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Research Article

PHYLLOREMEDIATION OF AIR POLLUTANTS VIA PLANT LEAVES AND PHYLLOSPHERIC MICROBES

Yusra Mariam* and Ragini Gothalwal

Department of Biotechnology, Barkatullah University, Bhopal-462026, Madhya Pradesh

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ABSTRACT

Rapid urbanization, increase in population growth rate, economic growth and development of industries has caused more pollutants and contaminants to enter in air and thus results in pollution. The occurrence of air pollution is because of hazardous or excessive amounts of substances that are introduced from either man-made or natural sources into earth's atmosphere. Polluted air is a mixture of oxides of nitrogen, sulfur, carbon, particulate matter, ozone, volatile organic compounds, solid particles and gases. Furthermore, polluted air is severely affecting the wellbeing of inhabitants as these pollutants can be directly inhaled resulting in respiratory ailments, cardiovascular disorders and damage to other organs and also climatic changes such as acid rain, smog, global warming. Scientists and researchers have invented various methods to remove contaminants from air like small air filters, diesel particulate filters, photo catalysis and activated carbon filtering as adsorbent for xylene and NO2, microbial degradation of contaminant through *in-situ* and *ex-situ* bioremediation and bio transformation. Various strategies have been imposed by the government to control air pollution but air still remains polluted. In order to find a large scale purifier, definitely mitigation of air pollutants by biological means like bioremediation that involves the use of microbes to breakdown the hazardous substances into non-toxic or less toxic substances. The pollutants deposited on exposed plant leaves and micro biome inhabiting on the aerial surface of leaves degrade the toxicant and utilize it for its own growth such as toluene reduction by yellow lupine plants along with *Burkholderia cepacia*, leaves associated with *Methylobacterium* and phenantherene degradation by Ixora plant species.

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INTRODUCTION

Air pollution is considered as world‘s largest environmental health risk. About 9 million deaths per year have been recorded as a result of air pollution worldwide in 2017. This ranges from 2% in developed countries and 15% in under-developed countries. It leads to 3.7 million premature deaths globally. It is responsible for climatic changes, global warming, greenhouse effect, acid rain, temperature inversion, and stratosphere ozone depletion. There are chances of an increase in global temperatures by 1 degree Celsius by 2025. There is a remarkable increase in urbanization due to population explosion and industrialization across the globe and it is expected that it will increase at the rate of 2.3% per year by 2030 in developing countries. The enhancement of urbanization is often co-related with rapid economic growth. The increase in GDP which means economic growth escalates the consumption of energy by the utilization of more resources, combustion of fossil fuels for cooking, heating, smoke from industries, power plants, automobile exhaust, burning of agricultural waste and biomass fuels and coal especially in rural areas has led to the enormous increment in air pollution. (Air Quality in Europe, 2015 report).

Air pollution as a whole and particulate matter and volatile organic compounds individually have been considered to be potential carcinogenic agents. Research showed that 2, 2300 deaths were estimated across the globe because of air-pollutant induced-lung cancer around 7 million people have died directly or indirectly from air pollution. In addition it also harms the ecosystem, plants, animals, water and soil. It leads to several other deadly ailments such as urinary bladder cancer, acute leukemia and lung cancer. Chronic obstructive disease due to tobacco smoking which is a form of indoor air pollution. They also provide evidence for the ill effects of exposure to a combination of cigarette smoking and ambient air pollution (ICEIT 2014, WHO Report 2016).

Corresponding author:* **Yusra Mariam
Department of Biotechnology, Barkatullah University, Bhopal-462026, Madhya Pradesh

Table 1 The adverse effects of air pollutants on human Health

S.no.	Air pollutants	Adverse effects on human health	References
1	O_3	Asthma, breathing disorders and lung cancer	Amann,2008
2	PM	Heart, bladder and lung cancer, nervous system illness	Anderson *et al.,* 2012
3	NO_2	asthmatic bronchitis, respiratory infections, decline in lung function growth and airway obstruction	Lambert *et al.,* 1993
4	SO_2	Eye irritation, infections of the respiratory tract, coughing, mucus secretion, asthma and chronic bronchitis, and cardiac disease	Qin *et al.,* 1993
5	CO	Neuropsychological impairment, headache, fatigue, dizziness, and nausea, fetal damage, myocardial ischemia	Dahms *et al.,* 1993
6	Volatile organic compounds	headache, central nervous system damage, dizziness, confusion, motion sickness, respiratory tract ailments, asthma and sensitization reactions	Wallace.,1991
7	Asbestos	lung cancer, skin irritation, mesothelioma	McDonald.,1991
8	Formaldehyde	nasopharyngeal cancer, irritation of eyes, skin and respiratory organs, sneezing-coughing	Wieslander *et al.*,1996

