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ROLE OF MYCORRHIZAL FUNGI IN ALLEVIATING HEAVY METAL STRESS IN PLANTS

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ABSTRACT

Heavy metal pollution in soil harms plant health, lowers agricultural production, and threatens the stability of ecosystems, making it a major environmental concern. Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), offer a natural way to reduce the harmful effects of heavy metals on plants. These fungi help plants take in more nutrients, keep their cells balanced, and activate their body's defenses against stress. In the soil around plant roots, they can trap heavy metals, stop them from moving up into the plant, and change how the plant's genes react to stress. AMF also produce a substance called glomalin, which helps bind metals in the soil and improves soil structure, making metals less available to plants. It is expected that combining phosphorus-solubilizing bacteria (PSB) with VAMF in contaminated soil could help plants survive better. This study looked at how different treatments—like using no treatment, VAMF alone, PSB alone, or both together—affected three types of vegetable plants: tomato, red chili, and spicy chili, grown in heavy metal-polluted soil. The research also checked how well these plants absorbed important metals like zinc and copper, as well as harmful ones like cadmium and nickel, and how this affected their growth and survival. These results could lead to new ways to deal with heavy metal pollution in soil.

KEYWORD: *Heavy metal, contamination, soil, ecosystem, agricultural*

INTRODUCTION

The growth and development of plants are harmed when there are high levels of heavy metals. Contaminants in the soil also affect the microorganisms living in it. Heavy metals in the soil stop many important physical, chemical, and molecular processes. These metals damage plants and cause problems like poor seed germination, loss of firmness, yellowing of leaves, cell death, aging, and finally plant death. Heavy metals also reduce the ability of plants to perform photosynthesis. When plants face heavy metal stress, they produce more antioxidant enzymes like peroxidase, catalase, and superoxide dismutase [1]. Lead and cadmium are two harmful heavy metals [2]. These metals affect many systems in plants, such as lead and cadmium [2-4]. Too much of reactive oxygen species and methylglyoxyl can cause damage to DNA, break down fats, oxidize proteins, stop enzymes from working, and sometimes make DNA interact with other parts of the cell. Heavy metals in the soil come mostly from fertilizers, pesticides, and wastewater that has metals in it. Burning fossil fuels also adds more heavy metals to the soil. In the last 200 years, the levels of cadmium, lead, and zinc in soil have gone up a lot [5]. To deal with too much metal, some plants have developed special defenses. These include trapping metals, producing nitric oxide and certain amino compounds, turning on stress proteins, blocking metal absorption and transport, and using the outer cell layer to push metals out. Some plants can store large amounts of heavy metals in their cell walls. Proteins like ferritins and metallothionins help plants handle the stress caused by heavy metals [6]. Soil also has harmful cadmium thiolate complexes that hurt both microorganisms and plants. These metals build up in the cell walls of plants and may end up in storage areas inside the plant cells [7, 8]. Some studies show that certain genes in plants called AM plants respond to metal stress by producing proteins like the 90 kD heat shock protein, glutathione-S-transferase, and metallothionein. This suggests these proteins may help trap harmful metals around the plant roots. Toxic metals in soil can be removed using methods like physical, chemical, and biological techniques. Mycorrhizal fungi are a kind of biological method used to clean up soil with heavy metals [9]. In areas with high levels of cadmium and zinc, a type of fungus called G. intraradices shows more hyphal growth, spore production, and spore germination [10]. These fungi can break down heavy metals, which makes them less harmful. In AM fungus cells, proteins like metallothionines help detoxify cadmium and copper. An Al-tolerant type of Gigaspora gigantia fungus also shows more hyphal growth when it forms a partnership with plants [11]. In Glomus species that have higher zinc levels, hyphal growth is also seen [12]. Most ectomycorrhizal and ericoid mycorrhizal fungi help plants survive in heavy metal polluted areas [13-15]. Endomycorrhizal fungi also help in taking up and trapping harmful metals in the soil. Mycorrhiza is the connection between fungi and the roots of higher plants. After entering plant roots, fungi grow hyphae, arbuscules, and vesicles. This connection helps in moving nutrients, especially phosphorus. Heavy metals like lead and cadmium stop many important plant processes, such as breathing, making food, managing nitrogen and proteins. High zinc levels in soil have similar effects. Using the right mycorrhizal fungi in areas with heavy metals can help reduce their harmful effects. The success of arbuscular mycorrhizal fungi is shown by the presence of arbuscules, vesicles, and hyphae in plant roots (Figure 1). This gives evidence of the mycorrhizal connection. Compared to plants not treated with mycorrhizal fungi in polluted areas, plants with mycorrhizal treatment are healthier. Heavy metals in the soil can also affect some mycorrhizal fungi. Studies show that heavy metals can interfere with spore formation and the growth of symbiotic fungal networks [10].

