Rhizosphere-Plant-Microbial system under Polycyclic Aromatic Hydrocarbon stress

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Abstract

Rhizosphere-plant-microbial association is a complex and intricate system susceptible to various organic pollutants including Polycyclic Aromatic Hydrocarbons (PAH). Since soil acts as a sink of PAH, their accumulation not only shifts the delicate rhizosphere-plant-microbe equilibrium, but also enters the food chain through plants. The manner in which the presence of PAH in rhizosphere affects rhizosphere-plant-microbial system is still unclear. This review aims to understand the effects of PAH on rhizosphere-plant-microbial interactions. It also explores the potential use of microbes to alleviate PAH stress in soil for effective and sustainable management.

Keywords: Bioaccumulation, Microbe-mediated remediation, Persistent Organic Pollutants, Rhizo-microbiota

1. Introduction

PAH are among the most notorious, cosmopolitan, toxic and persistent organic pollutants. They are ubiquitous in nature and in the last five decades, their global burden has increased by around 45%[1]. The average global PAH emission has been estimated to be 504 gigagrams/year in 2007 and is majorly contributed by developing Asian countries[2]. Africa, Europe, North America, Oceania and South America contribute 18.8%, 9.5%, 8.0%, 1.5% and 6.0%, respectively to worldwide PAH emissions[3]. The distribution and accumulation of PAH are not uniform and show significant regional variation. India (90 gigagram) and China (114 gigagram) are the major contributors of PAH annually[4]. This sharp rise is due to rapid industrialization, fossil-fuel-dependent transportation and other anthropogenic activities. Sources of PAH can be broadly classified as petrogenic (petroleum as the source) and pyrogenic (incomplete combustion of fossil fuels and biomass). Most of the PAH are potential carcinogens and their exposure or indirect consumption leads to serious health effects. They are considered as priority pollutants due to their 'three disease-causing' effects (carcinogenic, teratogenic and mutagenic) on humans[5]. In spite of being volatile and present in air, their presence in soil is of concern as they tend to accumulate in it.

Due to their hydrophobicity, around 90% of the global PAH is adsorbed in soil which not only makes it a major sink but also drastically changes the physicochemical properties of soil, thereby altering its structure and function[6]. Rhizosphere, the zone of interaction between soil and roots, is a diverse and intricate habitat hosting a wide range of algae, protozoa, arthropods, nematodes, bacteria and fungi. Among these, microorganisms play a significant role in regulating essential biogeochemical processes and also facilitate xenobiotic degradation. Biodegradation of soil pollutants such as pesticides, insecticides and PAH is a critical ecosystem service provided by rhizospheric microbes[7]. The presence of PAH in rhizosphere enhances their risk of entering the food chain as well as influences soil microbial diversity and dynamics[8].

Plants are key players that influence the entry, accumulation and movement of PAH in the food chain. They take up PAH either directly through roots or indirectly through the cuticle[9]. Higher the PAH concentration in soil, greater is the risk of their bioaccumulation and subsequent magnification in the plant. Excess PAH accumulation in plants is responsible for acute, chronic as well as latent injuries, that eventually disrupt its primary metabolic functions such as photosynthesis[10]. As plants regulate the growth and diversity of microbial communities through root exudates, when grown in high PAH the diversity of rhizospheric microbes as well as their endophytes is observed to be modified[11]. Therefore, the interaction between soil microbes, plants and PAH is a tripartite process and any change in one significantly affects not only the other two but also the food chain.

The interaction between rhizosphere-plant-microbe is delicate and sensitive to the presence of PAH. However, no study has addressed the effect of PAH toxicity on this complex-yet important system. This review summarizes the multifaceted interaction between rhizosphere-plant-microbes and analyses, how this system responds to increased PAH levels. It also explores microbe-mediated, sustainable mitigation measures for PAH polluted soil, to prevent their accumulation and magnification in food chain.

