Plant–Microbe Interaction in Attenuation of Toxic Wastes in Ecosystem

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Abstract

The use of plant–microbial interactions in mitigating the effect of toxic waste in the environment has increased tremendously as a result of the high success rate. This could be attributed to various survival mechanisms of plants–microbes in contaminated environment. However, important factors such as plants ability to produce biomass, active root proliferation and/or root activities with root symbiosis establishment and others determine the efficacy of phytoremediation technology which has proved to be effective. More rapidly growing plants with high phytoextraction abilities should be identified for the remediation of pollutants from soil. Plant–microbial interactions are very crucial for the sustenance of environmental sustainability through toxic waste attenuation.

Keywords

Bioremediation · Ecosystem · Plant · Microbes · Toxic wastes

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13.1 Introduction

Higher Plants live together with other biotic and abiotic components of the environment, thereby participating in a number of relationships. This is so as they cannot live in complete isolation from each other. The biotic components are the living forms of life which include microorganisms and higher animals, while the abiotic are the non-living things made up of the physical, chemical, and cultural features (Enerijiofi 2014). However, the interactions between plants, microorganisms, and other environmental constituents are quintessential for continuous survival of plants on earth as well as balance of the environment.

13.2 Plant Interaction with Soil

The interaction between plants and soil occurs in the region known as rhizosphere. However, Hiltner (1904) was first to draw attention to the scientific domain of the word rhizosphere which involves the promotion of microbial growth round the roots of leguminous plants. There exist different meanings of rhizosphere (Marschner 1995; Uren 2001). Uren (2001) defined rhizosphere as the interface between the soil and plant root which is characterized by lots of mineral nutrients, pH, redox processes, root exudates as well as lots of microorganisms which results from increased activities of microorganisms. The rhizosphere region of plants is made up of two regions; ectorhizosphere and endorhizosphere. The ectorhizosphere is the layer of soil that immediately surrounds the roots of plants while in the endorhizosphere, microorganisms colonize the internal tissues of the root. The health of soil determines the health of plant as well as humans, due largely to the dependence on its products for survival (Enerijiofi 2014). Mycorrhizae perhaps encompass the best conspicuous and nearby forms of mutualistic plant–fungal relationships (Fester et al. 2014).

13.3 Plant Interaction with Microbes

Though plant–microbial interactions are not visible to the human eye, they interact at different facets and levels. Almost, all plant organs undergo interactions with microbes at one phase or the other in their life and it is not essentially a harmful one for the plant. Plants as well as other living and non-living components make up a great chunk of diverse environments for microorganisms. The specific environments may include noxious combinations of compounds in which there may be inadequate supply of nutrients which are important in supporting the growth of microorganisms (Fester et al. 2014). The various classes of microbes like the prokaryotes and eukaryotes undergo interactions with plants and sustain their wellbeing in a variety of ways. These include enhancement of the growth of plant and harvest, control of diseases, ability to survive and recover from hostile ecological disorders such as lack of water, etc. (Adesemoye et al. 2009; Reid and Greene 2012).

They are associated with millions of other microbes. The functions of the aforementioned plant-associated microorganisms are still under investigation, though they are known to support plants which enable them withstand the abiotic and biotic stresses, thereby aiding the host in water and assimilation of other nutrients as well as the production of plant hormones, siderophores and inhibitory allelochemicals (Weyens et al. 2009a, b; Bulgarelli et al. 2013). However, under extreme contamination conditions, plants have a resilient influence on the microbial communities of soil and they are regularly in control of the building and power-driven firmness of a given system. Though in real situations, plants in association with microorganisms always seem to be the actual actors intervening the impact of plant on the transformation of contaminants (Ingham et al. 2011).

13.4 Positive Interactions Between Plant and Microbes in Soil

Series of microbes are famous in the colonization of the rhizosphere area. Though, members of the *Streptomyces* species are distinctive in a range of ways. Their pattern of growth is filamentous, colonise soil as well as plant roots and its aerial parts, dynamically yield antibiotics and save plants from attack by disease causing bacteria species, production of unsound biological compounds that are accountable for the exceptional bouquet of new forest soils. They could also be utilized as natural control mediators in numerous agrarian practices. The actual ingenious *Streptomyces* species are made use of as biofertilizer in improving the growth of plants due to their intrinsic growth-promoting proficiencies. Their ability to form endospore gives them comparative advantage in extant severe soil situations contrary to the non-spore formers in the soil. Also, *Streptomyces* species possess innate capability to produce diverse forms of lytic enzymes which provides them the ability to break caked organic mixtures which secrete nutrients that can be used by plants (Vurukonda et al. 2018). Plant growth-promoting bacteria (PGPB) can similarly be utilized in the reduction of heavy metal polluted soils. *Helianthus tuberosus* is rich in biomass and used in the production of bio-ethanol. However, when it is exposed to a specific PGPB that is secluded from plants on heavy metal polluted soil, its ability to withstand high concentrations of heavy metals increases. The bacteria were revealed to grow endophytically in the root ensuing substantial upsurge in cadmium absorption by the plant. More so, the plant exhibited a reduction of metal-induced pressure and an enhanced growth in the presence of bacteria. Thus, these PGPB can aid in remediation and in sustainable biomass production (Montalbán et al. 2017).