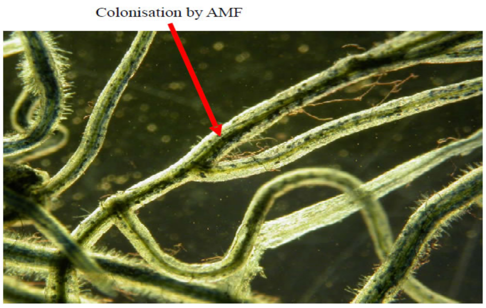

Figure 1. Fungal growth in plant roots showing a connection with arbuscular mycorrhizal fungi.

Some types of mycorrhizal fungi can handle stress from heavy metals. Among them, Glomus intraradices, Glomus mosseae, and other species in the Glomus group are especially important. So, choosing strains of mycorrhizal fungi that can handle heavy metals is a key step in growing healthy plants in areas with polluted soil.

This paper explains the possibility of using a cost-effective and environmentally friendly method called AMF-assisted GC phytoremediation. Also, it talks about the ways in which the relationship between plants and mycorrhizal fungi helps in cleaning up contaminated sites.

MYCORRHIZAL ASSOCIATION IN HEAVY METAL CONTAMINATED SOIL

AM fungal growth was found in very polluted soil [16, 17]. Researchers also found Glomus mosseae in heavy metal polluted areas [18]. The outer part of the mycelium of some AM fungi makes a protein called Glycoprotein (Glomalin) that can bind to heavy metals [19-22]. These metals stick to the binding sites. When plants team up with AM fungi, their ability to handle stress from free radicals (antioxidants) also improves [2, 23]. Several species in the Glomus group are important for these associations. In the past, some fungal strains were found that can handle heavy metal pollution. Many mycorrhizal fungi can deal with the stress caused by heavy metals [24, 25], as shown by various studies [12, 24, 26]. The level of tolerance to heavy metals varies between different fungal groups. If less tolerant strains are involved in the association, fungal growth is reduced. The presence of copper and cadmium in soil can stop mycorrhizal colonization [12, 24, 26, 27]. This shows how heavy metals can block certain processes in plants and fungi. The way mycorrhizal fungi and plants communicate through signals can explain how the presence of different heavy metals can either help or stop fungal growth.

Many plants release substances from their roots, like strigolactones and flavonoids, which attract mycorrhizal fungi. Fungi, in return, produce signals like lipochitooligosacharides, which plants can sense. In some cases, the presence of high amounts of heavy metals, like zinc, doesn’t stop these signals, meaning some fungi can handle high levels of certain metals. Because of this, specific mycorrhizal fungi can survive even in high metal concentrations. The hyphae of these fungi can bind to heavy metals, which stops them from moving into plants. This helps reduce the amount of toxic metals that reach the plants [28, 29]. Trees like pines that are treated with a fungus called Pisolithus tinctorius show better metal tolerance. Zinc-tolerant strains of Suillus bovinus help Pinus sylvestris resist heavy metals. Mycorrhizal associations can also trap heavy metals, possibly because the soil around the roots becomes slightly more acidic. This change can make metals less available to plants. The ability of mycorrhiza to reduce plant uptake of heavy metals might be linked to how soil pH changes.

Heavy metals like zinc are mostly stored in the fungal hyphae and in structures called arbuscules. When several Glomus species are paired with clover or ryegrass, they absorb a lot of zinc [30]. AM fungi also release a type of insoluble Glycoprotein (Glomalin) that can pull out copper, cadmium, and lead from polluted soil. One gram of Glomalin can remove 4. 3 mg of copper, 0. 08 mg of cadmium, and 1. 12 mg of lead from contaminated soil [31, 32]. Gohri and Paszwoski also said that these toxic metals are stored in fungal vesicles [32]. Kaldorf et al. (1999) found that metals in maize plants were reduced when the plants had Glomus species. Mycorrhizal fungi in metal contaminated areas are more tolerant than those in clean areas [12, 33].

REVIEW OF THE LITERATURE

Kumar, A., & Suprasanna, P. (2021). The degradation of land due to heavy metal accumulation from mining and industrial effluents has emerged as a serious concern for ecological sustainability. This review discusses various phytoremediation techniques such as phytoextraction, phytostabilization, and rhizofiltration. Special emphasis is placed on the role of arbuscular mycorrhizal fungi (AMF), which form symbiotic associations with plant roots and help mitigate metal toxicity. AMF-mediated bioremediation (mycorrhizoremediation) is highlighted as a potent approach for reclaiming metal-contaminated soils by enhancing nutrient uptake, stress resistance, and reducing heavy metal translocation to aerial parts.

