[23] Azevedo VG, Sartori S, Campos LM. CO2 emissions: A quantitative analysis among the BRICS nations. Renewable and Sustainable Energy Reviews. 2018;**81**:107-115

[24] Freund P. Anthropogenic climate change and the role of CO2 capture and storage (CCS). In: Jon G, Mathais S, editors. Geological storage of carbon dioxide (CO2): Geoscience, technologies, environmental aspects and legal frameworks. UK: Woodhead publishing; 2013. pp. 1-23

[25] Bertoni G, Ciuchini C, Tappa R. Measurement of long-term average carbon dioxide concentrations using passive diffusion sampling. Atmospheric Environment. 2004;**38**(11):1625-1630

[26] Satish U, Mendell MJ, Shekhar K, Hotchi T, Sullivan D, Streufert S, et al. Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. Environmental Health Perspectives. 2012;**120**(12):1671-1677

[27] Law J, Watkins S, Alexander D. In-Flight Carbon Dioxide Exposures and Related Symptoms: Associations, Susceptibility and Operational Implications. NASA-STD-3001 Technical Brief. 2010. Available from: https://www.nasa.gov/sites/default/files/atoms/files/co2_technical_brief_ochmo.pdf

[28] Fierro MA, O'Rourke MK, Burgess JL. Adverse Health Effects of Exposure to Ambient Carbon Monoxide. University of Arizona Report; 2001. Available from: https://www.scribd.com/document/310600769/Adverse-Health-Effects-of-Exposure-to-Ambient-Carbon-Monoxide

[29] Prockop LD, Chichkova RI. Carbon monoxide intoxication: An updated review. Journal of the neurological sciences. 2007;**262**(1-2):122-130

[30] World Health Organization, WHO. Guidelines for drinking water quality. 2011. Available from: https://www.who.int/publications/i/item9789241549950 [Accessed: January 14, 2022]

[31] Goldstein NJ, Cialdini RB, Griskevicius V. A room with a viewpoint: Using social norms to motivate environmental conservation in hotels. Journal of consumer Research. 2008;**35**(3):472-482

[32] Lin B, Zhu J. Changes in urban air quality during urbanization in China. Journal of Cleaner Production. 2018;**188**:312-321

[33] Pandey P, Yadav R. A review on volatile organic compounds (VOCs) as environmental pollutants: Fate and distribution. International Journal of Plant and Environment. 2018;**4**(02):14-26

[34] Campagnolo D, Saraga DE, Cattaneo A, Spinazzè A, Mandin C, Mabilia R, et al. VOCs and aldehydes source identification in European office buildings-the OFFICAIR study. Building and Environment. 2017;**115**:18-24

[35] Gonzalez-Martin J, Kraakman NJ, Perez C, Lebrero R, Munoz R. A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. Chemosphere. 2021;**262**:128376

[36] Cheung K, Daher N, Kam W, Shafer MM, Ning Z, Schauer JJ, et al. Spatial and temporal variation of chemical composition and mass closure of ambient coarse particulate matter (PM10-2.5) in the Los Angeles area. Atmospheric environment. 2011;**45**(16):2651-2662

[37] Yoon HI, Hong YC, Cho SH, Kim H, Kim YH, Sohn JR, et al. Exposure to volatile organic compounds and loss of pulmonary function in the elderly. European Respiratory Journal. 2013;**6**(6):1270-1276

[38] Ukaogo PO, Ewuzie U, Onwuka CV. Environmental pollution: Causes, effects, and the remedies. In: Microorganisms for Sustainable Environment and Health. Elsevier; 2020. pp. 419-429. DOI: 10.1016/C2018-0-05025-2

[39] Sánchez-Soberón F, Rovira J, Mari M, Sierra J, Nadal M, Domingo JL, et al. Main components and human health risks assessment of PM10, PM2. 5, and PM1 in two areas influenced by cement plants. Atmospheric Environment. 2015;**120**:109-116