2. Soil: A sink of PAH

PAH released from various anthropogenic activities accumulate in soil by wet or dry deposition. Soil serves as their primary and largest steady repository. Their lipophilicity makes them less available for biodegradation and hence, they accumulate in soil increasing their persistence in the ecosystem[12]. The distribution of PAH in the rhizosphere depends on their source and chemical properties, soil characteristics and environmental conditions[12]. The amount of PAH in soil is inversely proportional to its proximity to the emission source. Industrial and urban soils have more PAH contamination as compared to rural or remote areas[13]. Chemical properties of PAH also influence their bioavailability. Low molecular weight (LMW) PAH with two or three rings such as naphthalene, fluorene, phenanthrene and anthracene are present in negligible amounts as they undergo degradation, leaching and volatilization in the soil[14]. In contrast, high molecular weight (HMW) PAH such as pyrene, chrysene, benzo(*a*)pyrene and benzo(*a*)anthracene are abundant in soil as they are not degraded or transformed completely into simpler products due to their highly lipophilic, persistent and stable chemical composition[15]. It is known that 2-,3-,4-, 5- and 6-ring PAH contribute to >3%, >16%, 45%, >27% and >6% of the total PAH respectively in the soil of urban parks in China[16]. Thus, HMW PAH are the majorly responsible for soil contamination.

Based on the concentration of PAH, soil is classified as (i) unpolluted (<600 ngg^{-1}); (ii) slightly polluted (600-1000 ngg^{-1}); (iii) polluted (1,000-5000 ngg^{-1}); (iv) heavily polluted (5000-10,000 ngg^{-1}) and (v) very high polluted (>10,000 ngg^{-1})[6, 17]. Figure 1 summarizes the country-wise prevalence of PAH in soil based on the literature.

3. Significance and role of rhizospheric microbes

3.1 Diversity of microbes

Rhizosphere is a dynamic zone where numerous biochemical and biophysical processes take place that shapes and organizes soil's physical and functional attributes. Soil characteristics such as texture, pore volume and particle aggregation influence root-microbe associations. Interactions between soil and its microbiome are influenced by plant species and soil type, and are important for plant growth and matter turnover [18].

Bacteria are among the most abundant microbes in the rhizosphere, covering nearly 15% of the total root surface, dominated by phyla such as Proteobacteria, Actinobacteria, Firmicutes, Bacteroidetes and Acidobacteria[19]. Proteobacteria are present in greater numbers due to their ability to act on labile carbon sources and thus, grow at a fast rate making them capable of surviving in diverse rhizospheres[20]. Another dominant phylum is Acidobacteria that plays a key role in carbon cycling as it is capable of degrading cellulose and lignin[21]. Anaerobic bacteria belonging to *Latescibacteria and Planctomycetes*) dominate the rhizosphere whereas aerobic bacteria (*Parcubacteria, Firmicutes and Saccharibacteria*) are comparatively lesser in number due to reduced oxygen levels in the rhizosphere[22].

Along with bacteria, rhizosphere is well represented by fungi primarily belonging to the Ascomycota, Basidiomycota and Zygomycota[23]. Arbuscular mycorrhizal (AM) fungi are among the most ubiquitously present in the rhizosphere ecosystem globally and provide an array of services[5,25]. Moreover, several algae including species of *Arthrospira*, *Chlorella*, *Dunaliella*, *Nostoc* and *Aphanizomenon* are found in the rhizosphere that play a significant role in maintaining soil health by acting as both bioprotective and bio-stimulant agents[26].

Rhizosphere microbiome is sensitive and quickly responds to any change in its surrounding[24]. The physio-chemical properties of soil, type of vegetation and stage of the plant influence the diversity and abundance of microbes in rhizosphere.

3.2 Rhizosphere Microbes in Ecosystem Services

Rhizosphere microbes play a substantial role in various ecological services such as soil formation, decomposition of organic matter, biogeochemical cycles and degradation of soil contaminants[27]. The ecosystem services performed by microbes are categorized into regulating, supporting and provisioning services and are summarized in Supplementary Table 1.

