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Review

The soil pH and heavy metals revealed their impact on soil microbial community

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ABSTRACT

Soil microbial community is the main indicator having a crucial role in the remediation of polluted soils. These microbes can alter soil pH, organic matter in soils (SOM), soil physic-chemical properties, and potential soil respiration rate via their enzymatic activities. Similarly, heavy metals also have a crucial role in soil enzymatic activities. For this purpose, a number of methods are studied to evaluate the impact of soil pH (a key factor in the formation of biogeographic microbial patterns in bacteria) on bacterial diversity. The effects of pH on microbial activity are glamorous but still unclear. Whereas, some studies also indicate that soil pH alone is not the single key player in the diversity of soil bacteria. Ecological stability is achieved in a pollution-free environment and pH value. The pH factor has a significant impact on the dynamics of microbes' communities. Here, we try to discuss factors that directly or indirectly affect soil pH and the impact of pH on microbial activity. It is also discussed the environmental factors that contribute to establishing a specific bacterial community structure that must be determined. From this, it can be concluded that the environmental impact on soil pH, reducing soil pH and interaction with this factor, and reducing the effect of soil pH on soil microbial community.

1. Introduction

Microbes, especially bacteria and fungi, are sensitive to the concentration of hydrogen ions found in the environment. Large proteins (such as enzymes) are affected by pH (Zhang et al., 2017b). Their shape will change (they will be denatured) and often cause changes in the ion charge on the molecule (Slonczewski et al., 2009). Soil pH effect nutrient solubility in soil solution and the availability of nutrients to plants (Havlin, 2020; Hu et al., 2004). Moreover, soil bacteria and fungi also play various roles as decomposing agents that interrelate to increase essential nutrients' availability to plants. Lower soil pH will alter this interaction, soil carbon, and immobilize the plant nutrients, thereby delaying the release of nutrients to the plant (Rousk et al., 2010; Souza and Billings, 2022). However, the development of highly acidic soil with a pH of less than 5.5 may cause stunted plant growth due to factors such as aluminum toxicity or other heavy metals toxicity. Too high or too low pH causes the loss of microorganisms and ultimately decreases soil health. In addition, pH will affect the solubility and effectiveness of certain toxic chemicals (such as aluminum), and plants will absorb aluminum (Mossor-Pietraszewska, 2001; Yan et al., 2022). In other words, ferric sulfate is the fastest way to lower soil pH. Acidic soil limits the growth of roots and chances of root contact with bacteria to form nodules and inhibits the formation of nodules. At a more suitable pH, the activity of harmful soil microorganisms can also increase, which may require management (Khan et al., 2010a). Because most microorganisms have an optimal pH range for their survival and function. Under a

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strongly acidic or alkaline pH, due to poor microbial activity related to bacteria, the mineralization of organic matter that slowdown or stop (Khare and Arora, 2015; Shah et al., 2022). When alkaline or acidic soils are present, certain diseases thrive. Furthermore, the use of ammonium fertilizer, as nitrogen fertilizer in an appropriate amount, has a relatively small effect on soil pH (Itelima et al., 2018). Diammonium phosphate, mono ammonium phosphate, and ammonium sulfate are more acidic than urea or ammonium nitrate. Metal-resistant PGPR reduced the absorption of Cd and the expression of metal transporter genes in tomatoes under the toxicity of heavy metals and trigger the growth of photosynthetic pigments (Guo et al., 2020). Under metal toxicity, metal-tolerant PGPR reduced the absorption of Cd and the over-expression of heavy metals transporter genes in tomatoes. It improved the growth and photosynthetic pigments (Khanna et al., 2019).

Similarly, fungi and soil bacteria have various roles as decomposing agents. They have strong relationships with the release of nutrients to plants (Zhang and Zhang, 2022). When soil microorganisms decompose organic matter slowly releases nutrients back to the soil system for coming cover crops. Cover crops can avoid soil loss, leaching, volatilization or denitrification, and loss of nutrients. Effect of pH on soil bacterial diversity using pH alone may not have a major effect on soil bacterial diversity (Etesami, 2018). pH readings that are too high or too low will cause the loss of these microorganisms, which will reduce the soil's overall health. In addition, pH affects the solubility and effectiveness of certain toxic chemicals (such as aluminum), and plants may absorb them if the pH is turned off (Malik et al., 2018). The soil pH has a direct association with the bacterial community in the ecosystem which has a direct effect on acification of soil. Most microorganisms have an optimal pH range for survival and function (Yun et al., 2016). Under a strongly acidic or alkaline pH, due to poor microbes activities related to bacteria, the mineralization of SOM slows down or stop. As a result, certain diseases will increase under low soil pH (acidic) or high soil pH (alkaline) (Lehmann and Kleber, 2015).

While the use of Phosphate fertilizer has less effect on soil pH than nitrogen fertilizer because the application amount of phosphorus is low, and the acidification effect per kilogram of phosphorus is less than nitrogen fertilizer (Ng et al., 2022; Snyder et al., 2009). Phosphoric acid is the most acidified phosphate fertilizer. Potassium fertilizer has almost no effect on soil pH. Compost has little effect on soil pH (Geisseler and Scow, 2014). In Zhang et al. (2017) study found that, under the condition of no fertilization, the soil microbial biomass after fertilization increased by 15.1% compared with the condition of no fertilization, but under the condition of pH < 5, fertilization tended to reduce the soil microbial biomass and promote soil microbial biomass accumulation. It is observed that higher genetic diversity is more in the contaminated population compared with the uncontaminated population. Heavy metal pollutants have diverse effects on plant growth, soil health, and soil microbial activities, and biodiversity as well as more on genetic structure (Tang et al., 2019). The impact of heavy metals on microbes from studies that highlighted the potentially detrimental effect of heavy metals on soil microbial population that resulted in induced alterations in the denitrifying microbial community as shown by molecular markers (Sobolev and Begonia, 2008).

Moreover, the findings from Sobolev and Begonia (2008) Heavy metals have been discovered to have a significant impact on both the nitrifying and denitrifying microbial ecosystems. The relationship between each environmental element and the soil bacteria and its correlation with soil type are still being studied. The resistance mechanisms related to metals, soil pH, and denitrification must be identified (Philippot et al., 2007).

2. Factors effecting the microbial community in the soil

Previous studies have shown that there is a relationship between microorganisms and environmental factors, such as geographic location (Fierer and Jackson, 2006; Lauber et al., 2009) soil texture (Sessitsch et al., 2001), and land use (Cho et al., 2016; Cookson et al., 2007a; Hartman et al., 2008a; Jeyamkondan et al., 2001; Smit and Pilifosova, 2003), pH (Fierer and Jackson, 2006; Hartman et al., 2008b; Lauber et al., 2009), nutrients (Cookson et al., 2007b; Han et al., 2008; Welch, 2001) pollutants such as oil (Liang et al., 2011) and heavy metals (Kelly, 1999; Ronen et al., 2000; Sandaa et al., 2001). Among the above factors, pH is considered one of the most critical factors shaping the biogeographic pattern of microorganisms (Fierer and Jackson, 2006; Lauber et al., 2009).

