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Short communication: Coconut fiber mats enhance microbial abundance and vegetation establishment on post-eruption degraded land in Mount Batur, Bali, Indonesia

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Abstract. *Dewi NKDA, Damayanti NLPSD, Andriani AASPR, Wirawan IGP. 2026. Short communication: Coconut fiber mats enhance microbial abundance and vegetation establishment on post-eruption degraded in Mount Batur, Bali, Indonesia. Biodiversitas 27 (3): d270330. https://doi.org/10.13057/biodiv/d270330.* Degraded land affected by volcanic eruptions requires specific technologies to support revegetation. In the caldera of Mt. Batur, Bali, Indonesia, mats made from coconut fiber adapted from technology developed by Takino Filter Inc., Japan, were installed on sandy and rocky volcanic substrates to reduce surface soil erosion, limit surface runoff, retain organic matter, increase soil water retention capacity, and create favorable conditions for plant growth. This study aims to evaluate the impact of coconut fiber mats on soil microorganisms, arbuscular mycorrhizal fungus (AMF) and vegetation development in young volcanic soil. This study used exploratory comparative field observation due to limited replications. Soil microorganism abundance, AMF presence, and vegetation development were evaluated using microbiological, mycorrhizal, and molecular approaches. The results showed that the culturable soil microorganisms on PDA increased significantly under coconut fiber mats, reaching 7,976±16.88 CFU g^{-1}, which was much higher than in control plots without mats, which recorded 10.00±2.00 CFU g^{-1}. Four AMF genera (*Glomus*, *Gigaspora*, *Acaulospora*, and *Scutellospora*) were identified in soil under coconut fiber mats. Vegetation establishment included Gmelina, *Leucaena leucocephala*, Edelweiss, and grasses. The findings suggest that coconut fiber mats show promising preliminary evidence for enhancing soil biological recovery and promoting revegetation on degraded volcanic landscapes. This study was an exploratory comparative field observation with limited replication and without baseline data; therefore, the findings should be interpreted as associative evidence.

Keywords: Coconut fiber mats, culturable microorganisms, restoration, vegetation establishment, volcanic caldera

INTRODUCTION

Critical land refers to areas experiencing productivity decline due to physical, chemical, or biological disturbances. In volcanic landscapes such as Mt. Agung and Mt. Batur, Bali, explosive eruptions deposit lapilli and volcanic bombs that create extensive degraded land. Following the Mt. Batur eruption in 2000, approximately 3,565.51 ha of critical land were recorded in 2008 (Bappeda Provinsi Bali 2009). Restoration of such areas is challenging because volcanic sandy soils have low water retention, unstable structure, low organic matter, and limited nutrient availability, all of which restrict soil biological activity and slow ecosystem recovery (Musei et al. 2024). These conditions often lead to rapid drying, high surface erosion, and low seedling survival during early succession. Therefore, restoration of young volcanic land requires ecological approaches that can improve the physical, chemical, and biological functions of the soil simultaneously.

Organic matter is a key component in accelerating degraded soil restoration because it improves multiple soil functions at once. Organic inputs can enhance soil aggregation and structure, increase water-holding capacity, and reduce vulnerability to erosion and drought stress (Omokaro et al. 2024). They also provide energy and carbon for soil microorganisms, thereby stimulating microbial abundance and activity that support nutrient cycling, enzyme production, and organic carbon stabilization (Wang et al. 2025). Meta-analyses further show that ecological restoration generally increases soil organic carbon fractions across degraded landscapes, indicating that practices that build organic matter pools contribute significantly to overall soil recovery (Pan et al. 2025). In volcanic substrates that are naturally poor in organic carbon and biological activity, replenishing organic matter is therefore a central strategy for improving soil quality, strengthening ecosystem resilience, and supporting vegetation establishment.

Coconut fiber mats adapted from Takino Filter technology and implemented in the Batur Caldera since 2014 are one promising innovation. Coconut fiber materials have been widely reported to improve soil properties and support beneficial microbial communities, thereby enhancing plant growth and ecosystem recovery (Zhang et al. 2024; Mogale and Maluleke 2025). Several experimental studies indicate that coconut fiber organic mats can reduce runoff and soil loss by 40 to 60 percent, increase soil moisture, and enrich organic carbon necessary for soil microbial growth (Nissar et al. 2025). Verma et al. (2022) reported that structurally modified coir geomeshes significantly reduced runoff and enhanced early germination across different soil textures. Similarly, field applications of coconut coir matting combined with vegetation demonstrated substantial erosion reduction and improved plant root development under natural riverbank conditions (Azmi et al. 2023). Coconut fiber mats are also advantageous in tropical regions because they are biodegradable, locally available, and decompose gradually, providing long-term organic carbon inputs that support microbial activity. By covering the soil surface, these mats may stabilize the microclimate, reduce evaporation, and create favorable microsites for early plant establishment.