Scientists and researchers have used a variety of approaches to combat air pollution. To remove contaminants from the air small air filters, diesel particulate filters, photo-catalysis, and activated carbon filtering as adsorbents for xylene and NO2 are used. Control of Air Pollution by physical means includes an electrostatic precipitator that removes 99% of particulate matter present in exhaust from a thermal power plant. It has electrode wires that are maintained at several thousand volts which produce a corona releasing electrons that attach dust particles and cause a negative charge. The collecting plates attract charged dust particles. (Wei *et al.,* 2018)

The catalytic converter has expensive metals like platinum, palladium, and rhodium as catalysts fitted into automobiles to reduce the emission of harmful gases. As the exhaust passes the convertor unburned hydrocarbons are converted into CO and NO_3 is changed into CO_2 and N_2. Automobiles fitted with catalytic convertors should use lead-free petrol because it inactivates the catalyst. Catalytic oxidization and chemisorption methods have been used for indoor formaldehyde removal (Pei and Zhang, 2011, Wang *et al.,* 2013). Photo-catalysis as one of the most promising technologies has been used for eliminating VOCs and formaldehyde from indoor environments. The technique is highly chemically stable, prudent, and non-toxic and can remove a wide variety of organics under UV irradiation (Huang *et al.,* 2016). The methods used previously are expensive and need specialized instruments for remediation of contaminants by biological means through plant-based affordable phytoremediation technology (Gawronski *et al.,* 2017).

Phytoremediation: In order to find a long-term permanent cure to carcinogenic, mutagenic and harmful air pollutants is the use of biological means by the process of bio-remediation that involves the use of microbes to remove pollutants of certain types. The methods used previously are expensive and need specialized instruments (Gawronski *et al*., 2017).

As the name suggests, "phyto" means plants and "remediation" means treatment, so phytoremediation is a waste treatment technique used to absorb cancer-causing toxic pollutants such as particulate matter and volatile organic compounds from the surface of the Apoplast the oxides of nitrogen and sulfur are converted to plant usable form through genetic and biochemical modifications. These oxides contribute to plant growth and metabolism by participating in the nitrogen cycle, meeting plant nutritional needs and reducing pollution. Thus, phytoremediation is an effective environmental biotechnological approach in which plant leaves act as natural carriers and bio-filters of air pollutants, since the plant canopy area is 4 × 10 8 km², which is almost 78.4% of the total plant area. In addition to the globe, various micro-biome residing in the aerial surface of leaves, that is the phyllosphere, plant stems and roots, and endophytic parts. Several plant species with microbial communities on their leaves effectively reduce toxic air pollutants; for example, *Chenopodium murale* degrades volatile hydrocarbons in *Hedera spp.* removes particulate matter, *Zea mays* removes phenolic compounds, and *Zamioculcas zamiifolia* remediate formaldehyde and phenantherene degradation by Ixora plants species (Wei *et al.,* 2018).Phytotherapy: a long-term, sustainable treatment for carcinogenic, mutagenic and harmful air pollution is the use of biological agents with a bioremediation process that involves microbes to remove certain types of pollutants. Previously used methods are expensive and require special instruments. (Gawronski *et al.,* 2017). Some plants have property of deteriorating, degrading and mitigating toxic air pollutants into less toxic ones by using air phytoremediation technology(Omasa *et al.,* 2012). Microbiome like bacteria and fungi in association with plants roots and shoots as heterotrophs were utilized for microbial bio-degradation because microbes are natural decomposers and scavengers present everywhere in the environment (Ward *et al.,* 1980; Ma *et al.,* 2016).

Air–phytoremediation treatment method is basically used for the deterioration of indoor air pollutants but as far as ambient air pollutants are concerned due to lack of basic research cannot be degraded. It is a biochemical method that involves plant leaves and above ground organs of the plant acting as a carrier between pollutants and microbes. (Kumar *et al.,* 2019).

