Review

Potential of Coupling Heavy Metal (HM) Phytoremediation by Bioenergy Plants and Their Associated HM-Adapted Rhizosphere Microbiota (Arbuscular Mycorrhizal Fungi and Plant Growth Promoting Microbes) for Bioenergy Production

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Academic Editor: Zhao Yang Dong

Abstract

There is growing concern for the contamination of our soils and waters worldwide with heavy metals (HMs), as a result of indiscriminate use of agrochemicals for feeding growing population which require optimal use of resources and sustainable agricultural strategies. This can be simultaneously achieved by using microbes as bio-fertilizers, bio-protectants, and bio-stimulants, and suitable phytoremediation- plant capable of removing heavy metals contaminants from contaminated sites. There is a growing need to adopt such environmentally safe, attractive, and economical techniques that can remove most HMs contaminants as well as yield high biomass for bioenergy production. Phytoremediation and the microbes associated with the roots and inhabiting rhizospheres of the plants used for this purpose, has emerged as an alternative strategy. This article reviews the principles and application of this strategy, and provides an overview of the use of fast growing, non-food bioenergy plants, like Vetiver grass and industrial hemp, and their root-associated microbiota such as Arbuscular Mycorrhizal Fungi (AMF), Mycorrhiza Helping Bacteria (MHB), and Plant–Growth–Promoting-Rhizobia (PGPR) that can both tolerate and immobilize HMs in the roots, i.e. sequestrate contaminant HMs thereby protecting plants from metal toxicity. This mini-

review also focuses on other phytoextraction strategies involving rhizosphere microbes, such as (1) inoculating plants used for phytoremediation of HMs contaminated soil and water with rhizobial microflora, and (2) managing their population in the rhizospheres by using a consortium of site specific AMF, PGPR, and MHB, and N-fixing rhizobia as biofertilizers to Phyto-remediate derelict contaminated sites. Various crop management strategies such as Crop Sequencing and Intercropping or Co-cropping of, for example, mycorrhizal and non-mycorrhizal crops, or leguminous and non-leguminous crops, etc., can be employed for improved plant growth. Another possible strategy to exploit soil microbes is to employ pre-cropping with mycotrophic crops to exploit AMF for mycorrhizo-remediation strategy.

1. Introduction

Soil and water are integral part of our successful agriculture and is a source of nutrients for our, including animals, food. Their health is of paramount importance to mankind who benefit from a healthy soil and clean water, but unfortunately their health has declined over time due to many reasons such as soil degradation caused by erosion, toxic chemical spills, use of agrochemicals to produce more food for increasing human population, mining and industrial activities resulting in heavy metal and radioactive contaminated waste materials.

Many soil microbes have their origin in the soil or are closely associated with the roots of plants, i.e. rhizosphere. These microbes interact with plant roots and mediate nutrient availability, forming symbiotic associations with plant roots and have a substantial impact on humans. The rhizosphere-associated microflora of plants, including the plant beneficial growth promoting microbiota such as plant growth promoting rhizobacteria (PGPR) and universal and ubiquitous symbiotic arbuscular mycorrhizal fungi (AMF), can be used as bioresources for sustainable agriculture such as biofertilizers, bioprotectant against soil/root phytopathogens, bioformulations, etc. [1]. These microbes can colonize plant root cortices, survive endophytically, and their mutualistic activities are known to improve and enhance plant growth and health, i.e. increasing plant productivity in a sustainable way [2, 3]. Based on the relationship these PGPR develop with the plant roots, they have been divided into two groups, symbiotic and free-living [4]. The implications of these root rhizosphere associated symbionts such as mycorrhizal fungi, nitrogen- fixing rhizobia and free-living rhizosphere microbial populations, that enhance plant growth, need to be fully exploited and encouraged by inoculating nutrient poor or abiotically stressed agricultural soils with appropriate microbes [4]. Cultivation of non-agricultural plants to restore derelict and contaminated ecosystems through bioenergy plantation and associated microbes to stimulate plant growth and biomass production for generating bioenergy offers a practical solution for restoring degraded and contaminated derelict ecosystems [5].

