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Research Article

Native arbuscular mycorrhizal fungi and *Albizia saponaria* for potential revegetation of tropical post-asphalt mining and post-nickel mining areas

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Abstract

Native arbuscular mycorrhizal fungi (AMF) have been shown to effectively enhance the growth and nutrient uptake of *Vitex cofassus* grown on post-asphalt mining soils. However, their potential needs to be further evaluated across various mining substrates and different tree species. This study aimed to assess the effects of native AMF inoculation on the early growth performance of *Albizia saponaria* seedlings cultivated on post-asphalt mining and post-nickel mining media under greenhouse conditions. A completely randomized design was employed with seven treatments: control, *Racocetra crispi*, *Glomus intraradices*, *Glomus* sp., *Glomus* sp.-LW10, *Glomus* sp.-SW10, and Mycofer IPB or AMF mixture. Parameters observed after three months of growth included plant height, AMF root colonization percentage, total dry weight, mycorrhizal inoculation effect (MIE), and the uptake of phosphorus (P), nitrogen (N), calcium (Ca), and nickel (Ni). The results indicated that native AMF inoculation significantly improved early growth and total dry weight of *A. saponaria* seedlings. The highest MIE values were observed in the *G. intraradices* treatment, reaching 92.73% and 82.9%. Native AMF inoculation also enhanced the uptake of P, N, Ca, and Ni in plant tissues. These findings suggest that local AMF isolates can be effectively utilized to improve seedling quality and accelerate the success of revegetation programs on degraded post-mining lands in Indonesia.

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Introduction

Reclamation of post-mining land poses a significant environmental management challenge in tropical regions, particularly in Indonesia, where extensive areas of degraded land result from mineral and asphalt mining activities (Pratiwi et al., 2021; Albasri et al., 2023; Miswanto et al., 2025). Mining operations lead to the loss of topsoil layers, depletion of organic matter, and disruption of soil structure, all of which reduce the soil's ability to support plant growth (Nasution et al., 2024). In post-nickel mining areas, soils are characterized by high concentrations of heavy metals (Ni, Cr, Co), a low Ca/Mg ratio, and deficiencies in essential nutrients such as phosphorus (P), potassium (K), and nitrogen (N) (Prematuri et al., 2020). In contrast, post-asphalt mining soils are dominated by clay and clay loam fractions, have slightly alkaline pH, and exhibit low nutrient availability (Albasri et al., 2023; Tuheteru et al., 2025). Therefore, soil biotechnology-based restoration approaches are required to improve soil fertility and facilitate early plant growth at both the nursery and field stages. One promising soil biotechnological

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approach to address these challenges is the inoculation of arbuscular mycorrhizal fungi (AMF). Arbuscular mycorrhizal fungi (AMF) are mutualistic symbionts of most terrestrial plants that play a key role in enhancing nutrient uptake, particularly phosphorus (P), and improving plant tolerance to various abiotic stresses such as drought, salinity, and heavy metal toxicity (Bi et al., 2018; Begum et al., 2019).

In degraded lands resulting from mining activities, AMF function as natural bio-ameliorants by forming extensive hyphal networks that enhance soil aggregate stability, improve soil structure, and support root colonization (Begum et al., 2019; de Moura et al., 2022). The effectiveness of AMF varies among species; therefore, screening is necessary to identify the most effective isolates for land reclamation (Wulandari et al., 2024). Native AMF inoculation is considered more adaptive than commercial isolates, as native strains possess greater resilience and colonization ability under extreme environmental conditions (Brundrett and Tedersoo, 2018).

Studies conducted on post-mining lands in Sulawesi have shown that local arbuscular mycorrhizal fungi (AMF) can enhance the growth of several tree species, such as *Pericopsis mooniana*, *Pterocarpus indicus,* and *Kalappia celebica*, on nutrient-poor substrates (Husna et al., 2021a,b; 2025). In addition, the use of AMF originating from post-asphalt mining soils has been proven to improve growth, root biomass, and phosphorus uptake efficiency in *Vitex cofassus* seedlings grown on post-asphalt mining media (Tuheteru et al., 2025). However, no studies have yet examined the effects of local AMF on the early growth of native Sulawesi forest tree seedlings grown in soil media with contrasting characteristics, such as post-asphalt and post-nickel mining substrates.