Soil bioremediation is an important regulating service performed by the rhizosphere microbes. Genera of bacteria including *Acinetobacter, Burkholderia, Pseudomonas, Flavobacterium, Bacillus, Azotobacter,* and fungi such as *Aspergillus* are capable of degrading an array of soil contaminants[28,29]. Many species of mycorrhizal fungi are also involved in remediating soil pollutants such as organic hydrocarbons[30]. Microbes either use the organic pollutants as the carbon source, or degrade the toxic and complex compounds into simpler and lesser toxic forms[31]. Their efficiency and strategy are dependent on pollution load. A consortium of PAH degrading microbes removed 97.2% of pyrene from soil and inhibited its accumulation in host tissues[32]. Similarly, up to 90% of biodegradation of lindane (organochlorine pesticide) using *Paracoccus* sp. NITDBR1 has been reported[33]. Rhizospheric microbes are also known to efficiently degrade diesel-based contaminants. Diesel oil-contaminated soil was effectively mediated by an artificial consortium containing *Alcaligenes xylosoxidans*, *Pseudomonas fluorescens*, *Pseudomonas putida*, *Stenotrophomonas maltophilia* and *Xanthomonas* sp[34].

4. Plant–microbes–rhizosphere system under PAH stress

4.1 Physicochemical properties of soil

Soil across the globe is under constant threat of PAH which tend to accumulate on its particles. The degree of adsorption and desorption of these pollutants depends on redox conditions, pH, organic ligands and inorganic ions[35].

The molecular weight and ring structure of PAH govern their fate in the soil as well as influence soil characteristics[36,38]. The HMW tend to alter the physical characters of soil such as pore size, rate of filtration and aeration as they bind more firmly to the particles as compared to LMW PAH. Fine soil particles have lesser inter-particle space and a porosity-mediated effect that restricts the mobility of HMW PAH due to their greater hydrophobicity[37]. As a result, they tend to completely choke soil pores or partially replace them leading to reduced aeration and filtration capacity of soil.

Presence of PAH, affects physico-chemical properties of soil such as pH, CEC, humic acid, carbon and nitrogen content[39,40]. PAH also influence physical characteristics of soil such as grain size, water-holding capacity and porosity, leading to reduced aeration and choking of soil pores[37]. Fine grained particles i.e. silt and clay are more susceptible to PAH binding[41].

Alternately, properties of soil such as its size, pH and associated organic carbon, also determine the extent of PAH effect[38]. Fine soil particles provide lesser scope of PAH movement resulting in persistent toxicity and enduring effects[37]. The carbon-rich organic and fine-grained acidic soil is more susceptible to PAH contamination and is therefore difficult to bioremediate[42]. Prolonged exposure and subsequent accumulation of PAH in the soil and by extension rhizosphere, significantly lowers its quality and adversely affects the rate of seed germination, growth and eventually plant health[43].

In spite of their ubiquitous presence across soil in different parts of the world, there is limited information on the influence of PAH on soils and its processes. There is a large temporal and spatial variability of types and concentration of PAH, and therefore more region-specific studies are required to provide sustainable remediation solutions.

4.2 Impact on rhizo-microbiota

Rhizosphere microbes are highly sensitive to any change in the physico-chemical or edaphic properties of soil. Under the influence of pollutants, a shift in the diversity and growth patterns of the microbial population takes place. Biological activities in the rhizosphere such as microbial biomass and associated enzymatic activities are susceptible to organic pollutants including PAH[44]. The type of PAH influence community profile of rhizospheric microbiota. Studies have been focused on understanding the effect of PAH on microbial diversity, density and metabolic activity[45]. At high concentration, PAH are detrimental to their growth or even toxic to soil microbes. Contamination of PAH in rhizosphere may even decrease the diversity of some microbial populations and increase the density of aromatic ring dioxygenase-expressing bacteria (ARDB) due to an increase in concentration of organic carbon[11]. This could be the result of increased root exudation or accumulation of PAH around the roots due to its transport processes inside PAH accumulated plants. Soil microflora is highly sensitive to any soil perturbation and therefore known to be pollution indicators[46,47]. PAH stress in soil can lead to altered microbial diversity, activity and succession[48]. Influence on microbiome depends upon the type and molecular weight of the PAH[49]. For example, pyrene contaminated soils affected diversity and abundance of bacteria more than of fungi. Similarly, the density of gram-negative bacteria and AM Fungi increased around *Echinacea purpurea* grown in PAH-contaminated soil[50]. PAH mediated change in microbiome is due to altered carbon and nitrogen cycling, and accelerated metabolism of carbon in soil[51]. These studies indicate that PAH may negatively affect the ecological balance of the rhizosphere. High PAH contamination lowers the capacity of soil to degrade contaminants due to decreased microbial activity[42,51]. Any change in soil microbial diversity and population dynamics may alter the delicate balance of nutrient cycling. Moreover, any shift in rhizospheric community structure and function has direct implications on the growth of plants as well.