This mini review focusses on how to enhance the plant-based remediation, i.e. phytoremediation technology, by discussing the diversity of rhizosphere-associated microbes and their important role in combating impact of abiotic stresses caused by heavy metals contamination of agricultural soils via agricultural chemicals such as fertilizers, pesticides, etc., drought, floods, salinity, waterlogging, etc. caused by climate changes and biotic stresses caused by root disease causing pests, and plant pathogens etc. Large scale production of these microbes, specifically AMF, and their field inoculation strategies, will also be discussed. Biotechnological strategies using PGPR and AMF involved in remediation biotechnology such as (1) field inoculation of plants used for phytoremediation by using rhizosphere HM-adaptive microbiota for phytoremediation, (2) intercropping mycorrhizal crops with non-mycorrhizal crops, (3) co-cropping strategy, (4) pre-cropping with mycorrhizal crops, etc., will also be reviewed. This review will also discuss the major challenges facing the Mycorrhizo-Phyto-Remediation technology assisted by the root-associated microbes, AMF and PGPR. Biotechnological mechanisms involved in *In-Situ* HM-phytoremediation by merging Nanotechnology, Phytoremediation and rhizosphere microbes, using noon-agricultural bioenergy crops like hemp and Vetiver grass, against abiotic environmental stresses, i.e. coupling of phytoremediation and bioenergy production, will also be addressed.

2. Phytoremediation Strategies to Decontamination--Merits and Demerits

Plants and their root-associated native rhizosphere microbiota, including AMF and PGPR, are capable of absorbing, accumulating, biodegrading, or immobilising the contaminants in soil and water through biological, physical, and chemical processes, promoting plant growth, enhancing soil fertility and health [6]. It is critical to know more about the mechanisms of microbe-assisted phytoremediation to understand the complex processes involved and the role of these microbes [7-9]. Nano molecules, such as low molecular organic acids, are naturally produced by plants under environmentally stressed abiotic conditions [10]. Symbiotic AM fungi also secrete phytochelating-Hm-affinity transporter nanomaterials which immobilize (translocate) HMs into root cells, i.e. nano-mycorrhizo-phytoremediation [11]. For an illustrated account of the concept of nano-mycorrhizo-phytoremediation (NMPR) readers are referred to Khan [11, 12].

Depending upon the nature and properties of the contaminant, and the substrate characteristics, many strategies are used by the plants for phytoremediation, as below:

1. Phytodegradation or Phyto-transformation or Phyto-metabolization or Mineralization of the contaminant inside plant cells by specific enzymes (nanoparticles)
2. Phytovolatilization of certain metals/metalloids contaminants, primarily organic compounds, by the plant roots, converted into non-toxic forms, translocate them through the aerial parts of plant, and released into the atmosphere as vapours.
3. Phyto-mobilization or Phyto-stabilization or Phyto-immobilization of the contaminants into the plant root cells by the nanomaterials secreted by the plant root cells and inhibiting their release and diffusion into the soil
4. Phytoextraction or Phytoaccumulation or Phyto-absorption, or Phyto-sequestration of the contaminants by the plant roots and their translocation in the above ground parts of the hyperaccumulator plants
5. Phyto-filtration of the contaminants from an aqueous medium by the fully or partially submerged aquatic plant root system/rhizome

6. Rhizo-degradation of the contaminants by the heterogenous rhizosphere microbial community including universal myco-symbiont Arbuscular Mycorrhizal Fungi (AMF), and stimulating plant growth by Plant Growth Promoting Rhizobial Microbes (PGPR), which utilize plant metabolites for carbon and energy and exude enzymes (nano-molecules) to degrade the contaminants and stimulate plant growth

This mini review will discuss the role of plants and their rhizosphere-associated microbiota in phytoremediation (Rhizo-degradation, Phyto-sequestration, and Phyto-stabilization, etc.) of the soil and water Heavy Metals (HMs) contaminants, i.e. *in Situ* Nano-Mycorrhizo-Phytoremediation (NMPR) [11, 13].