Perennial ryegrass, *Lolium perenne* is an essential cool-season grass specie for fallow, silage and turf with a high yield has increased harvest and upright grass excellence as well as a compact system of root, greater tillering and fast capability to regenerate itself can easily withstand drought or to high salt concentration but PGPB are known to fully support its forbearance to dearth of water and high salinity (Su et al. 2017; He et al. 2018). Su et al. (2017) opined that valuable bacterium in soil like *Bacillus amyloliquefaciens* GB03 in a relationship with water absorbent mediator which consist in super permeable hydrogels can be used for controlling erosion in soil thereby significantly improving the ability of perennial ryegrass to withstand drought conditions. This holds true when linked to tender single components that previously were considered to improve the ability of the plant to resist drought relative to the control. In the same distinguishing method, an innovative isolated bacterium from a C4 persistent juicy xerohalophyte tree with exceptional ability to stand long absence of water and high salt concentration was made use to meaningfully enhance development and salinity forbearance of the perennial ryegrass. In addition, is the sequencing of the bacterial genome and identification of several genes supposedly associated with promoting traits during plant growth and decreasing of abiotic stress (He et al. 2018). PGPB can support the ability to withstand drought and high salinity.

Zhang et al. (2018) studied the affirmative role of *Rhizophagus irregularis* CD1 fungus as it affect growth and proliferation of plant and the Verticillium wilt resistance of cotton. They were able to study the synergistic proficiency of 17 cotton varieties to *R. irregularis* with the most efficient being Lumian 1 which was utilized in field trial for 2 years. Nevertheless, the existence of the mycorrhizal fungus considerably amplified growth of the plant and also ability to withstand plant malady against *Verticillium dahliae* wilt. However, the negative impact on *V. dahliae* presence possibly will be as a result of mycorrhiza-induced resistance which revealed that the growth of *R. irregularis* may proportionately prevent the growth of *V. dahliae* by letting loose as yet anonymous volatiles. Consequently, microbes are utilized to absolutely alter the growth abilities of plants in order to put them at a vantage position to be able to stand against biotic and abiotic pressures like lack of water and high salinity which might probably take place far more frequently with increasingly abating change in climatic conditions.

13.5 Plant–Microbial Interaction—An Overview

Plants have just lately been known as a metaorganism with a distinct microbiome and adjacent synergistic interactions with closely related microbes (Mendes et al. 2013). They are shielded by microorganisms with some pathogens while others display a helpful effect on plant growth and development. Hitherto, a few abound merely with no clear cut function in studies of microbial ecology. The plant roots are confined by a dense cover of microorganisms in the rhizosoil. Also, plant seeds are linked with the microorganisms and are famous for having intense effect on development of plant, since they are available all through seed germination which could also have a rich outcome on the ecosystem, wellbeing, and yield of plants. The microbiome of seed consists in endophytic and exophytic (Hawkins and Crawford 2018). Microorganisms are known to be powerfully effective in motivating series of important roles in soil ecosystem (Enerijiofi 2020). Microorganisms are relevant building blocks in the recycling of major nutrients and are associated with plant roots for fruitful nutrients supply as well as reducing the effect of pathogens, thereby giving support particularly for plant and animal health and generally for life on planet earth. The exceptional act and natural ingenuity of microorganisms particularly round the growing root of plants give credibility to the series of possible valuable microbes for the growth experienced in biotechnological field. This is relevant in improving crop yield, pathogens of plants, controlling of weeds, and more feasible methods of cleaning up polluted soils. This benign and extensive use of microorganisms has lots of prowess for making chemical methods extinct. This is found to be the relevance and its profound constituent of soils. Microorganisms are also used as soil quality indicators and in good working of the ecosystem (Enerijiofi 2020; Sherwood and Uphoff 2000).

13.6 Factors Affecting Interactions

Plant–microbial inter-relationship is implicated in the degradation of bulky quantities of contaminated waste arising from their possession of genetic metabolic machinery and their capability to withstand punitive environments. Consequently, they are a main actor in the cleanup of sites polluted with toxic wastes. Nevertheless, their potential to perform is reliant on various factors, though not limited to contaminant concentration and its chemical constituents, ability of plant–microbe interaction, and physicochemical characteristics of the location (Joutey et al. 2013). So, dynamics that affects the level of contaminants breakdown by interaction between plant and microbes is linked to plant–microbe and their nutritive supplies or related with the surrounding factors (Joutey et al. 2013).

13.6.1 Soil Factors

One of the chief ecological duties carried out by soil is filtration, others are buffering and transformation of contaminants of either organic or inorganic pollutants. This very important role guarantees worthy quality of underground water and safe production of food. When contaminants find their way to soil, they undergo series of reactions such as physicochemical, microbiological, and biochemical processes that keep, diminish, or lower their destructive capabilities. Essential characteristics of soil that affect the behaviour of pollutants encompass soil texture, quantity of soil organic matter, pH, levels of moisture, and temperature. The characteristics of soil pollutants besides are important. These include size, solubility, charge distribution, and molecular structure.

13.6.2 Plant Factors

Soils play host to series of minute forms of life. These include all classes of microorganisms viz-a-viz bacteria, fungi, nematodes, viruses, etc. The rhizosphere region, where the root of plants interacts with soil is known to contain the highest quantity of bacteria species (Ho et al. 2017). Nevertheless, the diversity of soil bacteria affects soils in any of the three means. The inter-relationship existing between soil bacteria and soil may be helpful, detrimental, or unbiased (Weyens et al. 2009a, b). The PGPB include the free living, those with explicit harmonious inter-relationships with plants, e.g. *Cyanobacteria*. PGPB can support the growth of plant openly by empowering the capacity to have a hold on controlling the levels of plant hormone and secondarily by decreasing the resistance impact of pathogenicity and plant growth by standing in as proxies of biocontrol (Glick 2012).

