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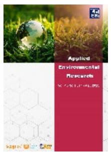

Review Article

Unraveling the Effects of Arbuscular Mycorrhizal Fungi on Plant Growth, Nutrient Content, and Heavy Metal Accumulation in the Contaminated Soil: A Meta-analysis

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Abstract

This study evaluated the effects of arbuscular mycorrhizal fungi (AMF) on plant growth, nutrient uptake, and heavy metal accumulation on polluted land using a meta-analysis approach. Data from 33 relevant studies were selected based on inclusion criteria, specifically articles in English, observational research, and investigating the role of AMF in plant growth and productivity on polluted land. The results showed that plants inoculated with AMF experienced significant accumulation of heavy metals in roots, such as Pb ($p<0.01$), Ni ($p<0.01$), Cr ($p<0.01$), Mn ($p<0.05$), Fe ($p<0.05$), and As ($p<0.05$). The AMF significantly reduced the accumulation of heavy metals such as Cr, Ni, Fe, and Cu on the upper part of fodder forage ($p<0.01$). Forage growth was also enhanced due to AMF. The AMF greatly increased the fresh weight, length, and phosphorus (P) content of fodder forage roots ($p<0.01$). It also increased the plant's biomass, fresh weight, dry weight, height, nitrogen (N), phosphorus (P), and potassium (K) contents ($p<0.01$). In conclusion, AMF is important in increasing plant growth, nutrient uptake and reducing heavy metal accumulation in forage on polluted land.

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Introduction

The development of forage as animal feed is a challenge given the limited fertile land. In this context, utilization of marginal land is an attractive alternative for forage development [1]. Marginal lands include mined land or land contaminated by heavy metals [2]. However, growth can be impaired by heavy metals that accumulate in plant tissues [3]. Heavy metals such as arsenic (As), chromium (Cr), nickel (Ni), iron (Fe), manganese (Mn), and lead (Pb) can damage and contaminate plants [4], damages the root physiological system [5–6]. Therefore, efforts are needed to reduce heavy metal accumulation in forage grown on polluted land [7].

One promising approach is the use AMF. AMF is a symbiotic relationship between fungi and plant roots, which can enhance plant growth and assist in nutrient uptake [8]. In addition, AMF is also known to have the potential to reduce heavy metal accumulation in plants [9]. However, other studies have shown that AMF can increase heavy metal uptake in bermudagrasses (*Cynodon dactylon* (L.) [10]. To understand the impact of AMF on forage growth, nutrient uptake, and feed safety evaluation on polluted land, a systematic review is needed that combines and analyzes data from relevant studies. Meta-analysis is an appropriate approach to integrate and analyze data from relevant studies [11].

The meta-analysis review plays an important role in this study. In agriculture and animal husbandry, AMF have been recognized as a beneficial plant symbiosis. [12–14]. However, research on the impact of AMF on fodder forage growth, nutrient uptake in polluted soils

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still has significant variation in results. By collecting data from multiple relevant studies, meta-analysis can provide a more comprehensive and objective picture of the impact of AMF on forage. Through thorough analysis of the collected data, meta-analysis can reveal common patterns, identify consistent trends, and reduce the bias of individual study results [13].

This study therefore aimed to evaluate the effects of AMF on plant growth, nutrient uptake, and heavy metal accumulation on polluted land by using a meta-analysis approach.

Methods

1) Search strategy, inclusion criteria and data extraction

A comprehensive search strategy was implemented to gather relevant articles from multiple sources, including Scopus (https://www.scopus.com/) databases and Google Scholar. The search was conducted between 2017 and 2022 using a predefined set of keywords, which included "arbuscular mycorrhizal fungi," "nutrient uptake," "heavy metals," "contaminated," "polluted," and "soil." Following the article search, a meticulous evaluation of the title and abstract of each article was performed. This review process involved the selection of articles that met specific inclusion criteria, with a focus on English-language observational research exploring the role of AMF in plant growth and productivity on polluted land.

During the article screening phase, a total of 850 articles were excluded as they were not relevant to the research theme. After this screening process, the number of articles was reduced to 50. Thoroughly reading the abstracts of these 50 articles allowed for a detailed evaluation of their alignment with the research parameters. As a result, a further 38 articles were eliminated as they did not meet the predetermined criteria. These criteria included 20 articles not pertaining to polluted land, 10 articles not aligning with the research parameters, and 8 articles lacking sufficient data for analysis.

After the rigorous screening and evaluation processes, a total of 12 articles were identified that closely aligned with the research criteria. These 12 articles were selected for further analysis, and their details are provided in Table 1 of this study. By employing this systematic research methodology, it ensures that relevant and high-quality articles addressing the impact of AMF on plant growth, nutrient uptake, and heavy metal accumulation in polluted land have been carefully analyzed and selected. This rigorous approach ensures the reliability and comprehensiveness of the research findings.