Phytoremediation strategy to decontaminate contaminated air, water, and soil, has several advantages as well as limitations, which should be considered when applying this nanotechnology [7]. Advantages include low cost, *in situ* technique using solar energy, aesthetically green, reducing surface runoff, leaching, and mobilization of contaminants, producing easily harvestable biomass produced for bioenergy production as well as for recovery of valuable metals (biomining), etc. On the contrary, it can only be applied to shallow soils, it is still under-developed and requires many environmentally imposed restrictions by regulatory authorities, it may cause spread of the contaminants to animals, including human, through food chain, and it is a slow process requiring longer time to treat as compared to the traditional physico-chemical techniques, etc. Also, the plants to be used for phytoremediation purposes need be fast growing, producing large biomass, tolerant to multiple contaminants, with profuse root system, easy to cultivate and harvest, etc. Phytoremediation potential of the indigenous and adaptive to HM-contaminated conditions weeds/plants growing on the contaminated site, and their rhizosphere-associated symbiotic (AMF, PGPR) and free living N fixing and P solubilizing microbiota should be selected, screened and evaluated for their use in the application in the nano- phytoremediation strategy and technology

3. Role and Significance of Plants and Their Root Associated Micrbiota in Enhancing HM-uptake

There is growing evidence that diverse microbial populations in the rhizospheres of plants growing on HM-contaminated sites play a significant role in phytoremediation. Recent researchers have found that nanoparticles (NPs), naturally produced by plants under environmentally stressed abiotic soil conditions, play a very important role in the contaminant's remediation [11]. Roots of plants growing in contaminated soils and water produce nano-molecules (NPs) (exudates) such as enzymes, phytochelators, organic acids, etc. which cause the formation of complexes of HMs through chelation, which decreases the toxicity of pollutants [6, 14]. Soil microbiota especially AM fungal communities, mycorrhiza-helping bacteria (MHB), and PGPR, associated with them, also play an important role in the decontamination by producing nano-sized NPs which enhance the process of nano-phytoremediation [15]. Mycorrhizal communities are recognised as powerful microbes enhancing nutrition, health, and growth of plant growing on HM-contaminated soils [6]. Phosphorus as the essential macronutrient occurs in natural soils in limited quantity and in unavailable forms. Most of the P- fertilisers applied in soils is precipitated and only a small fraction of it is available for absorption by plants. To promote plant growth on HM-contaminated soils for higher biomass production, to tolerate HM-induced stress, and to overcome P-deficiency, P-solubilizing bacteria (PSB) as biofertilizer provide an alternative to enhance plant growth on metal-stressed soil through biosynthesising nano molecules such as antibiotics supressing soil phytopathogens (biocontrol),

enzymes and siderophores to solubilize P, assisting nano-phytoremediation of metalliferous soils [16-18]. Recently Rubin and Gorres [19] reviewed the potential for mycorrhiza assisted phytoremediation by plants to mitigate nutrient pollution in different landscape and land-use contexts for reduced P-fertilizer amendments. The literature surveyed by these authors offers promising insight into how mycorrhizae can assist ecological restoration of derelict soil and water.

Surprisingly little research has been conducted on the mycorrhiza-assisted phytoremediation strategies for P-mitigation of aquatic ecosystems for improved water quality. Khan and Mohammad [13] discussed the application of waterlogging tolerant root-associated microbiota (AMF, PGPR, N-fixing rhizobia, etc.) in constructed-wetlands for *in situ* nano-mycorrhizo-phytoremediation (NMPR) of heavy metal contaminated wetlands and aquatic ecosystems and facilitating their recovery.