Recent ecological restoration studies suggest that combining organic fiber materials with biological agents such as arbuscular mycorrhizal fungi (AMF) can further enhance soil recovery and vegetation establishment. Organic mulches and fiber-based geomats have been reported to improve soil microhabitat conditions and promote functional microbial communities, especially AMF, which contribute to nutrient mobilization and plant tolerance under nutrient-poor and drought-prone conditions (Zhang et al. 2022; Liu et al. 2025). AMF also play an important role in ecological restoration by improving plant establishment, soil structure, and ecosystem resilience (Lethielleux-Juge 2025). In addition, coconut coir geomats can improve aggregate stability, porosity, and water infiltration, making them suitable for rehabilitation of erosion-prone landscapes (Nissar et al. 2025). These findings indicate that coconut fiber mats may function not only as erosion-control materials but also as supportive tools for biological recovery in degraded soils.

Despite this potential, field-based evidence linking coconut fiber mats with soil microorganism dynamics and vegetation development in young volcanic soils remains limited, particularly in the Mt. Batur caldera. Long-term field evidence connecting coconut fiber mats with culturable microbial abundance, AMF presence, and early vegetation establishment in post-eruption volcanic substrates is still scarce. Therefore, this study aimed to evaluate the impact of coconut fiber mats on culturable soil microorganisms, AMF presence, and early vegetation establishment in degraded volcanic soils of Mt. Batur, Bali, Indonesia. The results are expected to provide a scientific basis for more effective, adaptive, and sustainable nature-based restoration strategies in tropical volcanic ecosystems.

MATERIALS AND METHODS

Experimental design

This research was conducted on degraded volcanic land in the Mount Batur area, Bangli Regency, Bali, Indonesia (8°15′17.39″ S, 115°20′06.50″ E). The study was designed as an exploratory comparative field study to evaluate the long-term potential role of coconut fiber mats in supporting soil biological recovery and vegetation establishment on post-eruption volcanic substrates. The coconut fiber mats structure and field application are presented in Figure 1. The mats were composed of woven coir fibers designed to reduce surface erosion, retain moisture, and provide organic material input. The mats were made from processed coconut husk fibers that were mechanically extracted and woven into biodegradable mesh sheets. The porous structure allowed adequate water infiltration while reducing rainfall impact and surface runoff. No synthetic binders were added to the material.

This study was conducted as comparative field observation between plots covered with coconut fiber mats and adjacent uncovered plots. Coconut fiber mats were installed at the study site in 2014 and evaluated after approximately ten years of application, with field observations and sampling conducted in December 2024. The mats were applied at a density of six units, each measuring 6 m × 2 m, and placed directly on the soil surface without additional soil amendments. Since baseline (pre- installation) data and randomized plot allocation were not available, the results should be interpreted as associative evidence rather than strong causal inference. The study employed a comparative field design consisting of two treatments, namely land covered with coconut fiber mats and adjacent land without coconut fiber mats as control. Six coconut fiber mats were installed to support site rehabilitation, i.e. three mats were randomly selected as sampling units (n = 3), while the other three mats were maintained intact to minimize disturbance and support continuous rehabilitation. Within each plot, five soil cores were collected and composited. Sampling was conducted at three subsites within each treatment to capture spatial variability across the volcanic landscape.

Soil and root samples were collected from three coconut fiber mats using a diagonal sampling technique. At each subsite, five soil cores were collected from a depth of 0-20 cm and composited into a single 500 g soil sample to represent spatial heterogeneity. Root samples of the dominant host plant species, *Leucaena leucocephala* (*lamtoro*), were also collected from the same locations for arbuscular mycorrhizal fungi (AMF) analysis. The use of composite samples was intended to minimize local variability typical of young volcanic soils. Root samples for AMF colonization analysis were collected only from plots covered with coconut fiber mats, because no vegetation was established in the control plots. Therefore, root based AMF colonization could not be assessed in the control treatment due to the absence of plant roots.