2) Statistical analysis

The Hedges' d effect size was used to measure the difference between the use of AMF and not using AMF (control). This method was chosen because it can account for variation in sample size, measurement units, and statistical test outcomes, and is suitable for evaluating paired treatments [25]. The group that does not use AMF is considered the control group (C), while the group that uses AMF forms the experimental group (E). Effect size (d) is calculated using the formula;

$$d = \frac{Xe - Xc}{S} J \quad \text{(Eq. 1)}$$

Where Xe is the mean of the experiment (with the use of arbuscular mycorrhizal fungi) and Xc is the mean of the control (without the use of arbuscular mycorrhizal fungi), the difference between the means of E and C is divided by the pooled standard deviation (S). A positive effect size indicates higher values in the group that uses arbuscular mycorrhizal fungi, while a negative effect size indicates the opposite. The correction factor (J) adjusts for small sample size, which is;

$$J = 1 - \frac{3}{(4(Nc + Ne - 2) - 1)} \quad \text{(Eq. 2)}$$

and S is the pooled standard deviation, defined as:

$$S = \sqrt{\frac{(N^E - 1)(s^E)^2 + (N^C - 1)((s^C)^2)}{(N^E + N^C - 2)}} \quad \text{(Eq. 3)}$$

where N^E is the sample size of the experimental group, N^c is the sample size of the control group, S^E is the standard deviation of the experimental group and SC is the standard deviation of the control group. The variance of Hedges' d (v_d) is described as follows:

$$V_d = \frac{(N^C + N^E)}{(N^C N^E)} + \frac{d^2}{(2(N^C + N^E))} \quad \text{(Eq. 4)}$$

The cumulative effect size (d++) was formulated as follows:

$$d_{++} = \frac{(\sum_{i=1}^{n} W_i d_1)}{(\sum_{i=1}^{n} W_i)} \quad \text{(Eq. 5)}$$

where W_i is the inverse of the sampling variance: W_i = ¼ $1/v_d$. The precision of the effect size was described using a 95% confidence interval (CI), i.e. d±(1.96sd). All the above equations were derived from the study of Sanchez-Meca and Marin-Martinez [25]. The calculated effect size was statistically significant if CI did not reach a null effect size. A fail-safe number (N_{fs})

was calculated to identify publication bias caused by non-significant studies which were not included in the analysis. Nfs (fail-safe number), which is more than five times of sample size (N) and plus ten, was considered to provide evidence of a robust meta-analysis model. Nfs (fail-safe number) was calculated using the method of Rosenthal [26]. The smallest sample size from individual studies was applied as N. Cohen's benchmarks were used as standard judgement borders for effect size assessment. These benchmarks were: 0.2 for small, 0.5 for medium and 0.8 for large effect size. All of the above effect size-related calculations were performed using OpenMEE 2.0.

Table 1 Studies selected for the meta-analysis

Study	Country	AMF species	Host plant	Soil type	*AMF doses (g)	References
1	China	*Rhizophagus irregularis*	*Panicum virgatum*	Cadmium-contaminated soil	5	[14]
2	China	*Rhizophagus irregularis*	*Panicum virgatum*	Cadmium-contaminated soil	5	[14]
3	China	*Funneliformis mosseae*	*Cynodon dactylon L.*	Lead–zinc mine wasteland	10	[10]
4	China	*Diversispora spurcum*	*Cynodon dactylon L.*	Lead–zinc mine wasteland	10	[10]
5	Indonesia	*Glomus manihotis*	*Pennisetum purpureum cv Mott*	Gold mine tailings	5	[15]
6	Indonesia	*Glomus manihotis*	*Pennisetum purpureum cv Mott*	Gold mine tailings	10	[15]
7	Indonesia	*Glomus manihotis*	*Pennisetum purpureum cv Mott*	Gold mine tailings	15	[15]
8	Portugal	*Glomus manihotis*	*S. melongena*	Heavy metal(loid) contaminated soil	10	[16]
9	Portugal	*Glomus manihotis*	*S. melongena*	Heavy metal(loid) contaminated soil	10	[16]
10	Bulgaria	*Claroideoglomus claroideum*	*Origanum majorana L.*	Heavy metal polluted soil	5	[17]
11	Bulgaria	*Rhizophagus clarum*	*Origanum majorana L.*	Heavy metal polluted soil	5	[17]
12	Bulgaria	*Claroideo-glomus claroideum*	*Origanum majorana L.*	Heavy metal polluted soil	5	[17]
13	Bulgaria	*Funneliformis mosseae*	*Origanum majorana L.*	Heavy metal polluted soil	5	[17]
14	China	*Funneliformis mosseae*	*Zea mays*	Cadmium and lead contaminated soils	15	[18]
15	China	*Glomus versiforme*	*Zea mays*	Cadmium and lead contaminated soils	15	[18]
16	China	*Rhizophagus intraradices*	*Zea mays*	Cadmium and lead contaminated soils	15	[18]
17	China	*Funneliformis mosseae*	*Zea mays*	Heavy metal polluted soils	15	[19]
18	China	*Diversispora spurcum*	*Zea mays*	Heavy metal polluted soils	15	[19]
19	India	*Rhizophagus fasciculatus*	*Zea mays*	Heavy metal rich tannery sludge	10	[20]
20	India	*Rhizophagus intraradices*	*Zea mays*	Heavy metal rich tannery sludge	10	[20]
21	India	*Funneliformis mosseae*	*Zea mays*	Heavy metal rich tannery sludge	10	[20]
22	India	*Glomus aggregatum*	*Zea mays*	Heavy metal rich tannery sludge	10	[20]
23	Taiwan	*Glomus mosseae*	*Ipomoea aquatica Forsk*	Heavy metal contaminated	10	[21]
24	Taiwan	*Glomus mosseae*	*Ipomoea aquatica Forsk.*	Heavy metal contaminated	15	[21]
25	China	*Funneliformis mosseae*	*Zea mays*	Lead-zinc mine	10	[22]

Table 1 Studies selected for the meta-analysis (*continued*)

Study	Country	AMF species	Host plant	Soil type	*AMF doses (g)	References
26	India	*Glomus macrocarpum*	*Luffa aegyptiaca*	Cadmium contaminated soil	5	[23]
27	India	*Glomus monosporum*	*Luffa aegyptiaca*	Cadmium contaminated soil	10	[23]
28	India	*Glomus macrocarpum*	*Luffa aegyptiaca*	Cadmium and nickel contaminated soil	5	[23]
29	India	*Glomus monosporum*	*Luffa aegyptiaca*	Cadmium and nickel contaminated soil	10	[23]
30	India	*Glomus macrocarpum*	*Luffa aegyptiaca*	Nickel contaminated soil	5	[23]
31	India	*Glomus monosporum*	*Luffa aegyptiaca*	Nickel contaminated soil	10	[23]
32	China	*Glomus intraradices*	*Arachis hypogaea L. cv. Huayu*	Cadmium contaminated soil	5	[24]
33	China	*Glomus intraradices*	*Arachis hypogaea L. cv. Huayu*	Cadmium contaminated soil	10	[24]

Remark: * The weight of AMF in Table 1 represents the combined weight of spores and the carrier material.