[40] Priyamvada H, Priyanka C, Singh RK, Akila M, Ravikrishna R, Gunthe SS. Assessment of PM and bioaerosols at diverse indoor environments in a southern tropical Indian region. Building and Environment. 2018;**137**:215-225

[41] Smith SB, Gill CA, Lunt DK, Brooks MA. Regulation of fat and fatty acid composition in beef cattle. Asian-Australasian Journal of Animal Sciences. 2009;**22**(9):1225-1233

[42] Boogaard BK, Bock BB, Oosting SJ, Wiskerke JS, van der Zijpp AJ. Social acceptance of dairy farming: The ambivalence between the two faces of modernity. Journal of Agricultural and Environmental Ethics. 2011;**24**:259-282

[43] Kiurski JS, Marić BB, Aksentijević SM, Oros IB, Kecić VS, Kovacˇević IM. Indoor air quality investigation from screen printing industry. Renewable and Sustainable Energy Reviews. 2013;**28**:224-231

[44] Abdel-Shafy HI, Mansour MS. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egyptian Journal of Petroleum. 2016;**25**(1):107-123

[45] Pongpiachan S, Tipmanee D, Khumsup C, Kittikoon I, Hirunyatrakul P. Assessing risks to adults and preschool

children posed by PM2. 5-bound polycyclic aromatic hydrocarbons (PAHs) during a biomass burning episode in northern Thailand. Science of the Total Environment. 2015;**508**:435-444

[46] Domingo JL, Nadal M. Human dietary exposure to polycyclic aromatic hydrocarbons: A review of the scientific literature. Food and Chemical Toxicology. 2015;**86**:144-153

[47] Akyüz M, Çabuk H. Meteorological variations of PM2. 5/PM10 concentrations and particle-associated polycyclic aromatic hydrocarbons in the atmospheric environment of Zonguldak, Turkey. Journal of Hazardous Materials. 2009;**170**(1):13-21

[48] Lannerö E, Wickman M, van Hage M, Bergström A, Pershagen G, Nordvall L. Exposure to environmental tobacco smoke and sensitisation in children. Thorax. 2008;**63**(2):172-176

[49] Kim KH, Jahan SA, Kabir E, Brown RJ. A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. Environment International. 2013;**60**:71-80

[50] Hamid N, Syed JH, Junaid M, Mahmood A, Li J, Zhang G, et al. Elucidating the urban levels, sources and health risks of polycyclic aromatic hydrocarbons (PAHs) in Pakistan: Implications for changing energy demand. Science of the Total Environment. 2018;**619**:165-175

[51] Gryparis A, Forsberg B, Katsouyanni K, Analitis A, Touloumi G, Schwartz J, et al. Acute effects of ozone on mortality from the "air pollution and health: A European approach" project. American journal of respiratory and critical care medicine. 2004;**170**(10):1080-1087

[52] Siegel RL, Miller KD, Wagle NS, Jemal A. Cancer statistics, 2023. CA: a cancer journal for clinicians. 2023;**73**(1):17-48

[53] Rodríguez D, Cobo-Cuenca AI, Quiles R. Effects of air pollution on daily hospital admissions for cardiovascular diseases in Castilla-La Mancha, Spain: A region with moderate air quality. Air Quality, Atmosphere & Health. 2022;**15**(4):591-604

[54] Gu X, Wang T, Li C. Elevated ozone decreases the multifunctionality of belowground ecosystems. Global Change Biology. 2023;**29**(3):890-908

[55] Gawande P, Kaware J. Health and environmental effects of Sulphur oxides—A review. International Journal of Science and Research. 2015;**6**(6):1262-1265

[56] Jafarinejad S. Control and Treatment of Air Emissions. In: Jafarinejad S, Butterworth-Heinemann, editors. Petroleum Waste Treatment and Pollution Control. 2017. Pages 149-183. ISBN 9780128092439, DOI: 10.1016/B978-0-12-809243-9.00005-5. Available from: https://www.sciencedirect.com/science/article/pii/B9780128092439000055