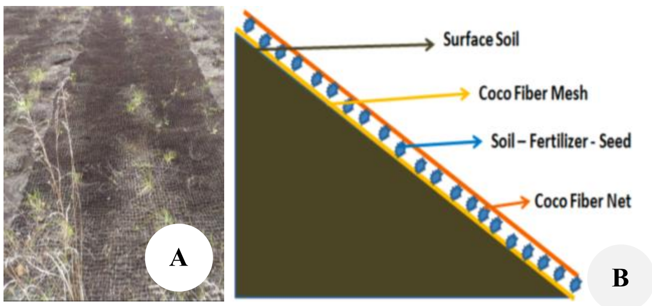

Figure 1. Structure and application of coconut fiber mats in this study. A. The mats applied in the field, B. the principle of application

Soil microorganism analysis

Microbial abundance was quantified using the plate count method on Potato Dextrose Agar (PDA), which primarily supports the growth of culturable fungi and other PDA tolerant microorganisms. Therefore, the results represent culturable microbial populations. No antibacterial agent was added to the medium therefore, colonies grown on PDA may include both fungal and bacterial microorganisms. Ten grams of soil were suspended in 90 mL of sterile distilled water and homogenized thoroughly. Serial dilutions were prepared from 10^{-1} to 10^{-6}, and 1 mL aliquots from appropriate dilutions were spread-plated onto Potato Dextrose Agar (PDA) medium. Each dilution was plated in triplicate. Plates were incubated at 28°C for seven days. Colony forming units (CFU) were counted from plates containing 30-300 colonies and expressed as CFU g^{-1} soil using the formula:

CFU g^{-1} = (Number of colonies × dilution factor) / volume plated (mL)

Isolation and identification of arbuscular mycorrhizal fungi

Seedlings used in this study were pre-treated with a commercial mycorrhizal inoculant by coating the seed surface prior to planting. However, detailed information regarding the inoculant composition (species/strain), formulation, and dosage was not available. Therefore, the AMF assessment in this study was intended to confirm the presence of AMF in the root zone after vegetation establishment rather than to evaluate the inoculant effectiveness. AMF spores were isolated using the classical wet sieving and decanting method.

In doing so, 100 g of soil was mixed in 1 L of water. Suspensions were stirred for 10 minutes and settled for 1-3 minutes. The supernatant was poured through a series of sieves: 1 mm, 500 µm, 212 µm, 106 µm, and 53 µm. Residues were rinsed and transferred to Petri dishes. Spores were examined under a stereo microscope and a compound microscope. AMF genera were identified based on morphological characteristics following INVAM (2020). Parameters observed included spore’s size and shape, wall layers and ornamentation, hyphal attachment type, color, and surface texture.

Root colonization was analyzed using clearing and staining. Root samples for AMF colonization analysis were collected only from plots covered with coconut fiber mats, because no vegetation was established in the control plots. Therefore, root based AMF colonization could not be assessed in the control treatment due to the absence of plant roots. In doing so, the following steps were carried out: roots were washed and cut into 1-3 cm segments, cleared in 10% KOH at 80-90°C for 10 minutes, neutralized and bleached in 3% H_2O_2, acidified in 1% HCl for 12 hours, stained in 0.05% Trypan Blue in lactoglycerol and observed at 100× magnification. AMF structures identified are Arbuscules, Vesicles, Intraradical hyphae (Huang et al. 2020).

PCR amplification was performed to confirm AMF presence in plant roots using AMF specific primers developed by Lee et al. (2008) using Forward primer NS31 5'-`TTG GAG GGC AAG TCT GGT GGC`-3' and Reverse primer AML2 5'-`GAA CCC AAA CAC TTT GGT TTC C`-3'. DNA was extracted from root tissue samples following standard molecular procedures. The PCR reaction mixture consisted of specific primers, reaction buffer, $MgCl_2$, dNTPs, and Taq DNA polymerase. PCR amplification was carried out under the following thermal cycling conditions: initial denaturation at 95°C for 5 minutes; followed by 35 cycles of denaturation at 94°C for 30 seconds, annealing at 58°C for 30 seconds, and extension at 72°C for 1 minute; with a final extension step at 72°C for 10 minutes. The amplified products were visualized by gel electrophoresis, and a DNA fragment of approximately 560 bp was detected. This molecular approach is commonly used in studies of arbuscular mycorrhizal fungi (AMF) ecology (Rosas-Moreno et al. 2023).