Both natural and man-made processes can cause soil acidification. The resulting pH change is usually an essential factor affecting soil bacterial diversity and community composition on different geographic scales (Liu et al., 2019). A quadratic model can fit the relationship between pH and bacterial diversity. Generally, the diversity of neutral soils is higher, and the diversity of acidic and alkaline soils is lower. Significant changes in soil microbial (Wang et al., 2022b). A large number of components along pH gradients are commonly observed, and acidophilic bacteria accumulate in low pH soils. Similar bacterial diversity and community composition trends were also observed in cultivated soils with artificial pH gradients (Rousk et al., 2010).

3. Soil pH and microbes

The soil pH of a compound is the acidity and alkalinity properties of the compound. Soil pH has an influence on the metabolic activities of microorganisms, and it increases and decreases the removal process (Asira, 2013; Nightingale et al., 2022). Measuring the pH value in the soil is a crucial indicator of microbial growth potential (Abatenh et al., 2017). Metabolic processes are very susceptible to high or lower pH. The microbial species such as *Clostridium, Bacteroides, Bradyrhizobium, Mycobacterium, Ruminococcus, Paenibacillus, and Rhodoplanes* are the most commonly found genera in Prostaglandin E (PGE) synthase (Frkova et al., 2020). The pH is the main soil property that determines the diversity, biomass, and microbial composition in PGE soil. The key process for the effect of pH on microbial communities could be mediating the availability of nutrients in the soil. Since ammonium sulfate increases nitrification, nitrogen is added to the PGE plot, reducing the soil's pH and accumulating soil carbon, thereby increasing the C/N ratio (Martínez-Alcalá and Bernal, 2020). Moreover, microbial activity is not linked with plant species productivity (Solis-Hernández et al., 2022). However, there is an active association between soil microbial production and plant species health. The response of plants to nitrogen treatment increases productivity and decreases species richness (Zhalnina et al., 2015). Soil microbes act as gatekeepers to maintain a balance between accumulation and release of soil organic matter (SOM) in the soil-atmosphere carbon exchange system (Malik et al., 2016). However, effective soil management strategies could be crucial to enhancing soil carbon storage. The relationship between microorganisms' ecological and physiological characteristics and the topsoil carbon content between geographically distributed soil and land use (Sheng and Zhu, 2018). The microbial processes that regulate carbon buildup at various pH levels. Land-use intensification slows down the acid of microbial decomposers in low-pH soil when the pH rises above the threshold (6.2), which increases the decomposition of carbon and causes carbon loss (Malik et al., 2018). It is important to understand how soil pH impacts processes that are interconnected with the biological, geological, and chemical elements of the soil environment, as well as how these processes, through anthropogenic interventions, generate changes in soil pH. Soil pH can be used in two broad categories, namely plant nutrition and soil remediation (bioremediation or physicochemical remediation) (Song et al., 2022). The relationship between soil pH determined by various cultivation methods and potential denitrification is still unclear. The results are exaggerated by both the original soil sample condition and the unknown changes during the cultivation process (Šimek and Cooper, 2002). The concept of optimal pH for denitrification is often put forward. However, the term is almost meaningless without reference to the specific properties of the process (Frostegård et al., 2022; Šimek and Cooper, 2002).

3.1. Soil pH effects on nitrogen fixation

It makes sense that low soil pH passively hinders the growth of broad bean and Nitrogen fixation (NF) (Mahmud et al., 2020). Further, dry biomass, grain yield, and nitrogen fixation lowered at low pH approximately between 4.7 and 5.4 than at the high pH levels (6.2–7.0), and developmental activities of nitrogenase activities were also delayed at low pH. Low soil pH has an adverse effect on broad beans' nitrogen fixation and growth (*Viciafaba* L.) (Prévost and Antoun, 2007). Broad bean kristall grows in dystrochrent pots at different pH and Ca levels. A non-destructive acetylene reduction method is used to measure nitrogen fixation. Exchangeable soil calcium has no significant effect on nitrogenase activities, total nitrogen uptake, and grain yield. At lower pH values such as 4.7 and 5.4, dry biomass, yield, and nitrogen fixation were significantly lower than higher pH values pH 6.2 and 7.0. Low pH delays nitrogenase activities. The reduction rate of acetylene is significantly correlated with plant nitrogen content (Sun et al., 2022). The N concentration in each plant part treated with pH 5.4 was as high as the N concentration in the treatment with higher pH. Therefore, the slight yield decrease in yield found at lower pH is considered a direct effect of H^+ activity in the soil on plant growth. However, at a pH of 4.7, plants showed symptoms of N deficiency in the early growth process, which indicates that the pH fixed by N_2 is limited (Alburquerque et al., 2013). Compared to pH 7.0, at low pH 4.7, 5.6 and 6.2, the dry matter yield of young plants that do not depend on Rhizobium N_2 fixation was significantly reduced (Mohammadi et al., 2012).

3.2. The type of soil parent material effect soil pH

The type of parent material in the soil affects the pH of the soil as well. The pH of soils that were formed from alkaline rocks or parent material is often higher than the pH of soils that were generated from acidic rocks as the parent material, rain has an additional impact on the pH level of the soil (Liu et al., 2022) by causing the leaching of basic cations, i.e. calcium (Ca^{2+}) and magnesium (Mg^{2+}), from the soil, which is replaced by acidic elements such as aluminum (Al) and iron (Fe). Therefore, the soil formed due to high rainfall is more acidic than the soil formed in low rainfall conditions (Ni et al., 2022). Additionally, the use of chemical fertilizers like urea (ammonium), might speed up the process of the soil becoming more acidic.

Similarly, the organic matter's decomposition also enhances soil acidity (Yu et al., 2022). According to Bordeleau and Prévost (1994) study, a low soil pH has a negative impact on the growth of broad beans as well as nitrogen fixation. This investigation was carried out to discover whether or not Camitigate mitigates the effects of pH, as well as whether or not a low pH primarily affects the growth of the host plant or symbiotic N_2 fixation. Growing conditions for the broad bean variety known as Kristall vary in terms of pH and calcium content (Schubert et al., 1990). A non-destructive acetylene reduction method is used to measure N_2 fixation. Exchangeable soil calcium has no significant effect on total nitrogen uptake, nitrogenase activities, and grain yield (Kapoor et al., 2022).

