ISSN 3082-5326

Research Article

Early Establishment Response of White Lauan (*Shorea contorta*) and Lamio (*Dracontomelon edule*) Seedlings to Microbial Inoculants in a Mine Reclamation Site

Doreen Mae D. Gayo [1], Dernie T. Olguera [2], Nympha E. Branzuela [3]
Leo E. Ong [4], Edgar B. Solis [5]

International Journal of Interdisciplinary Viewpoints
Vol. 2, No. 3, pp. 55–63, 2026
https://doi.org/10.64612/ijiv.v2i3.103

*[1]Southern Philippines Agri-Business and Marine and Aquatic School of Technology (SPAMAST)
[2-5]University of Southeastern Philippines, Tagum- Mabini
Correspondence: doreenmaegayo1@gmail.com

Abstract

The reclamation of mines is complicated as mine tailings can possess unfavorable soil characteristics like low pH, nutrient deficiencies/depletion, and potential heavy metal resources that hinder the initial establishment of vegetation. Arbuscular mycorrhizal fungi (AMF) and Bacillus-based bacterial consortia are microbial inoculations that are a sustainable method to enhance seedling survival, growth, and soil quality. The effects of AMF and Bacillus consortia on the early establishment, soil survivability, growth performance, and soil chemical properties of two native tree species: Shorea contorta (White Lauan) and Dracontomelon edule (Lamio) in a pre-existing mine tailing pond were evaluated. Seedling survival, stem diameter, and height were monitored over seven months, while soil pH, organic matter (OM), total nitrogen (N), available phosphorus (P), and potassium (K) were analyzed. White Lauan had high survival in all treatments (88.9–100%), with stem diameter development enhanced by co-inoculation with AMF and bacterial consortia. Lamio also had high survival (92.6–96.3%) and strong positive correlations between stem diameter and soil nutrients, particularly OM, N, P, and K. Co-AMF and bacterial inoculation improved OM in White Lauan plots, indicating strong synergy. While OM increased, N and P slightly declined, K generally increased, and no significant treatment effects on soil pH were observed. Correlation analysis showed species-specific responses, with Lamio more sensitive to soil nutrient status than White Lauan. Overall, microbial inoculation enhanced seedling establishment, growth, and soil fertility. AMF and Bacillus consortia were identified as a safe and effective strategy for mine tailing's reclamation and reforestation.

Keywords

mine reclamation, reforestation, arbuscular mycorrhizal fungi (AMF), bacterial consortia, seedling establishment, soil fertility

Received: 29 January 2026
Revised: 27 February 2026
Accepted: 15 March 2026
Published: 30 March 2026

Peer Review Statement
This article underwent a double-anonymous peer review process in accordance with the editorial policies of the International Journal of Interdisciplinary Viewpoints. Both authors and reviewers remained anonymous throughout the review process.
Open Access Statement
The International Journal of Interdisciplinary Viewpoints is a fully open-access, peer-reviewed journal. All articles are freely available online immediately upon publication without subscription or access fees.
Funding Statement
The authors received no financial support for the research, authorship, and/or publication of this article.
Conflict of Interest
The authors declared no conflicts of interest.
Data Availability Statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request.
Author Contributions
The authors contributed to conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing, and supervision. The author approved the final manuscript.
Ethics Statement
This study was conducted in accordance with ethical standards and approved by the appropriate Institutional Review Board (IRB). Informed consent was obtained from all participants prior to data collection.
Citation
Gayo, D. M., Olguera, D., Branzuela, N., Ong, L., & Solis, E. (2026). Early Establishment Response of White Lauan (Shorea contorta) and Lamio (Dracontomelon edule) Seedlings to Microbial Inoculants in a Mine Reclamation Site. *International Journal of Interdisciplinary Viewpoints* , *2*(3), 55–63. https://doi.org/10.64612/ijiv.v2i3.103

Introduction

Across many parts of the world, landscapes once rich with life now carry the silent weight of extraction. Mine reclamation has become more than a technical concern—it is a deeply human and ecological challenge that calls for restoration not only of land, but of balance. In these disturbed environments, the soil itself reflects a condition of stress, where heavy metal contamination and increased acidity create barriers to life. Plants that attempt to grow in such spaces often absorb bioavailable toxic elements, which disrupt nutrient uptake and slow their development. Acidic soils further intensify this struggle, as excess hydrogen ions interfere with the availability of essential minerals, leaving vegetation to survive through limited and often fragile adaptive strategies (Fazlioglu et al., 2021).