Soil enzymes are sensitive indicators of function and degradation potential of soil. Enzymes such as urease, alkaline phosphatase, polyphenol oxidase and dehydrogenase are used to determine PAH load through an assessment of the rhizo-microbiota[53]. There is a positive correlation between the presence of different PAH and the activity of dehydrogenase and urease[54].

4.3 Plant response to PAH stress

Increasing PAH concentration in soil is of concern due to their tendency to bioaccumulate and subsequently bio-magnify through absorption by plants. They not only affect germinability, growth, physiology and metabolic behaviour of plants, but also resource partitioning[57,58]. Exposure to low PAH concentration increased plant weight and reduced root area[55]. However, high PAH contamination in soil may completely inhibit plant growth and have phytotoxic effects, making them prone to other stressors [56,59]. Growth in high PAH soil leads to deformed trichomes, chlorosis, white spots, impaired root growth and development[54]. PAH even have the ability to penetrate cell membranes and eventually decrease water content, nutrient utilization, inhibit photosynthetic activity and electron transport in plants[58]. LMW PAH even can cause phytotoxic effect in plants such as impaired growth and development of plants[59].

Uptake of PAH by plants is governed by their concentration, water solubility, physicochemical state and even the soil type[36]. Additionally, their molecular weight is key determinant of their uptake. HMW PAH binds more firmly to soil particles making their removal through physical means a challenge[61]. PAH uptake and accumulation in plant, primarily a passive process, is limited due to their high partition coefficients in soil[62,63]. Root and shoot concentration factor, and transpiration stream concentration factor also determine their uptake and availability in plants[64].

Rhizosphere significantly influences PAH uptake by plants through direct and indirect influences[63,65]. Active rhizosphere facilitates PAH degradation, and decreases its bioavailability[66,67]. Factors such as microflora, root exudates, soil type, nutrients available and pollutant load influence the rhizosphere effect[68]. Aromatic compounds that are homologous to PAH as well as surfactant molecules released by plant roots generates rhizosphere effect that might contribute to an increase in microbial activity and rhizodegradation of PAH in contaminated soil[69,70].

Exposure to PAH induces oxidative stress in plants leading to increased levels of reactive oxygen species (ROS)[71]. *Arabidopsis thaliana* exposed to high phenanthrene concentration leads to an increase in ROS load which may surpass the capacity of the plant’s antioxidant systems[72].

A significant amount of PAH is accumulated in leaves, especially in cuticle and is dependent on morphological factors of leaf such as size, surface to volume ratio and wax content, as well as chemical properties such as lipophilicity and volatility of PAH[73]. Adsorption and intake of PAH not only increase toxicity in plants owing to bioaccumulation, but also make them available in vegetables and fruits[74]. Temperature is yet another important factor that determines accumulation of PAH in plants. High-temperature conditions enable PAH to exist in gas phase and low-temperature condition facilitate its accumulation in leaves.

The effect of PAH on plant growth and metabolism is species-specific. For example, the biomass of *Aeschynomene indica* increased whereas, the biomass of *Panicum bisulcatum* decreased to approximately 70% when both species were applied with same the PAH concentration[68,75]. They not only affect the growth and metabolism of plants, but also their endophyte population. Plant endophytes are highly sensitive to PAH contamination and result in an increase in specific PAH degrading endophytes in them. Therefore, endophytes can be explored for better PAH biodegradation in an eco-friendly manner.