The reduction rate of acetylene is significantly correlated with nitrogen level in plants. The N concentration in each plant part treated with pH 5.4 was as high as the N concentration in the treatment with higher pH (McGrath et al., 1995). Therefore, the slight decline in yield at low pH is considered a key factor in host plants' soil. However, at a pH 4.7, plants show symptoms of N deficiency in the early growth process, which indicates that the pH fixed by N_2 is limited (Dwivedi et al., 2015) compared to pH 7.0, at low pH 4.7, 5.6, and 6.2, the dry matter yield of young plant that does not depend on Rhizobium nitrogen fixation was remarkably reduced (Luciński et al., 2002).

4. Heavy metal viability in soil effect soil microbial activity

The contamination of the soil by heavy metals is the result of both natural processes and those brought about by humans. Heavy metals may have a negative effect on the health of the soil as well as the biological processes that take place in the soil over the long term (Awasthi et al., 2022; Kapoor et al., 2022). Soil enzyme activity is considered a sensor for any natural and man-made changes in the soil ecosystems. Similarly, carbon is produce as a result of microbial activities, also called microbial biomass carbon (MBC), which is well-thought-out to be a useful biological tool that is often affected by heavy metal pollution (Raiesi and Sadeghi, 2019). The rise in the concentration of heavy metals results in structural changes and disrupts the normal activities of the soil microbial communities. According to what was found, crops that had been growing for two weeks revealed changes in the microbial activity of the soil, and bacteria were shown to be more sensitive to these changes than fungi and actinomycetes, respectively (Garau et al., 2007). At a high concentration of heavy metals accumulation cadmium or lead (Cd/Pb), the molecular study of the DGGE profile indicates the structural changes in the bacterial community (Khan et al., 2010b; Zhang et al., 2012). Here, studying soil microbial activities and community structure can provide important information regarding toxic effects or harmful impacts on soil health by the accumulation of heavy metals (Ishizawa et al., 2020).

4.1. Heavy metals

Soil pollution has shown extensive effects on underground microorganisms. Soil pollution by heavy metals is a serious global environmental problem (Tyler et al., 1989). Experts estimate that more than 20 million hectares of farmland in China are polluted, accounting for 20% of the total land area (Ren et al., 2007). Soil microorganisms, free-living and symbiotic soil microorganisms in the rhizosphere of plants growing on metal-contaminated soil, can increase plant biomass production and enhance the phytoremediation process (Xie et al., 2016). However, heavy metals affect soil microorganisms' growth, morphology, and metabolism through dysfunction, protein denaturation, or destruction of cell membrane integrity (Ghorbani et al., 2002). Soil microbes are critical to the decomposition of soil organic matter; any reduction in microbial diversity or abundance may adversely affect plants' absorption of nutrients from the soil (Kamal et al., 2010). The increase in the content of heavy metals in the soil has a significant impact on the soil microbial community's population size and overall activities. According to the separation-based technology used, multiple studies have shown that heavy metal pollution can lead to changes in microbial populations (Gu et al., 2022a; Rajendran et al., 2022; Zhang et al., 2022).

4.1.1. The cadmium and lead revealed their effects on soil microorganisms

Although many heavy metals are required for plant health, animals and humans are in a specific concentration (Oladoye et al., 2022). However, the toxicity of heavy metals on plants varies by plant species, types of heavy metals, their concentration, soil physic-chemical properties, and soil pH (Nagajyoti et al., 2010). Similarly, heavy metals in the soils exert a toxic impact on soil microbiota which decreases their quantity and activity. The increase of heavy metal contents in the soil causes structural changes in soil microbial activities and community (Jiang et al., 2019).

Cadmium (Cd) is not an essential element for soil microbial or plant biological systems among heavy metals (Thakur et al., 2022). On the contrary, high concentration of and mobility of Cd in the soil have a negative effect on soil microbial activities and depend on soil physicochemical properties (Hassan et al., 2013). Therefore, the threshold level is estimated based on the total cadmium concentration concerning soil conditions. Very few studies linking the effects of cadmium to more bioavailability could minimize the problem (Zea et al., 2022).

Heavy metal pollution will seriously affect the soil ecosystem and soil health. The adverse effects of heavy metals are because of heavy metal toxicity to biological mechanisms such as mechanisms catalyzed by soil microbial community (Singh and Kalamdhad, 2011). Therefore, it is speculated that soil microbial communities can be used to indicate soil quality loss caused by heavy metal pollution and soil quality changes caused by reclamation (Sun et al., 2015). The total metal and soluble metal content in these soils increase as they approach the smelter (Nacoon et al., 2020). The increase in metal content negatively impacts the indicators of soil microbial activities, i.e. dehydrogenase activities and microbial community (number of plates). The microbial community structure also changes with the increase of pollution; remediation leads to a decline in solubility of heavy metals and an, higher biological activities, and sustainable population (Liu et al., 2020). The restored soil also showed metabolic characteristics more similar to the least contaminated parts, indicating that the microbial population has recovered. These data indicate that by managing these highly contaminated soils, microbial communities are valuable indicators of soil health (Gu et al., 2022b). Microbial loss is as we move to higher concentrations of heavy metals in the soil, diversity loss becomes apparent. The preliminary findings indicate the local soil bacterial or microbial population may have adapted changed the soil conditions because the test soil accepted the oil refinery waste water continues to be the last irrigation water for 15 years (Amoah-Antwi et al., 2020). Similar studies using different levels of soil heavy metals pollution, long-term effects of heavy metals on soil microbial population, and genetic diversity explore possible metal to microbial interactions and their likely outcomes on soil quality and health (Ahmad et al., 2005).

4.1.2. Heavy metals effects on soil microorganism's enzymatic activity

Heavy metals in the soil ecosystem inhibit the activities of urease and nitrate reeducates. After specific experimental periods, higher application of heavy metals inhibits the amidase activity (Hemida et al., 1997). Generally, heavy metals are elements with metallic characteristics, i.e. ductility, cation stability, conductivity, ligand specificity, relatively high density, and the high atomic weight with atomic numbers higher than 20 (Singh, 2020).

Cadmium (Cd) per gram soil, arsenic (As) 1000 mg g^{-1}, cobalt (Co), copper (Cu), chromium (Cr), nickel (Ni), and lead (Pb), meganese (Mn), 10,000 mg g^{-1} transfer the microorganisms can remediate contaminated soil directly or by bio-utilizing these metals available in the plant's rhizosphere. Approximately some plant species accumulate 100 mg of metal to the harvestable part. Soil microbial activity changes the soil health physic-chemical attributes of soils and biochemical properties and bioavailability of heavy metals (Karaca et al., 2010). In response to quickly quantify the impact of pollutants on microbial-mediated ecological processes in various ecosystems, the concepts of ecological dose (ED_{50}) and lethal concentration (LC_{50}) were proposed (Abdu et al., 2017; Giller et al., 2009). The soil chemical reactions are the leading indicators of nutrient solubility in soil and availability to plants. Extensive contents of toxic heavy metals in living tissue can cause severe organ damage, neurological disorder, and cause death (Nwuche and Ugoji, 2008).