It has some potential advantages which are as follows:

- It is a green and clean technology and will not cause secondary pollution. (Brilli *et al.,* 2018).
- It is a quite simple, affordable, reliable, easy to implement and sustainable technology (Gawronski *et al.,* 2017).
- The plants used for phytoremediation can be utilized as raw materials for energy and bio-based chemicals production (Zhu *et al.,* 2020).
- The use of this environment friendly technique by planting more trees will beautify the environment by urban greening. Building up of green belt especially around industrial areas. (Das, J., 2020)
- Mudhoo (2011) proposed the hypothesis that the superficial, but extensive nature of this technique makes it ideal for restoring agricultural soils by degrading disseminated industrial pollution.
- The remediation is done on site (*in-situ*), which saves transportation expenditure, and off-site (*ex-situ*) processing

costs. Roots of plants stabilize soil and prevent pollutant's movement through runoff and windblown dust. This is aesthetically appealing as compared to other methods. (Sharma *et al.,* 2014).

- It is an aesthetically appealing and solar energy-driven cleanup technology and on the other hand can detoxify major environmental toxicants.
- It is a cost-efficacious method since the cost of phytoremediation is 60-80% less than that of traditional or mechanical systems. (Raza, H., *et al.,* 2021)

Phyllosphere bacterial communities include *Proteobacteria* such as *Methylobacterium*, *Sphingomonas, Klebseilla, Scytonema, Azotobacter, Beijerinckia* has phyllosphere as their habitat (Vascher *et al.,* 2016).The plant-microbe interaction proved their evolutionary and adapter relationships. It was concluded that if plants and plants-associated microbes were exposed to pollutants for a long time they will start finding ways to cope with the stress conditions and develop mechanisms for the degradation of air pollutants and bioaccumulate in their plant parts to metabolize them either individually or in association, the studies revealed that diversity of microorganisms is co-related with plant diversity and ecosystem diversity (Laforest- Lapointe *et al.,* 2017).

Leaves interaction with pollutants: Leaves of plants were exposed all the time to dust particulates and pollutants like particulate matter, NO2, SO2, oxides of nitrogen and carbon monoxide(CO) were absorbed the stomata which terminates the gaseous exchange within the stomata results in reduction of photosynthesis causes diseases like chlorosis and necrosis in broad-leaved species and black spots and brown tips in conifers rather than NO2 is absorbed by the extra cellular matrix and converted into Nitrates and protons (H+). Carbon mono- oxide (CO) caused curling of leaves, retarded stem elongation and other diseases.

Das, J.,(2020) performed an experiment by calculating the APTI value of selected plant species in three areas (residential, commercial and industrial) with respect to particulate matter, NO2, CO, and SO2 for analyzing the ambient air quality through one way ANOVA analysis, it was concluded that the results in the industrial areas were more significant. In a study in industrial areas of Bengaluru, the trees species *Ficus religiosa*, *Azadirachta indica* and *Pongamia pinnata* were considered as sensitive on the basis of APTI values.

In another study in Coimbatore the plants of *Mangifera indica, Bougainvillea* species, *and Psidum quajava* depicted high APTI values whereas *Thevetia nerifolia,* and *Phyllanthus emblica* showed low Air pollution tolerance index values. The above research of ambient air quality assessment concluded that plants with high APTI values have the ability to survive in polluted environment around industrial zones by improving sequestration of carbon and utilizing oxides of nitrogen in plant growth by converting it into nitrates.(Balasubramanian *et al.,* 2018). The green-belts of these tolerant plants species will be built around industrial sites and oil refineries that will improve the air qualitatively and also afforestation is the pre-eminent way of assessing the air quality. Thus, the role of plants in urban removal of air pollutants will be taken into consideration.

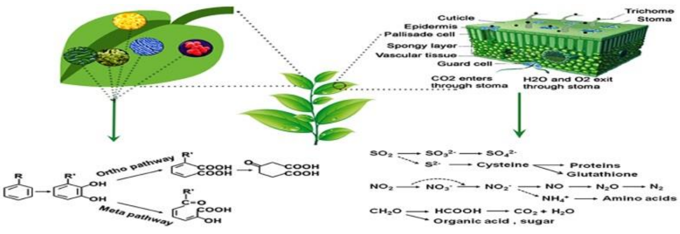

Figure *1* A schematic illustration of phyllosphere leaf interaction with pollutants showing assimilation of SO_2, NO_2, and CH_2O (formaldehyde) to simple organic compounds, amino acids, or proteins and degradation of VOCs into benzene and its derivatives via ortho pathway or Meta cleavage pathway. (Wei *et al., 2018)*