Within local landscapes shaped by mining, these environmental pressures become more immediate and visible. Establishing plant life in degraded soils is not simply a matter of planting—it is a process of negotiating with harsh and unyielding conditions. Yet beneath the surface, biological interactions offer pathways for renewal. Beneficial microorganisms such as arbuscular mycorrhizal fungi and plant growth-promoting bacteria (PGPB) play a crucial role in supporting plant establishment in stressed environments. These microorganisms enhance nutrient availability, produce phytohormones, suppress pathogens, and stimulate microbial activity, all of which contribute to improved seedling growth and survival (De Andrade et al., 2023). Endophytic bacteria further extend these benefits by enhancing plant growth and yield, strengthening resistance against pathogens, improving bioremediation potential, and inducing systemic resistance through bioactive compounds (Sen et al., 2026). Among these, Bacillus species—particularly Bacillus subtilis—have been widely recognized for their dual role as plant growth promoters and biological control agents, as well as their safety for agricultural use as classified by the US Food and Drug Administration as generally regarded as safe (GRAS) (Bolivar-Anillo et al., 2021). Their ability to form endospores allows them to persist in extreme soil environments, making them especially valuable in mine-degraded areas where they enhance nutrient availability, regulate plant growth, and improve stress tolerance (De Andrade et al., 2023).

Despite these promising developments, there remains a gap in understanding how these microbial relationships unfold under actual field conditions. Much of the existing knowledge is derived from controlled environments, where ecological complexities are minimized. There is still limited field-based evidence on how Bacillus-based bacterial consortia interact with arbuscular mycorrhizal fungi in supporting the early establishment of native tree species in mine-degraded soils. Furthermore, the species-specific responses of native forest trees—particularly in terms of survival, growth performance, and their influence on soil nutrient dynamics—are not yet fully explored in real mine reclamation settings. This limitation constrains the development of practical, evidence-based microbial strategies for ecological restoration.

In response to this need, the present study seeks to understand the role of microbial inoculation in supporting early plant establishment within a mine reclamation site in Maco, Davao de Oro. Specifically, it examines the combined effects of arbuscular mycorrhizal fungi and a bacterial consortium composed of Bacillus subtilis, Bacillus amyloliquefaciens, Bacillus licheniformis, and Bacillus mucilaginosus on two native tree species, Shorea contorta (White Lauan) and Dracontomelon edule (Lamio). By observing seedling survival, height increment, stem diameter growth, and soil chemical properties, the study offers grounded insights into how biological interventions can assist recovery in degraded soils. More importantly, it contributes to a deeper understanding of how life can be re-established in damaged ecosystems, supporting the development of sustainable and science-based mine rehabilitation strategies that are rooted in both ecological function and environmental care.

Methodology

Design

The study utilized a quantitative experimental research design, as it involved the deliberate manipulation of microbial inoculation treatments, specifically arbuscular mycorrhizal fungi (AMF) and Bacillus bacterial consortia, and the systematic measurement of seedling growth and soil responses under actual field conditions. This design was deemed suitable since the primary aim of the research was to find out whether microbial inoculants would make any significant contribution to the survival rates, growth performance and the chemical condition of the soil on which tree seedlings were planted in a reclaimed mine region that was in a degraded state. Quantitative approach was used because the results of the study were in a form of measures and numerical values of height of the seedlings, stem diameter, percentage of survival and concentrations of nutrients in soil which could be statistically compared across the treatments.

In addition, the experiment was designed as a Randomized Complete Block Design (RCBD) and the split-plot design. The choice of this design was made to reduce experimental error due to the variability of the environment within the study site e.g. differences in the texture and slope of soils, availability of moisture, and distribution of nutrients in the mine tailings area. The treatment in RCBD was randomly allocated in blocks whereby each treatment had the equal probability of being located in any plot position. The split-plot design was also used that enabled the microbial inoculation treatments to be better evaluated and the potential interaction effect of treatments and tree species to be taken into account. In general, the study design helped to obtain credible information regarding the efficacy of microbial inoculants within the reclamation conditions in reality.

Locale

The study was conducted in Maco, Davao de Oro, specifically within an old mine tailings pond area that is currently being utilized for mine reclamation and rehabilitation activities. The total experimental area covered approximately 290 m², which provided sufficient space for the establishment of treatment plots and replication blocks needed for the experimental design. The site was chosen because it represents a typical mine-degraded environment characterized by poor soil fertility, low organic matter, and limited vegetation cover. These conditions are common challenges in mine rehabilitation programs, making the area an ideal setting for testing microbial inoculation as a possible soil improvement strategy. Prior to the establishment of the experiment, it was pre-assessed to determine the state of soil, the density of vegetation, surface stability, drainage, and space appropriateness. This was done to determine whether the area was suitable to accommodate the planting activities and that experimental plots can be well established without being disturbed by erosion, flooding, and other physical disturbances. The site was also chosen because it is accessible and has a sufficient amount of open space and the findings of the study could be applied to the real reclamation activities in the area given the effort of rehabilitation of the mines that is ongoing in Maco.