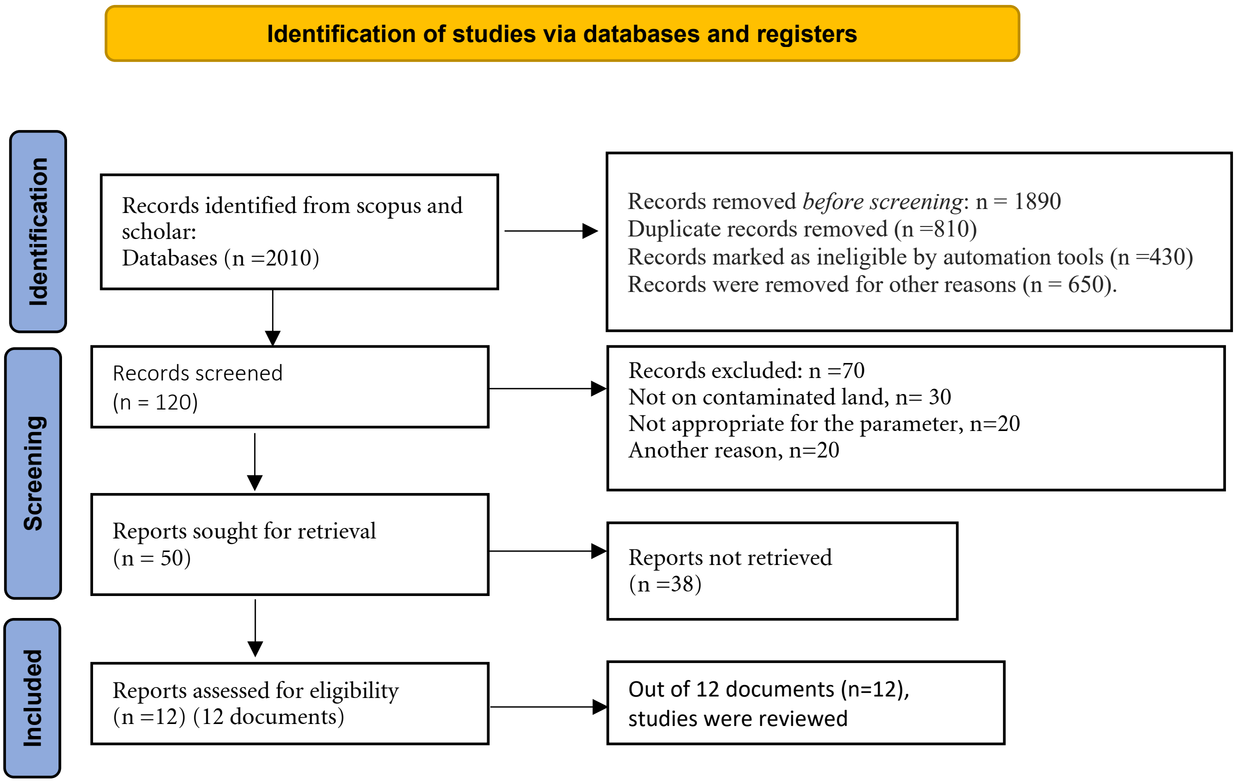

Figure 1 Flow chart of the literature selection process according to PRISMA protocols.

Results

1) Profile of selected studies

Not all findings can be considered reliable due to conflicting research results and small sample sizes, which may indicate the presence of publication bias. The fail-safe number (Nfs) plays a crucial role in determining the inclusion of studies for robust conclusions. It represents the minimum number of additional studies needed to render the initial effect size statistically insignificant. Suppose the Nfs value exceeds five times the sample size (N) plus 10, where N represents the sample size used to calculate the initial effect size. In that case, it is reasonable to assume that the result is reliable and subject to publication bias [26]. According to these fail-safe number rules, robust parameters included were: Ni root, Cr root, BCF (bioconcentration factor) root Pb, Pb shoot, Cu shoot, Fe shoot, Ni shoot, Cr shoot, TF (transfer factor) of Pb and TF of Cd, P root, fresh weight root, dry weight root, K shoot, P shoot, plant height, shoot length, shoot dry weight, and biomass. Figure 2 shows the detailed meta-analysis results tested according to Cohen's methodology for root heavy metals (ten parameters), shoot heavy metals (ten parameters), and plant growth and nutrient elements (15 parameters).