Microbes-abatement mechanism: Plants associated micro-biome helps in the nutrient enhancement and production of the plant growth promoting hormones like indole acetic acid (IAA) and production of 1-aminocyclopropane-1-carboxylate deaminase (ACC) that helps the plant against the physical factors like biotic and abiotic stress such as temperature, pressure, precipitation, etc. In phytoremediation certain factors like increased biomass to adsorb pollutants at surface improved scavenging capacity adsorbing capacity are characters that affect the remediation of particulates in air (Weyens *et al., 2009*). Growth of plants can be promoted by bacteria that act as bio-fertilizer which enhances the availability of nutrients to crops by fixing atmospheric polluted nitrogen and solubilizing phosphorus. The bacteria also fix nitrogen and improves physical properties of soil, produce growth promoting substances, and also solubilize inorganic phosphorus in association with the roots of plants which is utilized by plants. The production of reactive oxygen species (ROS) on the surface of pollutants affects the degradation and accumulation of particulate matter it was revealed that bacteria have antioxidant properties that detoxify ROS.As this ROS production on the surface of ultrafine particles is related to surface-associated EPFRs an action of bacteria on EPFR by reducing concentration of EPFR on the surface of particulate matter and neutralization of reactive oxygen species formed by EPFRs in the solution. Thus, plants associated microbes may support plants to fight against stress caused by particulate matter bounded pollutants and enhance phytoremediation efficiency.(Kelley *et.al.*,2012, Raj Kumar *et al.*,2013).

Banerjee and Ghoshal, (2010) has been suggested that the bacteria *Bacillus cereus* can deteriorate phenol through meta-cleavage pathway. A variety of naphthalene-scavenging microbes has been isolated from phyllosphere of the plant and examined for mineralization are *Alcaligenes denitrificans, Mycobacterium sp., Pseudomonas putida, Pseudomonas fluorescens, Pseudomonas paucimobilis, Pseudomonas. Vesicularis, Pseudomonas cepacia, Pseudomonas testosteroni, Rhodococcus. Corynebacterium venale, Bacillus cereus, Moraxella sp., Streptomyces sp., Vibrio and Cyclotrophicus*.

Degradation of phenanthrene was investigated in two road sides of Bangkok, Initially six plant species were collected and their degradation rates were analyzed. Karen Waight *et al.,* (2009) investigated the degradation of atmospheric phenanthrene deposited on plant leaves by phyllosphere bacteria such as *Pseudomonas oleovorans, Microbacterium foliorum, Rhizobium gallicum, Rhizobium etli* and *Deinococcus sp.*, *Deinococcus grandis* along with six different plant species in which he found that Ixora species. Plant leaves has the high efficiency of degrading phenanthrene deposited in their leaves in polluted areas because it has high number of degrading bacteria.

Plant-microbe interaction: Microbial interaction occurs in variety of ways where foliage especially leaf surface (phylloplane and phyllosphere) serves as ecological niche for microbes. They help the plants to survive under biotic and abiotic stress and helps in water and minerals uptake from roots, secretion of plant hormones, inhibitory allelochemicals. (Arshad *et al.,* 2007 and Bulgarelli *et al.*, 2013). Some plants species were recognized from previous researches as the potential scavenger and degrader of indoor and outdoor air pollutants and metabolize them (Nowak *et al.,* 2001).Basically microbial associations of plants play an important role in deterioration and decomposing aero-pollutants by release of allelo-chemicals that have detrimental effects on growth of airborne microorganisms and increased air humidity in indoor environment (Berg *et al.,* 2014).

In plants, adsorption and stabilization of particulate matter occurs on foliage and stems. Micro-organisms helps in plant growth promotion and particulate matter detoxification. Uptake of volatile organic compounds via leaves and stomata and roots. Microorganisms helps in degrading VOCs and perform sequestration and excretion of VOCs, furthermore organic and inorganic compounds adsorption and uptake occurs via stomata and cuticles and deteriorate pollutants through bio- fertilizers ultimately sequestered carbon and plant growth promotion and their methods of deterioration by microbes alone.(Weyens *et al.,* 2009).

phylloremediation which includes the plant-microbe interaction via plant leaves. Phylloremediation is derived from a Greek word "***phullon"*** which means leaf. This term was introduced firstly by Sandhu *et al.,* (2007).De Kempeneer *et al.,* (2004) carried out in his research that both plant leaves and leaf-associated microbes are able to mortify air pollutants, such as azalea leaves and the leaf- associated *Pseudomonas putida* detoxify volatile organic compounds. Barac *et al.,* (2004) found out that leaves of yellow lupine plants along with endophytic *Burkholderia cepacia* performs toluene reduction and popular leaves and the leaf-associated *Methylobacterium sp.* desensitized xenobiotic compounds.