[57] Chen C, Arjomandi M, Balmes J, Tager I, Holland N. Effects of chronic and acute ozone exposure on lipid peroxidation and antioxidant capacity in healthy young adults. Environmental health perspectives. 2007;**115**(12):1732-1737

[58] Shabala S. Regulation of potassium transport in leaves: From molecular to tissue level. Annals of Botany. 2003;**92**(5):627-634

[59] Demidchik V, Shabala SN, Coutts KB, Tester MA, Davies JM. Free oxygen

radicals regulate plasma membrane Ca^{2+}-and K^{+}-permeable channels in plant root cells. Journal of cell science. 2003;**116**(1):81-88

[60] Gawronski SW, Gawronska H, Lomnicki S, Saebo A, Vangronsveld J. Plants in air phytoremediation. In: Advances in Botanical Research. Vol. 83. United states, Elseviar; 2017. pp. 319-346. DOI: 10.1016/bs.abr.2016.12.008

[61] Agarwal A, Poelchau MH, Kenkmann T, Rae A, Ebert M. Impact experiment on gneiss: The effects of foliation on cratering process. Journal of Geophysical Research: Solid Earth. 2019;**124**(12):13532-13546

[62] Teiri H, Hajizadeh Y, Azhdarpoor A. A review of different phytoremediation methods and critical factors for purification of common indoor air pollutants: An approach with sensitive analysis. Air Quality, Atmosphere & Health. 2021;**15**:1-19

[63] Ciffroy P, Tanaka T. Modelling the fate of Chemicals in Plants. In: Ciffroy P, Tediosi A, Capri E, editors. Modelling the Fate of Chemicals in the Environment and the Human Body. Switzerland: Springer Cham; 2018. pp. 167-189. DOI: 10.1007/978-3-319-59502-3_8

[64] Mohan I, Goria K, Dhar S, Kothari R, Bhau BS, Pathania D. Phytoremediation of heavy metals from the biosphere perspective and solutions. In: Pollutants and Water Management: Resources, Strategies and Scarcity. USA: Wiley-Blackwell; 2021. pp. 95-127. DOI: 10.1002/9781119693635.ch5

[65] Winter K, Holtum JA. Facultative crassulacean acid metabolism (CAM) plants: Powerful tools for unravelling the functional elements of CAM photosynthesis. Journal of experimental botany. 2014;**65**(13):3425-3441

[66] Waghmode M, Gunjal A, Patil N, Shinde S. Composition and interconnections in Phyllomicrobiome. In: Phytomicrobiome Interactions and Sustainable Agriculture. USA: Wiley-Blackwell; 2021. pp. 277-292. DOI: 10.1002/9781119644798.ch15

[67] Molina L, Wittich RM, van Dillewijn P, Segura A. Plant-bacteria interactions for the elimination of atmospheric contaminants in cities. Agronomy. 2021;**11**(3):493

[68] Chen L, Yang JY, Wang D. Phytoremediation of uranium and cadmium contaminated soils by sunflower (Helianthus annuus L.) enhanced with biodegradable chelating agents. Journal of Cleaner Production. 2020;**263**:121491

[69] Gul I, Manzoor M, Hashmi I, Bhatti MF, Kallerhoff J, Arshad M. Plant uptake and leaching potential upon application of amendments in soils spiked with heavy metals (Cd and Pb). Journal of environmental management. 2019;**249**:109408

[70] Mousavi A, Pourakbar L, Moghaddam SS, Popović-Djordjević J. The effect of the exogenous application of EDTA and maleic acid on tolerance, phenolic compounds, and cadmium phytoremediation by okra (*Abelmoschus esculentus* L.) exposed to Cd stress. Journal of Environmental Chemical Engineering. 2021;**9**(4):105456

[71] Morikawa H, Erkin ÖC. Basic processes in phytoremediation and some applications to air pollution control. Chemosphere. 2003;**52**(9):1553-1558