13.6.3 Climate Factor

The change in global climatic condition is linked with lots of factors including increase in atmospheric temperature and high concentration of carbon (iv) oxide (Srivastava et al. 2014). The community of microbes in soil environment is known to play important function in cycling of carbon as microorganisms have enlarged potential to degrade organic matter in soil at high carbon (iv) oxide and nutrient concentration which are primarily affected by biotic and abiotic factors. There are no proof that can be traced to the influence of change in climatic condition on bioremediation except the physicochemical parameters which have influence on the metabolic process of the microbial community thereby affecting bioremediation (Sowerby et al. 2005; Castro et al. 2010; Srivastava et al. 2014). The extracellular enzymes production by microorganisms could be attributed to the microbial activities and physicochemical characteristics of the soil environment which are affected by the climatic conditions (Sowerby et al. 2005; Enerijiofi 2020). A study reported that an increase in temperature arising from change in climatic conditions positively boosts the community of microorganisms to properly utilize recalcitrant compounds in soil (Bardgett et al. 2008; Frey et al. 2013). Also, increase in the concentration of carbon (iv) oxide is directly proportionate to the bacterial richness and indirectly proportionate to the fungal richness (Frey et al. 2008; Castro et al. 2010). The reduction in fungal biomass at elevated temperature and during dry seasons is responsible for the reduction in the fungal/bacterial biomass ratio in soil (Sowerby et al. 2005). This showed reduced degree of organic matter recycling in the environment which in addition distorts the normal course of degradation by indigenous microorganisms that are skilled at cometabolic reaction in breaking down precarious compounds made possible by the availability of natural carbon. Baldrian et al. (2013) predicted that metabolic activities of microbes rise significantly if the temperature of soil increases arising from change in global climatic conditions.

13.6.4 Microbial Factors

The catabolic and anabolic abilities of microorganisms are referred to as microbial factor. The biotic factors influencing microorganism destructive activities of biological combinations have uninterrupted hindrance to enzymatic activities and multiplication routes of microbes involved in the degradation process. For example, inhibition can take place when there is struggle between microbes for limited resources like carbon, hostile inter-relationships between microbes, or the predation of microbes by bacteriophages and protozoa (Riser-Roberts 1998). The extent of breakdown of precarious waste is mainly due to the quantity of the toxic material as well as the catalytic agent that is available for the process to take place. In furtherance of the aforementioned, the extent to which the toxic waste is degraded is mostly due to the capability of the specific enzymes implicated, affinity for the toxic waste as well as the degree of the bioavailable fractions (Enerijiofi 2020). Also, adequate quantities of oxygen and nutrients should be present in readily available form as well as in precise amounts as this support the substantial growth and multiplication of microorganisms (Riser-Roberts 1998).

13.6.5 Environmental Factors

The soil type and the concentration of organic matter play important function in the capability of the noxious waste to adsorb to the compact surface of the soil. In absorption which is a corresponding procedure, toxic waste infiltrates into the major mass of the soil medium. However, both adsorption and absorption reduce the accessibility of the toxic waste to a greater chuck of plant and microbes interactions at the rhizosphere region and the degree of element absorbed is directly condensed. In the soil matrix, the ability of passing on gases like oxygen, carbon (iv) oxide, and methane is reduced in finely coarse soils and sediments and also when soils are water logged which arises from poor porosity. They also affect plant and microbial growth which regulates the degree and kind of biodegradation that occurs. The reduction–oxidation prowess of a soil is the ability of its electron compactness of the system. Energy is gained through the breakdown of compounds in which electrons are conveyed from one oxidized compound to another during electron transport chain known as electron acceptors. A low electron mass with $Eh > 50$ mV specifies breaking down and aerobic situations, while high electron mass ($Eh < 50$ mV) points to reduction and anaerobic conditions. Series of other additional environmental factors that affect biodegradation rate of toxic waste are temperature, pH, and moisture. Biological enzymes that have an important function in degradation pathway need an optimum temperature for best performance, below or above the optimum temperature is a proportionate degradation metabolic rate (van der Heul 2009). According to Riser-Roberts (1998), the degree of breaking down declines approximately by 50% for each 10 °C diminution in temperature. In terms of pH, breakdown takes place in a wide range, but, a pH range of 6.5–8.5 is mostly best for biodegradation process in most terrestrial and aquatic environments. The water content performs a very important function in the metabolism of toxic waste in the ecosystem because it regulates the solubility, type, and amount of decipherable materials as well as the growth of the microorganisms that partake in the process, osmotic pressure as well as pH of both aquatic and terrestrial ecosystem (Cases and de Lorenzo 2005).

13.6.6 Biological Factors

These are only noticeable when bioremediation techniques are being implemented. However, there exist many intrinsic characteristics of microorganisms that perform roles in the degradation of substrate. Example is plasmid-encoded genes that make available the exact enzyme for the specific substrates but, naturally, it has been known that microorganisms mostly bacteria have different specificity for diverse nutrients (Mars et al. 1997). The control of chemotaxis by bacterial cells places them at a vantage position to be able to degrade obstinate biological molecules (Pandey and Jain 2002). It is worthy to note that the use of single isolate is not as active as microbial communities in accomplishing comprehensive degradation of xenobiotic compounds. The microbial communities required for bioremediation is mostly reliant on complex interactions. Maphosa et al. (2010) posited that metagenomics which encompasses genome sequencing aid in making data available regarding the species of microorganisms that contribute to substrate degradation. More so, the peak of microbial growth conditions cannot be determined (Ingham et al. 2007). Microbes are important in ensuring proficiency in the working of ecologies on earth and issues influencing growth, development, arrangement, and richness of microorganisms and microbial populations may perturb the biomes (Nweke et al. 2007). Chakraborty et al. (2012) posited that Allelopathic response of plants in the terrestrial environment on the community of microorganisms may affect the degradative abilities of soil microorganisms negatively. Aerobic degradative actions of microbes are restricted by organic carbon solubility and lack of oxygen. However, certain microorganisms can utilize supplementary sources of biological carbon, electron acceptor, and energy as cometabolic substrates in so doing degrading the recalcitrants compounds, e.g. *Mycobacterium gilvum* can breakdown pyrene in the presence of oxygen in the rhizosphere of *Phragmites australis* concurrently with the breakdown of benzo(a)pyrene (Toyama et al. 2011). Pandey and Jain (2002) opined that injurious pressure applied by toxics on microorganisms quickly modifies their enzymes which play vital function in microbial degradation of refractory compounds.