Heavy metals are a serious threat to our industrial agriculture industrial activities. It has a negative impact on various soil properties, including soil enzyme activity (Karaca et al., 2010). In this contest, soil enzymes are natural molecules that catalyze the reactions of soil microorganisms which are mainly derived from microbes and plant species. Since the activity of enzymes plays a fundamental role in soil chemical and biological reactions, the inhibitory effect of enzymes on heavy metals has attracted widespread attention (Long et al.). Many researchers have fully demonstrated it in the past few decades. It is often proposed that the soil enzymatic activities are vital points of microbial reactions involving nutrient cycling, and natural or manmade factors affecting soil changes. For this purpose, soil enzymatic activities are usually used to assess the impact of human activities on soil health (Aponte et al., 2020). Therefore, this literature review aims to emphasize critical factors, assumptions and possibilities, and the relationship between heavy metals and soil enzymes (Karaca et al., 2010).

4.2. Effect of heavy metals pollution on soil microbial diversity

The removal of heavy metals from polluted soils is a necessity for the conservation of natural resources and the defense of living things (Ullah et al., 2015). Heavy metal contamination is a significant global environmental issue that has a negative impact on the growth of plants and the genetic diversity of populations (Xie et al., 2016). Additionally, it changes the make-up of the microbial communities in the soil as well as their activity levels. It was discovered that contaminated populations had a greater amount of genetic diversity than groups that were not affected. Pollution caused by heavy metals can have a negative impact on plant growth, the diversity and activity of soil microbes, and appears to have a more significant effect on the genetic structure of organisms (Custodio et al., 2022). Mining, manufacturing, and the use of synthetic products (e.g. pesticides, paints, batteries, industrial waste, and land application of industrial or domestic sludge) can result in heavy metal contamination of urban and agricultural soils (Qayyum et al., 2020). Heavy metals also occur naturally but rarely at toxic levels. Potentially contaminated soils may occur at old landfill sites (particularly those that accepted industrial wastes), old orchards that used insecticides containing arsenic as an active ingredient, fields that had past applications of wastewater or municipal sludge, areas in or around mining waste piles, and tailings, industrial areas where chemicals may have been dumped on the ground, or in areas downwind from industrial sites (Dotaniya et al., 2020). Excess heavy metal accumulation in soils is toxic to humans and other animals. Exposure to heavy metals usually is chronic (exposure over a more extended period of time), due to food chain transfer. Acute (immediate) poisoning from heavy metals is rare through ingestion or dermal contact but is possible (Hussain et al., 2009). Due to both human and natural processes, heavy metals are found in the soil. Heavy metals have the potential to have long-term harmful effects on soil ecosystem health and to adversely affect soil biological processes when present (Abdu et al., 2017).

Some effects of Pb and Cd on microbes. Have discussed (Table 1). Physiological changes in the above-ground parts of plants may affect nutrition's status, hormonal homeostasis and ROS production and translocation of small signal molecules do not what's going on inside and how its effect the activity of the microbes interacting mechanism that could be involved.

5. Microbial response to ecosystem stress in the environment

Microorganisms can adapt to long-term (several to decades) stress by changing their genetic abilities so that they can better adapt to stress or enhance their functions (Schimel et al., 2007). Microorganisms have various evolutionary and physiological adaptation mechanisms that can make them survive and remain active under environmental pressure (Schimel, 2018). The physiological stress response has a cost at the biological level, leading to changes in ecosystem carbon levels, energy, and nutrient flow (Malik et al., 2020). At large-scale direct effects on the physiology of active microbes and composition microbial community control. Further, the major role of pH on the plant under stress conditions is indicated (Pointing and Belnap, 2012). It is essential to determine whether or not bacterial metal tolerance is connected with the type of metal being studied because metals (such as cadmium and lead) and metalloids can both affect bacteria (arsenic) (Mejias Carpio et al., 2018) demonstrated that there is a statistically significant difference between the metals tested (As, Cd, Cr, Cu, Ni, Pb, Zn) and the overall microbial tolerance, with cadmium being one of the most toxic metals and arsenic and lead together having the least toxicity. Nevertheless, lead and cadmium were shown to be the metals with the highest toxicity levels in this investigation. Moreover, Plant growth-promoting characteristics are engaged in encouraging plant development and mitigating the toxic

Table 1
Responses of microbes to heavy metals.

Heavy metal	Ecosystem factor	Microbes	Remediation ability	References
lead (Pb) Cadmium (Cd)	A soil sample was used to numerate viable heterotrophic	Bacteria, fungi and actinomycetes	Damage cell membranes and destroy the structure of DNA	(Khan, S. et al., 2010a, 2010b)
Cd or/and Pb	microbial structure		Effect on soil enzyme activities and microbial community structure	(Pan and Yu, 2011)
lead (Pb) and cadmium (Cd)	AM fungi were grown in paddy soil under Cd, Pb and phosphorus.	Arbuscular mycorrhizal (AM) fungi	The interactions between V. baoshanensis and indigenous AM fungi were amended with Pb, Cd and P.	(Zhang et al., 2012)
lead (Pb)	The effects of AMF symbiosis changes on aerial partis of plan's physiology as a result of nutrients availability and the hormonal imbalance or ROS production, and the translocation of small signalling molecules	Arbuscular mycorrhizal (AM) fungi	Lead (Pb) Stress on Pb Accumulation, Plant Growth Parameters, Photosynthesis, and Antioxidant Enzymes in Robinia pseudoacacia L.	(Yang et al., 2015)
Pd(II), Cd (II), and Cu(II)	The experimental biosorption data for Cd(II), Pb(II) and Cu(II) ions by the Langmuir model	The dry fungal biomass of Phanerochaetechryosporium	The max. absorption of different heavy metal ions on the fungal biomass was obtained at slightly alkaline pH (6.0)and the biosorption equilibrium after 6 h.	(Say et al., 2001)
cadmium (Cd) and lead (Pb)	pigeonpea plants to grow in multimetal contaminated soils	Arbuscular mycorrhizal (AM) fungi	The high Cd and Pb accumulations in roots and nodules than in shoots significantly decreased in the presence of AM fungi	(Garg and Aggarwal, 2011)
Cd and Pb	Cd) and Pb stresses in Cajanuscajan (L.) Millsp. (pigeon pea)	Arbuscular mycorrhizal (AM) fungi	Effect of mycorrhizal inoculations on heavy metal uptake and stress alleviation of Cajanuscajan (L.) Millsp. genotypes grown in cadmium and lead-contaminated soils	(Garg and Aggarwal, 2012)
Cd, Pb, Hg, and As	Heavy metal ions binding by Penicilliumpurpurogenum are pH-dependent	fungus Penicillium purpurogen-um	This fungal biomass showed a preference for binding Cd(II),Pb(II) over As(III) and Hg(II). Elution of heavy metal ions was performed using 0.5 M HCl. The fungus Penicilliumpurpurogenum could be used for ten cycles for biosorption	(Say et al., 2003)