[72] Krishnasamy S, Lakshmanan R, Ravichandran M. Phytoremediatiation of metal and metalloid pollutants from farmland: An In-situ soil conservation. In: Biodegradation Technology of

Organic and Inorganic Pollutants. London, UK: IntechOpen; 2021. DOI: 10.5772/intechopen.98659

[73] Favas PJ, Pratas J, Varun M, D'Souza R, Paul MS. Phytoremediation of soils contaminated with metals and metalloids at mining areas: Potential of native flora. Environmental risk assessment of soil contamination. 2014;**3**:485-516

[74] KhKaraghool HA. The employment of Endophytic bacteria forPhytodegradation of pyridine. IOP Conference Series Earth and Environmental Science. 2021;**961**:961

[75] Kumar K, Shinde A, Aeron V, Verma A, Arif NS. Genetic engineering of plants for phytoremediation: Advances and challenges. Journal of Plant Biochemistry and Biotechnology. 2022;**32**:1-19

[76] Beckett KP, Freer-Smith PH, Taylor G. Particulate pollution capture by urban trees: Effect of species and windspeed. Global change biology. 2000;**6**(8):995-1003

[77] Roupsard P, Amielh M, Maro D, Coppalle A, Branger H, Connan O, et al. Measurement in a wind tunnel of dry deposition velocities of sub micron aerosol with associated turbulence onto rough and smooth urban surfaces. Journal of Aerosol Science. 2013;**55**:12-24

[78] Treesubsuntorn C, Thiravetyan P. Botanical biofilter for indoor toluene removal and reduction of carbon dioxide emission under low light intensity by using mixed C3 and CAM plants. Journal of Cleaner Production. 2018;**194**:94-100

[79] Ny MT, Lee BK. Size distribution of airborne particulate matter and associated metallic elements in an urban area of an industrial city in Korea. Aerosol and Air Quality Research. 2011;**11**(6):643-653

[80] Mate AR, Deshmukh RR. To control effects of air pollution using roadside trees. International Journal of Innovative Research in Science, Engineering and Technology. 2015;**4**(11):11167-11172

[81] Wolffe MC, Wild O, Long SP, Ashworth K. Temporal variability in the impacts of particulate matter on crop yields on the North China plain. Science of the Total Environment. 2021;**776**:145135

[82] Wu W, Huang ZH, Lim TT. Recent development of mixed metal oxide anodes for electrochemical oxidation of organic pollutants in water. Applied Catalysis A: General. 2014;**480**:58-78

[83] Vejerano EP, Rao G, Khachatryan L, Cormier SA, Lomnicki S. Environmentally persistent free radicals: Insights on a new class of pollutants. Environmental science & technology. 2018;**52**(5):2468-2481

[84] Kelly FJ, Fussell JC. Air pollution and public health: Emerging hazards and improved understanding of risk. Environmental geochemistry and health. 2015;**37**:631-649

[85] Kiruri LW, Khachatryan L, Dellinger B, Lomnicki S. Effect of copper oxide concentration on the formation and persistency of environmentally persistent free radicals (EPFRs) in particulates. Environmental science & technology. 2014;**48**(4):2212-2217

[86] Pandey VC, Bajpai O. Chapter 1 - phytoremediation: From theory toward practice. In: Pandey C, Bauddh K, editors. Phytomanagement of Polluted Sites. Vimal CP, Kuldeep B. editors. United states: Elsevier; 2019. pp. 1-49. ISBN 9780128139127,

DOI: 10.1016/B978-0-12-813912-7.00026-0. Available from: https://www.sciencedirect.com/science/article/pii/B9780128139127000260. DOI: 10.1016/C2017-0-00586-4

[87] Agarwal P, Sarkar M, Chakraborty B, Banerjee T. Phytoremediation of air pollutants: Prospects and challenges. In: Vimal CP, Kuldeep B, editors. Phytomanagement of Polluted Sites. United states: Elsevier; 2019. pp. 221-241. ISBN 9780128139127