Role of PGPR (rhizobacteria) in bioremediation of HM-contaminated soils is gaining importance in enhancing microbe-assisted nano-phytoremediation and phyto-management of contaminated soils [5, 20, 21]. These microbes play a multitude of roles in environmental protection, and research efforts in this direction have received renewed interest worldwide [22]. In combination with PGPRs biological system, microbial symbionts like N-fixing rhizobia and AMF, are emerging as an inexpensive decontamination alternative and ideal for efficient microbe-assisted nano-phytoremediation of HMs contaminated soils and waters [17, 23]. Chaudhry and Khan [24] studied the role of AMF and PGPR N-fixing symbionts in sustainable pant growth on nutrient- poor HM-contaminated industrial soils and found that the plants surviving on such sites were associated with N-fixing rhizobacteria and had a higher AM infection, i.e. a cumulative and synergistic effect of Plant-AMF-PGPR. The rhizobacterial microbiota effects the bacterial community structure in the ecosystem [25]. Another group of PGPR bacteria which are associated with mycorrhizal roots and AMF, known as mycorrhiza-helping microbes (MHB), is also collectively promote establishment of mycorrhizal symbiosis [26]. They are of great significance in the practical solution of the environmental problems in agriculture.

Soil and water *in situ* microbiota, of which PGPR and AMF are integral components, associated with the plants growing on contaminated sites, are also known to synthesise and secret HM-affinity transporter nanomaterials, NPs, which are capable to bind and transport the bioavailable HMs from contaminated soil/water into root cells, i.e. microbially assisted nano-phytoremediation [6]. Studies to utilize the mutual activities by plants and their associated PGPR/AMF, are promising areas in need of further research, and strategies like crop rotations, specific crop combination, intercropping legumes with grains, etc. (discussed below), offer additional microbe assisted nano-phytoremediation strategies.

4. Factors Influencing Microbe-assisted Nano Phytoremediation in Abiotically Stressed HM Contaminated soil and Water Environments

The microbial population in the rhizosphere of the plants growing on the HM-contaminated soils, such as fungi, bacteria, actinomycetes, protozoa and algae, can promote plant growth and facilitate its development by protecting and preventing attack by soil phytopathogens, and producing plant growth promoting nano-molecules such as auxins, gibberellins, cytokinin, etc., and solubilizing unavailable nutrients like P and N. Gusain and Bhandari [27] reviewed the key mechanisms employed by PGPR involved in enhanced plant growth and productivity. Roots of plants growing on HMs contaminated soils exudates a variety of chemical compounds (nano materials) like enzymes,

and secondary metabolites which play a significant role in determining the microbial populations in their rhizospheres and their symbiotic and protective associations between plant-roots and their rhizosphere associated PGPR, P-solubilizing bacteria, mycorrhizal-helping bacteria (MHB), and Arbuscular Mycorrhizal Fungi (AMF), which not only produce stress hormone Ethylene (nano molecules) in response to biotic and abiotic stresses, but also maintain soil fertility. These root-exudates exert direct effect on plant growth through N-fixation, P solubilization, and siderophores production; and indirectly by producing phytohormones (Indole Acetic Acid), secondary metabolites, and lytic enzymes. When a particular population of these PGPR is achieved, i.e. Quorum Sensing, then these PGPR initiate a concerted action [4].

AMF propagules in the rhizosphere of plants growing on HM-contaminated soils also recognise their host by signals released by host roots, allowing a functioning symbiosis. AM fungi produce nano molecules, i.e. an insoluble glycoprotein (Glomalin) which sequester HMs (phytostabilization) leading to bioremediation of contaminated soil. This process of phytoremediation can be enhanced by using fast-growing plants with extensive root system and large biomass producing non-agricultural plants such as Vetiver grass and industrial cannabis , or by increasing the bioavailability of HMs to enhance metal uptake by contaminated soil amendments with metal chelating agents such as EDTA, HEDTA, DTPA, EGTA, NTA, etc., to make HMs bioavailable and absorbed by plant roots have shown promises [28], or by enhancing plant growth to produce greater biomass by using plant growth regulators to increase HM uptake [29].