4.4 PAH stress on the rhizosphere-plant-microbial relationship

Active interaction between plants and rhizo-microbiota has been long recognized and is the fulcrum of biological activity in the rhizosphere. Microbes are dependent on plant exudates and other associated rhizodeposits for energy, and in turn facilitates critical processes in nutrient cycling, production of growth promoters and xenobiotic degradation. Plants under abiotic stress such as contaminants influence soil properties through root exudates[76]. This, in turn, affects the rhizosphere’s microbial communities and eventually alters plant performance. This is known as plant-soil feedback mechanism. Thus, rhizosphere-plant-microbes share an intimate relationship which not only symbiotic but is more of a cyclic relationship, wherein what happens in one has a direct bearing on the other, and ultimately affects all the three components. The health of rhizosphere and its microbial populations are important for plant health and productivity. Plants and rhizospheric microbes are a combined unit of the soil ecosystem, neither of them can be studied and considered separately.

Rhizosphere microbiome have the capability to degrade pollutants such as PAH[77]. Mere presence of rhizosphere accelerates the rate of PAH dissipation and degradation[75,78]. Interaction between plant-soil-microbiome is greatly influenced by plant species, physiology and photosystems, and life stages[79,80]. Rhizosphere of grasses provide better degradation of PAH due to their fibrous root systems[81]. However, in a comparative study, legumes were better in removal of PAH when compared to grasses[75].

This three-component rhizosphere-plant-microbial system quickly responds to any change in the physico-chemical properties and composition of soil. The addition of carbon-based pollutants such as PAH significantly influence all three components. The effect of PAH on this system is not restricted to morpho-physiological changes in plants, and its influence can be seen on plant-microbe signalling, nutrient allocation and resource partitioning[82]. Increased carbon allocation to roots and rapid utilization by microbes in *Phragmite australis* under hydrocarbon stress[83]. Studies have shown that plant hormones such as ethylene, Brassinosteroids, ethane, expansin, cytokinin, cytochrome P450, glutathione-S-transferase and endogenous abscisic acid play a significant role in the signalling pathway of PAH induced stress[84]. Glutathione S-transferase and ABC transporter play key role in transfer of PAH from rhizosphere into plant tissue[85]. PAH can affect the plant-rhizosphere-microbial interaction is a two-way process (Figure 2). PAH accumulated in plants affect its microbiota and physiology. This in turn, affect the lipophilic composition of root exudates, which facilitate PAH degradation, the presence of glucose, pyruvate and acetate increase PAH accumulation in rhizosphere. Presence of such compounds in root exudates in rhizosphere lowered the expression of PAH degrading genes such as nahG in *Pseudomonas fluorescens* HK44 present in rhizosphere resulting in increased bacterial biomass[86]. Therefore, direct or indirect effect of PAH on plants, microbes and rhizosphere may alter their natural interactions temporarily or permanently.

5. Significance of plant-microbe-soil in alleviating PAH stress

Due to their high concentration and prevalence, particularly in some parts of the world, PAH make way into the food chain, augmenting at each trophic level. Their effective and eco-friendly mitigation is thus, the need of the hour. PAH removal through chemical and photolytic oxidation, volatilization and sedimentation are costly and environmentally unsustainable[31]. Conversely, phytoremediation and microbial remediation, although cost-effective and ecologically, sustainable and are dependent on the physicochemical properties of soil, microbial profile and plant communities present in the rhizosphere environment and may show incomplete and slow degradation rates. Till now, studies have focused on microbe-assisted phytoremediation which uses either a single microbe or a consortium for remediation. However, the mechanism of action of interact a single microbe or consortia within the rhizosphere is not completely understood. Moreover, the rhizospheric ecosystem of higher plants has unique eco-biological characteristics which can be altered due to addition of such microbe(s). It may also be difficult to provide enough microbial population for complete biodegradation of the PAH.