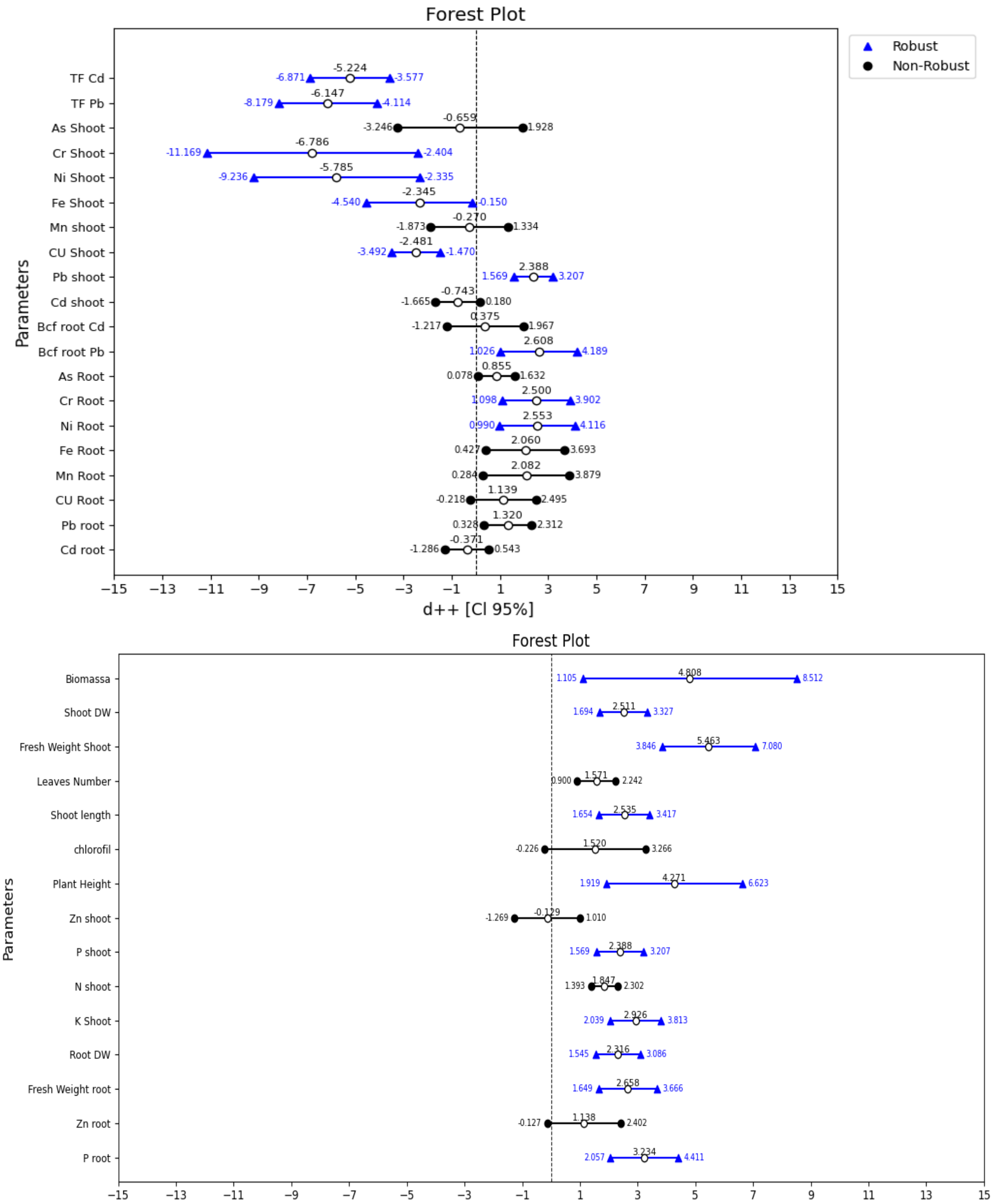

Figure 2 Forest plot of cumulative effect size (d++) and 95% confidence interval (CI) of AMF on heavy metal uptake (a), plant growth, and nutrient elements (b) in contaminated soil. Robust evidence of a meta-analysis model was identified using a fail-safe number (Nfs). A value of Nfs > 5N + 10 was considered to indicate the absence of publication bias. Conversely, if the fail-safe number was not robust, it suggested potential publication bias in the meta-analysis model.

2) The effects of AMF on plant growth, nutrient uptake, and heavy metal uptake in contaminated soil

The forest plot of Figure 2 (a and b) shows the cumulative effect size (d++) which referred to as the overall effect size. If the horizontal interval line of parameters crosses the zero vertical line, then there is no significant difference between AMF and non-AMF in contaminated soil. Inoculation of AMF was able to increase the accumulation of heavy metals in plant roots, especially Pb ($p<0.01$), Mn ($p<0.05$), Fe ($p<0.05$), Ni ($p<0.01$), Cr ($p<0.01$), As ($p<0.05$), bioconcentration of Pb ($p<0.05$), and bioconcentration of Pb ($p<0.05$). In addition, AMF can inhibit the uptake of heavy metals in plant shoots, especially Cd ($p<0.05$), Cu ($p<0.01$), Fe ($p<0.05$), Ni ($p<0.01$), Cr ($p<0.01$), TF Pb ($p<0.01$), and TF Cd ($p<0.01$). However, there was no significant difference between AMF and non-AMF in the accumulation of Cd and Cu in plant roots or Mn and As in plant shoots.

On the parameters of nutrient content in plant shoots (Figure 2(b)), it can be seen that the inoculation of AMF can increase the accumulation of P root ($p<0.01$), K shoot ($p<0.01$), fresh weight root ($p<0.01$), root dry weight ($p<0.01$), shoot N ($p<0.01$), shoot P ($p<0.01$), plant height ($p<0.01$), shoot length ($p<0.01$), leaf number ($p<0.01$), shoot fresh weight ($p<0.01$), shoot dry weight ($p<0.01$), and biomass ($p<0.05$). However, there was no difference between AMF and non-AMF ($p > 0.05$) on root Zn and shoot Zn.

Based on Cohen's benchmarks, the parameters of root heavy metals, i.e., Pb, Cu, Mn, Fe, Ni, Cr, and BCF Pb, are in the large effect size category, but in the small category in Cd and BCF Cd. Meanwhile, parameters of shoot heavy metal, i.e., Pb, Cu, Fe, Ni, Cr, TF Pb, and TF Cd, have medium effect sizes in As and small effect sizes in Mn. All parameters of growth and nutrient content of plants are in the large effect size category except Zn shoot, which is in the small category.