One leguminous tree species from Sulawesi selected to evaluate its growth response and dependency on native AMF inoculation was *Albizia saponaria* (Lour.) Blume. *A. saponaria* is a multipurpose tree species in the Fabaceae family, with significant ecological and economic value in tropical regions of Southeast Asia. This species is characterized by rapid growth, the ability to fix atmospheric nitrogen through symbiosis with rhizobia, and tolerance to nutrient-poor soils (Fern, 2024; Hikmat et al., 2025). Furthermore, *A. saponaria* has been reported to exhibit a strong response and high dependency on local AMF inoculation when grown in Ultisol soil media (Tuheteru et al., 2021). These characteristics make *A. saponaria* a promising candidate for revegetation of post-asphalt mining and post-nickel mining areas, with support from AMF inoculation.

The differences in substrate characteristics are expected to influence the effectiveness of AMF colonization and the physiological performance of inoculated plants. Therefore, understanding the early growth response of *A. saponaria* to native AMF inoculation from both substrates will provide valuable insights into the potential use of local fungi as natural biofertilizer agents for mining ecosystem restoration.

This study aimed to evaluate the early growth of *A. saponaria* seedlings inoculated with several native AMF species originating from post-asphalt mining soils. The results of this research are expected to provide a scientific basis for the application of mycorrhizal inoculation technology in forest seedling production, particularly for the reclamation and restoration of post-mining lands in Indonesia.

Materials and Methods

Post-mining soils

The post-asphalt mining and post-nickel mining soils were obtained from the disposal site of PT Wika Bitumen in Buton District and PT Pernick Sultra in North Konawe District, Southeast Sulawesi, Indonesia. The soils were stored in a greenhouse before use. The physical and chemical properties of the soils were analyzed at the Biotechnology and Environmental Laboratory, Faculty of Mathematics and Natural Sciences, Halu Oleo University, Kendari, and the results are presented in Table 1.

Preparation of AMF inoculum and inoculation

AMF inocula used were *Racocetra crispa*, *Glomus intraradices*, *Glomus* sp., *Glomus* sp.-LW10, and *Glomus* sp.-SW1, which were isolated from the rhizosphere of plants in post-asphalt mining soil (Tuheteru et al., 2022) and Mycofer IPB. The AMF inoculum was propagated in zeolite media using *Pueraria javanica*, which was grown for three months under greenhouse conditions at the Indonesian Mycorrhiza Association (AMI), Southeast Sulawesi Branch (6°38'07.35" S dan 106°49'31.72" E), Kendari, Southeast Sulawesi, Indonesia.

Polyethylene pots (15 × 20 cm) were filled with 1 kg of sterile planting media (a mixture of post-asphalt mining soil or post-nickel mining soil, river sand, and husk charcoals having a proportion of 3:1:1). AMF inoculum was produced by placing 20 g of inoculum of each treatment at 1-3 cm underneath the seedlings. Two new leaves of respective *A. saponaria* seedlings were transplanted into pots, followed by seedling maintenance, watering, and observation for three months (10 July-11 October 2024 and 09 July-10 October 2025). The seedlings were watered daily to field capacity with tap water. The daytime temperature in the nursery during the trial was 25 to 35 °C, with 80-89% relative humidity and a 12-hour photoperiod.

Seed germination and AMF treatment

A. saponaria seeds were collected from their trees at the Arboretum of the Botanical Garden of Halu Oleo University, Kendari, Southeast Sulawesi. The seeds were soaked in hot water at 50-60 °C for 24 hours to cool gradually, then germinated in a plastic sprout maker (20 × 20 × 5 cm) which has been perforated and contains sterile sand media at the Plastic House of the Indonesian Mycorrhizal Association (IMA), Southeast Sulawesi Branch.

Table 1. The physical and chemical properties of post-asphalt mining and post-nickel mining soils.