13.7 Microbial Diversity Implicated in Plant Interactions

A lot of studies have documented a number of microorganisms that are implicated in plant–microbe interactions (Montesinos et al. 2002; Garbeva et al. 2004; Vimal et al. 2017). Microbes found in soil are important in the preservation of soil role in both regular and succeeded agrarian soils arising from their involvement in significant practices like soil structure formation, decomposition of organic compounds, toxins elimination, and recycling of nutrients like carbon, etc. (van Elsas and Trevors 1997). Also, microbes perform important function in subduing soil borne diseases of plant, encouraging plant growth and fluctuations in flora.

Though microbiologists had studied the influence of different microorganisms on the firmness of environment role since the 1960s, Harrison et al. (1968) stated that there is now intensified attention of its influence on functioning and resilience of the ecology to turbulences in soil ecosystems. Microorganisms have established quite a number of approaches to ensure successful acclimatization to the environment of the plant, together with helpful or harmful interrelationships. Valuable interrelationships are triggered by synergetic or non-synergetic bacteria and by a very specific kind of fungi, the mycorrhizae. The harmful interrelationships of microorganisms with plants comprise different microbial types with contagious diseases upsetting the kingdom Plantae. In agricultural soils, perhaps 80% of the nitrogen fixed biologically originates from an extensive variety of soil bacteria like the *Rhizobium*, *Sinorhizobium*, and *Allorhizobium* of the family Rhizobiaceae in relationship with leguminous root of plants (Vimal et al. 2017). These endophytes generally invade the root structures of leguminous plants giving rise to nodules thereby stimulating the growth of plants unswervingly or incidentally (Zimmer et al. 2016).

The genetic basis of plant–microbial interaction is sturdily clarified by the gene-for-gene elicitor-receptor model. On this premise, numerous investigations have utilized plant pathogenic bacteria of the genera *Pseudomonas* and *Xanthomonas*. A group of genes have been rapt comprising of the hypersensitivity reaction (HR) and pathogenicity (hrp) which impact the limit of bacteria to create HR in non-host plants (Montesinos et al. 2002). Majority of plants are not proficient in gathering enough biomass for obvious steps of remediation within the sight of high degree of contaminants (Harvey et al. 2009; Chakraborty et al. 2005). The cleanup route of polluted ecosystem is restricted and delayed due to inadequate nutrient level. Soil microorganisms are assumed to exercise affirmative influence on the wellbeing of plant through mutualistic associations between them. Conversely, microorganisms are subtle to contamination and reduction in their population through the types as well as biomass which regularly take place in such polluted soils (Shi et al. 2002). A stress in the biotic or abiotic conditions through a little change in the physicochemical and natural characteristics of rhizospheric soils may prompt exceptional impact on plant–microbial interaction. The utilization of Plant growth-promoting microorganisms as inocula in rhizosphere is gaining more ground as its prospects is on the increase in phytoremediation process; though, it partially subject to the capacity of the plant to withstand the toxic nature of the metal and give adequate harvest. The exudates at the plant roots are utilized by microbes in the rhizosphere region as nutrients for growth and subsequent multiplication. It is projected that the amount of the remaining photosynthetic carbon transported to plant roots varies amid 30–60% and 10–20% of root requirements originates from rhizodeposition (Marschner 1995; Salt et al. 1998). The exudates are basically made up of low as well as high molecular weight organic acids. Their total amount determined in plant roots falls within the range of 10–20 mM, by and large consisting of acetate, lactate, succinate, oxalate, fumarate, malate and aconitate while the remainder of biological solutes in roots are sugars (90 mM) and amino acids (10–20 mM) (Jones 1998).

Bioremediation is the practice of eliminating environmental pollutants utilizing living organisms which are mostly microbes. This is one of the most reliable methods for cleanup and restoration of polluted ecosystems. The frequent use of some plants for cleanup of precarious toxins in the ecosystem in a recently developed method is known as phytoremediation. They are known as hyperaccumulators which grow optimally in heavy metals rich soil. Alkorta and Garbisu (2001) have reported phytoremediation to be real, in situ, artistically attractive, reduced effort socially acknowledged technique for the cleanup of contaminated soil. These cleanup may be through phytostabilization, rhizofiltration, phytoextraction, and phytovolatilization. It is not only cleanup of the ecosystem contaminations but plant–microbe interrelationship also adds to viable improvement of agriculture. These days, there exist a major issue in production of crops with decreased utilization of pesticides and inorganic fertilizers. So the use of PGPR to improve yield of harvests has demonstrated to be an earth benevolent technique as a substitute to such issues.

