



Interaction of Ammonifying Bacteria and AMF Associated With Pioneer Plants in Ex-Gold Mining

(Interaksi Bakteri Amonifikasi dan FMA pada Tumbuhan Pionir di Lahan PETI)

Hamzah^{1*}, Jenny Rumondang¹, Ria Rif'atunidaudina¹, Rajjitha Handayani¹, Suci Ratna Puri¹, Rizki Ayu Hardiyanti¹, & Dian Nisya¹

¹ Department of Forestry, Faculty of Agriculture, University of Jambi, Jalan Raya Jambi-Muaro Bulian Km. 15, Mendalo Darat, 36361, Jambi, Indonesia

Article Information:

Submission : 07 April 2026
Revised : 30 Mei 2026
Accepted : 30 Mei Mei 2026
Published : 02 Juni 2026

*Corresponding Author:

Hamzah
Department of Forestry, Faculty of
Agriculture, University of Jambi, Jalan
Raya Jambi-Muaro Bulian Km. 15,
Mendalo Darat, 36361, Jambi, Indonesia
e-mail: hamzah@unja.ac.id
Telp: +62 838-9796-8577

Makila 20 (1) 2026: 135-148

DOI:
<https://doi.org/10.30598/makila.v20i1.25332>



This article is an open access article distributed under the terms and conditions of the
Creative Commons Attribution-ShareAlike 4.0 International License

Copyright ©2026 Author(s): Hamzah,
Jenny Rumondang, Ria Rif'atunidaudina,
Rajjitha Handayani, Suci Ratna Puri,
Rizki Ayu Hardiyanti, & Dian Nisya
Journal homepage:
<https://ojs3.unpatti.ac.id/index.php/makila>
Journal e-mail: makilajournal@gmail.com
Research Article · Open Access

ABSTRACT

Gold mining activities degrade soil physical and chemical properties, increasing compaction, reducing drainage and aeration, lowering productivity, and limiting plant growth. This study evaluated soil fertility, physical and chemical characteristics of ex-illegal gold mining land, and identified arbuscular mycorrhizal fungi (AMF) species and ammonifying bacteria associated with pioneer plants used for phytoremediation. The results showed that high clay content limited water and nutrient infiltration. The average clay content increased from 42.41% in 2019 to 45.12% in 2021. Soil pH (H₂O and KCl) was acidic, ranging from 4.20 to 5.92. Organic carbon (0.96–1.87%) and total nitrogen (0.11–0.26%) were classified as low, indicating poor soil fertility. Among pioneer plants, *Melastoma malabathricum* showed the highest AMF spore abundance, with 37, 30, and 29 spores per 50 g of soil in 2019, 2020, and 2021, respectively. The highest population of ammonifying bacteria was found in the 2021, with a count of 46.3 x 10⁵ individuals per gram of soil. This study aims to identify the interactions between AMF and ammonifying bacteria associated with pioneer plants to support phytoremediation activities on ex-illegal gold mining land.

KEYWORDS: AGML, AMF, ammonifying bacteria, phytoremediation, rehabilitation

INTISARI

Aktivitas tambang emas memberikan dampak pada kondisi fisik tanah yang kompak, merusak drainase dan aerasi tanah, produktivitas lahan yang rendah dan pertumbuhan tanaman yang lambat serta menyebabkan lapisan top soil yang minim, kemasaman tanah yang tinggi, vegetasi dan unsur hara yang miskin. Tujuan dari penelitian ini adalah menganalisis kondisi kesuburan tanah, sifat fisik maupun sifat kimia di lahan pasca tambang emas dan mengidentifikasi jenis FMA dan kelimpahan bakteri amonifikasi pada tumbuhan pionir sebagai phytoremediant plant di lahan pasca tambang emas. Hasil penelitian menunjukkan kondisi tanah yang terlalu liat tidak dapat mendukung masuknya air dan nutrisi ke dalam tanah. Nilai rata-rata persentase liat pada tahun 2019, 2020, dan 2021

berturut-turut adalah 42,41%, 43,95%, dan 45,12%. Nilai pH H₂O dan KCl tergolong masam dengan rentang nilai 4,20–5,92. Nilai C-organik antara 0,96–1,87%, dan N-total antara 0,11–0,26 yang termasuk dalam kategori rendah. Jenis *Melastoma malabathricum* memiliki jumlah spora terbanyak pada tahun 2019, 2020, dan 2021 dengan masing-masing jumlah spora/50 g tanah sebesar 37, 30, dan 29. Populasi bakteri amonifikasi tertinggi terdapat pada tahun PETI 2021 dengan jumlah 46,3×10⁵ individu per gram tanah. Penelitian ini bertujuan untuk mengidentifikasi interaksi atau hubungan FMA dengan bakteri amonifikasi pada tumbuhan pionir sebagai upaya mendukung kegiatan fitoremediasi di lahan PETI.

KATA KUNCI: bakteri amonifikasi, fitoremediasi, FMA, PETI, rehabilitasi

INTRODUCTION

Indonesia is endowed with abundant natural resources, including mineral commodities such as coal, gold, kaolin, sand, gemstones, bentonite, and limestone. According to (Kementerian Energi Dan Sumber Daya Mineral, 2020), national gold production reached 24.88 tons in 2021, representing a 13.85% decrease compared to 28.88 tons in 2020. This decline followed a substantial reduction from 109.02 tons recorded in 2019. Data reported by Komunitas Konservasi Indonesia Warsi (Komunitas Konservasi Indonesia Waarsi, 2022) indicated that environmental degradation caused by illegal gold mining in Jambi Province covered approximately 45,896 ha, with the largest affected areas located in Sarolangun Regency, followed by Merangin, Bungo, and Tebo. The extent of damaged land increased markedly from 3,535 ha to 42,361 ha in 2021, while Bungo Regency recorded the largest cumulative area of illegal mining activities, reaching 8,801 ha.