Rhizoremediation is the use of plant and rhizospheric microbiota for the efficient degradation of PAH. The application of Plant Growth Promoting Rhizobacteria (PGPR) provides bidirectional benefit by efficiently degrading PAH and improving plant growth and development, which in turn help rhizospheric microbes to grow and survive in the rhizosphere[87]. Various studies have confirmed that degradation of PAH through rhizoremediation is far more efficient than other remediation techniques due to the exploitation of useful interactions of the host plant and their respective rhizo-microbiota. For example, >70% of pyrene degradation was documented in vegetated soil compared to that in the unplanted soil conditions (which was <40%) indicating that rhizo-microbiota along with host plant accelerated the degradation process[88].

Rhizo-microbiota of specific host plant may include microbes which are significant in plant growth and development, and a subpopulation possessing PAH degrading genes such as ARDB. Such type of healthy rhizo-microbiota may be created either naturally through microbial interaction within rhizosphere or artificially via microbiome engineering. The latter includes establishment of more efficient microbiome artificially into the rhizosphere which can degrade PAH completely. *In-situ* microbiome engineering may be achieved through augmentation (elevating the levels of specific microbial community via supplementing certain type of supplements), reduction (establishment of non-conducive environment for undesirable microbial function) or bio-inoculation (application of mixture of microbes involved in degradation)[89]. Plant-rhizosphere-microbial interactions need to be explored for better remediation of PAH-contaminated soil. Some of the beneficial interactions are summarized in Table 1.

6. Conclusion and future prospects

Prolonged exposure of soil to high PAH levels increases the risk of their bioaccumulation and magnification in food chain. PAH stress adversely affects the plant-soil-microbial interaction, ultimately disrupting several of the ecosystem functions and services. To come up with possible solution, it is imperative that this tripartite interaction is completely understood. Being a dynamic system, it is in a constant state of flux and shows several regional and local variation. Since most of PAH emissions are anthropogenic and associated with economic development, there seems to be no imminent near future solution for this menace. To reduce toxic effects of PAH and minimize the damage to ecosystem and health, sustainable solutions are required. Tapping the potential of soil microbes which can efficiently degrade PAH seems to be the best possible sustainable solution. Rhizoremediation is a promising tool in establishing a healthy host plant microbial zone and creating an efficient PAH degradation system. However, diversity of rhizosphere microbes involved in rhizoremediation and their functional genes are still not well understood. Exploring modern molecular technologies such as genomics, metabolomics, transcriptomics and proteomics for understanding the biochemistry of PAH degrading microbes will provide ample knowledge of potential genes, enzymes involved in degradation process. This will lead to development of genetically modified microbe or consortia and provide effective and sustainable solution for soil remediation from PAH stress.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Table 1: Plant-microbial system for effective PAH degradation

S. No.	Plant-microbial System	PAH degraded	Percentage degradation	Genes involved	Reference
1.	*Sorghum x drummondii and* Sphingomonadales	Fluorene, Phenanthrene, Fluoranthene an Pyrene	98%	*PAH-RHDα* and *nidA*	90
2.	Fire Phoenix and *Mycobacterium* sp	Total PAH	40.3–53.7%	-	91
3.	*Orychophragmus violaceus and Rhodococcus ruber* Em1	Total PAH	17.85%	*alkB* and *PAH-RHD*	92
4.	Populus deltoides *and Bacillus* sp. SBER3	Anthracene an Naphthalene	>75%	-	93
5.	*Populus deltoides* and *Kurthia* sp., *Micrococcus varian* *Deinococcus radiodurans* and *Bacillus circulans*	Anthracene an Naphthalene	>85%		94