Dhalaria, R., Kumar, D., Kumar, H., Nepovimova, E., Kuca, K., & Verma, R. (2020). This paper examines how AMF mitigate the toxic effects of heavy metals like cadmium, mercury, and lead on plant physiology. AMF reduce metal bioavailability by accumulating metals in vesicles, increasing antioxidant activity, secreting glomalin (which binds metals), and promoting nutrient absorption via extensive hyphal networks. These processes improve soil quality and reduce the reliance on chemical inputs. The review also discusses molecular mechanisms like gene activation for detoxification.

Lokhandwala, B. S., Singh, A., & Patel, R. (2017). This study focuses on the role of mycorrhiza-mediated phytostabilization in remediating metal-polluted soils. It describes mechanisms such as the secretion of organic acids, glomalin and metallothionein production, and root-zone modification that contribute to immobilization and detoxification of metals. AMF facilitate soil stabilization and metal complexation, minimizing environmental dispersion.

Miransari, M. (2017). Arbuscular mycorrhizal fungi (AMF) are explored for their role in enhancing plant tolerance to heavy metal stress through physiological, biochemical, and molecular adaptations. The chapter discusses AMF's ability to allocate metals to fungal structures, reduce oxidative stress, and trigger stress-responsive genes in host plants. This symbiosis is positioned as a robust and sustainable strategy in bioremediation and soil health restoration.

OBJECTIVE OF THE STUDY

1. To find out how different types of inoculants like the control group, phosphate-solubilizing bacteria, vesicular arbuscular mycorrhizae fungi, and a mix of both impact root colonization, plant growth, and how much of key nutrients like phosphorus and nitrogen plants take in, as well as how much of metal elements they absorb from soil that has high levels of heavy metals.
2. To find other methods to deal with the problem of high heavy metal levels in soil.

MATERIALS AND METHODS

The process of treating soil

To get rid of the native mycorrhizal fungi, a type of soil called ultisol that had low levels of phosphorus (1.9 mg per kg when extracted with water) from an Indian garden was heated twice at 80 degrees Celsius for 1,440 minutes. After the first heating, the soil was left at room temperature for a day before the second heating. Two weeks before the experiment began, the soil was combined with all the metals and nutrients, and the moisture level was kept at 15%. The soil was then left to sit at room temperature until the experiment started. For each kilogram of soil, 200 mg of nitrogen (from ammonium nitrate), 20 mg of phosphorus (from calcium dihydrogen phosphate), 100 mg of magnesium (from magnesium sulfate), 200 mg of potassium (from potassium sulfate), and 10 mg of iron (from ammonium iron citrate) were added.

Additionally, 2 mg of zinc (zinc sulfate), 2 mg of copper (copper sulfate), 2 mg of nickel (nickel sulfate), and 0. 2 mg of cadmium (cadmium sulfate) were also added per kilogram of soil (Kloke, 1980; Lee, 2005). Three plant species were used: red chili (Capsicum annuum L.cv. Gada), hot chili (Capsicum frutescens L. cv. Pusaka Brengolo), and tomato (Solanum lycopersicum L. cv. Ratna). The VAMF used in the study came from a strain known as G. mosseae, which is native to India. The fungus spores were mixed with the soil and placed in the soil. Before planting, each pot received up to 0. 01 kg of soil containing 20-25 VAMF spores.

Experimental design and plant treatment

Before being planted in the pots, the seeds were treated with 10% hydrogen peroxide for five minutes to remove any harmful bacteria. Then, they were soaked in saturated calcium sulfate for 240 minutes to help them sprout. After that, the seeds were treated with 20 mL of a solution containing B. subtilis (from the Universitas Laboratory) at a concentration of 109 CFU per mL.Each five-liter pot was filled with three kilograms of soil. After the plants sprouted, they were thinned to two per pot. The experiment was set up using a one-factor, randomized full block design. The treatments used were: 1) control (no added fungi), 2) VAMF only, 3) PSB only, and 4) both VAMF and PSB together. Each plant species was grown in 16 pots, with four pots for each treatment and four repetitions. The plants were grown in a greenhouse where the temperature stayed between 28 and 32 degrees Celsius, and the light was around 34,000 lux.

Analysis of plants

After eight weeks of growth, the roots and shoots were collected to check for mycorrhizal colonization and measure the dry weight of the plants (Chandrasekaran, 2022) and the levels of nutrients like nitrogen, phosphorus, zinc, copper, cadmium, and nickel. The percentage of root length that was colonized by VAMF was calculated using the gridline-intersect method on roots that had been stained with trypan blue (Kumar & Tapwal, 2022). The amount of phosphorus was measured using the Kjeldahl method, and nitrogen levels were determined using UV-Vis spectrophotometry. The concentrations of zinc, copper, nickel, and cadmium were measured using an atomic absorption spectrophotometer (Bhandari, 2018).