As soon as a site becomes contaminated, the masterpiece of the autochthonous microbial population in the site as well as the underground water will acclimatize to the new condition. The microbial species that are able to use the pollutants as foundation of substrates for growth will proliferate and turn out to be dominant (Liu and Suflita 1993; Gkorezis et al. 2016). The normal, non-planned process of xenobiotic breakdown by the native microbial species is known as normal diminution and it is considered the modest method of bioremediation. The Environmental Protection Agency (EPA, United States) describes innate remediation as a combination of degradation, dispersion, dilution, sorption, volatilization, chemical and biochemical balance of pollutants. Though, in earlier times, this “treatment” technique was regularly talk about as an important method, it gradually has become a vital instrument to remediate polluted sites. Natural attenuation is already a success for BTEX compounds which is associated with underground water (USEPA 2001). It has been useful mostly on locations with “low” public worth, especially when there is enough time, since cleanup could last a while when other kind of restoration technologies are not appropriate. Normal cleanup is not allowed at sites near home with great ecological worth, such as natural resorts. Time is also a restraining influence because the ability of native microorganisms to adapt could take decades, contingent on the nature of the xenobiotic that is available (Ojuederie and Babalola 2017). The by-products that arise from incomplete breakdown of other contaminants can be lethal. For example, toxic 1-napthol arises from oxygenic conversion of naphthalene, while the actual carcinogenic compound vinyl chloride comes from anaerobic conversion of tri-chloroethylene (Liu et al. 2007). Heavy metals are recalcitrant so they cannot be damaged by normal degradation; nevertheless, they are subjected to volatilization. Also, microorganisms that have appropriate catabolic genes may not be present on the site for all xenobiotic compounds, which is confirmed by the buildup of hazardous and obstinate mixtures found in the ecosystem (Vimal et al. 2017).

13.8 Plant–Microbial Interaction During Remediation

The interaction between plant and microorganisms can be accomplished through various immediate: nutrient transfer (originating from nutrient or siderophore production, air nitrogen fixation, enzymatic deterioration of organic matter in soil, or transformation of inorganic minerals to dissolvable constituents, particularly phosphorous), direct encouragement of growth through phytohormones, (for example, ethylene or indole acetic acid), antipathy towards pathogenic microorganisms, and mitigation of salt stress. The soil is exceptional in possessing a life-dependent structure and offers ecosystem services that are vital for global roles, comprising principally production, regulation of biogenic gases, earth's climate, biogeochemical and water cycling, as well as biodiversity maintenance (Magdoff and Es 2000; Welbaum et al. 2004). A substantial quantity of the land is polluted arising from different human influences and a steady upsurge of this level is anticipated in years ahead. The microorganisms inhabiting the soils form a very vital component of living things. The relationship between bacteria and plants in the different ecological niches including the rhizosphere contributes to the rise in promoting the growth by directly affecting plant anabolic and catabolic reactions in the absence of most important pathogen. These bacteria fit into different genera, including *Acetobacter, Achromobacter, Anabaena, Azotobacter, Bacillus, Hydrogenophaga, Kluyvera, Pseudomonas,* and *Rhizobium* (Bashan et al. 2008).

There are important factors that determine the efficiency of phytoremediation. These include setting up of important plants with the ability to produce biomass, vigorous root as well as root activities with the root network, aiding cleanup using plants in the rhizosphere region. Likewise, the association of different groups of microorganisms can be of advantage to the plant. In addition to the numerous positive interrelationships, there exists competition of resources between plants and microorganisms (Kaye and Hart 1997). Arising from the restrictions of scarce nutrients and its struggle, which usually take place at contaminated locations, the proliferation of microorganisms as well as biodegradability could be restricted (Joner et al. 2006; Unterbrunner et al. 2007). Though, supply of too much nutrients can be responsible for appropriate conditions for encouraging heterotrophic and pollutant bacteria that have become acclimatized, this may not essentially result in realizing improved rates of phytoremediation. This has been reported in the degradation of hydrocarbon in oil contaminated ecosystems. The degradation of the contaminant was not influenced or subdued by nutrient addition (Chaineau et al. 2005).

The microbial communities found in soil that show diverse competences of hereditary capabilities and endeavours can differ widely in soils which may also impact on the functioning capacities of soil, arising from their involvement in important metabolic reactions (Nannipieri et al. 2003). The relationship that exists between microorganisms is constrained by precise compounds and is accountable for significant natural processes, such as organic matter decomposition, and safeguarding of plant wellbeing just as soil quality (Barea et al. 2004). The development of enormous amounts of metabolically active inhabitants of useful microorganisms in soil is required for distinctive bioremediation (Metting Jr

1992). In the aforementioned microorganisms, the motivating aspects are high ability to acclimatize to different environmental conditions, fast growth rate, and biochemical resourcefulness to fully utilize different types of normal and xenobiotic chemicals for an entrenched ecosystem (Narasimhan et al. 2003).

13.9 Role of Plant Growth-Promoting Rhizobacteria

Plant growth-promoting rhizobacteria play critical function in the promotion of plant growth leading to viable agricultural development. They assist plant growth promotion by direct and indirect machineries. The direct consist in fixing of nitrogen in the atmosphere, solubilization of phosphorus, siderophore production for iron chelation, and providing siderophore–iron complex to plant resulting in the synthesis of different plant hormones. While indirect method includes control of pathogenic plant pathogens via antibiotics production, reduction of iron in the soil, and eventually encouraging the growth of plants. Plant growth-promoting Rhizobacteria are classified into two based on their association with host plant: (1) cooperative rhizobacteria, which assault and colonize the inward piece of the plant cell to endure, e.g. bacteria forming nodule, and (2) free-living rhizobacteria that exist outside the plant and are likewise popular as extracellular PGPR, e.g. *Azotobacter, Burkholderia*, and *Bacillus* (Babalola 2010; Khan 2006). Microbes like PGPR can improve the supply of supplements in the rhizosphere (Choudhary et al. 2011; Kumar et al. 2017). For instance, nitrogen, the best controlling variable related with the development of plant is not promptly open for plant use, yet *Azospirillum* existing in grain biological system can fix free nitrogen accordingly, advancing the yield of harvests (Tejera et al. 2005). Besides, phosphate is likewise provided in the accessible form by PGPR (Vacheron et al. 2013), making it to be promptly used by plants. Vejan et al. (2016) posited that Lavakush Yadav et al. (2014) completed a trial on PGPR strain like *Pseudomonas putida* and *Pseudomonas fluorescens* relating to their impact on take-up of uptake of nutrient during the growth of rice.