5. Other Microbe-assisted Nano-phytoremediation Stretegies

Managing the site adaptative rhizosphere microbial populations, such as AMF, PGPR, MHB, N-fixing rhizobacteria, etc., in the roots of plants used for nano-phytoremediation of HM-contaminated sites, could provide plants with benefits crucial for nano-phytoremediation and derelict ecosystem restorations. Roots of most of the plants growing on nutrient-poor HM-contaminated sites are often colonized by autochthonous and site-specific AMF and associated rhizobial microflora strains which are HM-tolerant [28].

Various microbe-assisted phyto-management strategies have been proposed to employ rhizosphere microbes for enhancing growth of plants used for nano-phytoremediation, increasing their biomass for bioenergy production purposes and thereby stabilizing and remediating metal-polluted terrestrial and aquatic ecosystems.

5.1 Crop Rotation Strategy

It is the planting of different crops sequentially on the same land strategy which improves the physicochemical properties of the soil. It is a vital component of organic farming which improves its fertility, e.g. crop rotation using N-fixing leguminous crops such as soybean improve soil nitrogen by fixing atmospheric N through microbes in its root nodules, which is available for subsequent non-leguminous crops like wheat, corn, oats, barley, etc., i.e. improving soil structure and its physicochemical properties by returning leguminous crop residues in the field, resulting in increased organic matter and N in soils and improved dynamics of microbial communities development in their rhizospheres [30]. When a single crop is planted over and over in the same field for many years, the soil health and structure, nutrient status and porosity slowly deteriorate. Crop rotation results in healthy root system, a pre- requisite for phytoremediation of HM-contaminated soils. Yang et al.

[31] used three types of income-generating oil crops i.e. rape, sunflower, and peanuts, in crop-rotation system for effective use and remediation of HM-contaminated agricultural soils under field conditions and compared the phytoextraction efficiencies of Cd and Pb. The authors concluded that the extraction under this crop-rotation system could be useful for local farmers to generate income during otherwise sparse phytoremediation period. Zhou et al, [32] also suggested an oil-crop-rotation system, in addition to creating economic benefits, can be used to phyto-remediate contaminated soils.

On the contrary to the positive effect, i.e. the increased biomass produced by using these phyto-management strategies, which also results in producing contaminated biomass due to enhanced translocation of HMs from the roots to the shoots of mycorrhizal bioenergy plants like industrial Cannabis [33]. Recently, Zhang et al. [34] also reported that AM mycorrhizal infection significantly promoted shoot phytoextraction of HMs such as Pb and Zn in sunflower. The bioaccumulation of HMs by mycorrhizal bioenergy plants growing on contaminated sites seems to be useful for phytoremediation, it does pose a human health threat to the consumers, It is recommended that the products of such bioenergy plants used for phytoremediation of contaminated soils and waters should not be offered for human and animal consumption.

5.2 Phyto-management Strategy

To combat the limitations of phytoremediation such as longer time required and the disposal of contaminated biomass, phyto-management strategies, such as use of chelation in soil extraction of HMs was suggested by some researchers [28], but use of such mostly persistent sequestrants can be toxic to useful microbiota such as PGPR and AMF. Fang et al. [35], on the other hand, found that the chelated enhanced soil microbial community structure and improve phytoextraction efficiency in the soil-plant system in contaminated soils.