[88] Doty SL, Andrew JC, Moore AL, Vajzovic A, Singleton GL, Ma CP. Enhanced phytoremediation of volatile environmental pollutants with transgenic trees. Proceedings. National Academy of Sciences. United States of America. 2007;**104**(43):1681616821

[89] Engel-Di Mauro S. Atmospheric sources of trace element contamination in cultivated urban areas: A review. Journal of Environmental Quality. 2021;**50**(1):38-48

[90] Farr C. Indoor Air Quality: Causes, Controls and Consequences. United Kingdom: Lancaster University; 2021

[91] Toome M, Randjärv P, Copolovici L, Niinemets Ü, Heinsoo K, Luik A, et al. Leaf rust induced volatile organic compounds signaling in willow during the infection. Planta. 2010;**232**:235-243

[92] Mikkonen A, Li T, Vesala M, Saarenheimo J, Ahonen V, Kärenlampi S, et al. Biofiltration of airborne VOC s with green wall systems—Microbial and chemical dynamics. Indoor Air. 2018;**28**(5):697-707

[93] Lomonaco T, Manco E, Corti A, La Nasa J, Ghimenti S, Biagini D, et al. Release of harmful volatile organic compounds (VOCs) from photo-degraded plastic debris: A neglected source of environmental pollution. Journal of hazardous materials. 2020;**394**:122596

[94] Barac T, Taghavi S, Borremans B, Provoost A, Oeyen L, Colpaert JV, et al. Engineered endophytic bacteria improve phytoremediation of water-soluble, volatile, organic pollutants. Nature biotechnology. 2004;**22**(5):583-588

[95] Sandhu A, Halverson LJ, Beattie GA. Identification and genetic characterization of phenol-degrading bacteria from leaf microbial communities. Microbial ecology. 2009;**57**:276-285

[96] De Kempeneer L, Sercu B, Vanbrabant W, Van Langenhove H, Verstraete W. Bioaugmentation of the phyllosphere for the removal of toluene from indoor air. Applied microbiology and biotechnology. 2004;**64**:284-288

[97] Sriprapat W, Roytrakul S, Thiravetyan P. Proteomic studies of plant and bacteria interactions during benzene remediation. Journal of Environmental Sciences. 2020;**94**:161-170

[98] Zhang X, Wang H, He L, Lu K, Sarmah A, Li J, et al. Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. Environmental Science and Pollution Research. 2013;**20**:8472-8483

[99] Wang S, Xing J, Zhao B, Jang C, Hao J. Effectiveness of national air pollution control policies on the air quality in metropolitan areas of China. Journal of Environmental Sciences. 2014;**26**(1):13-22

[100] Asif M, Saleem S, Tariq A, Usman M, Haq RAU. Pollutant emissions from brick kilns and their effects on climate change and agriculture. ASEAN Journal of Science and Engineering. 2021;**1**(2):135-140

[101] Kim KJ, Kim HJ, Khalekuzzaman M, Yoo EH, Jung HH, Jang HS. Removal ratio of gaseous toluene and xylene transported from air to root zone via the stem by indoor plants. Environmental Science and Pollution Research. 2016;**23**:6149-6158

[102] Roupsard P, Amielh M, Maro D, Coppalle A, Branger H, Connan O, et al. Measurement in a wind tunnel of dry deposition velocities of submicron aerosol with associated turbulence onto rough and smooth urban surfaces. Journal of Aerosol Science. 2013;**55**:12-24

[103] Hu H, Zhou Q, Li X, Lou W, Du C, Teng Q, et al. Phytoremediation of anaerobically digested swine wastewater contaminated by oxytetracycline via Lemna aequinoctialis: Nutrient removal, growth characteristics and degradation pathways. Bioresource technology. 2019;**291**:121853

[104] Yang L, Wang J, Yang Y, Li S, Wang T, Oleksak P, et al. Phytoremediation of heavy metal pollution: Hotspots and future prospects. Ecotoxicology and Environmental Safety. 2022;**234**:113403