No	Parameter	Post-asphalt mining soil		Post-nickel mining soil	
		Value	Criteria[a]	Value	Criteria[b]
1	pH H_2O	7.2	Neutral	7.84	
2	Organic C (Walkley and Black) (%)	7.56	Very high	4.30	High
3	Total N (Kjeldahl) (%)	0.13	Low	0.27	Moderate
4	C/N ratio	58	Very high	16	High
5	P_2O_5 (HCl 25%) (mg 100 g^{-1})	55	High	26.41	Moderate
6	K_2O (HCl 25%) (mg 100 g^{-1})	7	Very low	22.60	Moderate
7	P_2O_5 (Olsen) (ppm)	8	Low	-	-
8	K_2O (Morgan) (ppm)	49	-	-	-
9	Ca (NH_4-Acetate 1N pH 7) (cmol kg^{-1})	18.58	High	13.70	High
10	Mg (NH_4-Acetate 1N pH 7) (cmol kg^{-1})	1.47	Moderate	4.90	High
11	K (NH_4-Acetate 1N pH 7) (cmol kg^{-1})	0.10	Low	-	-
12	Na (NH_4-Acetate 1N pH 7) (cmol kg^{-1})	0.23	Low	-	-
13	CEC (NH_4-Acetate 1N pH 7) (cmol kg^{-1})	23.89	Moderate	18	Moderate
14	Base saturation (NH_4-Acetate 1N pH 7) (%)	85	Very high	-	-
15	Al^{3+} (KCl 1N) (cmol kg^{-1})	0.00	-	-	-
16	H+ (KCl 1N) (cmol kg^{-1})	0.07	-	-	-
17	Texture (pipet)				
18	Sand (%)	10		-	
19	Silt (%)	40	Clay	95.65	Silt
20	Clay (%)	50		4.35	
21	Fe (DTPA) (ppm)	7.3	Sufficient	128.72	Sufficient
22	Mn (DTPA) (ppm)	9.5	Sufficient	-	-
23	Cu (DTPA) (ppm)	1.2	Sufficient	-	-
24	Zn (DTPA) (ppm)	0.3	Deficient	-	-
25	Pb (Morgan Wolf) (ppm)	0.4	Normal		
26	Cd (Morgan Wolf) (ppm)	0.2	Normal		
27	$CaCO_3$ (Titrimetric) (%)	2.1	-		
28	Ni (AAS flame) (mg kg^{-1})			0.0047	
29	Cr (AAS flame) (mg L^{-1})			0.0262	

Notes: [a]Soil Research Center (2009). [b]Tuheteru et al. (2025).

The treatments tested in this experiment were (A) control, (B) *Racocetra crispa*, (C) *Glomus intraradices*, (D) *Glomus* sp., (E) *Glomus* sp.-LW10, (F) *Glomus* sp.-SW10, and (G) Mycofer IPB (post-asphalt mining media) or AMF Mixed (post-nickel mining media). The seven treatments were arranged in a completely randomized design with three replications.

Growth, dry weight, and nutrient determination

Seedlings were harvested after three months of growth. The samples were then oven-dried at 70 °C for 48 hours to determine their shoot and root dry weight. Roots were stained using the modified protocol from Vierheilig et al. (2005). A total of 30 pieces of fresh roots (± 1 cm long) were randomly taken from the plant roots. The origins were cleaned in 10% KOH for 2 days, then immersed in H_2O_2 solution for 10-20 minutes, and rinsed thoroughly. The roots were then soaked in a 0.2% HCl solution for 20 minutes and placed in a 0.05% Trypan Blue solution. Ten root samples were placed on a glass slide, a cover glass was applied, and the slide was observed under a microscope. Available P was measured in sodium bicarbonate extracts at pH 8.5 and quantified according to the Olsen method at 660 nm using a flow-injection automated ion analyzer. Available Ca was extracted with 1 N NH_4-Acetate, pH 7, and determined by atomic absorption. The Zn content was analyzed by digesting the sample with an acid mixture (HNO_3-H_2O_2) and measuring it using an Atomic Absorption Spectrophotometer (AAS). The Ni content was determined after digesting the sample with a mixture of HNO_3 and HCl at high temperature, followed by AAS analysis. Parameters and calculation methods are presented in Table 2.

Statistical analysis

The data were analyzed using analysis of variance (F test), followed by Duncan's Multiple Range Test (DMRT) at the 95% confidence level when the F test indicated a significant effect.

Table 2. Parameters and calculation methods.