The phenotypic and metabolic properties of five phyllosphere bacteria and their characterization has been carried out isolated from green leaves of Rosa-rogusa plant by using 16S rDNA sequencing causes isolates as *Pantoea agglomerans, Klebseilla terigena, Erwinia rhapontici* and two strains of *Rahnella aquatilis* considered as primary defense mechanism of host plants. The two isolates from *Rahnella aquatilis* isolates from the green leaves showed a substrate- inducible Gallate decarboxylase activity and antimicrobial activity. Gallate decarboxylase positive bacteria help in the regulation of the phyllosphere micro-flora of the green leaves. (Yasuyuki Hashidoko *et. al.,* 2002).

Pollutant Degradation and transformation Mechanism: Microbial bio-degradation is often characterized as an efficient process which is catalyzed via degrading enzymes. It depends on enhancement of degradation efficiency at enzyme level.

"Table 2'' Plants supported microbes that degrade and bio-remediate the pollutants

S.No.	Plants	Microbes	Pollutants	References
1	Arabidopsis.thaliana	*Hyphomicrobium sp.*	chloromethane	Nadalig *et al.*,2011
2	Azalea indica	*Pseudomonas putida*	toulene	Kempeneer *et al.*, 2004
3	Bougainvillea buttiana	*Enterobacter cloacae StaphylococcusA1 and Pseudomonas aeruginos*	Xylene	Sangthong*et al*.,2016
4	Ixora spp.	*Pseudomonas., Microbacterium., Rhizobium., and Deinococcus*	Phenantherene and polyaromatic hydrocarbons	Waight *et al*.,2007
5	Magnifera indica	*Pseudomonas.,Alcaligenes Micrococcus roseus*	hydrocarbons	Ilori *et al*.,2006
6	Oryza sativa	*Methylobaterium sp.,*	methanol	Kneif *et al*.,2012
7	Pisum sativum	*Microbacterium. Rhodococcus*	Phenantherene,octadeacne.crude-oil	Ali *et al*.,2012
8	W. religiosa	Pseudomonas, Mycobacterium,acetinobacter	Polyaromatic compounds	Iguchi *et al*.,2012
9	Zea mays	Pseudomonas CF600	Phenol	Sandhu *et al*.,2007
10	Zamioculcas zamiifolia	Pseudomonas aeruginosa and Bacillus cereus	Ethylbenzene	Toabaita *et al*., 2016

As phytoremediation have some disadvantages this implies water, depth, nutrient, atmospheric, physical, and chemical limitations, cost issues, suitability in a time of increasing air pollution conditions, disturbing the metabolism, biochemical processes in plants. Several studies showed that the plants species growing near polluted areas show high foliar levels of essential nutrients and heavy metals. Both roots and shoots have been reported to be able to remediate air pollutants but role of microbes has not been investigated Plant breeders and geneticist have lack of knowledge about biochemical conversion of pollutants & physiological features of plants leaves and endophytes. (Gawronski *et al.,* 2014, Weyens *et al.,* 2009).Plant shoots or the above-ground organs of plants occupied by bacteria, yeasts, and fungi are called phyllosphere (Last., 1955).

Lindow *et al.,* (2003) utilized the leaves of plants basically phyllosphere microbiology. This review focuses more on

The enzymes that are involved in the detoxification of organic and inorganic environmental pollutants are laccases, oxygenases, hydrolases, lipases and heavy metals transforming enzymes. Hydrolysis is an important biochemical phenomenon carried out by hydrolytic enzymes such as esterases and lipases present in microbes that can split the ester bond of recalcitrant pollutants to reduce their toxicity.Heavy metals like arsenic, lead, mercury are absorbed by certain aerobic prokaryotes, such *as Geobacter*, *Staphylococcus* and *Pseudomonas. (Lazaro et al., 2021)*