Analysis of statistics

The data was presented using the average and standard deviation of the repeated measurements. Before doing the analysis of variance in SPSS, the data was checked to see if it followed a normal distribution and had equal variances (IBM SPSS Statistics 23). A one-way analysis of variance and Duncan's multiple-range test (P < 0. 05) was used to compare the average root colonization, plant biomass, phosphorus and nitrogen levels, and metal concentrations (copper, zinc, cadmium, and nickel) for each plant species.

RESULTS

colonization of Root

Table 1 shows that when VAMF and PSB were used together, the roots of the plants had much more colonization compared to the other treatments.

Table 1 also shows how well the roots of vegetable plants grown in soil with heavy metals were colonized.

Treatments	Root colonization in vegetable plants (%)					
	Tomato		Red chili		Hot chili	
	Mean ± SD	CV	Mean ± SD	CV	Mean ± SD	CV
Control	4.9 ± 0.52 c[z]	10.5	5.9 ± 0.28 d	16.9	5.3 ± 0.36 d	6.9
VAMF	31.1 ± 0.70 b	2.3	43.0 ± 1.27 c	3.0	41.7 ± 1.73 b	4.2

Treatments	Root colonization in vegetable plants (%)					
	Tomato		Red chili		Hot chili	
	Mean ± SD	CV	Mean ± SD	CV	Mean ± SD	CV
PSB	29.8 ± 0.99 b	2.6	51.7 ± 0.56 b	0.7	38.7 ± 1.56 c	4.0
VAMF-PSB	43.1 ± 1.41 a	3.3	57.8 ± 2.05 a	3.6	51.9 ± 2.01 a	3.9

VAMF = vesicular arbuscular mycorrhizae fungi; PSB = phosphate-solubilizing bacteria; SD = standard deviation; CV = coefficient of variation. ^{z}Means with the same letters within each column do not differ statistically (Duncan, $P \leq 0.05$).

biomass of Plant

When compared to plants without VAMF, the biomass of the three vegetable species increased a lot after their roots were colonized by VAMF (Table 2).

Table 2 shows the biomass of vegetable plants grown in soil that had heavy metals in it.

Treatments	Plant biomass in vegetable plant (g)					
	Tomato		Red Chili		Hot Chili	
	Mean ± SD	CV	Mean ± SD	CV	Mean ± SD	CV
Control	3.10 ± 0.29 c^z	9.5	2.92 ± 0.22 c	7.6	2.72 ± 0.25 b	9.2
VAMF	4.10 ± 0.18 b	4.5	4.57 ± 0.25 b	5.5	3.90 ± 0.21 a	5.5
PSB	4.28 ± 0.21 b	5.0	4.80 ± 0.18 b	3.8	3.87 ± 0.18 a	4.9
VAMF-PSB	5.65 ± 0.31 a	5.5	5.87 ± 0.29 a	5.1	4.10 ± 0.36 a	8.9

VAMF = vesicular arbuscular mycorrhizae fungi; PSB = phosphate-solubilizing bacteria; SD = standard deviation; CV = coefficient of variation. ^{z}Means with the same letters within each column do not differ statistically (Duncan, $P \leq 0.05$).

Concentrations of phosphorus (P) and nitrogen (N)

When compared to the control, the levels of P and N were higher in plants treated with VAMF, PSB, and both together (Figures 1 and 2). The amount of P in the roots and shoots of all plant types showed that there was enough P for the plants (Figure 1). However, when compared to the normal levels of good nutrition, the amounts of N in the roots and shoots (Figure 2) were lower, indicating a poor nutritional state (Bergmann, 1992; Balemi & Negisho, 2012; Frydenvang et al. , 2015).