[105] Ho CP, Hseu ZY, Chen NC, Tsai CC. Evaluating heavy metal concentration of plants on a serpentine site for phytoremediation applications. Environmental earth sciences. 2013;**70**:191-199

[106] Verma VK, Singh YP, Rai JP. Biogas production from plant biomass used for phytoremediation of industrial wastes. Bioresource technology. 2007;**98**(8):1664-1669

[107] Zhang H, Cai X, Song Y, Bian Y, Xiao K, Zhang H. Influence of intermittent turbulence on air pollution and its dispersion in winter 2016/2017 over Beijing, China. Journal of Meteorological Research. 2020;**34**(1):176-188

[108] Li Y, Liu B, Xue Z, Zhang Y, Sun X, Song C, et al. Chemical characteristics and source apportionment of PM2. 5 using PMF modelling coupled with 1-hr resolution online air pollutant dataset for Linfen, China. Environmental Pollution. 2020;**263**:114532

[109] Yutthammo C, Thongthammachat N, Pinphanichakarn P, Luepromchai E. Diversity and activity of PAH-degrading bacteria in the phyllosphere of ornamental plants. Microbial ecology. 2010;**59**:357-368

[110] Wang Y, Fang L, Lin L, Luan T, Tam NF. Effects of low molecular-weight organic acids and dehydrogenase activity in rhizosphere sediments of mangrove plants on phytoremediation of polycyclic aromatic hydrocarbons. Chemosphere. 2014;**99**:152-159

[111] Li J, Zhang J, Larson SL, Ballard JH, Guo K, Arslan Z, et al. Electrokinetic-enhanced phytoremediation of uranium-contaminated soil using sunflower and Indian mustard. International Journal of Phytoremediation. 2019;**21**(12):1197-1204

[112] Alagić SČ, Jovanović VP, Mitić VD, Cvetković JS, Petrović GM, Stojanović GS. Bioaccumulation of HMW PAHs in the roots of wild blackberry from the Bor region (Serbia): Phytoremediation and biomonitoring aspects. Science of the Total Environment. 2016;**562**:561-570

[113] Glick BR. Using soil bacteria to facilitate phytoremediation. Biotechnology advances. 2010;**28**(3): 367-374

[114] Lin Q, Mendelssohn IA. Determining tolerance limits for restoration and

phytoremediation with Spartina patens in crude oil-contaminated sediment in greenhouse. Archives of Agronomy and Soil Science. 2008;**54**(6):681-90.4

[115] Shao B, Liu Z, Zhong H, Zeng G, Liu G, Yu M, et al. Effects of rhamnolipids on microorganism characteristics and applications in composting: A review. Microbiological Research. 2017;**200**:33-44

[116] Liu G, Xiao M, Zhang X, Gal C, Chen X, Liu L, et al. A review of air filtration technologies for sustainable and healthy building ventilation. Sustainable Cities and Society. 2017;**32**:375-396

[117] Liu H, Luo L, Jiang G, Li G, Zhu C, Meng W, et al. Sulfur enhances cadmium bioaccumulation in Cichorium intybus by altering soil properties, heavy metal availability and microbial community in contaminated alkaline soil. Science of The Total Environment. 2022;**837**:155879

[118] Irga PJ, Paull NJ, Abdo P, Torpy FR. An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system. Building and Environment. 2017;**115**:281-290

[119] Bandehali S, Parvizian F, Hosseini SM, Matsuura T, Drioli E, Shen J, et al. Planning of smart gating membranes for water treatment. Chemosphere. 2021;**283**:131207

[120] Ogut O, Tzortzi NJ, Bertolin C. Vertical green structures to establish sustainable built environment: A systematic market review. Sustainability. 2022;**14**(19):12349

[121] Tomson M, Kumar P, Barwise Y, Perez P, Forehead H, French K, et al. Green infrastructure for air quality improvement in street canyons. Environment International. 2021;**146**:106288

[122] Moya TA, Dobbelsteen AVD, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. Indoor and Built Environment. 2018;**28**:298-230