Parameter	Formula	Reference
Plant growth	Plant height and stem diameter were measured 1 cm above the soil medium at three months after transplantation. At the end of the study, the number of leaves was counted.	Tuheteru et al. (2025)
Dry weight	Drying all plant parts in an oven at 70 °C until a constant weight was reached, then weighing them to obtain the root, shoot, and total dry weight.	Husna et al. (2025)
Nodule	Number of nodules per root.	Husna et al. (2025)
The Mycorrhizal Growth Responses (MGR)	[total dry weight of mycorrhizal plant-total dry weight of non-mycorrhizal plant/total dry weight of non-mycorrhizal plant] × 100%.	Cavagnaro et al. (2003)
AMF colonization	[Σ number of fields of view colonized/Σ total observed field of view] × 100.	Vierheilig et al. (2005)
Mycorrhizal dependency (%)	(1-[b/a]) × 100; where b is the mean plant dry biomass of non-AMF treatments, and a is the mean plant dry biomass in treatments with AMF presence. Therefore, an MD>0 indicates plant biomass enhancement by AMF, while MD<0 indicates the opposite.	van der Heijden et al. (2003)
The content and uptake of N, P, Ca, and Ni	Content: the amount of nutrients contained in plant tissue and uptake: Multiplying the nutrient concentrations by the dry weights of the plants.	Wang et al. (2005)
The increase/decrease in nutrient uptake of AMF-treated seedlings relative to the controls	[nutrient absorption of AMF plant - nutrient absorption of non-mycorrhizal plant/nutrient absorption of non-mycorrhizal plant] × 100%.	Wang et al. (2005)

Results and Discussion

Colonization of AMF and MD

A. saponaria seedlings on post-asphalt mining media inoculated with Mycofer IPB had the highest colonization rate (97%), followed by *Glomus* sp.-SW10 (90.1%), *Glomus* sp.-LW10 (88.8%), and *Glomus* sp. (81.0%) (Table 1, $p<0.01$). On post-nickel mining media, the highest colonization rate was observed in the *Glomus intraradices* treatment (52.83%) (Table 1, $p<0.01$). The MD value for *G. intraradices* on both media was higher at 92.73% and 82.9%, respectively.

Plant growth

On post-asphalt mining land media, inoculation with *G. intraradices* significantly increased plant height and differed significantly from other treatments (Table 3). Three-month-old *A. saponaria* seedlings inoculated with *G. intraradices* had higher stem diameters and differed significantly from other treatments except for *Glomus* sp.-SW10. All AMF treatments significantly increased the number of plant leaves compared to the control. *A. saponaria* seedlings inoculated with *Glomus* sp.-SW10 had the highest number of root nodules and did not differ significantly from other treatments except for the control and *Glomus* sp.-LW10 treatments. In post-nickel mining media inoculation with *G. intraradices* significantly increased the height, diameter, and leaf number of three-month-old plants. It differed significantly from other treatments, except for AMF Mixed (Table 3). *G. crispa* significantly increased the number of root nodules and did not differ significantly from *G. intraradices*. The performance of the *A. saponaria* seedlings is presented in Figure 1.

Plant dry weight

On post-asphalt mining media, inoculation with *G. intraradices* significantly increased the dry weight of three-month-old *A. saponaria* and differed significantly from other treatments (Table 4). The increase in mycorrhizal growth (MGR) ranged from 376.9 to 1,523.1%. The SRR value ranged from 1.65 to 5.95. In post-nickel mining media, inoculation with *G. intraradices* significantly increased the dry weight of *A. saponaria* plants. It differed significantly from other treatments, except for AMF mixed in the root dry weight. The increase in mycorrhizal plant growth (MGR) ranged from 35.7 to 1,485.7%. The SRR value ranged from 0.94 to 1.35. There were no differences between treatments in the SQI variable.

Nutrient content and uptake

Inoculation with *G. intraradices* significantly increased the N and P levels of three-month-old *A. saponaria* plants in post-asphalt mining media (Table 5). In terms of P content, the *G. intraradices* treatment did not differ significantly from *R. crispa* and differed significantly from the other treatments.

There were no differences between treatments in terms of plant Zn levels (Table 5). Inoculation with *G. intraradices* significantly increased n and p uptake in three-month-old *A. saponaria* plants (Table 5). There were no differences between treatments in plant Zn uptake (Table 5). There were no differences between treatments in plant N and P content (Table 6).