Samples

The experimental units in the study were tree seedlings which were Shorea contorta (White Lauan) and Dracontomelon edule (Lamio). These tree species have been chosen as they are native and ecologically important in the Philippines, and may have utility in reforestation, biodiversity recovery and forest restoration projects. Native species are usually given priority in ecological rehabilitation as they are usually better adapted to the local environmental conditions and help in restoring natural forest ecosystems. The seedlings were acquired at a local nursery and they were picked on the basis of homogeneity in size and age to minimize variability of growth performance occurring due to the maturity of seedlings rather than effects of treatment. It was also significant to use seedlings of the same developmental stage to make sure that any difference in growth observed in the experiment time could be attributed to microbial inoculation treatment and environmental conditions. This utilization also fits the restoration research and mine rehabilitation initiatives which highlight the significance of planting native trees as a result of their long-term success in stabilizing the ecosystem, forming habitats, and soil enhancement.

Collection

The study employed field-based data collection procedures to assess seedling growth performance and soil health. Seedling growth performance was recorded on a monthly basis for a total duration of seven months, allowing the researchers to monitor seedling establishment and growth patterns over time. Seedling survival was assessed at the end of the study period and was expressed as the number of living seedlings per plot, which was used to determine by measuring seedling height and stem diameter. The growth performance was determined by measuring the height and the stem diameter. The height of the seedlings on the soil surface to the apex of the plant was measured using a steel measuring tape. The stem diameter was taken at the basal part of the stem using digital vernier caliper in order to ensure that any alterations in the stem thickness was accurately recorded. The reason behind using these growth parameters is that they are typical measures of the vigor of the plants and effective establishment, particularly in stressed environment like mine tailings. Soil samples were collected before planting to establish baseline soil conditions and after the experiment to determine treatment effects. For baseline assessment, the initial soil sample was collected from the experimental site prior to plot establishment and was submitted to Davao Trade Exponents, Inc. Soil Analytical Laboratory for chemical analysis. This initial laboratory analysis served as the reference point for determining the original soil fertility status of the mine tailings area before the application of microbial inoculation treatments. After the experimental period, soil samples were again collected per plot to evaluate any changes in soil chemical properties attributable to the treatments. Approximately 1 kg of soil per plot was collected, air-dried, and properly labeled prior to submission to the Department of Agriculture–Caraga Region Regional Soils Laboratory. Parameters analyzed included soil pH, organic matter, total nitrogen, available phosphorus, and exchangeable potassium.

Ethical considerations

The study followed ethical standards in conducting field experiments and laboratory analysis. Permissions were secured from relevant authorities and stakeholders before establishing plots in the mine reclamation site. Proper coordination was conducted with the site managers to ensure that the experiment did not disrupt ongoing rehabilitation programs. Data integrity was maintained by ensuring accurate measurement procedures, proper labeling of samples, and secure documentation of results. Laboratory analyses were conducted in accredited laboratories to ensure reliability and validity of soil test results. The study also followed institutional guidelines in handling and reporting data responsibly.

Analysis

Descriptive and inferential statistics were used to analyze the data. Descriptive statistics such as means and percentages were used to summarize seedling survivability, height increment, stem diameter growth, and soil properties. Inferential statistics were applied using Analysis of Variance (ANOVA) to determine significant differences among treatments. When significant differences were observed, the Least Significant Difference

(LSD) test was used for post-hoc comparison of treatment means. Statistical significance was set at $p \leq 0.05$. Pearson correlation analysis was also performed to determine relationships between soil chemical properties and seedling growth parameters.

Results and Discussion

During the seven-month establishment period, both White Lauan and Lamio seedlings exhibited consistently high survivability across all treatments, indicating generally favorable site conditions for early growth. Mean survivability ranged from 88.9% to 100% in White Lauan and 92.6% to 96.3% in Lamio, while minimum survivability remained above 66.7% across treatments. These results suggest that both species can establish successfully under post-mining field conditions and that microbial inoculations did not negatively affect survival. Field and restoration studies have shown that arbuscular mycorrhizal fungi (AMF) inoculation can increase seedling survival, drought resilience, and tolerance to harsh conditions, highlighting its potential benefit in degraded environments (Pereira et al., 2021)

Table 1
Seedling Survivability of White Lauan and Lamio

	White Lauan		Lamio	
Treatment	Mean Survivability (%)	Minimum Survivability (%)	Mean Survivability (%)	Minimum Survivability (%)
T1- Control	96.3%	88.9%	96.3%	88.9%
T2- AMF	100%	100%	96.3%	88.9%
T3- BC	88.9%	66.7%	92.6%	88.9%
T4- AMF + BC	96.3%	88.9%	92.6%	88.9%

Note. Reduced survivability (88.9%) in T3 was observed in a plot located on uneven terrain resembling a short hill, highlighting site heterogeneity effects.