3) The effect of AMF species subgroups on the uptake of heavy metals in plants, growth, and nutrient uptake

Several species of AMF show a significant positive influence on enhancing the uptake of heavy metals in shoots (Figure 3), such as *G. mosseae, G. constrictum, F. mosseae, G. versiforme, R. irregularis,* and *R. intraradices* for Pb uptake; and *G. monosporum* and *G. macrocarpum* for Cd uptake. However, some species exhibit a negative (inhibitory) effect on the uptake of heavy metals in shoots, such as *R. irregularis, D. spurcum, R. fasciculatus, G. aggregatum,* and *G. intraradices* for Cd; *G. constrictum, R. fasciculatus, R. intraradices, F. mosseae,* and *G. aggregatum* for Cu; *R. fasciculatus, R. intraradices, F. mosseae,* and *G. aggregatum* for Ni; *R. fasciculatus, R. intraradices, F. mosseae,* and *G. aggregatum* for Cr. Meanwhile, species that show no significant effect include *G. coronatum* and *G. intraradices* for Pb; *G. coronatum* for Cu; *G. mosseae* for Ni; *G. mosseae* for Cr; *G. manihotis*; *F. mosseae*; and *D. spurcum* for As.

In the root parameter, several species of AMF exhibit a significant positive effect on enhancing the uptake of heavy metals in roots (Figure 4), such as *R. fasciculatus* and *G. aggregatum* for Cd; *G. manihotis* for Pb; *R. fasciculatus, R. intraradices, F. mosseae,* and *G. aggregatum* for Cu; *R. fasciculatus, R. intraradices, F. mosseae,* and *G. aggregatum* for Ni; *R. fasciculatus, R. intraradices, F. mosseae,* and *G. aggregatum* for Cr; *G. manihotis, R. fasciculatus, R. intraradices, G. aggregatum,* and *R. clarum* for BCF Root Pb; *R. intraradices* and *G. aggregatum* for BCF Root Cd. However, some species show a negative (inhibitory) effect on the uptake of heavy metals in roots, such as *G. versiforme* for Cd; *G. macrocarpum* and *G. monosporum* for Cd; *F. mosseae* and *D. spurcum* for Pb; *C. claroideum, R. clarum, Claroideoglomus claroideum, R. fasciculatus, R. intraradices,* and *G. aggregatum* for Pb; and *G. constrictum* for Cu. Meanwhile, species that exhibit non-significant effects are *R. irregularis, F. mosseae, D. spurcum, G. manihotis, C. claroideum, R. clarum, R. intraradices, G. mosseae, G. intraradices,* and *Claroideo-glomus claroideum* for Cd; *G. mosseae* for Ni; *G. manihotis* and *G. mosseae* for Cr; *G. manihotis, F. mosseae,* and *D. spurcum* for As.

In terms of plant growth parameters (Figure 5(a)), several arbuscular mycorrhizal fungal species exhibit a significant positive influence. Arbuscular mycorrhizal species like *C. claroideum, R. clarum, Claroideo-glomus claroideum, F. mosseae, F. etunicatum, G. macrocarpum,* and *G. monosporum* can help plants gain dry weight. Some arbuscular mycorrhizal species, like *G. constrictum, F. mosseae, G. manihotis,* and *F. mosseae,* also make plants much heavier when they are fresh. Some species, like *G. constrictum, C. claroideum, F. etunicatum, G. intraradices,* and *R. clarum,* can greatly increase the dry weight of roots.

Several types of AMF have a big effect on helping plants take in more N, P, and K (Figure 5(b)). Such as *G. constrictum, G. mosseae, F. mosseae,* and *G. coronatum* enhance K uptake signi-ficantly. *G. constrictum* and *G. mosseae* contribute to N uptake. *R. irregularis, G. constrictum, F. mosseae,* and *G. versiforme* affect P uptake in roots significantly, while *R. irregularis, G. constrictum, F. mosseae, G. versiforme, R. intraradices,* and *G. mosseae* impact P uptake in shoots significantly.

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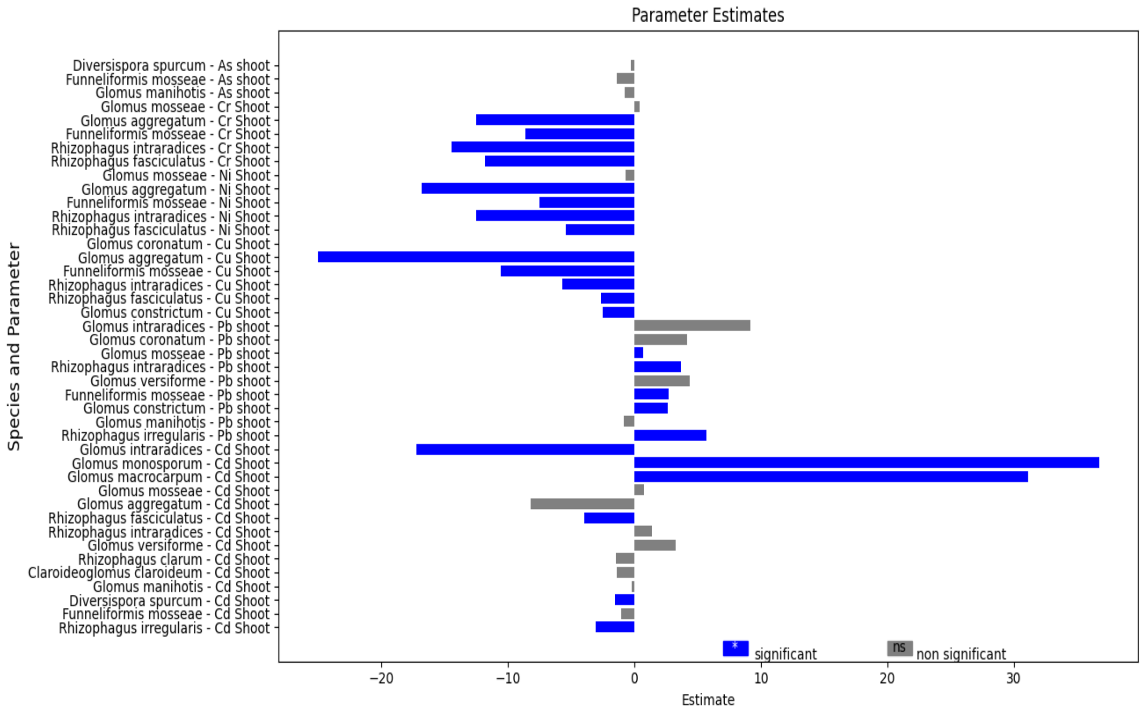