Table 3. AMF colonization and growth of three-month-old *A. saponaria* seedlings grown with or without mycorrhizal fungi under greenhouse conditions.

Treatment	Mycorrhizal Colonization (%)*	Height (cm)	Stem Diameter (mm)	Leaf Number	Nodule
Post-asphalt mining media					
Control	11.2±2.72 c	6.90±0.46 d	0.40±0.10 c	5.7±0.67 b	0.00±0.00 c
Gigaspora crispa	65.9±3.74 b	29.17±1.53 b	1.10±0.12 abc	15.3±1.33 a	1.00±0.58 bc
Glomus intraradices	65.0±5.75 b	**41.23±3.39 a**	**1.70±0.15 a**	**19.3±2.03 a**	2.00±0.58 ab
Glomus sp.	81.0±10.14 ab	22.37±1.73 c	0.90±0.44 bc	16.7±0.33 a	2.33±0.33 ab
Glomus sp-LW10	88.8±4.42 a	20.87±0.61 c	1.00±0.10 abc	16.7±1.45 a	0.00±0.00 c
Glomus sp.-SW10	90.1±6.05 a	22.43±1.85 c	**1.27±0.33 ab**	15.3±1.86 a	**3.00±0.58 a**
Mycofer IPB	97.0±0.12 a	19.60±1.15 c	0.87±0.03 bc	15.0±1.53 a	2.33±0.88 ab
Pr>F	<.0001	<.0001	0.0372	0.0004	0.0047
Post-nickel mining media					
Control	0.80±0.81 c	**3.63**±0.22 d	0.53±2.47 c	8.00±0.58 c	0.67±0.33 c
Gigaspora crispa	32.27±3.45 b	8.07±0.47 bc	0.76±0.02 bc	8.00±0.58 c	**4.00±0.58 a**
Glomus intraradices	52.83±3.96 a	**12.10±0.81 a**	**1.21±0.11 a**	**11.3±0.67 a**	**3.67±0.67 ab**
Glomus sp.	30.47±3.33 b	7.03±1.11 c	0.90±0.11 b	8.67±0.88 bc	0.67±0.33 c
Glomus sp-LW10	31.93±2.78 b	7.97±0.71 bc	0.79±0.15 bc	9.00±0.58 bc	0.33±0.33 c
Glomus sp.-SW10	14.87±1.24 bc	6.17±0.35 cd	0.89±0.08 b	8.67±0.33 bc	0.00±0.00 d
AMF Mixed	35.20±1.82 ab	**10.63±1.79 ab**	**0.99±0.18a b**	**10.3±0.67 ab**	2.67±0.33 b
Pr>F	0.0014	0.0003	0.0088	0.0167	0.0047

Notes: Average values followed by different letters in the same column are significantly different at DMRT (p<0.05); *Mean±SE.

Figure 1. Performance of three-month-old *A. saponaria* seedlings (left) and roots (right).
Notes: A (control), B (*Racocetra crispa*), C (*Glomus intraradices*), D (*Glomus* sp.), E (*Glomus* sp.-LW10), F (*Glomus* sp.-SW10), and G (Mycofer IPB).

Table 4. Dry weight, mycorrhizal dependency (MD), the mycorrhizal growth responses (MGR), and shoot root ratio (SRR), of *A. saponaria* seedlings three months old, grown with or without mycorrhizal fungi under greenhouse conditions.