White Lauan had more variability in the survivability of treatments. Survival was maximum with AMF inoculation (T2 = 100%), which suggests that AMF has the possibility of being involved in seedling establishment. This is supported by findings that AMF improves plant performance and survival in degraded soils through enhanced nutrient and water uptake (Arif et al., 2023). The bacterial consortia treatment (T3; mean = 88.9%, minimum = 66.7%) had the lowest survivability, which was explained by lower survivability in one of the replicates (A3T3R3, 6/9) because of the soil mound condition. High microtopographic elevation can decrease the ability of soil to retain moisture and can have more runoff which is detrimental to the early survival of seedlings (Zhang et al., 2023). Conversely, survival was higher with the combined inoculation treatment (T4; mean = 96.3%, minimum = 88.9%) indicating that a co-inoculation treatment could be of use to buffer local environmental stress. A study by Miranda et al. (2023) demonstrated that Co-inoculation of beneficial microbes improves plant nutrient acquisition and stress tolerance relative to single treatments in degraded soils. Lamio demonstrated consistent high survivability irrespective of treatment with an average of between 92.6 and 96.3 as well as a minimum of 88.9 with which it was established irrespective of the type of inoculation. All in all, it can be concluded that the high survival of both the species means that White Lauan and Lamio are well adapted to early establishment in post-mining habitats, and that AMF and bacterial consortia inoculations were generally conducive to seedling survival.

The initial soil chemical properties were compared with the final values obtained after inoculation to determine the degree of changes in soil fertility indicators during the course of study (Table 2). Plant nutrients are readily accessible when the soil pH is close to a neutral (6.0- 7.0). In this study, it was found that the soil pH of both White Lauan and Lamio in all treatments reduced as compared to the original state. The minimum pH (5.713) was recorded in AMF treatment and the maximum pH (5.963) was recorded in AMF +BC treatment in White Lauan. In the case of Lamio, the pH was 5.733 in AMF treatment and 6.073 in AMF+BC treatment. The acidity of the natural soil could be explained by the acidification of the soil as a result of the natural microorganism activity and decomposition of organic matters resulting in the release of protons (H +) and organic acids into the soil solution.

The increase in organic matter (OM) in all treatments was observed in both species. The highest OM (3.203) of AMF +BC treatment was found in White Lauan whereas the least increase (1.730) was found in control. Lamio also exhibited increased OM, with the AMF treatment showing the highest accumulation (2.333%). The increase in OM suggests that microbial inoculants increased the dynamics of decomposition of the organic residues and increased the retention of nutrients in soil. Most treatments had reduced nitrogen (N) content, which depicted plant uptake and short-term immobilization of microbes. In White Lauan, N reduced to 0.079% in the control and also remained near the original values (0.136%) in AMF+BC treatment. Similar tendencies were observed in Lamio, where the percentage of N varied between 0.092-0.105 among inoculated soils. Phosphorus (P), also declined in all treatments, probably because it was absorbed by plants, although inoculants of microbes might have helped make part of the P available. The lowest P (10.923 ppm) was found in the BC treatment in White Lauan and Lamio had the comparatively higher P at the AMF+BC treatment of 13.440 ppm. Potassium (K) levels generally increased after inoculation. In White Lauan, K was highest in AMF and AMF + BC treatments at 115 ppm, whereas Lamio showed the highest K in the control (124.333 ppm). The increase in K indicates enhanced

nutrient release from soil organic matter and microbial activity, providing greater availability for plant uptake. Overall, microbial inoculation positively influenced soil nutrient dynamics by enhancing OM accumulation, improving N retention, facilitating P availability, and increasing K content, although pH declined slightly due to natural acidification processes. The observed changes in soil chemical properties after inoculation provide a basis to evaluate the specific effects of bacterial consortia and AMF treatments on soil fertility. Accordingly, the influence of bacterial consortia on the chemical properties of the soil was evaluated using the treated groups of inoculated (T3 and T4) and the control (T1) and AMF-only-treated one (T2). No significant treatment effects on soil pH were observed, which implies that bacterial inoculation, with AMF alone or with AMF, did not pose a significant effect on soil acidity within the course of the experiment.