Based on the synchronization results of ex- illegal gold mining land (PETI) inventory data conducted by (Kementerian Energi Dan Sumber Daya Mineral, 2020), 18 PETI locations were identified within Contract of Work (KK) and Mining Business Permit (IUP) areas. Outside the Mining Business Permit Area (WIUP), illegal mining activities are distributed across 13 provinces, including Jambi Province. Gold mining activities significantly alter soil physical and chemical properties, resulting in soil compaction, reduced soil porosity and aeration, and impaired water infiltration, which collectively decrease land productivity and inhibit plant growth (Tuheteru *et al.*, 2021). Furthermore, post-mining soils are commonly characterized by minimal topsoil thickness, high soil acidity, poor vegetation cover, limited nutrient availability, and elevated mercury (Hg) concentrations ranging from 2.4 to 4.17 ppm (Aryanti & Hera, 2019). According to Hindersah *et al.* (2018), post-gold mining soils typically exhibit low cation exchange capacity (CEC), low available phosphorus (P) and potassium (K), low base saturation, and reduced soil organic carbon (SOC) content. (Ridwansyah *et al.*, 2020) reported that approximately 47% of illegal gold mining activities

in Merangin Regency have resulted in environmental degradation, including areas located in Teluk Sikumbang Village, Muara Siau District. The extent of post-mining land in this area increased from 1.5 ha in 2019 to 1.8 ha in 2020 and further expanded to 6 ha in 2021, highlighting the urgent need for revegetation and land rehabilitation interventions.

Successful revegetation of degraded post-mining land requires prior soil remediation to restore soil structure, fertility, and ecological function through appropriate and efficient biotechnological approaches. The application of arbuscular mycorrhizal fungi (AMF) and ammonifying bacteria has been widely recognized as a promising strategy to improve soil quality, particularly by enhancing nitrogen mineralization and phosphorus availability, which are essential for plant establishment and growth. These soil microorganisms play a critical role in promoting plant development, improving nutrient uptake efficiency, and increasing plant tolerance to heavy metal stress (Hnini *et al.*, 2024). Microbial-based remediation technologies have therefore emerged as effective strategies for mitigating heavy metal contamination and supporting phytoremediation processes in post-mining ecosystems by facilitating the uptake, transformation, and stabilization of organic and inorganic pollutants in plants, particularly in tree species (Gómez *et al.*, 2019).

Understanding the interaction between arbuscular mycorrhizal fungi and ammonifying bacterial populations in illegal gold mining land is essential for developing practical and science-based phytoremediation strategies. Therefore, this study aims to (1) characterize the physical and chemical properties of ex-illegal gold mining land, (2) identify the abundance of AMF spores and ammonifying bacteria associated with pioneer plants (3) evaluate the relationship between AMF and ammonifying bacteria associated with pioneer plants, (4) assess their ecological role in supporting phytoremediation and post-mining land rehabilitation.

Previous studies on ex-illegal gold mining land rehabilitation have primarily focused on soil physicochemical degradation, heavy metal contamination, phytoremediation potential of pioneer plants, and the individual roles of AMF or soil bacteria in improving soil quality. However, information regarding the ecological interaction between AMF and ammonifying bacteria in the rhizosphere of pioneer plants growing on ex-illegal gold mining land remains very limited, particularly under highly acidic and nutrient-poor soil conditions. In addition, little is known about how these microbial interactions contribute to nitrogen mineralization, nutrient cycling, and phytoremediation processes during natural revegetation of degraded mining ecosystems. Therefore, understanding the relationship between AMF and ammonifying bacteria associated with pioneer vegetation is essential to support the development of effective biological rehabilitation strategies for ex-illegal gold mining land.

METHODS

Study Area

This study was conducted in ex- illegal gold mining land located in Teluk Sikumbang Village, Muara Siau District, Merangin Regency, Jambi Province, Indonesia (**Figure 1**). Laboratory analyses were carried out at the Forest Soil and Physiology Laboratory, Universitas Gadjah Mada, and the Silviculture Laboratory, Universitas Jambi, from June to November 2025. The study area is located at approximately 2.19° S and 102.74° E at an elevation of >50 m above sea level and is characterized by a humid tropical climate.

Three illegal gold mining land sites representing different years of mining abandonment were selected purposively, namely PETI 2019, PETI 2020, and PETI 2021. These sites differed in the duration of natural revegetation following mining activities. PETI 2019 covered approximately 1.5 ha and consisted of four observation plots, PETI 2020 covered 1.8 ha with five plots, while PETI 2021 consisted of thirteen plots to better represent site variability. An adjacent non-mined area was used as a control site. The study focused on pioneer plant species naturally growing on post-mining land, namely *Melastoma malabathricum* L., *Chromolaena odorata*, and *Cyperus odoratus*, which are commonly found in degraded mining ecosystems and considered potential phytoremediation species.