Vegetation assessment

Vegetation assessment was conducted to evaluate plant establishment on areas covered with coconut fiber mats. Grasses, shrubs, and naturally occurring species were counted within the mat covered area. Observations were carried out systematically to document the composition of early successional vegetation colonizing the degraded volcanic substrate. Vegetation data were presented descriptively and no diversity indices were calculated.

Plant identification was performed in the field using morphological characteristics such as leaf shape, growth habit, stem structure, and overall plant form. Species identification was supported by regional field guides and relevant botanical references. The assessment focused on plant species commonly associated with disturbed or nutrient-poor environments, which are indicative of early stages of ecological recovery. Vegetation data were used to describe patterns of plant establishment under coconut fiber mat treatment and to support the evaluation of their role in facilitating vegetation development on degraded volcanic land.

Statistical analysis

Data on soil microorganism abundance (CFU g^{-1} soil) were analyzed using a comparative statistical approach between treatment plots with coconut fiber mats and control plots without mats. Prior to analysis, data normality was assessed descriptively. Because the sample size was small ($n = 3$), normality testing was limited; therefore, statistical results should be interpreted cautiously. Differences between treatments were evaluated using an independent samples t-test at a significance level of $p<0.05$. Statistical analyses were performed using SPSS software version 25. Results are presented as mean values ± standard deviation (SD). Due to limited replication (n=3 plots per treatment), statistical analysis was considered exploratory. Differences were tested using independent samples t-test ($p<0.05$), and results are presented as mean ± SD.

RESULTS AND DISCUSSION

Soil microorganisms population

The results showed that the microbial population under coconut fiber mats was approximately 798 fold higher than the control. In the control plots, the average population of soil microorganisms was relatively low. The mean culturable microbial abundance on PDA medium was 7,976 ± 16.88 CFU g^{-1} soil in plots covered with coconut fiber mats, whereas the control plots showed only 10.00 ± 2.00 CFU g^{-1} soil. The independent t-test indicated a significant difference between treatments ($p = 0.032$). These results are summarized in Table 1 and Figure 2. Although microbial populations were detected in both treatments, the magnitude of difference between the control and mat-covered plots highlights the important role of coconut fiber mats in stimulating early biological recovery. The improved microenvironment under the mats may have enhanced microbial survival and reproduction by protecting the soil surface from extreme environmental conditions, such as high solar radiation and rapid drying. These findings are consistent with previous studies reporting that organic mulches and fiber-based soil covers can enhance microbial biomass and activity by modifying physical and chemical soil properties. The statistical analysis further supports this observation. However, the limited number of replicates reduces statistical power and limits broad generalization.

The result of this study indicates that although microbial growth was still possible in the untreated volcanic substrate, the overall abundance remained very limited. The low microbial population in the control plots reflects the harsh conditions of the degraded volcanic soil, which is characterized by coarse texture, low organic matter content, and poor moisture retention. Such conditions restrict the availability of energy sources and suitable microhabitats for soil microorganisms to grow and proliferate. In contrast, plots covered with coconut fiber mats showed a substantial increase in soil microorganism abundance. The average population represents a sharp increase compared to the control treatment. This pronounced difference suggests that the presence of coconut fiber mats created a more favorable environment for microbial development. The coconut fiber material likely contributed to the development of organic substrates that could be utilized by microorganisms as carbon and energy sources. In addition, the mats may have improved soil moisture retention and reduced surface temperature fluctuations, both of which are important factors supporting microbial activity in degraded soils.

Overall, these results demonstrate that coconut fiber mats have a strong positive effect on soil microorganism abundance in degraded volcanic soils at Mount Batur. The enhancement of microbial populations represents an important initial step in soil biological recovery, as microorganisms play a key role in nutrient cycling, organic matter transformation, and the development of soil structure.

Coconut fiber mats were associated with higher culturable microbial abundance. Coconut fiber helps regulate soil temperature and maintain moisture due to its high water-holding capacity. Being a natural material, coconut fiber leaves no harmful residues in the soil. Higher microbial populations accelerate organic matter decomposition, making nutrients more available for plant uptake (Azmi et al. 2025). Coconut fiber contains hemicellulose (8.50%), cellulose (21.07%), lignin (29.23%), pectin (14.25%), and moisture (26.0%), which support microbial colonization (Nissar et al. 2025). The high carbon content of coconut fiber serves as an energy source for soil microorganisms, stimulating microbial growth. Organic fiber-based soil covers, such as coconut coir mats, significantly increase soil microbial biomass, moisture, and enzymatic activity, thereby accelerating early ecological restoration. Mulching with natural fibers enhances the diversity of soil bacterial and fungal communities, especially in degraded volcanic landscapes (Vieira et al. 2024). Coconut coir substrates can influence soil microbial communities and root associated microbiota, contributing to improved plant performance (Xu et al. 2024).