Certain rhizospherical strains possess the capability to give up a variety of substrates such as antimicrobials, hydrocyanic acid, indoleacetic acid (IAA), siderophores which is integral to expanding the bioavailability and admission of hefty metals by plant root, for both fundamental (e.g. Fe and Mn) and superfluous (e.g. Cd) nutrients (Barber and Lee 1974; Crowley et al. 1991; Salt et al. 1998). An examination was completed which indicated connection between metal opposition and metal activation capacities of rhizobacteria under weighty metal pressure. Phosphate solubilizers had the most extensive level of the biochemical movement of all segregates and against metal opposition; trailed by siderophore makers and in conclusion acid producers. This points to the fact that the aforementioned group of microorganisms is utilized by rhizobacteria and be responsible for metals mobilization in soil (Abou-Shanab et al. 2005). The take up and movement of non-essential elements might differ significantly and regularly influenced by different genera and form of minor elements. To the varying degree, the various metals display different rates of mobility, and the conscription rate might remain higher for some than others for a specific metal inside a plant.

13.10 Hormones in Enhancing Growth During Remediation

Some rhizospheric microorganisms produce plant hormones which support root growth and in so doing discharge root secretions. The plant secretions incorporate carbohydrates, amino acids, lipophilic mixes, and chelating specialists secreted from the roots of plants and set forth constructive outcomes to keep up an assortment of microbial networks in the rhizosphere (Anderson et al. 1993). Plants that are low in phosphorus try to summon phosphorous components that are accessible in soil by expanding citrus extract level in root exudates (Hooda 2007). A coagulated oil alluded to as mucigel is needed for root entrance which is emitted by it cells and adds to expanding the root mass apically during growth in the soil. The microbes in soil use these mixes for development to create the plant rhizosphere (Anderson et al. 1993). The survival of plants in contaminated and nutrient limiting environments is stimulated via inter-relationships existing between microorganisms associated with plant roots and plants itself in the rhizosphere. Several metal ions have low bioavailability due to their reduced solubility in aqueous solution and resilient affinity for soil particles which render them immobile thereby hampering utilization by plants. However, microbes that colonize the roots of plant can contribute to increased metal uptake by increasing the bioavailability (Hooda 2007).

13.11 Role of Endophytes and Mycorrhiza

The degradation of contaminants has also been implicated in endophytic microorganisms as well as those involved in plant–microbial interactions. The endophytic bacteria colonize internal plant tissues without necessarily impeding plant development (Lodewyckx et al. 2002; Schulz et al. 2006). Plant–endophyte interactions are such that plants provide nutrients and shelter for the endophyte, whereas the latter provide growth enhancement conditions for the plant through the production and release of useful metabolites (Bacon and White 2000; Garbeva et al. 2001; Tan and Zou 2001). Generally, many common easily grown endophytic species are *Pseudomonaceae, Burkholderiaceae*, and *Enterobacteriaceae* (Mastretta et al. 2006). This association has also been exploited in remediation of contaminants. The photoautotrophic capacities of plants make for the possibility that associating rhizospheric microorganisms would have the capacity to biodegrade and/or utilize petroleum hydrocarbons even when they are poorly soluble in water. Haichar et al. (2008) earlier reported that the soils with enhanced plant cover usually had more diverse microorganisms and as such are most likely to be easily remediated. Plants release exudates, mucilages, lysates, vitamins, organic acids, ligands, enzymes, or otherwise rhizodeposits (Olson et al. 2003). These are carbon sources that enhance soil microbial proliferation and eventual biodegradative capacities (Chaudhry et al. 2005).

13.12 Mechanism of Rhizoremediation

The ability of plants to cleanup contaminants from either terrestrial or aquatic environments relies basically on its rooting capacities. The root is the major organ for nutrient absorption, adsorption, and accumulation. Plant capacities to associate with soil microorganisms that are critical for plant development also rest, to a very large extent, on the roots. Therefore, bioremediation of contaminants is better appreciated at rhizospheric levels. There are a number of mechanisms of contaminant remediation in the roots—this however depends first on the types of contaminants. Whereas inorganic contaminants are basically absorbed or adsorbed either by direct flow or upon enhancement by ligand and chelators, organic contaminants are degraded or sequestered around the rhizosphere or rhizoplane. The role of microorganisms in achieving these capacities is imperative. The process of bioremediation can be carried out either using oxygen or not, according to the requirement of the organism involved. This means bioremediation can be of two form, aerobic or anaerobic (Malik and Ahmed 2012). It is however common to ascribe the mechanism of remediation to aerobic route due to the overly abundance of aerobic organisms involved in bioremediation. Below are the equations for bioremediation.

Aerobic biodegradation:

$$\begin{aligned}&\text{Biota} + \text{Hydrocarbon compound} + \text{Oxygen } (\mathrm{O_2}) \pm \text{Enzyme(s)}\\&\quad = \text{Biota} + \text{Water} + \text{Residue(s)}\end{aligned}$$

Anaerobic biodegradation:

$$\begin{aligned}&\text{Biota} + \text{Hydrocarbon compound} + \text{Carbon (iv) oxide} \pm \text{Enzyme(s)}\\&\quad = \text{Biota} + \text{methane } (\mathrm{CH_4}) + \text{Water} + \text{Residue(s)}\end{aligned}$$

Many genera of bacteria have been reported to be useful in bioremediation. Among the aerobic bacteria involved are *Bacillus, Micrococcus, Sphingobium, Rhodococcus*, those of the anaerobic are *Pelatomaculum, Desulphovibrio, Desulfotomaculum, Aromatoleum aromaticum, Dechloromonas aromatica*, *Desulfitobacterium hafniense* (Cao et al. 2009), and *Syntrophus* (Shimao 2001; Jayasekara et al. 2005).