Materials and Tools

The materials needed for this study include: Melzer's solution, PVLG solution, distilled water, peptone medium, Nessler's reagent, *Chromolaena odorata*, *Cyperus odoratus*, and *Melastoma malabathricum* L., litter samples, and understory plant samples. The tools required include: soil drill, shovel, thermohygrometer, pH meter, machete, airtight plastic, rope, cooler box, Erlenmeyer flask, dropper, micropipette, porcelain plate, soil rings, markers, 250 µm, 53 µm, and 38 µm sieves, glass beakers, centrifuge tubes, petri dishes, microscope slides, cover slips, stereo binocular microscopes, and soil sample bottles.

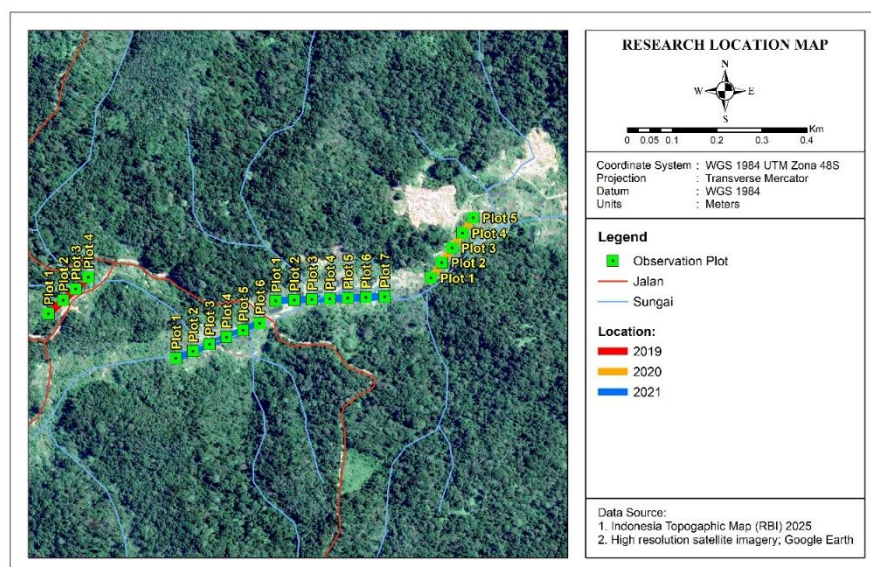


Figure 1. Research Location Map

Research Design and Soil samples

This study employed a field survey and laboratory-based descriptive quantitative approach to evaluate soil properties, AMF abundance, and ammonifying bacterial populations associated with pioneer plant rhizospheres. Sampling was conducted using a purposive sampling method based on the dominance of pioneer vegetation at each PETI site. Observation plots measuring 20 × 20 m were established at each mining year category. Within each plot, rhizosphere soil samples were collected from the rooting zone (0–20 cm depth) beneath the selected pioneer plants.

For each plant species, three soil subsamples were collected randomly within each plot and subsequently composited into one representative sample. Approximately 200 g of rhizosphere soil was collected per composite sample using a soil auger. Soil samples were stored in sterile plastic bags, transported in a cooler box, and processed immediately for microbiological analyses. Litter samples were also collected from the same plots using five sampling points per plot. The litter material was separated into litter and fragmented fractions prior to oven drying at 70°C for 24 h until constant weight was achieved. Litter biomass was then expressed as ton ha^{-1} .

Soil Physical and Chemical Analysis

Soil physical properties analyzed included bulk density and soil texture. Bulk density was determined using the gravimetric core method, while soil texture (sand, silt, and clay fractions) was analyzed using the ASTM 152 H hydrometer method. Soil chemical analyses included soil pH, organic carbon (C-organic), and total nitrogen (N-total). Soil pH was measured electrometrically using both H_2O and KCl solutions. Organic carbon content was determined using the furnace combustion method, while total nitrogen was analyzed using the Kjeldahl method. All soil analyses were conducted following standard laboratory procedures at the PT. Wiwiadi Bintang Sains Laboratory.

Isolation dan Quantification of AMF

AMF spores were isolated from rhizosphere soil samples using the wet sieving and centrifugation method. Approximately 50 g of air-dried soil from each sample was suspended in water and sequentially passed through 250 μm , 53 μm , and 38 μm sieves to separate spores from soil particles and organic debris. The spore suspension obtained from the sieving process was further purified through centrifugation before observation under a stereo binocular microscope. AMF spores were then counted manually based on observable morphological characteristics such as shape, color, and wall appearance. The abundance of AMF was expressed as the total number of spores per 50 g of soil. This quantification was used to evaluate the relative abundance of AMF associated with pioneer plant rhizospheres in ex-illegal gold mining land.

Enumeration of Ammonifying Bacteria

The abundance of ammonifying bacteria was determined using the Most Probable Number (MPN) method. Soil suspensions were prepared by serial dilution using sterile distilled water and inoculated into peptone medium. Following incubation, Nessler's reagent was added to detect ammonium production as an indicator of ammonification activity. The bacterial population was calculated based on MPN tables and expressed as individuals g^{-1} dry soil. Enumeration of ammonifying bacteria were conducted following standard laboratory procedures at the Forest Soil and Physiology Laboratory, Universitas Gadjah Mada.