Figure 3 Forest plot of the effects of AMF species on the uptake of heavy metals in shoots in contaminated soil. A negative value (-) on the graph indicates that the AMF species inhibits the absorption of heavy metals by the host plants. Conversely, a positive value (+) signifies that the AMF species enhances the absorption of heavy metals by the host plants.

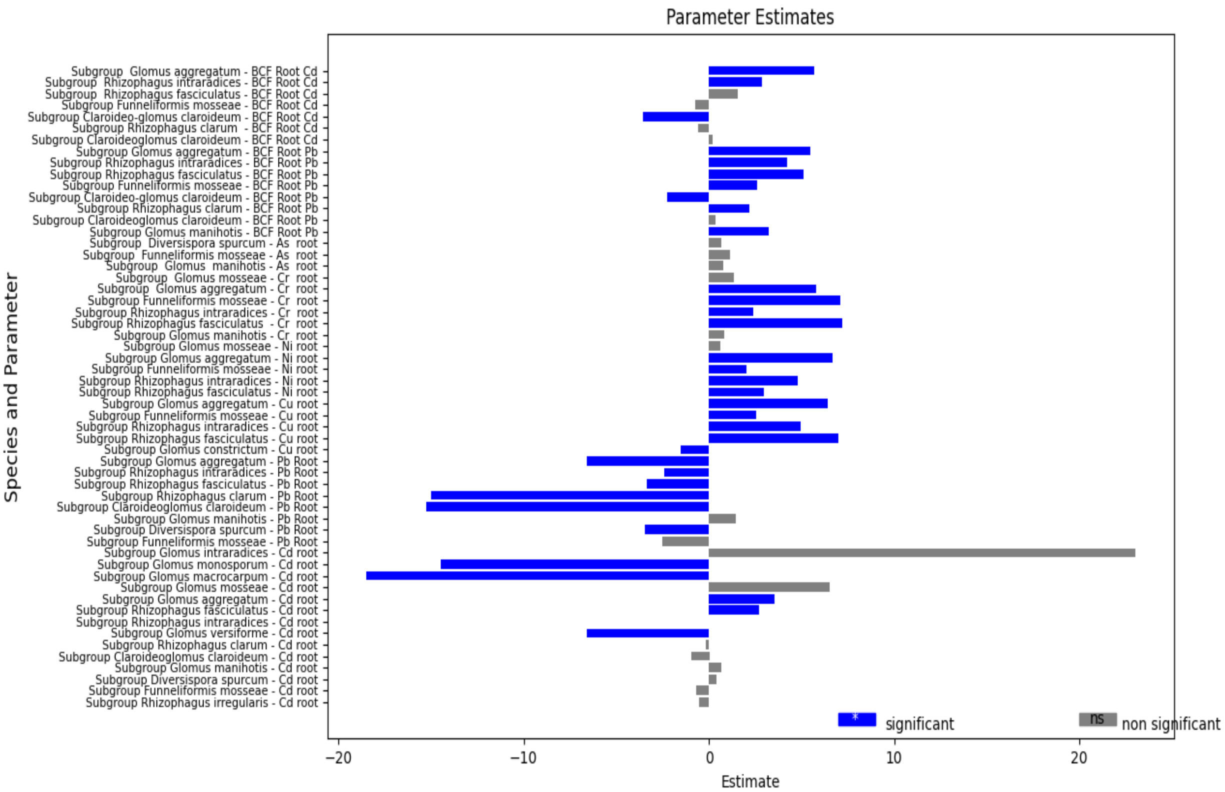

Figure 4 Forest plot of the effects of AMF species on the uptake of heavy metals in roots in contaminated soil. A negative value (-) on the graph indicates that the AMF species inhibits the absorption of heavy metals by the host plants. Conversely, a positive value (+) signifies that the AMF species enhances the absorption of heavy metals by the host plants.