Enhancing microbial activity under fiber mats can contribute to soil carbon sequestration and improve long-term soil health. Coconut fiber amendments stimulate beneficial saprophytic fungi, enhancing nutrient cycling and soil aggregation. The significant increase in soil microorganisms in plots covered with coconut mats can be attributed not only to improved moisture retention but also to enhanced soil microhabitat complexity (Nissar et al. 2025). Coconut fiber provides a porous matrix that supports microbial colonization, protects microorganisms from desiccation, and slows temperature fluctuations, factors essential for microbial survival in volcanic sandy soils, which are typically low in organic matter and highly permeable. Furthermore, the decomposition of coconut fiber contributes labile carbon sources, which stimulate microbial respiration and enzyme activity. As microorganisms begin degrading hemicellulose, cellulose, and lignin, they initiate the formation of soil organic aggregates, improving soil structure and increasing nutrient availability for plants. The microbial community stimulated by coconut fiber includes Saprophytic fungi, which decompose organic materials and beneficial bacteria, including arbuscular mycorrhizal fungi (AMF), which enhance nutrient uptake. These microbial interactions accelerate soil rehabilitation in degraded volcanic environments (Hu et al. 2023).

Recent global studies have demonstrated similar microbial responses to organic fiber-based soil covers. Natural fibers create microbial hotspots, increasing functional diversity and enzymatic activity (Zhang et al. 2022). The addition of biodegradable mulches boosts carbon mineralization rates, supporting early soil recovery in a disturbed landscape (Cano et al. 2025). Coir-based substrates significantly enhance fungal-to-bacterial ratios, indicating more stable soil organic matter formation. In sandy volcanic soils, microbial biomass responds rapidly to organic inputs, leading to improved soil fertility and nutrient cycling. These findings further validate the effectiveness of coconut fiber as a low-cost, sustainable amendment for rehabilitating degraded volcanic land (Cano et al. 2025).

Table 1. Vegetation growth on land covered with coconut fiber mats

Vegetation	Total		
	Mats 1	**Mats 2**	**Mats 3**
Gmelina	0	0	1
Leucaena leucocephala	10	5	7
Edelweiss	2	0	3
Grasses	24	11	30

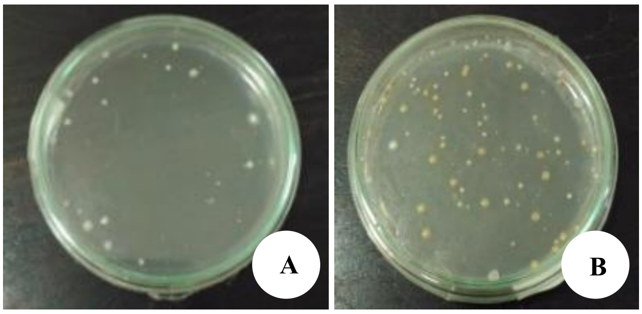

Figure 2. Culturable soil microorganisms on PDA medium: A. Representative PDA plate from plots without mats; B. representative PDA plate from plots covered with coconut fiber mats

Figure 3. Arbuscular mycorrhizal fungi (AMF) spores observed under Microscope (100×). A. *Gigaspora*, B. *Scutellospora*, C. *Glomus*, D. *Acaulospora*

Isolation and identification of arbuscular mycorrhizal fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) are important symbiotic soil organisms that form mutualistic associations with plant roots and play a key role in supporting plant establishment in nutrient-poor and degraded soils. Through their extensive hyphal networks, AMF enhance the absorption of water and essential nutrients, particularly phosphorus, which is often limited in young volcanic substrates. The presence of AMF is therefore considered a critical biological indicator of early soil recovery in degraded lands, where unfavorable soil conditions strongly constrain plant survival. In this study, AMF spores were successfully isolated from soils treated with coconut fiber mats, indicating that these materials supported conditions suitable for AMF occurrence under field conditions. The presence of AMF spores suggests that the coconut fiber mats indirectly facilitated the establishment of mycorrhizal fungi by improving the soil microenvironment and supporting host plant growth. Organic fiber materials may provide a more stable habitat, reduce soil surface disturbance, and maintain higher soil moisture levels, all of which are favorable for AMF development. Four AMF spore genera were identified in soils covered with coconut fiber mats, as shown in Figure 3. The detection of four AMF genera suggests the presence of several AMF groups during the early restoration stage.