Treatment	Dry weight (g)			MD (%)	MGR (%)	SRR
	Roots	Shoots	Total			
Post-asphalt mining media						
Control	0.04±0.004 b	0.09±0.012 d	0.13±0.016 c	-	-	2.54±0.104 cd
Gigaspora crispa	0.15±0.01 b	0.69±0.08 bc	0,85±0.09 b	84.78±6.29	553.8±34.5	4.53±0.36 b
Glomus intraradices	**0.93±0.39 a**	**1.18±0.05 a**	**2,11±0.43 a**	92.73±3.96	**1,523.1**±81.3	**1.65±0.45 d**
Glomus sp.	0.24±0.06 b	0.59±0.09 bc	0,83±0.15 b	80.53±7.35	538.5±17.7	2.62±0.24 c d
Glomus sp-LW10	0.14±0.02 b	0.51±0.09 c	0,65±0.10 bc	80.30±7.84	376.9±21.3	3.53±0.34 c
Glomus sp.-SW10	0.27±0.05 b	0.88±0.19 b	1,15±0.24 b	77.29±17.22	784.6±30.7	3.16±0.11 c
Mycofer IPB	0.09±0.01 b	0.54±0.06 c	0,61±0.07 bc	73.83±10.68	369.2±58.7	5.95±0.40 a
Pr>F	0.0134	<.0001	0.0003	-	-	<.0001
Post-nickel mining media						
Control	0.07±0.01 c	0.07±0.01 d	0.14±0.01 d	-	-	0.96±0.04 b
Gigaspora crispa	0.90±0.01 bc	0.10±0.02 cd	0.19±0.03 cd	26.3±12.1	35.7±20.6	1.10±0.05 ab
Glomus intraradices	**0.35±0.04 a**	**0.47±0.02 a**	**0.82±0.06 a**	82.9±1.00	**485.7**±35.6	**1.35±0.10 a**
Glomus sp.	0.14±0.02 b	0.13±0.02 cd	0.27±0.03 c	48.1±10.2	92.8±41.3	0.95±0.02 b
Glomus sp-LW10	0.12±0.01 bc	0.16±0.02 c	0.27±0.03 c	48.1±3.90	92.8±15.2	1.35±0.08 a
Glomus sp.-SW10	0.14±0.01 b	0.16±0.02 c	0.30±0.02 c	53.3±4.30	114.3±17.5	1.19±0.19 ab
AMF Mixed	**0.33±0.01 a**	0.31±0.04 b	0.64±0.05 b	78.1±3.00	357.1±70.1	0.94±0.10 b
Pr>F	<.0001	<.0001	<.0001	-	-	0.0270

Notes: Average values followed by different letters in the same column are significantly different at DMRT (p<0.05); *Mean±SE.

Table 5. N, P, and Zn content and uptake of *A. saponaria* plant cultivated with or without AMF in post-asphalt mining media at nursery conditions after three months.

Treatment	Content (mg g^{-1})			Uptake (mg $plant^{-1}$x 10^{-3})		
	N	P	Zn	N	P	Zn
Control	2.33±0.067 b	0.00027±0.000009 c	0.00047±0.000268	290±44.3 c	0.037±0.005 b	0.033±0.023
Racocetra crispa	2.93±0.133 b	0.00052±0.000036 ab	0.00100±0.000202	2,510±379.0 b	0.447±0.078 b	0.867±0.273
Glomus intraradices	4.17±0.819 a	0.00069±0.000113 a	0.00093±0.000140	**9,430±790.7 a**	**1.560±0.586 a**	**1.967±0.235**
Glomus sp.	2.33±0.088 b	0.00046±0.000142 bc	0.00113±0.000230	1,960±435.7 b	0.420±0.208 b	1.033±0.395
Glomus sp-LW10	2.13±0.033 b	0.00032±0.000013 bc	0.00146±0.000286	1,390±241.1 bc	0.213±0.043 b	1.00±0.355
Glomus sp.-SW10	2.30±0.058 b	0.00037±0.000038 bc	0.00176±0.000878	2,670±603.4 b	0.440±0.123 b	2.300±1.347
Mycofer IPB	2.23±0.033 b	0.00033±0.000018 bc	0.00086±0.000150	1,390±138.3 bc	0.210±0.032 b	0.5667±0.162
Pr>F	0.0053	0.0142	0.3959	<.0001	0.0116	0.1551

Table 6. N, P, and Ni content and uptake of *A. saponaria* plant cultivated with or without AMF in post-nickel mining media at nursery conditions after three months.