RESULT AND DISCUSSION

Soil development is influenced not only by the type of vegetation on it, but also by the presence of microorganisms in the soil. Soil itself is a collection of minerals and organic matter that can accept additional material or substances from outside. The role of microorganisms in soil is to accelerate the decomposition of organic matter. The decomposition process also involves ammonification bacteria, which play a role in the mineralization of organic N into NH_4^+ . The process of free N fixation by microorganisms can range from 10–100 kg/ha, reaching more than 50–100 kg/ha in tropical and subtropical areas (A.M., 2019). This depends on the total number of microorganisms in the soil and is influenced by other factors. Nitrogen is an important nutrient for plants. To meet nitrogen requirements, ammonification bacteria are key in converting organic matter into NH_4^+ (Wang *et al.*, 2018).

After mining activities, the soil's condition becomes critical or different from its condition before mining. In Table 1, the bulk density values range from 0.54 to 0.62 g/cm^3 at a depth of 0–5 cm. Soil bulk density is the ratio of the dry weight of the soil to the volume of soil pores. High bulk density is influenced by soil processing; the higher the bulk density, the denser the soil, which will affect root growth. In Table 1, the bulk density value is very low, which is influenced by the amount of organic matter in the soil. In addition, the values of the three soil textures are dominated by a high

percentage of clay, so that the average soil texture class for each year falls into the clay category. Soils with high clay content often exhibit low permeability, which restricts water infiltration and limits the movement of nutrients within the soil profile (Osman, 2013). In Table 1, the average clay percentage values for 2019, 2020, and 2021 are 42.41%, 43.95%, and 45.12%, respectively, with the highest value being 48.56% in the control group. Clay soil texture affects soil pore density, making it small so that roots cannot develop easily, and nutrient availability is low, resulting in limited organic matter and a low bulk density value. High clay content tends to increase the accumulation of heavy metals such as Fe, Al, and Pb due to the ability of clay colloids to adsorb metal ions, which are potentially toxic to plant growth. This makes clay soil a potential contaminant reservoir.

Post-mining soil conditions generally have physical and chemical properties that are not conducive to plant growth. An imbalance in the threetypes of soil texture can cause water absorption to be disrupted, microorganism populations to be reduced or even eliminated, and a lack of naturally formed nutrients. Changes in the soil profile after mining introduce metals that are toxic to plant growth. This means that not all types of plants can grow in these conditions. Only plants that have the ability to accumulate metals in the form of biomass can adapt. The change in the soil profile from layer C to the top layer means that there is no longer any topsoil on post-mining land. As a result, post- mining soil is often coarser due to an increase in sand and clay particles. This is in line with research (Amri *et al.*, 2020), showing that the soil types found in post-gold mining areas are dominated by silty clay, clay foam, and sandy loam.

Table 1. Soil characteristics: bulk density and soil texture

PETI Year	Plot	Bulk Density (g/cm ³)	Mean Values of Soil texture (%)		
			Sand	Silt	Clay
2019	P1	0.55	35.83	21.76	42.41
	P2	0.55			
	P3	0.62			
2020	P1	0.57	24.97	31.08	43.95
	P2	0.61			
	P3	0.54			
2021	P1	0.59	25.38	29.50	45.12
	P2	0.58			
	P3	0.54			
Control	P1	0.60	31.33	20.11	48.56
	P2	0.50			
	P3	0.60			

Table 2. Soil chemical characteristics: pH, organic carbon (C-organic), and total nitrogen (N-total)

PETI Year	pH H ₂ O (Mean ± SD)	pH KCl (Mean ± SD)	C-organic (%) (Mean ± SD)	N-total (%) (Mean ± SD)
2019	5.31 ± 0.34 (Masam)	4.34 ± 0.04 (Sangat masam)	1.48 ± 0.37 (Rendah)	0.19 ± 0.01 (Rendah)
2020	5.29 ± 0.55 (Masam)	4.48 ± 0.39 (Sangat masam)	1.45 ± 0.03 (Rendah)	0.17 ± 0.01 (Rendah)
2021	5.05 ± 0.33 (Masam)	4.36 ± 0.07 (Sangat masam)	1.04 ± 0.08 (Rendah)	0.12 ± 0.01 (Rendah)
Control	5.44 ± 0.02 (Masam)	4.44 ± 0.06 (Sangat masam)	1.52 ± 0.28 (Rendah)	0.25 ± 0.01 (Sedang)

Notes:

- Soil pH: <4.5 = *very acidic*; 4.5–5.5 = *acidic*; 5.6–6.5 = *slightly acidic*.
- Organic C (%): <1.0 = *very low*; 1.0–2.0 = *low*; 2.0–3.0 = *moderate*; >3.0 = *high*.
- Total N (%): <0.10 = *very low*; 0.10–0.20 = *low*; 0.21–0.50 = *moderate*; >0.50 = *high*.

Low organic matter also affects the pH value of acidic soil, which has the potential to present metals that are harmful to plants (Shaaban, 2024). Based on soil chemical characteristic data, all 2019–2021 PETI sites as well as the control site exhibit soil conditions dominated by high acidity, with H₂O pH values ranging from 5.05 to 5.44—classified as acidic—while KCl pH values range from 4.34 to 4.48, classified as highly acidic. These conditions indicate low base saturation and high nutrient leaching due to soil degradation on post-gold-mining land. Organic carbon content at all sites was low (1.04–1.52%), indicating a lack of soil organic matter, which plays a crucial role in improving soil structure, cation exchange capacity, and nutrient availability. Total nitrogen (N) content in PETI sites was also low (0.12–0.19%), whereas in the control sites it was moderate (0.25%), indicating that PETI activities have the potential to cause topsoil loss and reduce soil nitrogen reserves. These findings align with the study by (Sagiarti *et al.*, 2020), which reported that soils with low organic carbon content tend to have low total nitrogen content because organic matter is the primary source of soil nitrogen.