Bacteria have mercury resistance systems which constitute a set of operon genes *mer* operon, which reduces ionic mercury ($Hg^{2}+$) to the volatile elemental form (Hg^{0}).Generally ,the *mer* operon contains various linked genes in a cluster that are responsible for the transport and transformation of inorganic and organic mercury. A *mer* operon contains enzyme organomercurial lyase (MerB), which carried out the demethylation process by splitting the methyl group to generate methane (CH4) and Hg(II). Furthermore, another enzyme mercuric reductase (MerA) reduces the Hg(II) to the volatile form. Apart from that ,there are 5 inner membrane-spanning proteins named as MerT, MerC, MerE MerF and MerG that carried out the transportation of Hg^2+ to the cytoplasm, whereas Hg^2+ was further reduced by MerA. *Pseudomonas azotoformans QDZ-1* bacterial strain contains an esterase enzyme *ChbH* is responsible for the hydrolysis of cyhalofop-butyl (CB) to cyhalofopacid (CA). An amide herbicide, arylamidase AmpA, purified from *Paracoccus sp. FLN-7*, catabolize the amido bond cleavage of amide herbicides, such as propanil, propham, and chlorpropham. Similarly bacteria has *pbr* operon having two transcription units *pbrUTR* and *pbrABCD.* (Xu *et al.,* 2021)

The lead resistance model allows Pb^2+ removal from the cytoplasm by PbrA; it is then sequestered as a phosphatase salt with the inorganic phosphate produced by PbrB in the periplasm medicated by metallothionein genes bmtA and smtAB *Providencia vermicola* Subsequently, For combating Arsenic air pollutants some notable bacterial species have *ars, aio,* and *arr* operons. The arsenite oxidase (Aio) system can take electrons from arsenite and oxidized them into arsenate, and the arsenate respiratory reductase (Arr) system catalyzes the reduction of arsenate to arsenite at the end of the respiratory chain. Under aerobic conditions, As(V) enters the cell via phosphate uptake systems (PstA, PstB). As(V) is then reduced by the arsenate reductase ArsC to As(III).In aio operon, As(III) is oxidized in the periplasm by arsenite oxidases (AioAB) into the less bioavailable form As(V).(Sharma *et al., 2017).*

Phylloremediation of Poly-aromatic hydrocarbons (PAHs): Poly-aromatic hydrocarbons (PAHs) are colorless, white or pale organic compounds having only hydrogen and carbon atoms and multiple aromatic rings in their structures where electrons are localized. PAHs generated from these sources can bind to air and form the smallest particles in the air. (Fiala et al., 1999).Poly-aromatic hydrocarbons are a group of chemical compounds that are found naturally in coal, crude oil, and gasoline. They are also produced during the incomplete combustion of coal, oil, gas, wood, and garbage, organic -matter, emissions from vehicles and electricity generation from power plants, tobacco smoking, agricultural, industrial, household activities like cooking. (Jain *et al.,* 2002)

Microbial degradation of organic compounds carried out by enzymes such as Laccases and oxygenases. Laccases are broad spectrum enzymes utilized for the degradation of many phenolic compounds, including phenols, polyphenols, and PAHs and PCBs. Zeng *et al.,* (2016) indicated that bacterial laccase CotA from *Bacillus subtilis* oxidized Poly-aromatic hydrocarbons along with a copper-independent way having higher laccase activity. Laccases carried out degradation of phenolic compounds, poly-aromatic hydrocarbons and Polychlorinated Bis-phenyls that oxidize the enzyme directly results in the formation of phenoxy radicals and undergone through phenolic coupling or oxidative coupling via either C-O or C-C bonds. Furthermore, Laccases enzymes carried out oxidation and polymerization of phenolic compounds and convert them into non-toxic or less toxic polymers. This degradation mechanism are the most promising environment friendly approach of bioremediation technology. However, laccases can be also be used to catalyze the oxidation of aromatic recalcitrant with the help of some redox mediators. Process. Aryl radicals are obtained from Polyaromatic hydrocarbons followed by the production of quinones in a catalysis activity of laccases enzyme which can be improved by adding copper metal during PAHs oxidation process. These mechanisms such as phenoxyl radical mediated coupling responsible for the degradation of phenolic compounds.(Hu *et al.,*2007).

Oxygenases are of two types Mono-oxygenases and di-oxygenases that are responsible for desulfurization, dehalogenation and the oxidative release of nitro group and hydroxylation of various aromatic compounds. Two common alkane mono-oxygenases are AlkB-related mono-oxygenases and the cytochrome P450 family proteins which are flavin-binding and thermophillic soluble long-chain alkane mono-oxygenase *AlmA* and *LadA* also carried out the hydroxylation of long-chain alkanes (Xu *et.al.,* 2020).