Treatment	**Content (mg g^{-1})**			**Uptake (mg plant^{-1})**		
	N	**P**	**Ni**	**N**	**P**	**Ni**
Control	0.28±0.0088	0.56±0.0491	0.053±0.002 4c	0.040±0.0048 c	0.080±0.0121 b	0.0076±0.0007 c
Racocetra crispa	0.29±0.0033	0.73±0.1665	0.066±0.0030 c	0.055±0.0075 c	0.147±0.0533 b	0.0126±0.0016 c
Glomus intraradices	0.30±0.0176	0.99±0.2734	**0.191±0.0426 a**	**0.252±0.0315 a**	**0.840±0.2786 a**	**0.1620±0.0483 a**
Glomus sp.	0.29±0.0088	0.72±0.0907	0.067±0.0120 c	0.077±0.0113 c	0.187±0.0101 b	0.0186±0.0054 c
Glomus sp-LW10	0.28±0.0088	0.83±0.0404	0.078±0.0212 c	0.078±0.0095 c	0.229±0.0359 b	0.0221±0.0078 c
Glomus sp.-SW10	0.29±0.0033	0.71±0.2184	0.103±0.0023 bc	0.085±0.0067 c	0.204±0.0479 b	0.0306±0.0025 c
AMF Mixed	0.30±0.0088	1.12±0.1660	**0.155±0.0175 ab**	0.191±0.0143 b	**0.713±0.0986 a**	0.1015±0.0188 b
Pr>F	0.5601	0.2991	0.0015	<.0001	0.0015	0.0005

Table 7. The increase/decrease of nutrient uptake in *A. saponaria* seedlings.

Treatment	**Increase/decrease of nutrient uptake (%)**			**Treatment**	**Increase/decrease of nutrient uptake (%)**		
	N	**P**	**Zn**		**N**	**P**	**Ni**
Post-asphalt mining media				**Post-nickel mining media**			
Control	-	-	-	Control	-	-	-
Racocetra crispa	765.5	1,108.1	2,527.3	*Racocetra crispa*	37.5	83.8	65.8
Glomus intraradices	3,151.7	4,116.2	5,860.6	*Glomus intraradices*	530.0	950.0	2,031.6
Glomus sp.	575.9	1,035.1	3,030.3	*Glomus* sp.	92.5	133.8	144.7
Glomus sp-LW10	379.3	475.7	2,930.3	*Glomus* sp-LW10	95.0	186.3	190.8
Glomus sp.-SW10	820.7	1,089.2	6,869.7	*Glomus* sp.-SW10	112.5	155.0	302.6
Mycofer IPB	379.3	467.6	1,617.3	AMF Mixed	377.5	791.3	1,235.5

For the variables of Ni content and N, P, and Ni uptake, the *G. intraradices* treatment did not differ significantly from the other treatments except for the AMF mixed treatment for the variables of Ni content and p uptake (Table 6). AMF inoculation increased the uptake of P, N, Zn, and Ni in *A. saponaria* seedlings under nursery conditions (Table 7). In post-asphalt mining media, the increase in N, P, and Zn uptake ranged from 379.3-3,151.7%, 467.6-4,116.3%, and 1,517.3-5,860.6%, respectively. The increase in N, P, and Ni uptake by *A. saponaria* plants on post-nickel mining media was 37.5-530%, 83.8-950%, and 65.8-2,031.6%, respectively.

The results of this study indicate that AMF inoculation, especially *G. intraradices*, can improve the quality of *A. saponaria* seedlings in degraded soils, both in post-asphalt mining and post-nickel mining media. The effectiveness of *G. intraradices* is likely due to its ability to expand plant root networks via external hyphae, thereby increasing the efficiency of water and nutrient absorption, particularly phosphorus and nitrogen (Tian et al., 2023). Research by Barea et al. (2016) shows that *G. intraradices* has a high capacity to increase phosphorus availability in nutrient-poor soils. In addition, *G. intraradices* has been shown to increase plant resistance to environmental stress, with high adaptability and sporulation (Jansa et al., 2008; Bending et al., 2014; Ouhaddou et al., 2025). This study also supports these findings by showing significant increases in growth, dry weight, and nutrient uptake in plants inoculated with *G. intraradices* in post-mining media.

A. saponaria seedlings inoculated with AMF on post-asphalt mining and post-nickel mining media had dry weights approximately 3-15 and 0.35-4 times greater than the control, respectively. These results are consistent with those of Amir et al. (2018), who found that *Metrosideros laurifolia* mycorrhizal seedlings had dry weights approximately 4 times those of the control on serpentine soil media. Increased dry weight of mycorrhizal plants on serpentine press has also been reported in *Sorghum vulgare* (Amir et al., 2012). Tuheteru et al. (2021) reported that the application of local FMA increased the total dry weight of three-month-old *A. saponaria* seedlings grown on red-yellow podzolic soil (Ultisol) by 11 times compared to the control.