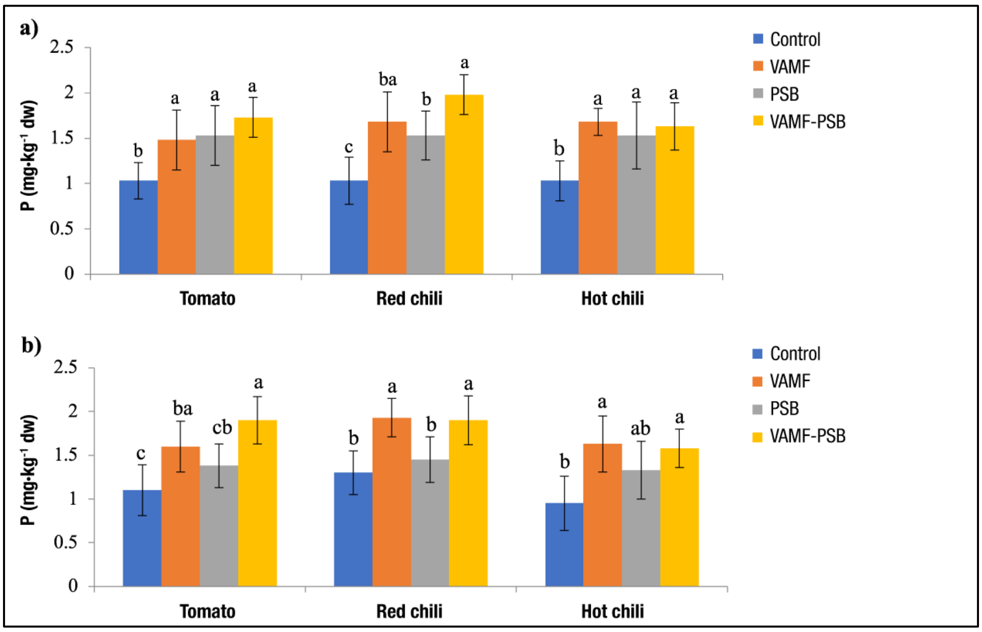

Figure 1 P concentrations in three vegetable types that were treated with vesicular arbuscular mycorrhizae fungi (VAMF), phosphorus-solubilizing bacteria (PSB), and a mix of both (VAMF-PSB) are shown in Figure 1 (a) for roots and (b) for shoots. Dry weight is shown as dw, and standard deviation is shown as bars. In each vegetable type, columns with the same letters don't show a big difference (Duncan, P < 0. 05).

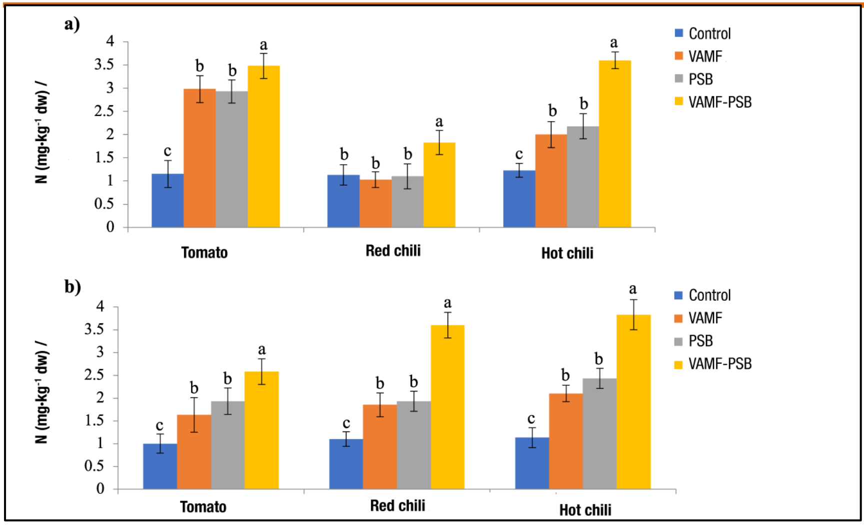

Figure 2. N concentrations in three vegetable types that were treated with VAMF, PSB, and VAMF-PSB are shown in Figure 2 (a) for roots and (b) for shoots. Dry weight is represented as dw, and standard deviation is shown as bars. In each vegetable type, columns with the same letters don't differ much (Duncan, P < 0. 05). Compared to the usual N concentration, the N levels stayed low even though they increased in the VAMF, PSB, and VAMF-PSB treatments (Figure 2).

Heavy Metal Concentration

The levels of Cu, Zn, Cd, and Ni were higher in the roots than in the shoots for the three plant types, even though applying VAMF, PSB, or VAMF-PSB reduced Cd and Ni levels in the shoots of the plants (Figures 3, 4, 5, and 6).

Comparing with other treatments, VAMF-PSB increased the Zn content in the roots (Figure 4a), which also led to a significant increase in zinc in tomato shoots. Cd levels in the roots were not affected by VAMF-PSB (Figure 5a). In contrast to the control, each co-inoculation treatment lowered Cd levels in the shoots of all plants (Figure 5b).