effects that heavy metals have on plants. These effects can be caused by heavy metals (Tirry et al., 2018). Research on the impacts of cadmium on rice plant habitats has primarily concentrated on the connection between cadmium pollution in paddy soils and cadmium concentrations in rice (Soderland et al., 2010). Because of the many functions that they perform in the cycle of nutrients, the symbiosis of plants, and the detoxification of harmful chemicals used to control plant pests and plant growth, microbial communities play important roles in soil (Ivshina et al., 2014). These roles are important because of the many functions that microbial communities perform. The effects of heavy metals on root exudations, soil microbial activity, soil enzyme activity, and other aspects of soil biology have been the subject of a great number of research. On the other hand, there is now only a limited amount of research available regarding how heavy metals affect the overall microbial community found in soil (Feng et al., 2022).

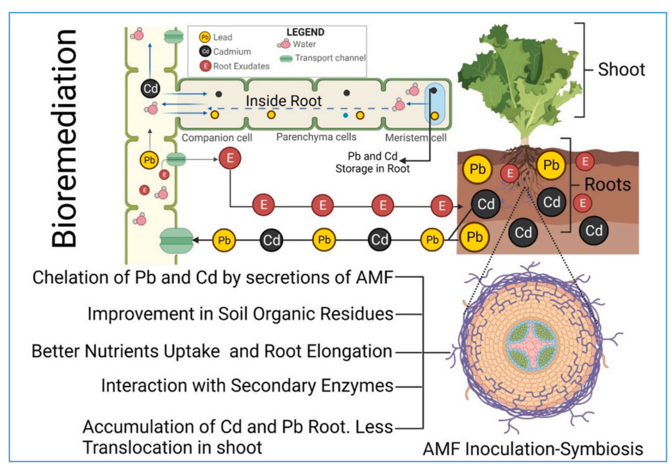

Fig. 1. The AMF inoculation role on the tolerance of plants to Pb. AMF inoculation can increase the level of Lead (Pb), and Cadmium (Cd) in roots but inhibit the root-to-leaf translocation of Pb.

5.1. Bioremediation technology and microbes role

Bioremediation is major prove which strengthen the role of microbial activity in the cleaning of pollutant in the ocean after significant oil spills and natural disasters (Fig. 1). By using natural bacteria to eliminate pollutants in the ocean, its need to protect and encourage aquaculture farmers and their attempts to solve global food production problems (Al-Majed et al., 2012). Bioremediation technology is of inestimable value for recovering contaminated water bodies and soil. In short, bioremediation techniques is a pollutant management tool that uses microbes to remove or minimize pollutants in effected places or the environment. Microorganisms can adapt to long-term (several decades) stress by changing their genetic abilities (Singh and Walker, 2006) so that they can better adapt to stress or enhance their functions. Drought stress is considered abiotic stress experienced by soil microbes (Martinez-Gutierrez and Aylward, 2022). Environmental stress on microbial cells is any conditions that deviate from the optimal growth conditions that lead to a decrease in growth rate or any situation that stimulates the expression of known stress response genes (Das et al., 2016).

Microorganisms are suitable for destroying pollutants by their enzymatic activities to take environmental pollutants as the source. For a better bioremediation process, microbes need to attack on heavy metals through enzymatic activities and utilize them as less harmful elements (Abatenh et al., 2017; Ojuederie and Babalola, 2017). Plant-microorganism interactions play a vital part in the adaptability to heavy metal polluted settings and thus, can be researched in depth to develop microbe-assisted phytoremediation methods (Gonzalez Henao and Ghneim-Herrera, 2021). However, Biochemical and molecular pathways are utilised by bacteria (White et al., 2016), while the Metal detoxification, mobilization, immobilization, transformation, transport, and distribution are all examples of biochemical pathways that have a part in microbial tolerance (Mejias Carpio et al., 2018). As phytoremediation is a variety of processes that take place as a result of interactions between plants, their environments, and the atmosphere. In the case of contaminated soil caused by heavy metals, there are four phytoremediation processes that have been identified: phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration (Ma et al., 2016).

Regular turning of contaminated soil, coupled with water, will increase aeration, pollutants distribution, nutrients depletion, and degradation activity of microbes, ultimately triggering the bioremediation rate, which can be gained via biotransformation and assimilation and mineralization (Ramírez-García et al., 2019). It has been reported that bacteria, fungi, and plants release a high concentration of enzymes that enhance the biodegradation of toxic substances (Karigar and Rao, 2011). Bioremediation is a cost-effective and environmentally benign method that uses enzymes produced by microorganisms to lessen the toxicity of contaminated sites. Reduce pollution while also generating new, beneficial compounds. Studies on oxidoreductase and hydrolase have revealed a lot of information on enzyme mechanisms that are important in bioremediation (Sangwan and Dukare, 2018). Enzymatic activities carried out by diverse microorganisms engaged in the biodegradation of various contaminants are discussed in the past study. It is necessary to overcome the limitation of its usefulness (Singh and Walker, 2006).

Mostly the bioremediation systems occurs in the presence of oxygen or aerobic conditions however anaerobic or absence of oxygen also cause microbial degradation of refractory molecules. Fungi and bacteria rely on intracellular and extracellular enzymes to repair stubborn, lignin, and organic pollutants (Karigar and Rao 2011). Bioremediation transforms impurities mediated by microbes into less harmful substances (Vargas-de la Cruz and Landa-Acuña, 2020). Microbes play a key role in bioremediation because they influence contaminants through enzymes and transform them into harmless byproducts. Consequently, In order for bioremediation to be effective, environmental circumstances must be altered so that microorganisms can grow and degrade at a quicker rate. Because of this, bioremediation can only be used when conditions allow for their growth and activity (Wang et al., 2022a).

Microorganisms have various evolutionary and physiological adaptation mechanisms, which can make them survive and remain active under environmental pressure. The physiological stress response has a cost at the biological level, leading to changes in energy and nutrient flow and ecosystem-level (López-Maury et al., 2008). Firstly considers some general aspects of how microorganisms experience environmental stress and how they respond. Then, we discussed the effects of drought and freezing, two critical ecosystems stresses, on microbial physiology and community composition (Schimel, 2018). Even under limited stress conditions, microbial communities effect the physiological costs of soil microorganisms and they significant changes the fate of nitrogen (N_2) and carbon (C). For example, microbial synthesis of osmotic substances needs to survive a drought, they may consume 5% of the annual net primary production value in the grassland ecosystem, and after adapting to low-temperature conditions, the Arctic tundra soil changes from nitrogen fixation in the growing season to Mineralized nitrogen in winter (Kutsch et al., 2009). It is suggested that integrated microbial ecology is more effective in ecosystem ecology. It requires full integration into the physiological ecosystem of microbes' process ecology and population biology (Schimel et al., 2007).