Table 2
Soil physic-chemical properties under arbuscular mycorrhizal fungi (AMF) and bacterial consortia (BC) in White Lauan and Lamio

		White Lauan				Lamio			
Characteristics	Initial	Control	AMF	BC	AMF+BC	Control	AMF	BC	AMF+BC
pH	6.27	5.720	5.713	5.846	5.963	5.790	5.733	6.036	6.073
OM (%)	1.26	1.730	2.033	2.076	3.203	2.153	2.333	1.920	1.916
N (%)	0.137	0.079	0.091	0.099	0.136	0.103	0.105	0.092	0.094
P (ppm)	20	14.806	13.516	10.923	12.156	11.616	12.140	13.126	13.440
K (ppm)	75	101.333	115	98.333	115	124.333	98.666	107.333	105.333

Organic matter exhibited a more variable response, consistent with studies showing that plant genotype can influence the magnitude and direction of microbial effects on soil processes, including organic matter dynamics (Rotoni et al., 2024). Although bacterial consortia alone (T3) did not significantly increase OM compared with the control, a significant interaction between variety and inoculation was observed. In particular, the combined AMF + bacterial consortia treatment (T4) resulted in higher OM values in white lauan, suggesting a potential synergistic effect of dual microbial inoculation. This may be associated with enhanced root biomass production, increased microbial activity, as co-inoculation of AMF with beneficial bacteria has been shown to increase soil organic carbon fractions, microbial biomass carbon, and carbon-cycling enzyme activities compared with single inoculations or uninoculated controls, suggesting synergistic effects on soil carbon dynamics and residue decomposition. Conversely, there was no significant difference between treatment with respect to total nitrogen, available phosphorus and exchangeable potassium. Although in some inoculated plots small numerical effects of N and K were found, these effects were not large enough to suggest a consistent treatment effect, possibly simply because the period of the study was short and the nutrient transformations in the soil are slow. All in all, bacterial consortia demonstrated a possibility to enhance the soil organic matter, especially, when used with AMF and in a variety of ways. Nevertheless, the short-term impacts on the other chemical properties of soil were minor, which suggests that more time-intensive assessment might be required to reveal any changes in the soil fertility that can be measured.

Table 3
Comparison of Inoculation at each level of Variety

	Organic Matter (%)	
Inoculation	White Lauan	Lamio
1- Control	1.7300 b	2.1533 a
2- AMF	2.0333 b	2.3333 a
3- Bacterial Consortia	2.0767 b	1.9200 a
4- AMF + Bacterial Consortia	3.2033 a	1.9167 a

Means with the same letter are not significantly different using LSD test at p<0.0.5

Table 3 shows the interaction effect of variety and inoculation treatments on soil organic matter content. In White Lauan the use of AMF and bacterial consortia (T4) combined with one another led to the highest organic matter content, when in Lamio no apparent benefit of T4 was evident in comparison with other treatments. This opposite reaction of the two types of response is the source of such a large variety × inoculation interaction observed during the analysis. Nonetheless, the effect of modification in soil characteristics at the treatment level is not always directly proportional to the growth response because performance of plants can be affected by species-specific sensitivity to nutrient availability in the soils. Pearson's correlation analysis was conducted to

evaluate associations between soil chemical properties and early growth performance of White Lauan and Lamio seedlings. Soil parameters included pH, organic matter (OM), total nitrogen (N), available phosphorus (P), and exchangeable potassium (K), while growth performance was assessed using stem diameter and height increment.

Differences in correlation patterns between the two species indicate species-specific responses to soil conditions. Such species-level variation in soil factor–growth relationships has been observed across plant types and ecosystems, where particular soil chemical properties show stronger associations with growth traits in some species than others due to their differing nutrient uptake strategies (Prinandhika et al., 2023). Overall, organic matter showed the strongest relationship with nutrient dynamics, highlighting its importance as a key soil quality indicator during early establishment. Soil organic matter acts as a reservoir for nutrients and influences soil chemical and biological processes that support nutrient availability and plant growth, with its content often explaining a large portion of variation in soil fertility indicators and correlated plant growth responses (Voltr et al., 2021).

The correlation analysis of White Lauan showed the development of generally weak and insignificant relations between the soil quality parameters and the growth performance thus indicating that the seedling growth was not as sensitive to short-term variability in the soil fertility as shown in Table 4. There were weak correlations between soil pH and most of the measured variables, which meant that the pH of soil did not have much impact on nutrient availability and growth as estimated in the study. Such patterns are consistent with correlation analyses of key soil fertility indicators in agricultural soils, where some soil chemical properties showed weak associations with other fertility parameters, emphasizing that not all soil nutrients respond strongly with plant growth metrics under variable conditions (Yashaswini KP & SM Prasanna, 2025). Only the correlation between available phosphorus and potassium showed a significant positive correlation ($r = 0.648$, $p < 0.05$), indicating that there is a similarity in the behavior of these nutrients or a common source in the soil. There was a statistically significant positive correlation between total nitrogen and organic matter ($r = 0.954$, $p < 0.001$) that again supports organic matter as the main store of soil nitrogen. Whereas moderate positive relationships were found between OM and stem diameter and between total nitrogen and stem diameter, the correlation occurred not statistically. There were also no significant correlations of height increment with soil parameters. These results imply that White Lauan could be less sensitive to seasonal change in the nutrient content in soil or can have slower nutrient uptake (Marschner, 2023).