Increased growth, root nodules, and dry weight of plants are closely related to increased absorption of phosphorus and other nutrients N and Zn in mycorrhizal plant tissues (Table 5). *A. saponaria* seedlings inoculated with AMF on post-asphalt mining and post-nickel mining media had increased nutrient uptake of N by 0.35-4, P (3-31), and Zn (16-68), as well as N (0.37-5.3) and P 0.83-9.5 times greater than the control. One mechanism of P uptake is through higher production of phosphatase enzymes in the rhizosphere, thereby mobilizing inorganic P into a form available to plants. The detailed mechanism of P uptake by AMF has been reviewed by Wang (2017).

This research agrees with several previous research results on various media conditions of post-mining land, such as high P uptake in *Pterocarpus indicus* and *Vitex cofassus* plants in post-asphalt mining media conditions (Husna et al., 2025; Tuheteru et al., 2025), *K. celebica* plants in gold tailings media (Husna et al., 2021), *P. mooniana* in post-nickel mining media conditions (Husna et al., 2016), and *Amygdalus pedunculata* in coal mining (Bi et al., 2018). In addition, FMA reduces metal toxicity by immobilizing metals on hyphal walls and vesicles and by increasing plant antioxidant synthesis (Begum et al., 2019; Wang et al., 2024). This explains the ability of *A. saponaria* mycorrhizal seedlings to grow better even in nutrient-poor media. In addition to improving growth, AMF colonization also increases *A. saponaria* plants' dependence on local FMA inoculation.

In this study, the MD values ranged from 73.83% to 92.73% (post-asphalt mining media) and 26% to 82% (post-nickel mining media), with the highest MD values generally observed in the *G. intraradices* treatment. The results of this study indicate that locally isolated AMF from post-asphalt mining land can enhance the growth of *A. saponaria* plants under less favorable conditions. Compatibility of native AMF with *A. saponaria* is possible due to several factors, namely 1) native AMF is suitable for media conditions; 2) local AMF is compatible with root exudates produced by *A. saponaria* roots; and 3) genotypically, local AMF can absorb and conduct water and nutrients to the host plant (Tuheteru et al., 2025). The results of this study indicate that *A. saponaria* is highly dependent on *G. intraradices*. High dependence (MIE 91%) of *A. saponaria* was also reported by Tuheteru et al. (2021).

Based on these results, *A. saponaria* nurseries at the nursery scale need to be equipped with *G. intraradices* or other AMF. Several similar studies report that inoculation with local AMF increases photosynthesis rates, available P, and seedling survival when transferred to the field (Husna et al., 2021; Wulandari et al., 2024). Thus, the application of local AMF at the nursery stage is an efficient bioamelioration approach to improve seedling quality and accelerate revegetation success on post-mining degraded land. The results of this study also emphasize the importance of selecting local AMF isolates from extreme ecosystems, as these isolates have adaptive capabilities to the physical and chemical conditions of the local soil. Native AMF from post-asphalt mining land, specifically *G. intraradices*, has been shown to increase nutrient uptake and growth of A. saponaria compared to non-mycorrhizal plants. This supports the concept that specific symbiosis between fungi and host plants plays a key role in colonization effectiveness (Brundrett and Tedersoo, 2018). Therefore, integrating native AMF inoculation technology into forestry seedling programs is a strategic step to strengthen the sustainability of mine ecosystem restoration in Indonesia.

Conclusion

Native AMF inoculation has been shown to increase initial growth, dry weight, and uptake of N, P, Zn, and Ni in *Albizia saponaria* seedlings planted in post-asphalt mining and post-nickel mining media. *Glomus intraradices* isolates had the most significant effect on growth and nutrient uptake efficiency compared to other treatments. The application of native AMF from post-asphalt mining land has been proven effective in improving seedling quality and resistance to degraded environmental conditions. These findings support the use of native AMF and *A. saponaria* as an essential component in sustainable post-mining land restoration strategies in Indonesia.

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