Moreover, the study focused on cyanobacteria, which are essential major producers and have contributed to fixing carbon budgets in many terrestrial and marine environments (Gao et al., 2016). Cyanobacteria have survived for about 3 billion years in a period of dramatic changes in environmental conditions and exist in extreme environments, from dry desert shells to hot springs (Rampelotto, 2010). Many cyanobacteria fix nitrogen, release hydrogen as a by-product, and are also part of the global harmful algal bloom. Therefore, they are currently being studied as potential sources of clean biofuels, fixed nitrogen and carbon sources, and the production of secondary metabolites (Abed et al., 2009).

Incessantly, people have realized that microbial communities have a special part in the detoxification of soil ecosystems' pollutants. In past, this process was called bioremediation or bio-recovery (Abatenh et al., 2017). The role of microorganisms in bioremediation must be understood for better use. The application of principles of microbial ecology will improve the method. To remove contaminated soil in situ, promoting microbial degradation has caused a lot of research (Dua et al., 2002). In particular, the rhizosphere is an area with enhanced microbial activity, enhancing the transformation and degradation of pollutants (Verma and Kuila, 2019). The provision of nutrients and oxygen, the addition of stimulants, and use of plants are considered common methods to enhance bioremediation (Ma et al., 2016).

6. Futures perspective and concluding remarks

Bioremediation is another biological mechanism that recycles waste into other organisms that can be used and reused. Today, the world is facing environmental pollution problems. In this situation, microorganisms are key players for substitute solutions to minimize environmental issues.

1-The metabolic activity of microorganisms is amazing so that they can survive in all parts of the biosphere. Under various environmental conditions, the nutritional abilities of microbes are entirely different from those being used for the bioremediation process.
2-Bioremediation is closely related to microorganisms' all-inclusive functions, involving the detoxification, immobilization, degradation, and eradication of heavy metals pollutants and hazardous substances in the surrounding. The key principle of biodegradation is to degrade and to convert pollutants, i.e. hydrocarbons, petroleum, heavy metals, pesticides, and dyes. It is carried out through metabolism through enzymatic means, which dramatically affects solving many environmental problems.
3 The biodegradation rate mainly depends on the two types of biological and abiotic conditions. Currently, different world regions have adopted different methods and strategies in this region. For example, biological stimulation, biological amplification, natural ventilation, biological piles, and biological attenuation are standard. All bioremediation technologies have their advantages and disadvantages because it has its specific application.

By understanding the microbes to plant interaction, the use of microorganisms for sustainable agriculture to handle future environmental challenges and perspectives needed to be studied. Furthermore, the perspectives and opportunities for controlling pH influence naturally occurring microbial populations (including those that cannot be cultured).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Asira, E.E., 2013. Factors that determine bioremediation of organic compounds in the soil. Acad. J. Interdiscipl. Stud. 2, 125, 125.

Awasthi, G., Nagar, V., Mandzhieva, S., Minkina, T., Sankhla, M.S., Pandit, P.P., Aseri, V., Awasthi, K.K., Rajput, V.D., Bauer, T., 2022. Sustainable amelioration of heavy metals in soil ecosystem: existing developments to emerging trends. Minerals 12, 85.

Cho, S.-J., Kim, M.-H., Lee, Y.-O., 2016. Effect of pH on soil bacterial diversity. J. Ecol. Environ. 40, 1–9.

Cookson, A.L., Bennett, J., Thomson-Carter, F., Attwood, G.T., 2007a. Molecular subtyping and genetic analysis of the enterohemolysin gene (ehxA) from Shiga toxin-producing Escherichia coli and atypical enteropathogenic E. coli. Appl. Environ. Microbiol. 73, 6360–6369.

Cookson, W., Osman, M., Marschner, P., Abaye, D., Clark, I., Murphy, D., Stockdale, E., Watson, C., 2007b. Controls on soil nitrogen cycling and microbial community composition across land use and incubation temperature. Soil Biol. Biochem. 39, 744–756.

Custodio, M., Espinoza, C., Peñaloza, R., Peralta-Ortiz, T., Sánchez-Suárez, H., Ordinola-Zapata, A., Vieyra-Peña, E., 2022. Microbial diversity in intensively farmed lake sediment contaminated by heavy metals and identification of microbial taxa bioindicators of environmental quality. Sci. Rep. 12, 1–12.

Feng, X., Wang, Q., Sun, Y., Zhang, S., Wang, F., 2022. Microplastics change soil properties, heavy metal availability and bacterial community in a Pb-Zn-contaminated soil. J. Hazard Mater. 424, 127364.

Fierer, N., Jackson, R.B., 2006. The diversity and biogeography of soil bacterial communities. Proc. Natl. Acad. Sci. USA 103, 626–631.

Frostegård, Å., Vick, S.H., Lim, N.Y., Bakken, L.R., Shapleigh, J.P., 2022. Linking meta-omics to the kinetics of denitrification intermediates reveals pH-dependent causes of N2O emissions and nitrite accumulation in soil. ISME J. 16, 26–37.

Gonzalez Henao, S., Ghneim-Herrera, T., 2021. Heavy metals in soils and the remediation potential of bacteria associated with the plant microbiome. Front. Environ. Sci. 15.

Gu, Y., Tan, X., Cai, X., Liu, S., 2022a. Remediation of as and Cd contaminated sediment by biochars: accompanied with the change of microbial community. J. Environ. Chem. Eng. 10, 106912.

Gu, Z., Feng, K., Li, Y., Li, Q., 2022b. Microbial characteristics of the leachate contaminated soil of an informal landfill site. Chemosphere 287, 132155.

Geisseler, D., Scow, K.M., 2014. Long-term effects of mineral fertilizers on soil microorganisms—a review. Soil Biol. Biochem. 75, 54–63.

Han, X.-Y., Huang, Q.-C., Li, W.-F., Jiang, J.-F., Xu, Z.-R., 2008. Changes in growth performance, digestive enzyme activities and nutrient digestibility of cherry valley ducks in response to aflatoxin B1 levels. Livest. Sci. 119, 216–220.

Hartman, W.H., Richardson, C.J., Vilgalys, R., Bruland, G.L., 2008a. Environmental and anthropogenic controls over bacterial communities in wetland soils. Proc. Natl. Acad. Sci. USA 105, 17842–17847.