Table 4
Correlation coefficients of plant growth and nutrient status of White Lauan with AMF with or without Bacterial Consortia

Variables	Soil pH	P (ppm)	K (ppm)	Total N	OM	Height (cm)	Diameter (mm)
Soil pH	1.000						
P (ppm)	0.079	1.000					
K (ppm)	0.135	0.648*	1.000				
Total N	0.087	-0.214	0.305	1.000			
OM	0.256	-0.138	0.414	0.954***	1.000		
Height (cm)	0.216	-0.010	0.071	0.281	0.177	1.000	
Diameter (mm)	0.001	-0.209	-0.209	0.020	0.551	0.556	0.548

Lamio on the other hand showed several strong and statistically significant correlations between soil chemical characteristics and growth performance, which was indicative of greater sensitivity to soil fertility status as shown in Table 5. Available phosphorus was positively correlated with the soil pH ($r = 0.774$, $p = 0.01$), implying that soil pH conditions were positively correlated with phosphorus availability and consistent with findings that phosphorus availability tends to increase toward near-neutral pH due to reduced fixation and greater solubility of phosphate forms in soil (Ahmed, 2023). Potassium was also significantly positively correlated with available phosphorus ($r = 0.836$, $p < 0.01$), and potassium had significant positive correlations with total nitrogen ($r = 0.664$, $p < 0.05$) and organic matter ($r = 0.63$, $p < 0.05$), indicating the correlation of nutrient cycling under the effect of OM. Strong positive relationship of total nitrogen with organic matter ($r = 0.976$, $p < 0.001$), which aligns with wee- documented trends in soils where organic matter serves as a major reservoir of nitrogen. Previous studies have reported that as organic matter content increases, total nitrogen also increases, highlighting how organic matter accumulation enhances nitrogen availability and retention in soils (Wu et al., 2022).

There was also a significant and positive relationship between phosphorus, potassium, total nitrogen and organic matter and increment of the stem diameter, showing that a better soil nutrient status promoted stem development in Lamio. But the height growth was not significantly correlated with the soil parameters, which implies that height increase can be affected by genetic factors and environmental factors rather than by short-term changes in nutrients (Taiz et al., 2022). This observation is supported by studies in tree plantations where soil chemical and physical properties were not significantly correlated with tree height, indicating that height growth may be less sensitive to soil fertility when nutrients are not limiting (Shreejana Panthi et al., 2022).

Table 5
Correlation coefficients of plant growth and nutrient status of Lamio with AMF with or without Bacterial Consortia

Variables	Soil pH	P (ppm)	K (ppm)	Total N	OM	Height (cm)	Diameter (mm)
Soil pH	1.000						
P (ppm)	0.774***	1.000					
K (ppm)	0.486	0.836***	1.000				
Total N	-0.075	0.392	0.664*	1.000			
OM	-0.108	0.370	0.631*	0.976***	1.000		
Height (cm)	0.104	0.002	-0.018	-0.066	-0.048	1.000	
Diameter (mm)	0.418	0.643*	0.606*	0.606*	0.582*	-0.121	1.000

Diameter growth of White Lauan stems in cm increased by 9.41 -11.24 cm across treatment. The greatest increase was obtained with the combined use of AMF + bacterial consortia (T4 = 11.24 mm), followed by bacterial consortia (T3 = 10.64 mm), the control (T1 = 9.99 mm), and finally AMF (T2 = 9.41 mm). These tendencies indicate that inoculation by bacteria, especially the one with AMF, might lead to better early stem thickening, which could be achieved by providing increased nutrient accessibility and growth reactions to phytohormones (Yu et al., 2022). The differences between treatments were however not significant in the seven months establishment period. The range of the height increment was between 50.15 cm (T2) and 64.61 (T3), and the bacterial consortia treatment had the highest increment. The sample values of the combined treatment (T4 = 54.20 cm) and the control were similar, and AMF alone gave the lowest value of height increment. It has been reported that similar height stimulation of tree seedlings inoculated with Bacillus spp. is due to the increased nutrient uptake and phytohormone production (Liu et al., 2022) and that these effects were not significant in the current study.

In Lamio, the increase in stem diameter ranged between 8.63-9.26 mm with a maximum increase in AMF alone treatment (T2 = 9.26 mm) and then by the combined treatment (T4 = 9.07 mm). When using the control (T1 = 8.63 mm) and bacterial consortia only (T3 = 8.66 mm), similar results were obtained. This tendency indicates that Lamio reacts better to AMF inoculation which is corroborated by the fact that AMF is reported to boost nutrient uptake, specifically phosphorus, and increase early growth performance in tree species (Wang et al., 2019). Nevertheless, differences among treatments were minimal.The increase in height of Lamio was varying between 21.5 cm (T2) to 27.7 cm (T4), in which AMF plus bacterial consortia treatment gave the greatest increase. The results showed a difference in the nutrient uptake and AMF efficiency, although dual inoculation caused complementary effects in nutrient uptake, the differences were not sufficient to produce clear treatment separation during early establishment. (Savastano and Bais, 2024).