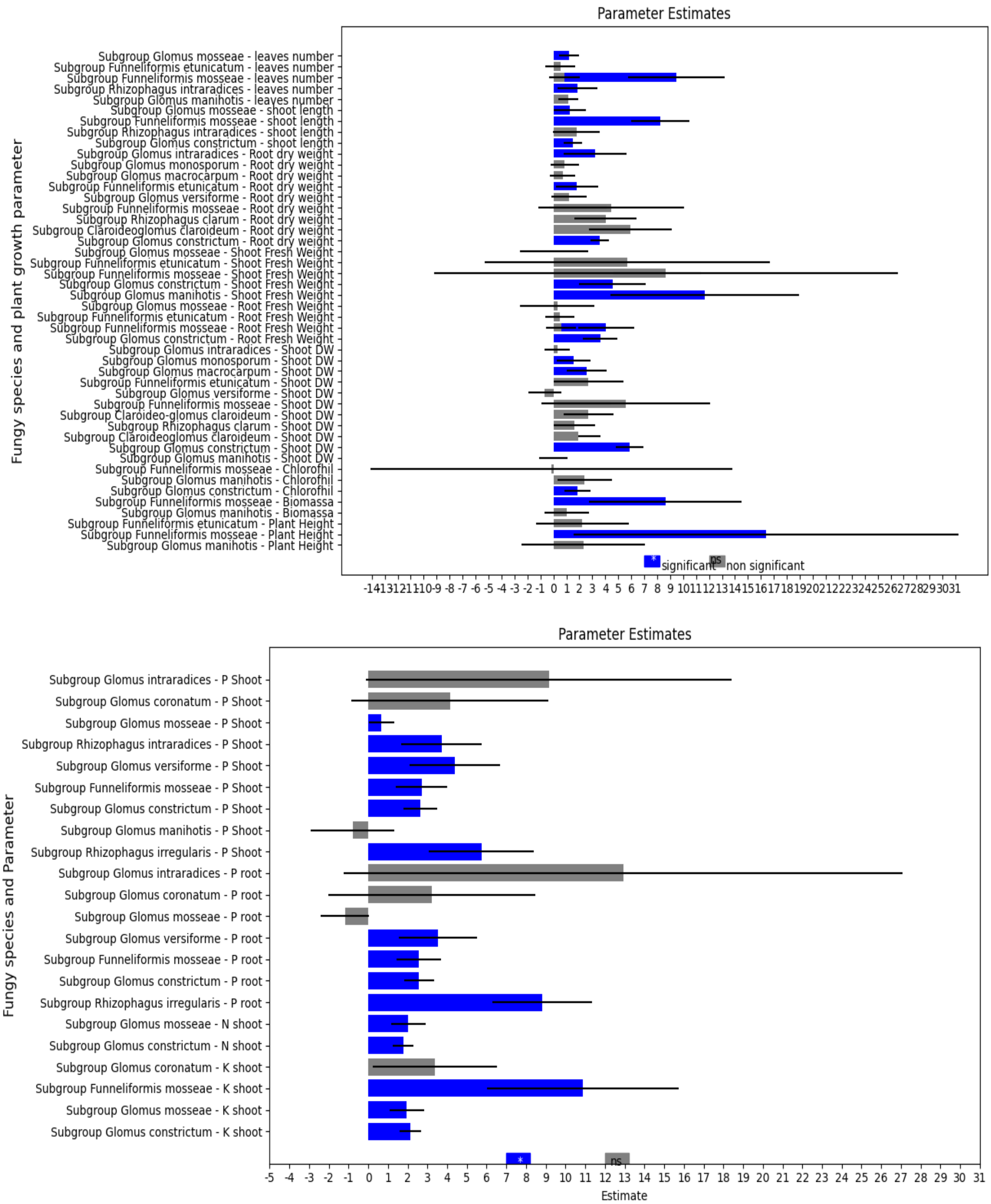

Figure 5 A forest plot of the effects of AMF species on plant growth (a) and nutrient (N, P, and K) uptake (b) in contaminated soil the central line (horizontal bar) in this plot represents the average estimate of the impact of fungal species on the measured plant growth parameter. In the blue bars (significant), the central line reflects a significant impact. In the gray bars (non-significant), the central line represents a non-significant impact that is still measurable. This helps to understand the magnitude of the fungal species' influence on plant growth, whether it is significant or not.

Discussion

1) The effect of AMF on heavy metal content in roots

Meta-analysis studies indicate that AMF have a significant influence on the uptake or accumulation of specific heavy metals in roots. The following are the results of scientific studies related to the influence of AMF on heavy metal content in roots, with heavy metal parameters such as Cd, Pb, Cu, Mn, Fe, Ni, Cr, As, BCF root Pb (bioconcentration factor of lead in roots), and BCF root Cd (bio-concentration factor of cadmium in roots). The meta-analysis study found that AMF play a highly effective role in the uptake and accumulation of these heavy metals in roots. In this context, 'effective' refers to the ability of AMF to reduce the levels of heavy metals in the soil by absorbing and storing them within the root tissues of the plants infected by these fungi.

In this study, several heavy metal parameters such as Pb, Mn, Fe, Ni, Cr, and As have been investigated. The results indicate that AMF can significantly enhance the accumulation of these heavy metals in infected plant roots [20]. Thus, plants that have a symbiotic relationship with AMF have a better ability to accumulate and store heavy metals in their roots compared to non-infected plants. This finding aligns with the research results [29-30], which indicate that AMF can enhance the uptake of heavy metals in plant roots. Numerous studies have demonstrated that AMF are one of the approaches for the remediation of heavy metal-contaminated soil through phytoremediation [29, 31, 34].

Furthermore, the study also evaluated the BCF of heavy metals Pb and Cd in roots. BCF is a measure of the relative concentration of heavy metals in plant root tissues compared to the concentration of heavy metals in the soil where the plants grow. The research results indicate that AMF have a significant influence on increasing the value of BCF root Pb ($p<0.01$), indicating their ability to accumulate Pb in plant roots. [17] also reported that AMF were able to increase the BCF values in plants grown in heavy metal-contaminated soil. However, AMF did not have a significant effect on BCF root Cd. [31] reported that F. mosseae was able to decrease the BCF value of Cd and was suitable for use in Cd phytostabilization. The results of this study contrast with those indicating that AMF were able to enhance Cd accumulation in maize roots [32], *Cannabis sativa* L. [33].