Hartman, Z.C., Appledorn, D.M., Amalfitano, A., 2008b. Adenovirus vector induced innate immune responses: impact upon efficacy and toxicity in gene therapy and vaccine applications. Virus Res. 132, 1–14.

Havlin, J.L., 2020. Soil: Fertility and Nutrient Management, Landscape and Land Capacity. CRC Press, pp. 251–265.

Hu, Z.-H., Wang, G., Yu, H.-Q., 2004. Anaerobic degradation of cellulose by rumen microorganisms at various pH values. Biochem. Eng. J. 21, 59–62.

Ivshina, I., Kostina, L., Kamenskikh, T., Zhuikova, V., Zhuikova, T., Bezel, V., 2014. Soil microbiocenosis as an indicator of stability of meadow communities in the environment polluted with heavy metals. Russ. J. Ecol. 45, 83–89.

Jeyamkondan, S., Jayas, D., Holley, R., 2001. Microbial growth modelling with artificial neural networks. Int. J. Food Microbiol. 64, 343–354.

Kapoor, A., Sharma, R., Kumar, A., Sepehya, S., 2022. Biochar as a means to improve soil fertility and crop productivity: a review. J. Plant Nutr. 1–9.

Kelly, J.M., 1999. The role of damping in seismic isolation. Earthq. Eng. Struct. Dynam. 28, 3–20.

Khan, M.S., Zaidi, A., Ahemad, M., Oves, M., Wani, P.A., 2010a. Plant growth promotion by phosphate solubilizing fungi–current perspective. Arch. Agron Soil Sci. 56, 73–98.

Khan, S., Abd Hesham, E.-L., Qiao, M., Rehman, S., He, J.-Z., 2010b. Effects of Cd and Pb on soil microbial community structure and activities. Environ. Sci. Pollut. Control Ser. 17, 288–296.

Khare, E., Arora, N.K., 2015. Effects of Soil Environment on Field Efficacy of Microbial Inoculants, Plant Microbes Symbiosis: Applied Facets. Springer, pp. 353–381.

Lauber, C.L., Hamady, M., Knight, R., Fierer, N., 2009. Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the continental scale. Appl. Environ. Microbiol. 75, 5111–5120.

Liang, M.-Q., Zhang, C.-F., Peng, C.-L., Lai, Z.-L., Chen, D.-F., Chen, Z.-H., 2011. Plant growth, community structure, and nutrient removal in monoculture and mixed constructed wetlands. Ecol. Eng. 37, 309–316.

Liu, Z., Shi, Z., Wei, H., Zhang, J., 2022. Acid rain reduces soil CO_2 emission and promotes soil organic carbon accumulation in association with decreasing the biomass and biological activity of ecosystems: a meta-analysis. Catena 208, 105714.

Long, Y., Huang, S., Sun, J., Peng, D., Zhang, Z., Markedly boosted peroxymonosulfate-and periodate-based fenton-like activities of iron clusters on sulfur/nitrogen codoped carbon: key roles of a sulfur dopant and compared activation mechanisms. Nitrogen Codoped Carbon: Key Roles Sulf. Dopant Comp. Activat.n Mech.

Ma, Y., Oliveira, R.S., Freitas, H., Zhang, C., 2016. Biochemical and molecular mechanisms of plant-microbe-metal interactions: relevance for phytoremediation. Front. Plant Sci. 7, 918.

Mahmud, K., Makaju, S., Ibrahim, R., Missaoui, A., 2020. Current progress in nitrogen fixing plants and microbiome research. Plants 9, 97.

Malik, A.A., Puissant, J., Buckeridge, K.M., Goodall, T., Jehmlich, N., Chowdhury, S., Gweon, H.S., Peyton, J.M., Mason, K.E., van Agtmaal, M., 2018. Land use driven change in soil pH affects microbial carbon cycling processes. Nat. Commun. 9, 1–10.

Martinez-Gutierrez, C.A., Aylward, F.O., 2022. Genome size distributions in bacteria and archaea are strongly linked to evolutionary history at broad phylogenetic scales. PLoS Genet. 18, e1010220.

Mejias Carpio, I.E., Ansari, A., Rodrigues, D.F., 2018. Relationship of biodiversity with heavy metal tolerance and sorption capacity: a meta-analysis approach. Environ. Sci. Technol. 52, 184–194.

Mossor-Pietraszewska, T., 2001. Effect of aluminium on plant growth and metabolism. Acta Biochim. Pol. 48, 673–686.

Nacoon, S., Jogloy, S., Riddech, N., Mongkolthanaruk, W., Kuyper, T.W., Boonlue, S., 2020. Interaction between phosphate solubilizing bacteria and arbuscular mycorrhizal fungi on growth promotion and tuber inulin content of Helianthus tuberosus L. Sci. Rep. 10, 1–10.

Ng, J.F., Ahmed, O.H., Jalloh, M.B., Omar, L., Kwan, Y.M., Musah, A.A., Poong, K.H., 2022. Soil nutrient retention and ph buffering capacity are enhanced by calciprill and sodium silicate. Agronomy 12, 219.

Ni, S., Wen, H., Wilson, G., Cai, C., Wang, J., 2022. A simulated study of surface morphological evolution on coarse-textured soils under intermittent rainfall events. Catena 208, 105767.

Nightingale, J., Carter, L., Sinclair, C.J., Rooney, P., Dickinson, M., Tarbin, J., Kay, P., 2022. Assessing the influence of pig slurry pH on the degradation of selected antibiotic compounds. Chemosphere 290, 133191.

Oladoye, P.O., Olowe, O.M., Asemoloye, M.D., 2022. Phytoremediation technology and food security impacts of heavy metal contaminated soils: a review of literature. Chemosphere 288, 132555.

Rajendran, S., Priya, T., Khoo, K.S., Hoang, T.K., Ng, H.-S., Munawaroh, H.S.H., Karaman, C., Orooji, Y., Show, P.L., 2022. A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. Chemosphere 287, 132369.

Ramírez-García, R., Gohil, N., Singh, V., 2019. Recent advances, challenges, and opportunities in bioremediation of hazardous materials. Phytomanag. Pollut. Sites 517–568.

Rampelotto, P.H., 2010. Resistance of microorganisms to extreme environmental conditions and its contribution to astrobiology. Sustainability 2, 1602–1623.

Ronen, G., Carmel-Goren, L., Zamir, D., Hirschberg, J., 2000. An alternative pathway to β-carotene formation in plant chromoplasts discovered by map-based cloning of Beta and old-gold color mutations in tomato. Proc. Natl. Acad. Sci. USA 97, 11102–11107.