Conclusion and Recommendations

The findings of the study indicate that microbial inoculation can greatly increase early tree growth, especially in terms of stem development, which is one of the major signs of seedling activity and successful colonization in degraded environments. This enhancement can be explained by the fact that, microbial inoculants are able to enhance the cycling of nutrients and their availability within the soil, which enables seedlings to have easier access to the required elements that support growth. White Lauan (Shorea contorta) and Lamio (Dracontomelon edule) also showed good survival rates during the observation period and this confirmed their good adaptability and resilience to severe conditions of mine tailings. The reason why they should be used in the initial phase of mine rehabilitation and reforestation is due to their survival performance which makes it often hard to plant them in areas that have low quality of soil. It was also found that the nutrient availability affected stem diameter significantly and therefore early seedling development may be more evident during the early stages of development by thickening stems instead of height strategy. Conversely, most of the soil chemical parameters had no significant effect on height growth implying that it may take more time before vertical development can be observed to be more pronounced, even after the treatment has been applied. It is noteworthy that organic matter

was found to be the single important soil variable that takes part in the Variety x Inoculation affect, which highlights its extreme importance in sustaining the activity of microbes and triggering plant growth during inoculation regimens. The high levels of correlations between organic matter, total nitrogen, phosphorus, and potassium also demonstrate the role played by nutrient cycling in enhancing the establishment and growth of the seedlings, which fits the main goals of the study.

Based on these results, bacterial consortia in combination with inoculation by arbuscular mycorrhizal fungi (AMF) is suggested as a viable strategy in mine reclamation projects, especially in the areas with very low soil fertility. The fact that Lamio responded to microbial inoculation with positive growth of its stems further supports this recommendation and shows that microbial inoculation could enhance the early performance of some species more efficiently. Besides, the work states the importance of conserving and enhancing the content of soil organic matter, as it proved to be the most significant soil variable linked to the inoculation effect and a significant contributor to nutrient cycles, soil productivity, and stability of the microbial population. It is necessary to maintain the organic matter by the proper management of the soil to guarantee continuous supply of nutrients and provide the soil with good conditions in a longer period to develop the plants. In addition, further studies are required in terms of longer intervals of observation to track the increase in height and the development of the trees in general since initial vertical growth is not necessarily directly indicative of the total benefits of the better soil fertility and microbial improvement. White Lauan and Lamio should be put at the forefront of reforestation and rehabilitation efforts since they have high survival rates and stress tolerance ensuring they have high potentials of surviving the unfavorable nature of the mine tailings. Generally, the research recommends the adoption of an intervention strategy of microbial inoculation, close management of soil fertility by focusing on organic matter and adoption of robust native trees species to hasten recovery of mine sites and enhance ecosystem regeneration.

References

Arif, A., Husna, H., Tuheteru, F. D., Saleh, I., Albasri, A., Nurdin, W. R., ... & Hadijah, M. H. (2023). Effect of arbuscular mycorrhizal fungi inoculation on content and nutrient uptake of four-month-old Angsana (Pterocarpus indicus Willd.) plants in post-gold mining land in Bombana, Southeast Sulawesi. *Journal of Tropical Mycorrhiza*, *2*(1), 37-44. https://doi.org/10.58222/jtm.v2i1.50

Bolivar-Anillo, H.J, González-Rodríguez, V. E., Cantoral, J. M., Darío García-Sánchez, Collado, I. G., & Garrido, C. (2021). Endophytic Bacteria Bacillus subtilis, Isolated from Zea mays, as Potential Biocontrol Agent against Botrytis cinerea. Biology, 10(6), 492–492. https://doi.org/10.3390/biology10060492

de Andrade, L. A., Santos, C. H. B., Frezarin, E. T., Sales, L. R., & Rigobelo, E. C. (2023). Plant growth-promoting rhizobacteria for sustainable agricultural production. *Microorganisms*, *11*(4), 1088. https://doi.org/10.3390/microorganisms11041088

Fazlioglu, F., Keskin, G. P., Akcin, O. E., & Tugba Ozbucak. (2021). Mining and quarrying activities tend to favor stress-tolerant plants. Ecological Indicators, 127, 107759–107759. https://doi.org/10.1016/j.ecolind.2021.107759

Liu, Y.-M., Zheng, F., Liu, Z.-H., Lan, H.-B., Cui, Y.-H., Gao, T.-G., Roitto, M., & Wang, A.-F. (2022). Enhanced Root and Stem Growth and Physiological Changes in Pinus bungeana Zucc. Seedlings by Microbial Inoculant Application. Forests, 13(11), 1836. https://doi.org/10.3390/f13111836

Marschner, P. (2023). Marschner's Mineral Nutrition of Plants (4th ed.). Academic Press.