Overall, this meta-analysis study supports the important role of AMF in reducing the concentration of heavy metals in soil by accumulating them in infected plant roots. With the help of arbuscular mycorrhizal fungi, this finding could help scientists come up with better ways to clean up heavy metal-contaminated soil.

2) The effect of AMF on the content of heavy metals in shoots

The meta-analysis study on the effect of AMF on the content of heavy metals in plant shoots in contaminated soil shows that these fungi have a positive effect on reducing the uptake of heavy metals by plant shoots. This study involves the following parameters: Cd shoot, Pb shoot, Cu shoot, Mn shoot, Fe shoot, Ni shoot, Cr shoot, As shoot, TF Pb, and TF Cd. The results of this study indicate that AMF have a positive effect on reducing the uptake of heavy metals in plant shoots grown in contaminated soil. This means that when plant shoots are infected with arbuscular mycorrhizal fungi, the plant's ability to absorb and accumulate heavy metals such as Cd, Pb, Cu, Mn, Fe, Ni, Cr, and As in its shoots decreases. Several recent researchers have also reported that AMF have the ability to inhibit the translocation of heavy metals to the shoots [28, 34-35].

Furthermore, this study also analyzed the translocation factor (TF) of the heavy metals Pb and Cd in plant shoots. TF is a measure of the plant's ability to transfer heavy metals from the roots to the aboveground parts of the plant, particularly the shoots. The meta-analysis results show that AMF have a positive effect on reducing TF Pb and TF Cd, indicating that these fungi help inhibit the transfer of heavy metals from the roots to the plant shoots. This suggests that AMF can reduce the accumulation of heavy metals in plant shoots grown in contaminated soil. Putra et al. [15] reported that AMF are highly effective in reducing the TF values of Cd and Pb.

Overall, this meta-analysis study reveals that AMF have a significant positive effect on reducing the uptake of heavy metals in plant shoots growing in contaminated soil. These findings indicate the potential of AMF as an effective tool in reducing the risk of heavy metal accumulation in plant shoots and can serve as a valuable strategy in efforts to remediate heavy metal-contaminated soil.

3) The effect AMF on plant growth and productivity in heavy metal-contaminated soil

The analysis results indicate that AMF have a significant effect on enhancing certain plant growth parameters but do not affect other parameters. The study demonstrates that the presence of AMF has a positive impact on plant biomass. Plant biomass is a measure of the total weight of organic material produced by plants, and an increase in biomass indicates that AMF can enhance plant productivity in heavy metal-contaminated soil [36]. Furthermore, both plant dry weight and root dry weight were positively influenced by arbuscular mycorrhizal fungi. This indicates that the fungi are capable of strengthening the plant's root system and enhancing the uptake of nutrients required for plant growth [37].

The study indicates that AMF may have a positive impact on the fresh weight of plants and roots. Fresh weight measurements in plants provide insights into water content within plant tissues, while the fresh weight of roots is indicative of the growth and development of the plant's root system. It is important to exercise caution in making definitive claims about plant productivity. To better establish the benefits of AMF on plant growth,

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a comparison of key plant performance factors between plants grown without AMF and those subjected to AMF inoculation is recommended [38]. Additionally, the presence of AMF appears to positively influence the number of leaves, shoot length, and plant height. An increased leaf count suggests an enhanced capacity for plant photosynthesis, which could contribute to improved plant productivity. Moreover, greater shoot length and plant height are indicative of robust plant growth, suggesting the potential for higher yields.

The meta-analysis study revealed that AMF play a significant role in influencing the nutrient content of plants, particularly P, N, and K. These nutrients are vital for plant growth, and the study by Wu et al. [39] demonstrated that AMF can enhance nutrient uptake and utilization, even in heavy metal-contaminated soil.

In terms of nutrient content, the meta-analysis study found that AMF influence the levels of P, N, and K in plants. These nutrients are essential components for plant growth, and the increased levels of P, N, and K indicate that AMF can enhance nutrient uptake and utilization by plants in heavy metal-contaminated soil [39].

However, the study results also indicate that AMF do not have a significant impact on chlorophyll content, Zn in shoots, or Zn in plant roots. Chlorophyll content serves as a primary indicator of plant photosynthetic capacity, and the lack of influence by AMF on chlorophyll suggests that these fungi may not directly affect the photosynthesis process [40]. The findings of this study differ from those of the previous studies [41–42] which demonstrated that AMF can enhance plant chlorophyll content. Furthermore, in contrast to those findings, plants growing in heavy metal-contaminated soil often experience the accumulation of heavy metals such as Zn, but AMF do not have a significant impact on zinc accumulation in plants.

Overall, this meta-analysis study provides strong evidence that AMF have a positive effect on root growth and plant productivity in heavy metal-contaminated soil. These fungi are capable of enhancing plant biomass, dry weight of plants and roots, fresh weight of plants and roots, leaf count, shoot length, plant height, as well as the content of P, N, and K in plants. Although they do not have a significant impact on chlorophyll content and zinc accumulation in plants, the role of AMF in improving the quality of heavy metal-contaminated soil and enhancing plant productivity is crucial in the context of environmental management and sustainable agriculture.

Conclusion

AMF plays a significant role in enhancing forage growth, nutrient uptake, and reducing heavy metal accumulation in shoots on contaminated land. AMF are interesting because they can help clean up heavy metal-contaminated soils through phytoremediation by storing heavy metals in plant roots. However, further monitoring is needed regarding the accumulation of Pb by AMF. In the context of assessing the potential safety of livestock feed, monitoring should be conducted to ensure that forage inoculated with AMF on contaminated land is safe for animal consumption.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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