Morphological analysis of arbuscular mycorrhizal fungi (AMF) spores on mats revealed variations in genus composition that reflected differences in microhabitat conditions across treatments. Soil analysis revealed the presence of *Gigaspora*, *Scutellospora*, *Acaulospora*, and *Glomus*. Coconut fiber mats increase soil aggregation through hyphal binding, enhance phosphorus uptake, improve drought resistance, and support early successional plants in degraded ecosystems. They also improve moisture retention and root-zone temperature, which promotes AMF spore survival and colonization. These findings align with recent global studies showing that four AMF genera were documented in soils under mats.

Arbuscular mycorrhizal fungi (AMF) are fungal symbionts that associate with plant roots. AMF root colonization was observed in *L. leucocephala* (*lamtoro*) roots collected from mat covered plots. In contrast, root colonization could not be evaluated in the control plots because no plants grew there, leaving no root samples. Therefore, quantitative comparison of AMF colonization between treatments was not possible, as control plots lacked vegetation and root samples for assessment. The results of AMF identification in plant roots are presented in Figure 4.

Microscopic examination of stained root samples collected from plants growing on coconut fiber mats confirmed the presence of internal AMF colonization. Root colonization structures observed in *L. leucocephala* included intraradical hyphae and vesicles (Figure 4). Root samples from control plots could not be collected because no vegetation was established in the control area; therefore, comparative colonization between treatments could not be assessed. Fungal structures, including hyphae and vesicles, were observed within the root cortex, indicating successful colonization of the plant roots. The sampled roots belonged to *L. leucocephala*, which established only in plots covered with coconut fiber mats. Root colonization was not observed in control plots without mats, as plant growth was absent.

These results indicate that coconut fiber mats provide a suitable microenvironment for the presence and persistence of AMF in young volcanic soils. The organic material and improved moisture conditions under the mats likely supported AMF survival and root colonization during early stages of vegetation establishment. Overall, the findings demonstrate that coconut fiber mats facilitate biological interactions between soil microorganisms and plant roots, contributing to the early recovery of soil biological functions in degraded volcanic land. The results presented in Figure 3 confirm that arbuscular mycorrhizal fungi successfully colonized the plant roots. AMF colonization plays an essential role in improving soil structure and plant health. AMF colonization occurs when fungal spores germinate, develop hyphae, and penetrate plant root tissues, forming a symbiotic association. The interconnected network of roots and fungal hyphae functions as a "biological web" that gathers soil minerals, organic matter, and other essential nutrients. Microbial exudates, particularly polysaccharides and glomalin, a glycoprotein produced by AMF hyphae, act as natural binding agents that stabilize soil aggregates (Umer et al. 2025).

The use of coconut fiber mats provides a favorable microenvironment that enhances microbial activity, including AMF proliferation, compared to unprotected soils. This microenvironment improves soil moisture retention, reduces temperature fluctuations, and supplies organic carbon that supports fungal growth. AMF are among the most beneficial microorganisms for plant growth on critical and degraded lands because they increase nutrient acquisition, improve drought tolerance, enhance soil aggregation, and promote plant survival under stressful conditions. Therefore, isolating and identifying AMF in soils with and without coconut fiber mats is crucial to understanding how coconut-fiber biotechnological interventions influence soil microbial communities.

Recent studies support the essential ecological role of AMF in degraded land restoration. AMF contribute significantly to soil carbon sequestration and aggregate stability, especially in sandy and volcanic soils (Yang et al. 2021). Their extensive hyphal networks increase nutrient uptake efficiency and improve plant establishment in nutrient-poor substrates (Berruti et al. 2016) . Organic mulching and fiber-based soil covers have also been shown to increase AMF colonization rates, microbial biomass, and soil enzymatic activity. In addition, studies highlight that glomalin-related soil proteins (GRSP) strongly contribute to long-term soil stability and resilience in disturbed ecosystems (Ji et al. 2024). These findings align with the results of the present study, demonstrating that coconut fiber mats support AMF establishment and enhance soil health in volcanic critical lands.