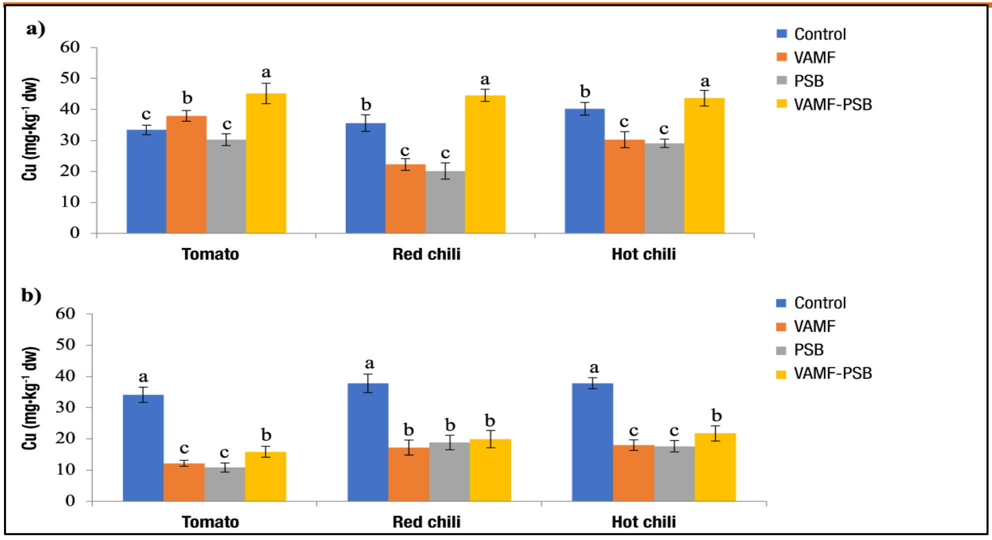

Figure 3 Cu levels in three types of vegetables treated with vesicular arbuscular mycorrhizae fungi (VAMF), phosphorus-solubilizing bacteria (PSB), and combined treatment (VAMF-PSB) : part a is for roots and part b is for shoots. Dry weight is marked as dw, and standard deviation is shown with bars. In each vegetable type, the columns with the same letters are not significantly different (Duncan test, $P < 0.05$).

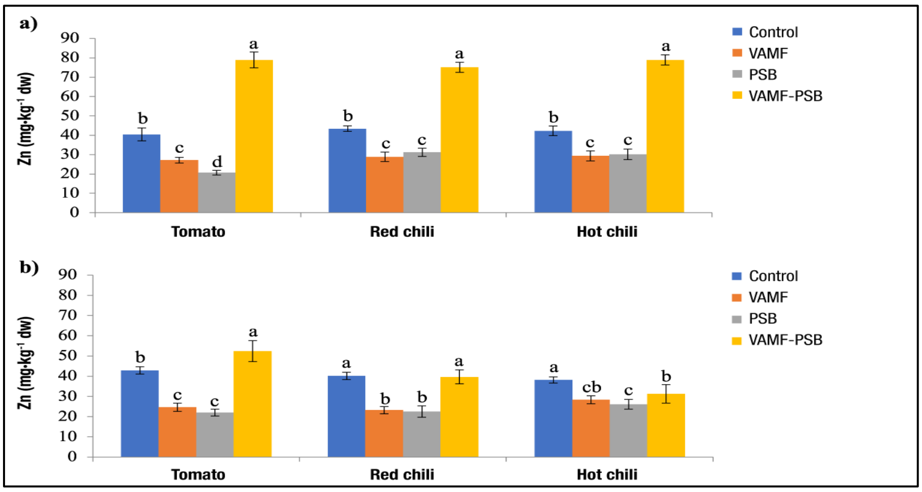

Figure 4 Zn levels in the same three vegetable types treated with VAMF, PSB, and VAMF-PSB are shown in: part a for roots and part b for shoots. Dry weight is again marked as dw, and standard deviation is shown with bars. Columns with the same letters in each vegetable type do not show significant differences (Duncan test, $P < 0.05$).

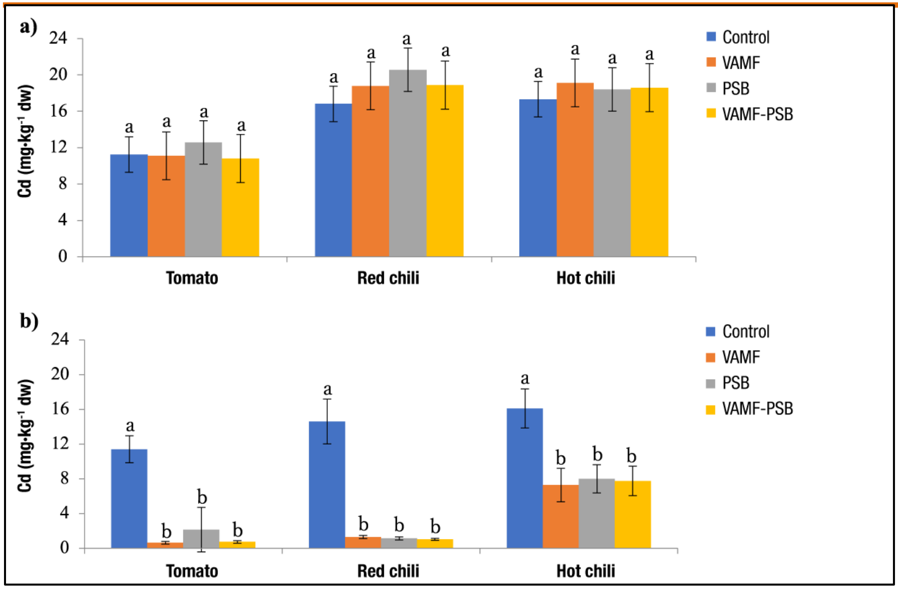

Figure 5 Cd levels in the same three vegetable types treated with VAMF, PSB, and VAMF-PSB are shown in: part a for roots and part b for shoots. Dry weight is marked as dw, and standard deviation is shown with bars. Columns with the same letters in each vegetable type do not show significant differences (Duncan test, P < 0. 05).