Loss *et al.,* (2019) reported that BapA gene in *Aspergillus* fungus species encodes in P450 mono-oxygenases which is essential for metabolic utilization of Benzo (α) pyrene (BAP) which is a main component of Poly-aromatic hydrocarbons (PAHs). Besides, Zhang *et al., (2009)* found out that the para nitro-phenol (PNP) catabolic pathway of the *Pseudomonas sp.,* converts PNP to para-benzoquinone by the process of de-nitration. Naphthalene is a poly-aromatic hydrocarbons (PAHs) which is detoxified by a wide variety of bacteria from the genus *Pseudomonas*, *Rhodococcus,* and *Mycobacterium sp.* Some Common NDOs are multi-copper enzymes comprizing an electron transport chain and a terminal oxygenase.Di-oxygenase enzymes carry out the hydroxylation of aromatic hydrocarbons via aerobic metabolism which initiates oxidation of benzene ring with the help of di-oxygenase enzymes by introducing two hydroxyl groups to aromatic compounds. (*Figure 2A*).

Biphenyl-using bacteria catabolize biphenyl and polychlorinated bis-phenyls (PCBs) to chlorobenzoic acids using biphenyl dioxygenase (BPDO) via an oxidative pathway. Like NDO enzymes, BPDO is composed of three components. Catalytic component (BphAE), ferredoxin (BphF) and ferredoxin reductase (BphG), which act as an electron transfer from NADH to BphAE. (Xu *et al.,* 2020). (Figure 2B)

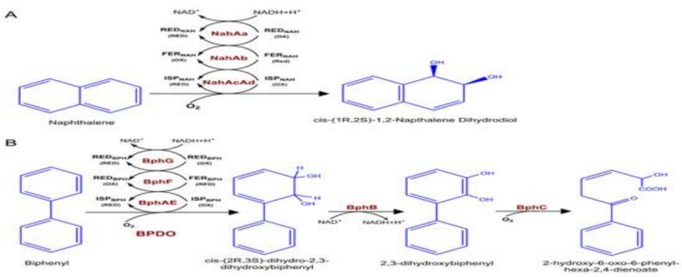

Figure 2 Naphthalene and biphenyl catabolic pathway enzymes and metabolites. (A) Naphthalene catalyzed by three-component NDO to cis-(1R,2S)-1,2-napthalene di-hydrodiol. (B) The four enzymatic steps of the bacterial biphenyl metabolic pathway catalysis by BPDO. Reduction-reduction; oxidation- oxidation.(Xu et.al.,2020).

Phylloremediation of SO_2, Ozone and VOCs: Phylloremediation of SO2, ozone, and volatile organic compounds: sulfur dioxide is one of the harmful pollutants. SO2 can be photo chemically or catalytically oxidized to atmospheric sulfur trioxide (SO3) and sulfate (Bufalini. 1971). During sulfur assimilation, sulfate is reduced to organic sulfhydryl groups (R-SH) by sulfate-reducing bacteria, fungi, and plants. Sulfur-oxidizing bacteria such as *Beggiatoa* and *Paracoccus* are capable of oxidizing reduced sulfur compounds such as H2S to inorganic sulfur and thiosulfate, forming sulfuric acid (Pokoma and Zabranska. 2015). Ozone is formed when heat and sunlight cause chemical reactions between nitrogen oxides and volatile organic compounds (VOCs) in the atmosphere. Ozone does not break down directly, but plants have developed mechanisms to counteract ozone toxicity. O3 can be removed from the air by chemical reactions with reactive compounds released by plants, which are mostly mono-terpenes (Di Carlo *et al.*, 2004).

VOCs are substances that have high vapor pressures at normal room temperature and play an important role in ozone formation in photochemical reactions with low water solubility, acute toxicity, and genotoxicity. They can be broken down when the leaves of the plant absorb gaseous pollutants through the stomata of the leaves and detoxify them. In addition to plant leaves, several rhizosphere bacteria *Pseudomonas putida*, such bacteria isolated from soil, water, and various tissues of plants in a polluted environment (Yu *et al.*, 2015) identified a fungal strain *Aspergillus sydowii* capable of growing in the presence of formaldehyde.