To further confirm the presence of AMF spore infection in plant roots, the root samples were also analyzed by PCR using AMF-specific primers NS31 and AML2. PCR amplification confirmed the presence of AMF DNA (560 bp band), but this method does not identify AMF genera without sequencing. AMF spores and root colonization were not detected in the control plots. This is likely due to the absence of established vegetation in the control area, resulting in limited host roots for AMF colonization and reduced spore recovery. The visualization of the PCR amplification results is presented in Figure 5.

The results of the AMF analysis using PCR showed that the control treatment consisted of free water added to the primer mix solution to ensure that no contamination occurred from tools, materials, or environmental factors during the procedure. As expected, no band appeared in the control lane, confirming the absence of contamination. In contrast, clear DNA bands of approximately 560 bp were detected in samples from Mat 1, Mat 2, and Mat 3, indicating the presence of internal AMF spores within the plant roots. This confirms successful colonization of the host roots by AMF.

The phylogenetic group Glomeromycota, to which AMF belong, comprises several genera, including *Glomus*, *Diversispora*, *Entrophospora*, *Scutellospora Acaulospora*, *Otospora*, *Kuklospora*, *Gigaspora*, *Pacispora*, *Geosiphon*, *Ambispora*, *Archaeospora*, *Intraspora*, and *Paraglomus*. Morphological identification using the wet sieving method and comparison with the INVAM guide showed that AMF spores were detected only in soil collected from mat-covered plots. Morphological observation identified four genera, namely *Scutellospora*, *Gigaspora*, *Acaulospora*, and *Glomus* (Figure 2). Quantitative spore density was not measured in this study; therefore, AMF data are presented descriptively.

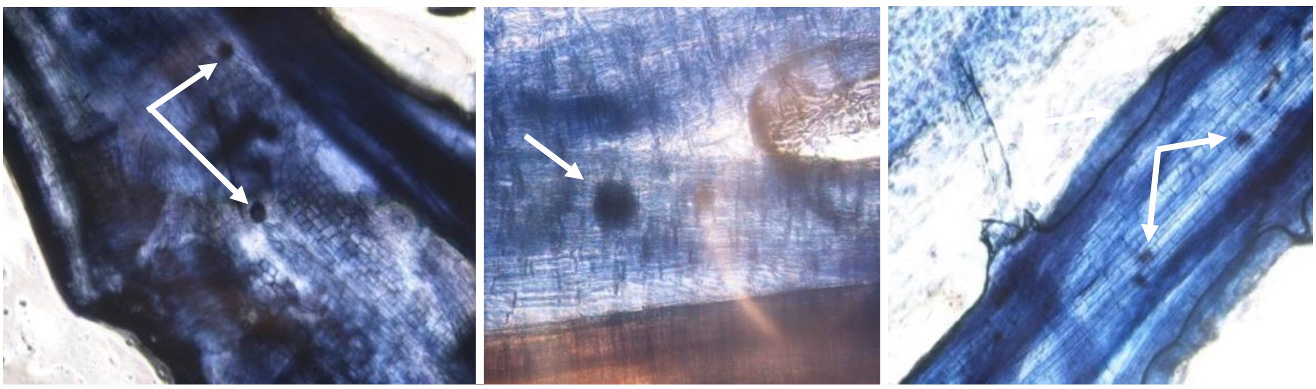

Figure 4. Internal colonization of Arbuscular mycorrhizal fungi (AMF) spores in plant roots on soil covered with mats (100× magnification)

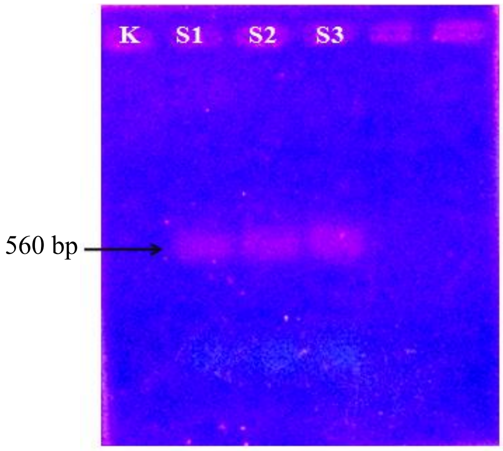

Figure 5. Results of arbuscular mycorrhizal fungi analysis using the PCR technique. K: negative control (water). S1-S3: root DNA samples from *Leucaena leucocephala* collected from mats at plots 1-3