6.	Alfalfa (*Medicago sativa* L.) and *Ensif* *meliloti*, *Pseudomonas kunmingensis*, *Rhizobium petrolearium* and *Stenotrophomonas* sp.	Phenanthrene	20-60%	-	95
7.	*Jatropha curcas* and *Pseudomonas aeruginosa* PDB1, *Pseudomonas fragi* DBC, *Klebsiella pneumoniae* AWD5, *Alcaligenes faecalis* BDB4 and *Acinetobacter* sp. PDB4	Pyrene	97.2%	*nod*, *nahR*, *nahAF*, *catA*, *kshA*, *hsaC*	100
8.	Ryegrass and *Acinetobacter* sp. or AMF	Phenanthrene and Pyrene	>90%		96
9.	Ryegrass (*Lolium multiflorum*) and *Arthrobacter pasce* strain (ZZ21) and/or *Bacillus cereus* strain (Z21)	Fluoranthene	74.9%		97
10.	Alfalfa (*Medicago sativa* L.) and *Bacillus* s and *Flavobacterium* sp.	Total PAH	25.8%		98
11.	*Vertiveria zizanioides* and *Bacillus* and *Pseudomonas sp.*	Total PAH	88-89%		99

Figure Legends

Figure 1: Country-wise PAH contamination in soil.

Supplementary Table 2 titled "Country-wise distribution of PAH" with corresponding references has been attached as supplementary information.

The map has been prepared using mapchart.net.

Figure 2: Rhizosphere-plant-microbe system under PAH stress

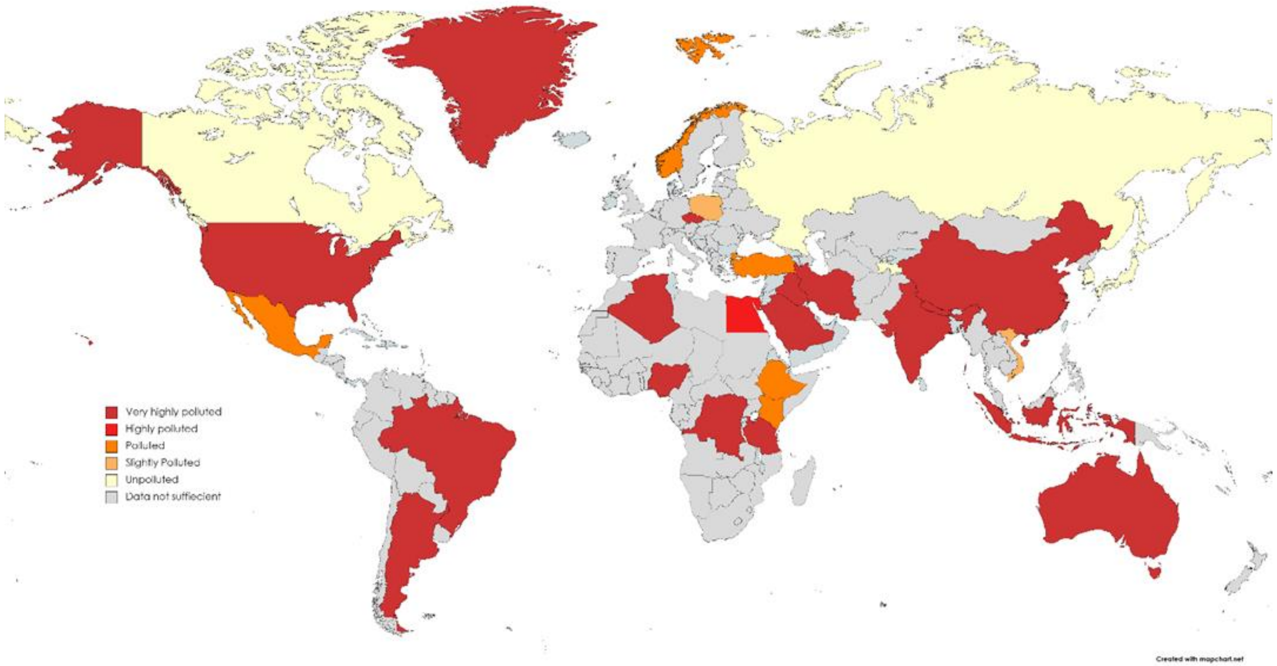
Very highly polluted
Highly polluted
Polluted
Slightly Polluted
Unpolluted
Data not sufficient
Created with mapchart.net