[123] Modirrousta S, Mohammadi Z. Necessity and methods of designing green buildings in cities and its effect on energy efficiency. European Online Journal of Natural and Social Sciences Proceedings. 2015;**4**:304-314

[124] Khalifa AA, Khan E, Akhtar MS. Phytoremediation of indoor formaldehyde by plants and plant material. International Journal of Phytoremediation. 2022;**25**:1-12

[125] Prakash G, Soni R, Mishra R, Sharma S. Role of plant-microbe interaction in phytoremediation. In: In Vitro Plant Breeding towards Novel Agronomic Traits: Biotic and Abiotic Stress Tolerance. Switzerland: Springer Cham; 2019. pp. 83-118. DOI: 10.1007/978-981-32-9824-8_6

[126] Vafaie Moghadam A, Iranbakhsh A, Saadatmand S, Ebadi M, Oraghi AZ. New insights into the transcriptional, epigenetic, and physiological responses to zinc oxide nanoparticles in Datura stramonium; potential species for phytoremediation. Journal of Plant Growth Regulation. 2021;**41**:271-281

[127] Kazemi M. Screening of native plant species for phytoremediation potential in Pb-Zn mines in Iran. Environmental Resources Research. 2021;**9**(1):89-98

[128] Fleck R, Gill RL, Pettit T, Irga PJ, Williams NL, Seymour JR, et al. Characterisation of fungal and bacterial dynamics in an active green wall used for indoor air pollutant removal. Building and Environment. 2020;**179**:106987

[129] Kurade MB, Ha YH, Xiong JQ, Govindwar SP, Jang M, Jeon BH.

Phytoremediation as a green biotechnology tool for emerging environmental pollution: A step forward towards sustainable rehabilitation of the environment. Chemical Engineering Journal. 2021;**415**:129040

[130] Rai A, Yamazaki M, Saito K. A new era in plant functional genomics. Current Opinion in Systems Biology. 2019;**15**:58-67

[131] Jonathan A. Vegetation Climate Interaction: How Vegetation Makes the Global Environment. Switzerland: Springer Cham; 2003. DOI: 10.1007/978-3-642-00881-8

[132] James CA, Strand SE. Phytoremediation of small organic contaminants using transgenic plants. Current Opinion in Biotechnology. Switzerland: Springer Cham; 2009;**20**:237-241. DOI: 10.1007/978-3-642-00881-8

[133] Sana B. Bio resources for control of environmental pollution. In: Biotechnological Applications of Biodiversity. Berlin, Heidelberg: Springer; 2014. pp. 137-183

[134] Miri S, Naghdi M, Rouissi T, Kaur BS, Martel R. Recent biotechnological advances in petroleum hydrocarbons degradation under cold climate conditions: A review. Critical Reviews in Environmental Science and Technology. 2019;**49**(7):553-586

[135] Adams GO, Fufeyin PT, Okoro SE, Ehinomen I. Bioremediation, biostimulation and bioaugmention: A review. International Journal of Environmental Bioremediation & Biodegradation. 2015;**3**(1):28-39

[136] Glick BR, Patten CL. Molecular Biotechnology: Principles and Applications of Recombinant DNA. USA: Wiley-Blackwell; 2022. ISBN: 978-1-683-67366-8. Available from: https://www.wiley.com/en-us/Molecular+Biotechnology%3A+Principles+and+Applications+of+Recombinant+DNA%2C+6th+Edition-p-9781683673668

[137] Siani L, Papa R, Di Donato A, Sannia G. Recombinant expression of Tolueneo-xylene monooxygenase (ToMO) from *pseudomonas stutzeri* OX1 in the marine *Antarctic bacterium Pseudoalteromonas haloplanktis* TAC125. Journal of Biotechnology. 2006;**126**(3):334-341

[138] Erkin OC, Takahashi M, Morikawa H. Development of a regeneration and transformation system for *Raphiolepis umbellata* L., "Sharinbai" plants by using particle bombardment. Plant Biotechnology. 2003;**20**:145-152