In general, the pH conditions in post-mining areas are high, with low nutrient content and high levels of toxic metals (Hermansyah *et al.*, 2022). Low N-total values indicate low nitrogen availability in the soil, which is due to low organic matter decomposition (Oktavia *et al.*, 2014). This can be seen from the nitrogen content in the soil in all years of PETI opening, which is classified as low, i.e., below 0.2%. The decomposition process of organic matter is greatly influenced by physical environmental conditions such as limited water and high temperatures, which can reach 40°C in post-mining land. Thus, these conditions are not conducive to the activity of microorganisms, especially bacteria that play a role in nitrification and ammonification. Under these conditions, the microorganisms that are possible are arbuscular mycorrhizal fungi (AMF). The results of analysis the number of AMF spores in PETI land under phytoremediation plant stands are presented in **Table 3**.

The marginal post-mining soil conditions mean all vegetation can grow and adapt to these conditions. Phytoremediation plants, such as *M. malabathricum*, *C. odorata*, and *C. odoratus* (Table 3), can adapt because they are hyperaccumulators that help reduce toxic metal levels in the soil (Gisic *et al.*, 2021). Several studies have also report that *M. malabathricum* can stimulate the absorption of Ca and Mg. Research (Sabeti *et al.*, 2024) shows, high concentration of Al dan Fe in *M. malabathricum*, indicating its ability as a hyperaccumulator plant. This study did not examine the metal content, but given the large amounts present, this indicates a process of metal accumulation in the study area. Arbuscular Mycorrhizal Fungi (AMF) are a group of fungi from the Glomeromycota phylum (Smith & Read, 2008) whose existence is influenced by soil chemical properties such as pH (Nugroho &

Prasetya, 2023) (E. J. Tuheteru *et al.*, 2023) and host type. The wide distribution of Glomeraceae in Hg-contaminated soil makes it a potential candidate for mycorrhizal remediation (Mi *et al.*, 2023).

AMF colonization on plant roots can increase the absorption of nutrients in the soil (Shi *et al.*, 2023). According to (Hashem *et al.*, 2016), AMF can increase plant tolerance to harmful metals. In Table 3, the year PETI 2020 had the highest number of AMF spores, namely 73 AMF spores/50 g of soil, with the species *M. malabathricum* having the highest number of spores in 2019, 2020, and 2021, with 37, 30, and 29 spores/50 g of soil, respectively. To reduce hazardous metals in the soil, phytoremediation plants absorb metal compounds through their roots and accumulate them in their leaves, a process often referred to as phytostabilization and phytoextraction (Bhatti *et al.*, 2018). AM fungi can be beneficial for plant life and growth in a variety of biotic and abiotic environmental conditions, such as heavy metal toxicity (Husna *et al.*, 2019) and waterlogging (F. D. Tuheteru *et al.*, 2016). The presence of AMF can increase plant protection from harmful metals and enhance the rates of phytostabilization and phytoextraction (Leung *et al.*, 2013). In the study, the highest number of spores was found in *M. malabathricum* plants, which may aid in the absorption of toxic metals from the soil. This is also supported by the fact that this species is found in all years of the PETI land. *M. malabathricum* L. deposits Pb metal on cell walls that have been absorbed by the roots. Some heavy metals, such as Al, interfere with plant growth; but in *M. malabathricum* L., Al stimulates growth efficiency and nutrient absorption.

Table 3. Number of AMF spore abundance (per 50 g of soil)

PETI Year	Phytoremediant Plants	Number of AMF spores (50 g of soil)
2019	<i>Melastoma malabathricum</i>	37
	<i>Chromolaena odorata</i>	8
	Total	45
2020	<i>Melastoma malabathricum</i>	30
	<i>Chromolaena odorata</i>	11
	<i>Cyperus odoratus</i>	32
	Total	73
2021	<i>Melastoma malabathricum</i>	29
	<i>Chromolaena odorata</i>	12
	<i>Cyperus odoratus</i>	21
	Total	62

The special ability of AMF will appear when soil conditions are very critical. AMF will associate with plant roots, which have the main function of absorbing water and nutrients. Association Arbuscular mycorrhiza (AM) is an integral and functional part of plant roots, and is widely recognised as enhancing plant growth in severely disturbed sites, including those contaminated with heavy metals. The presence of FMA spores in the soil indicates an association between FMA and the roots of phytoremediation plants, particularly *M. malabathricum* (Table 3). The number of AMF spores has a positive relationship with the success of phytoremediation plants in post-gold mining land. AMF acts as a bio-accelerator that enhances the ability of plants to grow and absorb heavy metals (phytoremediation) in extreme environments (Boorboori & Zhang, 2022). The

mutually supportive relationship between *M. malabathricum* and the number of AMF spores in the soil around this plant indicates an interaction that aids the adaptation of *M. malabathricum* to post-mining soil conditions. In addition, the presence of AMF spores indicates a process of nutrient and water absorption to support the growth and metal accumulation process by *M. malabathricum*.