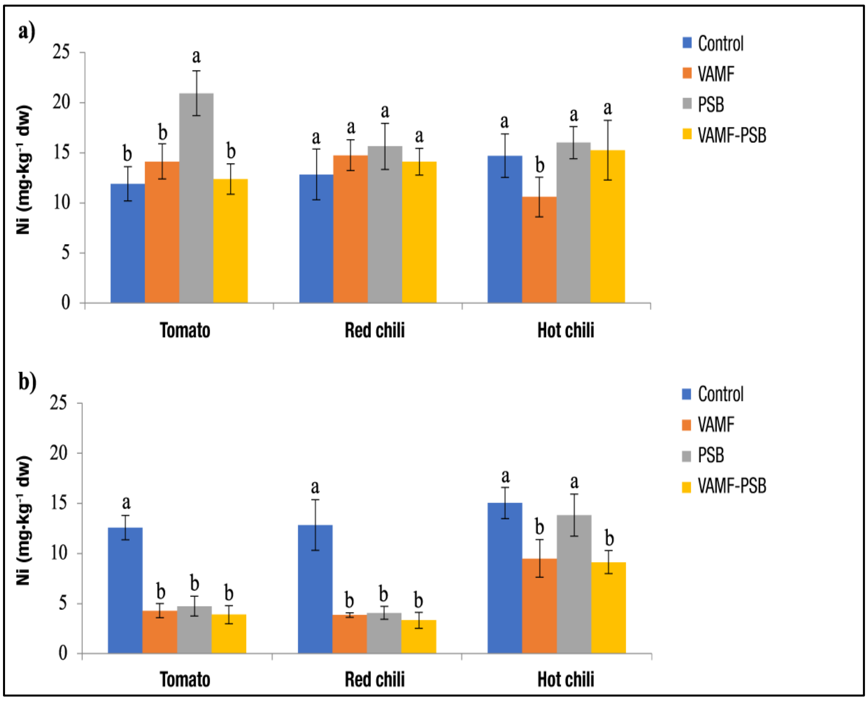

Figure 6 Ni levels in the same three vegetable types treated with VAMF, PSB, and VAMF-PSB are shown in : part a for roots and part b for shoots. Dry weight is again marked as dw, and

standard deviation is shown with bars. Columns with the same letters in each vegetable type do not show significant differences (Duncan test, P < 0. 05).

DISCUSSION

Regardless of whether plants were inoculated, Sun et al. (2018) found that cadmium levels in the roots were higher than those in the shoots for all the plant varieties tested. On the other hand, the role of AMF varies depending on whether the farming is in lowland or highland areas. Because of a failure in a tailings dam, Zhao et al. (2023) saw that adding two AMF species, G. intraradices and G. mosseae, greatly increased the amount of cadmium in the polluted land areas. However, in the area downwind of a smelter that is heavily affected by smoke and dust, using G. mosseae significantly reduced cadmium levels. It also lowered cadmium in the top layers of the tailings pond. AMF helps plants deal with cadmium by improving their ability to take up phosphorus, trapping cadmium in their cells, and changing the chemical structures in their cells (You et al. , 2022). When Gao et al. (2023) looked at the effects of AMF on cereals grown in a controlled greenhouse setting, they found that cadmium stress was reduced by between 5. 14 and 33. 6%. This was done by lowering the amount of a harmful product created in plant cell membranes called MDA by 12. 9%, and by increasing the levels of substances that help the plant deal with stress, like soluble proteins, sugars, and total prolines, by between 14. 8% and 36. 0%.

Narwal et al.(2018) found that rice plants treated with AMF absorbed 32. 4% more zinc than plants that weren't treated. The presence of AMF greatly increased how much zinc plants could take in. In a study by Zaheer et al. (2019), applying PSB also improved zinc absorption in plants, which is similar to what was found with AMF. These results match our findings, which are shown in Figure 4a. In this study, using VAMF or PSB increased the zinc levels in the roots, which in turn raised the zinc content in the tomato shoots.

Brunetto et al. (2023) found that pre-treating plants with specific AMF strains, Rhizophagus clarus X UFSC 14 and Rhizophagus intraradices X UFSC 32, greatly reduced copper levels after a long time of exposure. PSB might also help increase the concentration of key metals like copper, similar to the effect of AMF. According to Lin et al. (2018), PSB significantly boosted the way copper moves from the roots to the leaves and stems, and as the concentration of PSB increased, the ability of Wedelia trilobata to remove copper from the soil also improved.