The process by which the microorganism carry out remediation can be ascribed to mineralization, a process whereby the pollutant is converted into intermediate substance, usually according to the pathway the organism uses in remediation. The whole process involves absorbing the pollutant into the cell, followed by the release of enzymes and organic acids such as citric acid, and malic acid, etc., which acts on them thereby converting them into intermediate product. However, before absorption the pollutants are converted into less toxic compound by complete oxidation using an electron acceptor, oxygen in the case of aerobic respiration.

13.13 Enzymes and Genetic Implications of Hydrocarbon Biodegradation

In most cases of hydrocarbon pollution, the process of remediation is usually preceded by the release of extracellular enzymes such as oxygenase. This is usually observed in fungi which are known to degrade their substrate extracellularly before taking it in using enzymes such as lignin peroxidases (LiP), laccases, etc. (Asemoloye et al. 2017). These enzymes are typically involved in the breakdown of substrate by cleaving to the bond and metabolizing hydrocarbon contaminant into phenols or trans dihydrodiols (Bogan and Lamar 1995). The functionality of these enzymes has been reported to be affected by the length and complexity of the hydrocarbon chain of the pollutant. However, some microbes have cytochrome P450 enzymes which are capable of converting long chain hydrocarbon into isoforms. Such enzymes have been isolated from *Candida* species which were able to utilize long chain aliphatic hydrocarbon. A typical example is the alkaneoxygenase which is able to oxidize alkane and some other methane monooxygenases which contain copper (Scheller et al. 1998; Van Beilen and Funhoff 2005).

13.14 Synergistic Rhizosphere Mechanisms for the Removal of Hydrocarbons in Polluted Soils

Biodegradation requires reduced energy and it involves the use of life organisms in the cleaning up of contaminated soils (Segura and Ramos 2013). It is a generally accepted technology because of its cost effectiveness and more ecofriendly when compared to other conventional remediation methods. Using this method, one major challenge is the ability to establish the plant in the remediation process, due to the toxic property of the pollutant. The roots of plants are important in the remediation of both land and soil but with increase in the rooting ability of the plant in the land or water to be remediated there is increase the rate of remediation by way of reducing the amount of contaminant left in the field (Gunawardana et al. 2011). Some level of pollution will however inhibit the rate of rooting in plants, this has been the major problem in rhizoremediation (Abhilash et al. 2012; Li et al. 2013; Ukaegbu-Obi and Mbakwem-Aniebo 2014). Ways have been looked into, to be able to increase root proliferation in this type of situation, such as trying different form of techniques. Treatment of root of plants in hydrocarbon polluted soils with organic fertilizers and selected microbes is known to improve plants abilities to remediate polluted soils. The microbes which can be native or introduced have been said to symbiotically promote root system of the plant (Escalante-Espinosa et al. 2005; Huang et al. 2004;

Johnson et al. 2005; Joner et al. 2006; Leigh et al. 2006; Gerhardt et al. 2009; Weyens et al. 2009a, b; Glick 2010; Guo et al. 2014).

13.14.1 Biosurfactants

Most microbes, including bacteria, yeast, and the filamentous fungi have been reported to synthesize several biomolecules. Many of these biomolecules produced by these organisms have shown surface activity, because they comprise both hydrophilic and lipophilic properties. These compounds are made up of a water loving acids, peptide positive and negative charged ions, and a hydrophobic moiety of unsaturated or saturated hydrocarbon chains or lipids (Banat et al. 2010). They can be of two type, the first being the low mass compounds called biosurfactants, known for reducing surface and interfacial tensions, and they include lipopeptides, glycolipids, and proteins (Nguyen and Sabatini 2011; Banat et al. 2014; Dobler et al. 2016; Santos et al. 2016). The high mass are the bioemulsifiers such as the lipopolysaccharides, polysaccharides. Bioemulsifiers balance out oil-in-water emulsions and possess reduced ability to bring down surface pressure than biosurfactants (Neu 1996; Smyth et al. 2010a, b; Uzoigwe et al. 2015). The aforementioned properties have been attributed to enhance microbial growth by expanding the surface territory among oil and water through emulsification, as well as through expansion of the pseudosolubility by apportioning into micelles (Volkering et al. 1997). The whole procedure will enhance the bioavailability of the contaminant to degradation by microorganisms (Mulligan 2009; Pacwa-Plociniczak et al. 2011; Lawniczak et al. 2013).

Typical examples have been reported, like the case of *Bacillus circulans* which produces lipopeptide and *Pseudomonas aeruginosa* which produces both lipopeptides and protein-starch-lipids have increased biodegradation (Bordoloi and Konwar 2009; Das et al. 2008). Another is the comparative study between Triton X-100 and the commercial rhamnolipid JBR-515 (Jeneil Biosurfactant Company, USA) using *Burkholderia multivorans* (NG1) shows that Triton X-100 increased bioavailability by emulsification and sustained interfacial take-up, while the rhamnolipid mixture JBR-515 considerably did not emulsify hydrocarbons, improving bioavailability in its place by solubilization of the micelle (Mohanty and Mukherji 2013). Colores et al. (2000) have however posited that the presence of surfactants of biological origin and that of non-biological origin may be inhibitory to the process of biodegradation. This is because the Micelle cores formation which will trap the organic contaminants can create a hydrophilic barrier between the organic contaminant and the hydrophobic microorganisms making it less available for degradation (Colores et al. 2000).