Table 4. Litter accumulation and the ammonification bacteria population

PETI Year	Litter Accumulation (ton/ha)			Bacterial Population/g of soil ($\times 10^5$)	Correlation between Bacterial Population and Total Litter Accumulation	
	L	F	Total		R2	Equation
2019	0.29	0.42	0.72	23	0,464	$y = 28,834x + 8,6076$
2020	0.35	0.33	0.68	21.3		
2021	0.36	0.42	0.77	47.3		
Control	0	0	0	10.5		

Remarks: L= litter (freshly fallen organic matter, undecomposed), F= fragmented (organic matter under active fermentation and initial stages of decomposition)

The sensitive response of soil microorganisms to changes in environmental conditions makes the presence of ammonification bacteria one of the indicators of soil quality in an area (Wolińska *et al.*, 2016). Ammonification bacteria are microorganisms that play an active role in the nitrogen cycle, breaking down amino acids contained in litter into ammonium (NH_4^+). The highest population of ammonifying bacteria was found in PETI 2021, with a total of 46.3×10^5 individuals/g of soil, followed by the highest litter accumulation in the same year at 0.78 ton/ha (Table 4). This indicates a positive correlation between litter accumulation and microbial activity in the soil. The higher rate of N mineralization in non-cultivated soil was due to the availability of organic matter and higher soil microorganism activity (Wolińska *et al.*, 2016), where the presence of ammonifying bacteria is influenced by the availability of organic material derived from litter.

Based on the regression analysis (Table 4), the linear regression equation obtained is $y = 28,834x + 8,6076$ with a coefficient of determination is linearly followed by an increase in the ammonifying bacterial population, demonstrating that substrate availability from litter accounts for 46,4% of the bacterial population, while the remainder is influenced by other environmental factors. The increase in the population of ammonifying bacteria was noticeable in each year of PETI, compared to the control location (Table 4), although it remained in the category of a very low ammonifying bacteria population. In fertile soil conditions, each g of soil contains 108 ammonifying bacteria (Zaman *et al.*, 2004). The low population of ammonifying bacteria at the control location was due to the unavailability of litter at that location.

The population of microorganisms and their activity are highly dependent on soil pH. Low pH values significantly reduce microbial activity and decrease the population of ammonifying bacteria in the soil (Pelczar & Chan, 1988). The average soil pH at the study site was 5-5.4, which is classified as acidic soil (Table 2). The effect of pH on the growth of ammonifying bacteria is related to enzymes activity. If soil acidity is excessive, it will disrupt enzymes activity. Two types of enzymes are involved in ammonium production: (1) extracellular enzymes that break down organic nitrogen

polymers, and (2) intracellular enzymes that degrade organic components within cells (Suryani, 2022).

The dominant plants in the area post-PETI are phytoremediation plants, ranging from *Melastoma malabathricum*, *Chromolaena odorata*, and *Cyperus odoratus* (Table 3). The accumulation of litter from the residues of these phytoremediation plants only reaches the fragmented stage without the presence of humus. This condition indicates that the decomposition process is slow, which is also related to the low population of ammonification bacteria, as microorganisms that play a role in the initial mineralization process (Huang *et al.*, 2019). This shows the importance of litter decomposition and nutrient release on the soil surface, which facilitates greater nutrient flow in the soil. This study has significant practical relevance for post-mining land rehabilitation, particularly in phytoremediation strategies, where increasing litter accumulation through the selection of plants that produce easily decomposable residues can be applied to enhance the population of ammonifying bacteria, thereby accelerating N mineralization and soil fertility recovery. This implementation not only supports ecological rehabilitation but also contributes to the sustainability of land productivity and minimizes long-term environmental impacts.

CONCLUSION

Soil conditions on post-mining land (PETI) have undergone severe degradation, characterized by low organic content, a clay-dominated soil texture, acidic pH, and limited nutrient availability, particularly nitrogen. High clay content results in small soil pores, poor aeration, and accumulation of heavy metals that can inhibit plant growth. Low organic matter and acidic pH also reduce soil microorganism activity, including ammonification bacteria, which play a crucial role in nitrogen mineralization. Nevertheless, several phytoremediation plants such as *M. malabathricum*, *C. odorata*, and *C. odoratus* are able to grow and adapt to these marginal lands. The presence of these plants contributes to the phytoremediation process through phytostabilization and phytoextraction of heavy metals in the soil. These plants are also associated with AMF which help improve N uptake and plant tolerance to toxic metals. The highest number of AMF spores was recorded in PETI 2020, with *M. malabathricum* being the most common plant species and exhibiting the highest number of spores throughout the observation period. The ammonification bacteria population showed an increased every PETI year, peaking in 2021, in line with the increase in litter accumulation. However, the population remained low due to the acidic soil pH and physical conditions that were not conducive to microbial activity. The slow decomposition of litter indicates low activity of microorganisms involved in initial mineralization. Overall, the post-mining soil recovery process is highly dependent on the roles of soil microorganisms, phytoremediation vegetation, and improvements in soil physical and chemical conditions to increase nutrient availability and support long-term fertility. The ability of *M. malabathricum*, *C. odorata*, and *C. odoratus* to grow in marginal

soil conditions indicates that these three species have the potential to be used as phytoremediation plants. Rehabilitation must be carried out in stages, focusing not only on revegetation, but also on the application of organic materials and soil conditioners, supported by phytoremediation plants as vegetation to prepare the land before planting forestry crops. However, this study was limited to the assessment of AMF spore abundance and ammonifying bacterial populations and did not include analyses of heavy metal concentrations in plant tissues or AMF root colonization. Therefore, further studies integrating metal accumulation, root colonization, and microbial interaction analyses are necessary to better understand the mechanisms and effectiveness of phytoremediation in ex- illegal gold mining land ecosystems.