Panthi, S., Mandal, R. A., & Mathema, A. B. (2022). Correlation of Tree Diameter, Height and Biodiversity with Soil N, P and K. *American Journal of Life Sciences*, *10*(6), 123-130. https://doi.org/10.11648/j.ajls.20221006.12

Pereira, S., Santos, M., Leal, I., Tabarelli, M., & Santos, M. G. (2021). Arbuscular mycorrhizal inoculation increases drought tolerance and survival of Cenostigma microphyllum seedlings in a seasonally dry tropical forest. Forest Ecology and Management, 492, 119213. https://doi.org/10.1016/j.foreco.2021.11921

Prinandhika, G. M., Supriyadi Supriyadi, Purwanto Purwanto, & Dewi, W. S. (2023). Assessing Soil Quality and Identifying Key Indicators in Agroforestry Systems in Sumberejo Village, Wonogiri Regency, Indonesia. International Journal of Design & Nature and Ecodynamics, 18(4), 1003–1010. https://doi.org/10.18280/ijdne.180429

Rehman, M. M. U., Zhao, L., Khattak, S., Xiao, Y. L., Iqbal, A., Khan, W., ... & Xiong, Y. C. (2025). Amplification effects of AM fungus and rhizobacteria on carbon efficiency in wheat-soil system under drought stress via priming rhizosphere activities. *Applied Soil Ecology*, *215*, 106467. https://doi.org/10.1016/j.apsoil.2025.106467

Rotoni, C., Leite, M. F. A., Wong, L. C., Pinto, C. S. D., Stürmer, S. L., Agata Pijl, & Kuramae, E. E. (2024). Cultivar governs plant response to inoculation with single isolates and the microbiome associated with arbuscular mycorrhizal fungi. Applied Soil Ecology, 197, 105347–105347. https://doi.org/10.1016/j.apsoil.2024.105347

Savastano, N., & Bais, H. (2024). Synergism or Antagonism: Do Arbuscular Mycorrhizal Fungi and Plant Growth-Promoting Rhizobacteria Work Together to Benefit Plants? International Journal of Plant Biology, 15(4), 944–958. https://doi.org/10.3390/ijpb15040067

Sen, A., Johns Saji, Parammal Faseela, Zhang, C., Shibin Mohanan, & Xia, Y. (2026). Exploring the Functional Roles of Endophytic Bacteria in Plant Stress Tolerance for Sustainable Agriculture: Diversity, Mechanisms, Applications, and Challenges. Plants, 15(2), 206–206. https://doi.org/10.3390/plants15020206

Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2022). Plant Physiology and Development (7th ed.). Sinauer Associates.
Voltr, V., Menšík, L., Hlisnikovský, L., Hruška, M., Pokorný, E., & Pospíšilová, L. (2021). The Soil Organic Matter in Connection with Soil Properties and Soil Inputs. Agronomy, 11(4), 779. https://doi.org/10.3390/agronomy11040779

Wang, J., Fu, Z., Ren, Q., Zhu, L., Lin, J., Zhang, J., Cheng, X., Ma, J., & Yue, J. (2019). Effects of Arbuscular Mycorrhizal Fungi on Growth, Photosynthesis, and Nutrient Uptake of Zelkova serrata (Thunb.) Makino Seedlings under Salt Stress. Forests, 10(2), 186. https://doi.org/10.3390/f10020186

Wu, X., Wang, L., An, J., Wang, Y., Song, H., Wu, Y., & Liu, Q. (2022). Relationship between Soil Organic Carbon, Soil Nutrients, and Land Use in Linyi City (East China). Sustainability, 14(20), 13585–13585. https://doi.org/10.3390/su142013585

Yashaswini KP, & SM Prasanna. (2025). Correlation and regression analysis of key soil fertility parameters in agricultural soils. International Journal of Agriculture and Nutrition, 7(6), 26–30. https://doi.org/10.33545/26646064.2025.v7.i6a.231

Yu, L., Zhang, H., Zhang, W., Liu, K., Liu, M., & Shao, X. (2022). Cooperation between arbuscular mycorrhizal fungi and plant growth-promoting bacteria and their effects on plant growth and soil quality. PeerJ, 10, e13080–e13080. https://doi.org/10.7717/peerj.13080

Zhang, K., Xia, J., Su, L., Gao, F., Cui, Q., Xing, X., Dong, M., & Li, C. (2023). Effects of microtopographic patterns on plant growth and soil improvement in coastal wetlands of the Yellow River Delta. Frontiers in Plant Science, 14, 1162013–1162013. https://doi.org/10.3389/fpls.2023.1162013