Another case observed in *Pseudomonas aeruginosa* is the use of a mechanism not so different to pinocytosis for the uptake of rhamnolipid-coated hexadecane droplets which can be referred to as the internalization of biosurfactant layered hydrocarbon droplet. Some microbes have been reported to even emulsify hydrocarbons without absorbing the hydrocarbon. This have prompted the attention to the surface property of the cell to be associated with emulsification, due to the connection of the oil–water interface by broad hydrophobic communications as opposed to explicit acknowledgment of the substrate. It is said that the microorganisms cells may serve as fine strong units at interface, meaning that stationary-phase or hydrophobic microorganisms can settle oil–water emulsions by clinging to the oil–water interface because of the cell surface hydrophobicity in a population of different microbes, the production of biosurfactants by the microbes or the plants or the one introduced into the medium may be suitable substrate for species that naturally degrade hydrocarbon, thus reducing the remediation yield. Biosurfactant of external and internal origin is however poisonous to certain microorganisms by impairing permeability of the membrane, hence meddling with chemotaxis driven motility, and upsetting the formation of biofilm.

Biofilms, bacterial networks encompassed by self-produced polymeric matrices reversibly committed to a passive surface are a survival strategy against harsh physicochemical environments, to aid exchange of cations, gene transfer, and regulation of redox ability of their ecosystem (Costerton et al. 1995; Gorbushina and Broughton 2009; Shemesh et al. 2010). Biofilm milieus are made up of extracellular polysaccharides (EPSs), deoxyribonucleic acids, and proteins (Sutherland 2001; Branda et al. 2005; Rinaudi and Gonzalez 2009), with EPS influencing the water holding capacity, thickness, moisture content, and mechanical firmness of biofilms (Flemming and Wingender 2010).

Biofilms, however, have the property of enhancing PHC bioremediation courses by aggregating the accessibility of the contaminant (Wick et al. 2002; Johnsen and Karlson 2004). The production of high molecular weight compounds is usually proportional to the formation of production of biofilm; therefore, in the event that release of polymers by microbes is trailed by production of biofilms on the superficials of inexplicable hydrocarbons. This put those microbes particularly well prepared for the management of unruly combinations due to their great microorganism biomass inside biofilm. However, biofilm formation enhances remediation process by preserving best situations of pH, limited concentrations of solute as well as redox ability in the presence of the cells.

13.15 Environmental Factors Affecting Bioremediation of Contaminants by Plant–Microbe Interactions

Competition for resource and interference by chemicals lead to harmful associations among plants. Also, exudates from plants root are a possible factor that can affect the three instruments of intervention. For some species of plant, the exudates from root perform vital function as phytotoxins (i.e. allelopathy). Also, these exudates are crucial for improvement of interrelationships among some plants parasite and their hosts. Lastly, release from the roots also performs crucial secondary roles in the struggle for resources, this is done by interfering with soil chemistry, various soil processes, and the population of microorganisms. Root exudates sometimes control positive interactions between plants. In some situations, root exudates induce plant defence that helps decrease vulnerability to infections from pathogen, but in opposite conditions, these immunities result in the manufacture and discharge of green volatiles which attracts killers of plant adversaries. Also, the different influences of releases from the root positively impact on the soil processes, and population of microorganisms as well as the surrounding plants.

Allelopathy or chemical enhanced plant interference is one method used by plants to have a lead on their rivals. Plants do this by producing and releasing potent phytotoxins to inhibit or diminish the instituting, growth, or existence of vulnerable plant neighbours, this will help reduce or eliminate competition and then increase the availability of resources. Some of the phytotoxins released could be located in rotten foliage and root matter that might have been discarded by the plant. These phytotoxins show differences in their chemical structures, mechanisms of activity and influence on plant growth and metabolism. The various phytotoxins present in root exudates affect various processes like the production of metabolites, photosynthesis, root growth, etc.

Root exudates are critical factors required for establishing important relationships between microorganisms and plant roots or even between other biota and plant roots. Plant capacity for survival also rests on this. Plant association with other biota may not necessarily be always beneficial. Whereas some associations are synergistic, others could be parasitic, neutral, or commensalistic. Root exudates can influence better association.

13.16 Conclusion

This paper reviewed toxic waste, plant–microbial interactions, survival mechanisms of plants–microbes and their interactions in contaminated environment. It also took a cursory view on the genetic implications of plant–microbes interactions involved in the conversion of toxic waste in the ecosystem. Environmental factors affect enzyme responses during ecosystem cleanup. These can be as little as can induce free radical activity that would change the course of enzyme activity that would ultimately influence remediation capacities and performance. It re-echoes the overwhelming importance of synergistic relationship between plants and their counterpart rhizospheric microbes during the conversion of toxic waste making it a better and sustainable alternative for the elimination of poisonous wastes (organic and inorganic) within the surrounding. Microbes and plants have innate natural machineries that support their survival under environmental conditions and eliminate the toxics from the ecosystem. Additional fast developing plants with great phytoextraction potentials need to be identified for the cleanup of contaminants in soil.

13.17 Future Perspectives

There are new ways of studying plant–microbial interactions. These are chromatography, sequencing, microscopy, mass spectrometry, phospholipid fatty acid (PLFA), real-time PCR (RT-PCR), etc. Additional development in this genomic age will open up avenues for improved knowledge of the inter-relationships of endophytes, plant–pathogen and plant protection. There is need for improved remediation techniques to meet the challenge of pollution. In plants, together with their microbiomes, lies huge unexploited potential for purifying both environmental pollution particularly soil.

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