Figure 1

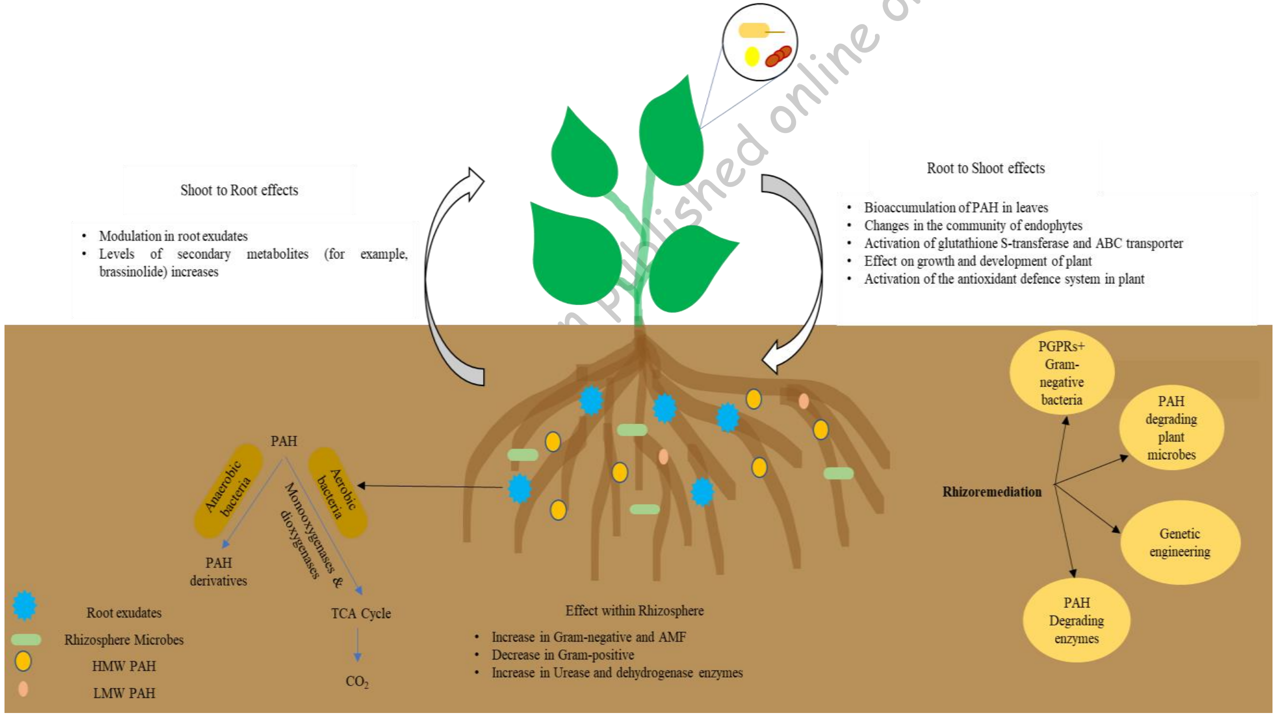
Shoot to Root effects
Modulation in root exudates
Levels of secondary metabolites (for example, brassinolide) increases
Root to Shoot effects
Bioaccumulation of PAH in leaves
Changes in the community of endophytes
Activation of glutathione S-transferase and ABC transporter
Effect on growth and development of plant
Activation of the antioxidant defence system in plant
PAH
Anaerobic bacteria
Aerobic bacteria
Monooxygenases & dioxygenases
PAH derivatives
TCA Cycle
CO2
Root exudates
Rhizosphere Microbes
HMW PAH
LMW PAH
Effect within Rhizosphere
Increase in Gram-negative and AMF
Decrease in Gram-positive
Increase in Urease and dehydrogenase enzymes
Rhizoremediation
PGPRs+ Gram-negative bacteria
PAH degrading plant microbes
Genetic engineering
PAH Degrading enzymes

Figure 2