Exploiting PGPR and N-fixing microbes in crop rotation scenario offers an efficient, cost effective alternative to improve reclamation of HM-contaminated soils [17]. PGPR (Rhizobia) in the nodules of leguminous plants produce Nod Factors (NFs) in response to root exudates which stimulate nodulation. Inside the leguminous nodules, the symbiotic N-fixation (SNF) process takes place. Rhizobacteria such as free-living in the soil or symbiotic N-fixing microbes in the root nodules of legumes, PGPR and MHB are closely associated and adaptive living with AMF in the symbiotic organs [26]. They assist AMF in colonising the plant root, enhancing P solubilization by producing enzymes (nano molecules) [36]. Plants growing under nutritionally poor condition in soils, such as HM-contaminated soils, are found by various researchers to be mycorrhizal and their mycorrhizospheres harbour PGPR [23]. Like AMF, PGPR are also ubiquitous members of the soil microbial community and exert beneficial effects on plants by suppressing soilborne phytopathogens. Using mixed inoculum of AMF and PGPR has a potential to form a useful component of a sustainable phyto-management system for reclaiming derelict land through Nano-Mycorrhizo-Phyto -Remediation (NMPR) strategy.

5.3 Co-cropping or Mixed Cropping or Inter-cropping Strategy

Mixed cropping, also known as co-cropping, involves planting two or more crops simultaneously in the same field to increase productivity and maximum use of land resources including their rhizosphere microbiome community. Recently, Brereton et al., [37] compared, using 16SrRNA gene

amplification, sequencing and differential abundance analysis, three crops with complementary functions, namely *Festuca arundinacea, Salix miyabeana* and *Medicago sativa*, on contaminated soils, and compared to rhizosphere biomes of each crop in monoculture and in co-cropping, These authors found that the majority of differentially abundant rhizosphere-associated bacterial species were maintained in co culturing pairs, with pairs having higher number of differentially abundant taxa than monocultures in all cases, i.e. co-cropped pairs had more rhizosphere-associated bacteria than their monocultures. These findings suggest that co-cropping strategies could improve phytoremediation of contaminated soils. Fuksova et al., [38] investigated the effects of co-cropping of hyperaccumulator (*Thlaspi caerulescens*) and non-hyperaccumulator (*Salix dasyclados*) on bioaccumulation of trace elements in moderately and highly HMs (As, Cd, and Pb) contaminated soils and found that co-cropping enhanced bioaccumulation (phytoextraction) of *Zn* in *T. caerulescens* shoots. When phytoextraction potential of a co-planting system was evaluated, in a greenhouse experiment, using a shrub (*Salix interior)* and a herbaceous species (*Trifolium pratense*), and compared with monocultures, by Lachapelle et al., [39] it was found that co-planting increased the phytoextraction potential than monoculture, although no AMF/PGPR effects were investigated by the these authors.

Although, intercropping has been considered as a sustainable agricultural practice that can reduce the impact of pollution of agricultural soils, its potential benefits in phytoremediation of HM contaminated agricultural farms has rarely been examined [40]. These authors recommended a nationwide adoption of maize-soybean co-culturing system in China and demonstrated the co-benefits of intercropping as a sustainable farming method in terms of simulated gain on crop production, decrease in fertilizer application, and reduction in ammonia emission as a result of below ground mutualistic interactions between intercropped crops and their rhizosphere microbes involved in denitrification, decomposition, etc. However, as pointed out by the authors, although intercropping is a labour-intensive practice, it involves greater cost in terms of machinery and the layout, its benefits in terms of alleviating air pollution reduction in external environmental and health costs, and safeguarding a sustainable food supply justifies adoption of this strategy.

5.4 Cropping with Native HM-adapted AMF/PGPR-inoculated Plants for in Situ Nano-Mycorrhizo-Phytoremediation (NMPR)

The plant-based remediation, i.e. phytoremediation, can further be enhanced with the use of both plants and rhizosphere microbiota (PGPR, AMF, MHB, etc.). The integration of the three components, i.e. high biomass producing bioenergy crops, soil, and plant growth-promoting rhizobial (PGPR) microbiota, particularly AMF, will synergistically further improve the process of nano phytoremediation of HM-contaminated habitats, i.e. nano-mycorrhizo-phytoremediation – NMPR [6]. The role of native microbes (AMF/PGPR) is essential for nano-remediation of contaminated soil and water assisted by microbes. The role they play in the biodiversity and sustainability of these ecosystems is not fully explored and exploited for enhanced nano-phytoaccumulation, nano-phytostabilization, nano-rhizodegradation and nano-phytodegradation [11, 41].