ACKNOWLEDGEMENTS

The authors hereby extend their profound appreciation to the Institute for Research and Community Service, Universitas Jambi, for the provision of research funding and for its support throughout the reporting and evaluation processes. Appreciation is also conveyed to the Faculty of Agriculture, Department of Forestry, Universitas Jambi, for their institutional support and contributions to the completion of this study.

REFERENCES

- A.M., S. (2019). Determination of the Number of Ammonification Bacteria and Activity of the Ammonification Process in Soils and their Relevance for the Development of the of Soil Health Parameter. *Current Investigations in Agriculture and Current Research*, 6(2). <https://doi.org/10.32474/CIACR.2019.06.000231>
- Amri, F., Hindersah, R., Kurnani, B., Sunardi, Cahyandito, M., & Nursyamsi, D. (2020). Physical and chemical natures of post artisanal gold mine area at Kebunlado Village of Riau Province. *Indonesian Mining Journal*, 23(1), 9-19. <https://doi.org/10.30556/imj.Vol23.No1.2020.1062>
- Aryanti, E., & Hera, N. (2019). Sifat Kimia Tanah Area Pasca Tambang Emas: (Studi Kasus Pertambangan Emas Tanpa Izin di Kenegerian Kari Kecamatan Kuantan Tengah, Kabupaten Kuantan Singingi). *Jurnal Agroteknologi*, 9(2), 21. <https://doi.org/10.24014/ja.v9i2.5681>
- Bhatti, S. S., Kumar, V., Sambyal, V., Singh, J., & Nagpal, A. K. (2018). Comparative analysis of tissue compartmentalized heavy metal uptake by common forage crop: A field experiment. *CATENA*, 160, 185-193. <https://doi.org/10.1016/j.catena.2017.09.015>
- Boorboori, M. R., & Zhang, H.-Y. (2022). Arbuscular Mycorrhizal Fungi Are an Influential Factor in Improving the Phytoremediation of Arsenic, Cadmium, Lead, and Chromium. *Journal of Fungi*, 8(2), 176. <https://doi.org/10.3390/jof8020176>
- Gisic, R. M., Simic, Z. B., Grbovic, F. J., Rajicic, V. R., & Brancovic, S. R. (2021). Phytoaccumulation of metals in three plants species of the Asteraceae family sampled along a highway. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 49(2), 12180. <https://doi.org/10.15835/nbha49212180>
- Gómez, L., Contreras, A., Bolonio, D., Quintana, J., Oñate-Sánchez, L., & Merino, I. (2019). *Phytoremediation with trees* (pp. 281-321). <https://doi.org/10.1016/bs.abr.2018.11.010>
- Hashem, A., Abd_Allah, E. F., Alqarawi, A. A., & Egamberdieva, D. (2016). Bioremediation of adverse impact of cadmium toxicity on *Cassia italica* Mill by arbuscular mycorrhizal fungi. *Saudi Journal of Biological Sciences*, 23(1), 39-47. <https://doi.org/10.1016/j.sjbs.2015.11.007>