Rousk, J., Bååth, E., Brookes, P.C., Lauber, C.L., Lozupone, C., Caporaso, J.G., Knight, R., Fierer, N., 2010. Soil bacterial and fungal communities across a pH gradient in an arable soil. ISME J. 4, 1340–1351.

Sandaa, R.-A., Torsvik, V., Enger, Ø., 2001. Influence of long-term heavy-metal contamination on microbial communities in soil. Soil Biol. Biochem. 33, 287–295.

Sessitsch, A., Weilharter, A., Gerzabek, M.H., Kirchmann, H., Kandeler, E., 2001. Microbial population structures in soil particle size fractions of a long-term fertilizer field experiment. Appl. Environ. Microbiol. 67, 4215–4224.

Shah, G.M., Ali, H., Ahmad, I., Kamran, M., Hammad, M., Shah, G.A., Bakhat, H.F., Waqar, A., Guo, J., Dong, R., 2022. Nano agrochemical zinc oxide influences microbial activity, carbon, and nitrogen cycling of applied manures in the soil-plant system. Environ. Pollut. 293, 118559.

Sheng, Y., Zhu, L., 2018. Biochar alters microbial community and carbon sequestration potential across different soil pH. Sci. Total Environ. 622, 1391–1399.

Šimek, M., Cooper, J., 2002. The influence of soil pH on denitrification: progress towards the understanding of this interaction over the last 50 years. Eur. J. Soil Sci. 53, 345–354.

Smit, B., Pilifosova, O., 2003. From Adaptation to Adaptive Capacity and Vulnerability Reduction, Climate Change, Adaptive Capacity and Development. World Scientific, pp. 9–28.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133, 247–266.

Soderland, P., Lovekar, S., Weiner, D.E., Brooks, D.R., Kaufman, J.S., 2010. Chronic kidney disease associated with environmental toxins and exposures. Adv. Chron. Kidney Dis. 17, 254–264.

Solis-Hernández, A.P., Chávez-Vergara, B.M., Rodríguez-Tovar, A.V., Beltrán-Paz, O.I., Santillán, J., Rivera-Becerril, F., 2022. Effect of the natural establishment of two plant species on microbial activity, on the composition of the fungal community, and on the mitigation of potentially toxic elements in an abandoned mine tailing. Sci. Total Environ. 802, 149788.

Song, P., Xu, D., Yue, J., Ma, Y., Dong, S., Feng, J., 2022. Recent Advances in Soil Remediation Technology for Heavy Metal Contaminated Sites: A Critical Review. Science of The Total Environment, 156417.

Souza, L.F., Billings, S.A., 2022. Temperature and pH mediate stoichiometric constraints of organically derived soil nutrients. Global Change Biol. 28, 1630–1642.

Sun, S., DeLuca, T.H., Zhang, J., Wang, G., Sun, X., Hu, Z., Wang, W., Zhang, W., 2022. Evidence of endophytic nitrogen fixation as a potential mechanism supporting colonization of non-nodulating pioneer plants on a glacial foreland. Biol. Fertil. Soils 1–13.

Thakur, M., Praveen, S., Divte, P.R., Mitra, R., Kumar, M., Gupta, C.K., Kalidindi, U., Bansal, R., Roy, S., Anand, A., 2022. Metal tolerance in plants: molecular and physicochemical interface determines the "not so heavy effect" of heavy metals. Chemosphere 287, 131957.

Tirry, N., Joutey, N.T., Sayel, H., Kouchou, A., Bahafid, W., Asri, M., El Ghachtouli, N., 2018. Screening of plant growth promoting traits in heavy metals resistant bacteria: prospects in phytoremediation. J. Genet. Eng. Biotechnol. 16, 613–619.

Ullah, A., Heng, S., Munis, M.F.H., Fahad, S., Yang, X., 2015. Phytoremediation of heavy metals assisted by plant growth promoting (PGP) bacteria: a review. Environ. Exp. Bot. 117, 28–40.

Wang, A., Fu, W., Feng, Y., Liu, Z., Song, D., 2022a. Synergetic effects of microbial-phytoremediation reshape microbial communities and improve degradation of petroleum contaminants. J. Hazard Mater. 429, 128396.

Wang, Z., Bai, Y., Hou, J., Li, F., Li, X., Cao, R., Deng, Y., Wang, H., Jiang, Y., Yang, W., 2022b. The changes in soil microbial communities across a subalpine forest successional series. Forests 13, 289.

Welch, R., 2001. Impact of Mineral Nutrients in Plants on Human Nutrition on a Worldwide Scale, Plant Nutrition. Springer, pp. 284–285.

White, G.F., Edwards, M.J., Gomez-Perez, L., Richardson, D.J., Butt, J.N., Clarke, T.A., 2016. Mechanisms of bacterial extracellular electron exchange. Adv. Microb. Physiol. 68, 87–138.

Xie, Y., Fan, J., Zhu, W., Amombo, E., Lou, Y., Chen, L., Fu, J., 2016. Effect of heavy metals pollution on soil microbial diversity and bermudagrass genetic variation. Front. Plant Sci. 7, 755.

Yan, L., Riaz, M., Liu, J., Yu, M., Cuncang, J., 2022. The aluminum tolerance and detoxification mechanisms in plants; recent advances and prospects. Crit. Rev. Environ. Sci. Technol. 52, 1491–1527.

Yu, W., Huang, W., Weintraub-Leff, S.R., Hall, S.J., 2022. Where and why do particulate organic matter (POM) and mineral-associated organic matter (MAOM) differ among diverse soils? Soil Biol. Biochem. 108756.

Zea, M., Souza, A., Yang, Y., Lee, L., Nemali, K., Hoagland, L., 2022. Leveraging high-throughput hyperspectral imaging technology to detect cadmium stress in two leafy green crops and accelerate soil remediation efforts. Environ. Pollut. 292, 118405.

Zhang, L., Chung, J., Jiang, Q., Sun, R., Zhang, J., Zhong, Y., Ren, N., 2017. Characteristics of rumen microorganisms involved in anaerobic degradation of cellulose at various pH values. RSC Adv. 7, 40303–40310.

Zhang, M., Zhang, T., Zhou, L., Lou, W., Zeng, W., Liu, T., Yin, H., Liu, H., Liu, X., Mathivanan, K., 2022. Soil Microbial Community Assembly Model in Response to Heavy Metal Pollution. Environmental Research, 113576.

Zhang, W., Zhang, M., An, S., Xiong, B., Li, H., Cui, C., Lin, K., 2012. Ecotoxicological effects of decabromodiphenyl ether and cadmium contamination on soil microbes and enzymes. Ecotoxicol. Environ. Saf. 82, 71–79.

Zhang, Y., Zhang, T., 2022. Culturing the uncultured microbial majority in activated sludge: a critical review. Crit. Rev. Environ. Sci. Technol. 1–24.