6. Mass Production of Native HM-adaptive Microbes

Mass production of inoculum of these microbes and their inoculation strategies are being reviewed by Adholeya et al., [42] Mass production of AMF spores/propagules is possible by using conventional modes of pot-culture, aeroponic or hydroponic, ultrasonic biotechnological techniques [13, 43-50]. These technologies involve the extraction of viable and indigenous AMF propagules from the HM-contaminated soils, establishing their pot cultures using seeds/seedlings/vegetatively propagated plants like Vetiver grass, etc., followed by their transfer to hydroponic/aeroponic chambers for mass production of mycorrhizal roots which are then sheared and dried to produce the end product, i.e. AMF/PGPR inoculum. This powdered inoculum product can be applied to the polluted site for *in situ* NMPR by using various inoculation strategies such as broad casting, root-dipping, seed coting, in-furrow applications, seedling inoculation, tablet, granules or pellets formulations [42]. This *in Situ* microbe assisted nanotechnology can be applied for *in-Situ* NMPR of HMs contaminated wetlands and aquatic ecosystems by using floating Constructed Wetland using waterlogging-tolerant plant and root-associated microbiota [12].

7. Concluding Remarks & Major Challenges

Global issue of Heavy Metal contamination of our soils, water, and air is affecting human health and diminishing our food and energy resources, and the World is facing crisis. There is an urgent need to address these problems by reclaiming the wasted/degraded/contaminated and derelict land and water for food and energy production. HM-contaminant- resisting plants and their root-associated indigenous microbes can assist us in this regard but unfortunately the future prospects of happening this in agricultural industry has many limitations. As pointed out by Gusain and Bhandari [27], the successful application of NMPR technology is dependent on the survival of these introduced PGPR microbial inoculants in the contaminated sites, their compatibility with the crops and the indigenous rhizosphere microbiota, and the site environmental factors. A cumulative effect of Plant-Soil- AMF/PGPR Consortium, and environmental factors influencing these parameters results in nano-remediation of contaminated soil, which is a very complex process. Exploiting these microbes, as biofertilizers, bioprotectants against soil and root pathogens, bio-formulators, etc., in various scenarios of crop rotation, pre-cropping, co-cropping, etc. strategies [51] and for improving plant productivity in a sustainable way [3], requires more data before adopting the NMPR strategy for nano-phytoremediation of contaminated soils [6, 11]. As Gamalera *et al.,* [51] pointed out that, eventual successful phytoremediation of HMs contaminated soils is likely to include a more complete understanding of the role of PGPR and AMF in this process to exploit their synergistic mechanisms for promoting nano-remediation of contaminated soils and water. NMPR technology needs to be commercially exploited for degraded/contaminated ecosystem management and restoration, and sustainability. The NMPR technology is an emerging technology providing an alternative option to be employed to remediate HM-contaminated agricultural, mining and industrial soils and water by using fast growing and yielding high biomass plants which could be used for production of bioenergy [52-55]. Future of AMF/PGPR assisted nano-phytoremediation, using indigenous microbes, mass produced inoculum rather than commercial culture collections isolates, is still in research and development phase and it requires field-based studies before commercially adopting it [6]. The potential of using engineered nanoparticles (NPs) and their role in NMPR of contaminated air, water and soil environments will revolutionize, as pointed by Khan [6],

world environment by novelty, fast growth to meet global food demand, and protection of our soil, air and water environments from pollution [56, 57]. Recent interests in NMPR technology is evident by many books, book chapters, review articles and research findings, etc. being published during the last 5 years dedicated to plant-microbe interactions, indicate the significance of the role played by the rhizosphere microbiota assisting nano-remediation of our resources [19, 58-63].

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

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