Phylloremediation of NO_X: There are several oxides of nitrogen (N) accumulated in the atmosphere nitrogen dioxide (NO_2), nitric oxide (NO), nitrous oxide (N_2O)nitrogen trioxide (N_2O_3), and nitrogen trioxide (N_2O_5). Among them, the USEPA regulates NO_2 only because it is the most prevalent form of NOx generated via man-made activities. (USEPA, 1999). Plants absorb gaseous NO_2 more rapidly than NO because NO_2 reacts rapidly with water while NO is almost insoluble in water. When the two gases occurred in the same concentration, the uptake of NO_2 per unit leaf area was observed three times greater than NO.When NO and NO_2 are absorbed and dissolved in the extracellular solution of leaves, they form nitrate (NO_3) and NO_2 in equal amounts and proton (H+). NO_3 is then utilized by plants in the same way as it is absorbed from roots and used as a nitrogen source for synthesizing amino acids and proteins. Nitrogen dioxide could be a plant signal molecule that improves plant growth. Morikawa *et al.* (2004) indicated that about one-third of NO_2-derived N absorbed by leaves was converted into a previously unknown *Kjeldahl*-unrecoverable organic nitrogen, which comprise a novel heterocyclic 12 1, 2, 3 thiadiazoline derivative and nitroso- and nitro-organic compounds.

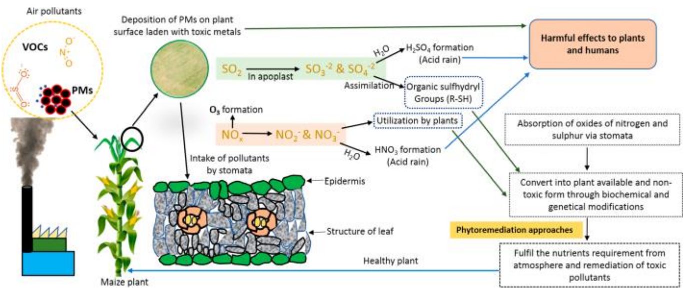

Figure 3 Schematic representation of phytoremediation and utilization of air borne toxic pollutants by plants. (Kumar et el., 2019)

Nitrifying bacteria including species of the genus *Nitrosomonas*, *Nitrosococcus*, *Nitrobacter*, and *Nitrococcus* oxidizes ammonia to hydroxylamine and nitrite oxido-reductase enzyme oxidizes nitrite to nitrate. Phyllosphere diazotrophic bacteria, like *Beijerinckia*, *Azotobacter*, and *Klebsiella* and also *Cyanobacteria*, such as Nostoc, Scytonema, and Stigonema can use atmospheric dinitrogen (N2) as a source of nitrogen (Whipps *et al.*, 2008). N_2 is fixed by the nitrogenase enzyme encoded by nif genes and the gene nifH has been widely used for analysis of their community structure (Fürnkranz *et al.*, 2008; Rico *et al.*, 2014).

Phylloremediation of CO_2: Phylloremediation of carbon dioxide: By 2025, global temperatures may increase by one degree Celsius. CO2 emissions and the presence of other greenhouse gases in the environment are the result of natural processes such as respiration and volcanic eruptions, as well as human activities. Deforestation and burning of fossil fuels. According to a report by the World Meteorological Organization (WMO), the concentration of carbon dioxide in the earth's atmosphere has reached a high level. It was detected in millions in December 2018. To fix and split carbon dioxide from the atmosphere, the process of photosynthesis is more efficient. A biological mitigation strategy called "phytoremediation" has been used to clean up greenhouse gases, heavy metals, pesticides, xenobiotics, organic compounds, and toxic aromatic pollutants. This is a cost-effective way to reduce global warming and air pollution through plant-microbe interactions. Plants absorb carbon dioxide from the atmosphere and transform it into organic substances. The plant's root and shoot system helps bind carbon dioxide thanks to the plant's assimilative capacity. Different plant species have different carbon fixation capacities. Plants grown in urban areas and near industries are better able to capture carbon dioxide and reduce air pollution (Satyanarayana *et al.*, 2021).

CONCLUSION

Air pollution is detrimental to human health, ecosystem and environment. A number of air pollutants pose severe health risks and can sometimes be fatal even in small amounts. The scientists, academia, environmentalists and researchers can utilize the potential of plants for sustainable development in both under-developed and developed countries through this viable waste treatment method**.** *Phylloremediation* will improve the quality of air by degrading air pollutants via phyllosphere which is an ecological niche for various microorganisms such as bacteria, fungi, and yeast. Microbes-abatement mechanism and plant- microbe interaction played an important role in degradation of ozone, particulate matter, CO_X, NO_X, Polyaromatic hydrocarbons and volatile organic compound. More diverse plants and dimensions of indigenous micro- organisms should be used in phylloremediation in future as technology.

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