- Hermansyah, H., Lulu, Y., Eddy, I., & Marsi, M. (2022). Analysis On The Characterictis OF Ex-Mining Soil After 5 Years And 10 Years Or Revegetation. *Media Konservasi*, 26(3), 239–247. <https://doi.org/10.29244/medkon.26.3.239-247>
- Hnini, M., Rabeh, K., & Oubohssaine, M. (2024). Interactions between beneficial soil microorganisms (PGPR and AMF) and host plants for environmental restoration: A systematic review. *Plant Stress*, 11, 100391. <https://doi.org/10.1016/j.stress.2024.100391>
- Huang, Y., Li, D., Wang, L., Yong, C., Sun, E., Jin, H., & Huang, H. (2019). Decreased enzyme activities, ammonification rate and ammonifiers contribute to higher nitrogen retention in hyperthermophilic pretreatment composting. *Bioresource Technology*, 272, 521–528. <https://doi.org/10.1016/j.biortech.2018.10.070>
- Husna, Mansur, I., Budi R., S. W., Tuheteru, F. D., Arif, A., Tuheteru, E. J., & . A. (2019). Effects of Arbuscular Mycorrhizal Fungi and Organic Material on Growth and Nutrient Uptake by Pericopsis mooniana in Coal Mine. *Asian Journal of Plant Sciences*, 18(3), 101–109. <https://doi.org/10.3923/ajps.2019.101.109>
- Kementerian Energi Dan Sumber Daya Mineral. (2020). *PerMen ESDM Nomor 2 Tahun 2020*. Kementerian Energi Dan Sumber Daya Mineral.
- Komunitas Konservasi Indonesia Waarsi (KKI-Warsi). (2022). *Kian Meluas, Areal PETI di Provinsi Jambi Capai 45.896 Hektar*. IMCNews.
- Leung, H.-M., Wang, Z.-W., Ye, Z.-H., Yung, K.-L., Peng, X.-L., & Cheung, K.-C. (2013). Interactions Between Arbuscular Mycorrhizae and Plants in Phytoremediation of Metal-Contaminated Soils: A Review. *Pedosphere*, 23(5), 549–563. [https://doi.org/10.1016/S1002-0160\(13\)60049-1](https://doi.org/10.1016/S1002-0160(13)60049-1)
- Mi, Y., Bai, X., Li, X., Zhou, M., Liu, X., Wang, F., Su, H., Chen, H., & Wei, Y. (2023). Soil Mercury Pollution Changes Soil Arbuscular Mycorrhizal Fungal Community Composition. *Journal of Fungi*, 9(4), 395. <https://doi.org/10.3390/jof9040395>
- Nugroho, W. A., & Prasetya, B. (2023). Eksplorasi Mikoriza Arbuskular Pada Beberapa Sistem Penggunaan Lahan Pertanian Di Desa Ngawonggo, Kecamatan Tajinan, Kabupaten Malang. *Jurnal Tanah Dan Sumberdaya Lahan*, 10(1), 25–35. <https://doi.org/10.21776/ub.jtsl.2023.010.1.3>
- Oktavia, D., Setiadi, Y., & Hilwan, I. (2014). The Physical and Cehmical Soil Properties on Heath Forest and Ex-Tin Mined Land in East Belitung District. *Jurnal Silvikultur Tropika*, 5(3), 149–154.
- Osman, K. T. (2013). *Forest Soils*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-02541-4>
- Pelczar, M. J., & Chan, E. C. S. (1988). Dasar-dasar mikrobiologi Jilid 2. Penerbit UI, Jakarta.
- Ridwansyah, M., Hidayat, S., Heriberta, & Anwar, N. (2020). Water Pollution, Income Loss and Health Impact as Externalities from Illegal Gold Mining: A Case Study from Two Districts in Jambi Province, Indonesia. *International Journal of Innovation, Creativity and Chang*, 12(3), 211–224.
- Saberi, S., Halmi, M. I. E., Ramle, N. A., & Mahmud, K. (2024). Metals Accumulation of Tropical Shrub *Melastoma malabathricum* L. (Melastomataceae) Populations and Their Relation To Soil Edaphic Factor. *Malaysian Applied Biology*, 53(1), 113–125. <https://doi.org/10.55230/mabjournal.v53i1.2793>
- Sagiarti, T., Okalia, D., & Markina, G. (2020). Analisis C-Organik, Nitrogen Dan C/N Tanah Pada Lahan Agrowisata Beken Jaya Di Kabupaten Kuantan Singingi. *Jurnal AGROSAINS Dan TEKNOLOGI*, 5(1), 11–18. <https://doi.org/10.24853/jat.5.1.11-18>
- Shaaban, M. (2024). Acidic Soils. In *Planet Earth: Scientific Proposals to Solve Urgent Issues* (pp. 293–306). Springer International Publishing. https://doi.org/10.1007/978-3-031-53208-5_13
- Shi, J., Wang, X., & Wang, E. (2023). Mycorrhizal Symbiosis in Plant Growth and Stress Adaptation: From Genes to Ecosystems. *Annual Review of Plant Biology*, 74(1), 569–607. <https://doi.org/10.1146/annurev-arplant-061722-090342>
- Smith, S. E., & Read, D. (2008). *Mycorrhizal Symbiosis*. Elsevier. <https://doi.org/10.1016/B978-0-12-370526-6.X5001-6>
- Suryani, Y. (2022). Fisiologi Mikroorganisma. In *Gunung Djati Publishing*.
- Tuheteru, E. J., Tuheteru, F. D., Hartami, P. N., Burhannudinnur, M., Prakoso, S., Husna, H., Albasri, A., & Asraria, D. (2023). Soil properties change, and arbuscular mycorrhizal fungi associated with plants growing on the post-gold mining land of Bombana, Indonesia. *Journal of Degraded and Mining Lands Management*, 11(1), 4863. <https://doi.org/10.15243/jdmlm.2023.111.4863>

- Tuheteru, F. D., Husna, Basrudin, Arif, A., Albasri, & Mustafa, I. (2021). Vegetation composition in gold post-mining land of PT. Sultra Utama Nickel, Bombana District. *IOP Conference Series: Earth and Environmental Science*, 883(1), 012065. <https://doi.org/10.1088/1755-1315/883/1/012065>
- Tuheteru, F. D., Kusmana, C., Mansur, I., . I., & Tuheteru, E. J. (2016). Potential of Lonkida (*Nauclea orientalis* L.) for Phytoremediation of Acid Mined Drainage at PT. Bukit Asam Tbk. (Persero), Indonesia. *Research Journal of Botany*, 11(1-3), 9-17. <https://doi.org/10.3923/rjb.2016.9.17>
- Wang, C., Wang, N., Zhu, J., Liu, Y., Xu, X., Niu, S., Yu, G., Han, X., & He, N. (2018). Soil gross N ammonification and nitrification from tropical to temperate forests in eastern China. *Functional Ecology*, 32(1), 83-94. <https://doi.org/10.1111/1365-2435.13024>
- Wolińska, A., Szafranek-Nakonieczna, A., Banach, A., Błaszczuk, M., & Stępniewska, Z. (2016). The impact of agricultural soil usage on activity and abundance of ammonifying bacteria in selected soils from Poland. *SpringerPlus*, 5(1). <https://doi.org/10.1186/s40064-016-2264-8>
- Zaman, M., Matsushima, M., Chang, S. X., Inubushi, K., Nguyen, L., Goto, S., Kaneko, F., & Yoneyama, T. (2004). Nitrogen mineralization, N₂O production and soil microbiological properties as affected by long-term applications of sewage sludge composts. *Biology and Fertility of Soils*, 40(2), 101-109.