These findings are consistent with our results, which showed that all the plant types studied in heavy metal-contaminated soil had higher levels of zinc and copper because of mycorrhizal colonization with PSB, compared to using VAMF or PSB. However, there have been many conflicting results when it comes to cadmium. Some studies found that mycorrhizal infection increased the uptake of cadmium by plant roots (Han et al. , 2021). AMF can increase the absorption of cadmium in corn, which is linked to how much the root shape changes and how much low molecular weight organic acid is produced (Chen et al. , 2022). Other research has found that AMF can lower cadmium leaching from sand by decreasing its availability and increasing its uptake by the roots of maize (Yu et al. , 2022).

According to Yang et al. (2018), adding PSB to polluted soil helps plants take in more Cd. You et al. (2021) say that AMF helps plants grow better and manages how they handle different amounts of harmful trace elements, which makes Cd less harmful to P. australis. It's well known that even small amounts of Cd, like 0. 5 micrograms per gram of soil, can be dangerous to plants (Zhi et al. , 2020). Cd can cause the plant to make reactive oxygen species (ROS), which can damage cell membranes by causing lipid peroxidation and increasing membrane leakage (Su et al. , 2019). Nafady and Elgharably (2018) found that using native AMF G. aggregatum in the shoots reduced Cd levels, but using G. intraradices increased Cd levels.

Since plants take in P and Cd together through their roots, more P in the soil can lower the amount of Cd that ends up in the plant shoots (Zhao et al., 2020). Looking at Figure 1, co-inoculation with VAMF-PSB increased P levels, and this was linked to lower Cd levels in the shoots. From these results, it seems that VAMF-PSB treatment may help reduce heavy metal absorption in polluted soil, except for hot peppers, which may help plants grow better and stay alive.

In this study, control plants had higher Cd levels than infected ones.Also, Cd and Ni levels were higher in the roots than in the shoots (Figures 5 and 6). Kuang et al. (2023) noted that AMF injection greatly increased Cd levels in the roots but lowered them in the shoots. The N levels in roots and shoots are affected by the type of inoculant in a similar way as Cd (Figure 5). The significant rise in root Ni was linked to VAMF and PSB treatments (Figure 6a), but Ni didn't build up in the shoots (Figure 6b). It's possible that VAMF protects plants from metal toxicity by keeping metals in the roots and reducing their movement into the shoots through fungal hyphae. Since VAMF increases P levels in low-phosphorus soils, they may help crops take in more nutrients. When used together, VAMF and PSB may help plants take in more P from heavy metal-polluted soil (Figure 1). Wu et al. (2019) say that PSB helps improve available N, P, and K in the soil, which can increase N and P levels in the leaves. Therefore, PSB could help plants take in important nutrients like P, Cu, and Zn while reducing toxic metal levels in the shoots or roots.

Depending on whether a metal is essential, VAMF can help plants take in certain metals and avoid harmful ones, showing promise for use in metal-contaminated soils. Tan et al. (2023) say that AMF hyphae can act as a metal adsorbent, lowering metal levels in the soil and helping plants grow better in metal-polluted soil. The growth benefits of VAMF in plants don’t affect how much metal they take in. The impact of AMF colonization on metal absorption depends on the plant type, even if the metal levels are similar. The metal concentrations given also affected how plants responded. Each tested plant type showed positive growth response to VAMF colonization. These differences could be due to varying levels of hyphae colonization and growth rates depending on the host plant species, which links to the plant's ability to take in P. Some VAMF-host plant combinations might have better hyphae growth, which can help with P uptake and higher plant biomass.

VAMF improved the biomass of all three tested plant species in heavy metal-polluted soil. This happens because VAMF helps plants take in more water and minerals and absorb nutrients like P. VAMF also helps plants resist and recover from stress from heavy metals. These benefits come from the arbuscular mycorrhizal interface, which allows the exchange of nutrients, signals, and protective substances between the plant and fungus (Wahab et al. , 2023). In heavily disturbed areas, especially those with heavy metal contamination, VAMF can improve plant growth and survival. Reports show that VAMF is important for metal buildup and tolerance.

CONCLUSION

Compared to plants infected with only VAMF or PSB, plants co-inoculated with VAMF-PSB had more VAMF root colonization and higher P and N levels in both the roots and shoots. As a result, the plants' biomass increased. For the three plant species studied, the amounts of Cu, Zn, Cd, and Ni were higher in the roots than in the shoots. The type of inoculant helped distinguish between non-essential metals (Cd, Ni) and essential ones (Cu, Zn). These results suggest that using VAMF and PSB together could improve plant life in horticulture production in heavy metal-contaminated soils.

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