The presence of AMF contributes significantly to improving soil quality, soil health, and energy flow within soil food webs. Potential improvements in soil quality are inferred based on observed biological indicators and supported by previous literature, as soil chemical and physical parameters were not directly measured. Their ecological roles include: (i) enhancing soil structure through the formation of stable aggregates, (ii) supporting nutrient cycling and preventing nutrient loss from the ecosystem through an extensive hyphal network, (iii) transferring plant-derived hydrocarbons (photosynthates) to soil organisms, which becomes an energy source within the soil food web, (iv) producing epigeous and hypogeous sporocarps that serve as food sources for soil fauna, mammals, and other organisms, (v) providing a food resource through hyphae and fruiting bodies, especially in ectomycorrhizal species, (vi) promoting beneficial soil microorganisms such as nitrogen-fixing bacteria and phosphate-solubilizing microbes, (vii) increasing soil carbon content, which plays a vital role in soil health and fertility, (viii) expanding the effective absorption area for water and nutrients through external hyphal networks, (ix) enhancing plant growth by protecting roots from soil pathogens and toxic elements (Wahab et al. 2023).

AMF significantly improve soil aggregation, increase soil organic carbon, and enhance plant resilience under stress conditions such as drought, low fertility, and erosion-prone soils (Huang et al. 2020). Moreover, AMF diversity is widely used as a biological indicator of soil ecosystem health (Berruti et al. 2016). These findings support the importance of AMF colonization observed in this study and highlight the crucial role of coconut fiber mats in promoting AMF development in volcanic critical lands.

Vegetation growth on coconut fiber mats

Vegetation growth was observed only on land covered with coconut fiber mats. Tree seedlings of Gmelina, *L. leucocephala*, and edelweiss were deliberately transplanted at the beginning of the restoration program. Seedlings were manually planted into prepared pits in the volcanic substrate, and coconut fiber mats were installed around the planting area to improve microenvironmental conditions. In contrast, grasses were not planted but emerged naturally as part of spontaneous vegetation colonization. A total of four plant groups were recorded during the observation period, and their abundance is presented in Table 1. Among these, *L. leucocephala* and grasses were the most commonly found across all plots covered with mats, whereas Gmelina and Edelweiss appeared in smaller numbers. The number of plants varied among mats 1, 2, and 3, suggesting differences in local growing conditions within the treated area. In contrast, no vegetation was found in plots without coconut fiber mats.

The vegetation growth recorded on coconut fiber mats indicates early vegetation colonization dominated by four plant groups. Overall, these observations indicate that coconut fiber mats created a more favorable environment for early plant establishment on degraded volcanic soil. The mulching properties of coconut fiber, such as improved moisture retention, enhanced aeration, and moderated soil temperature contribute significantly to the successful growth of early vegetation (Liu et al. 2025). On the other hand, the loose, sandy soil and low water-holding capacity of the untreated land likely limited seed germination and early plant survival. The assessment was based on species presence and abundance without applying quantitative diversity indices and without statistical comparison due to the limited number of observed plots.

The vegetation performance is strongly linked to the presence of mycorrhizal fungi, which form mutualistic associations with plant roots. This mutualistic symbiosis provides reciprocal benefits and has been widely recognized as an effective biological enhancement for agricultural crops, forest species, and revegetation plants. Mycorrhizal inoculation acts as a natural biofertilizer that improves plant growth through several mechanisms (Diagne et al. 2020). First, mycorrhizae enhance nutrient uptake, especially phosphorus, which is often limited in degraded soils. Second, they function as a biological barrier, reducing root infection by soilborne pathogens. Third, mycorrhizae improve plant resilience under drought and extreme moisture conditions by enhancing water absorption efficiency. Fourth, they stimulate the production of growth hormones such as auxins, which regulate root and shoot development. Finally, mycorrhizae support crucial soil biogeochemical processes that enhance soil fertility and long-term ecological stability (Ma et al. 2022).

In addition to the benefits provided by mycorrhizal fungi, coconut fiber itself contributes significantly to plant development. Coconut coir contains essential macronutrients and micronutrients including calcium (Ca), sodium (Na), magnesium (Mg), phosphorus (P), potassium (K), and nitrogen (N), which support early plant growth. Its high water holding capacity, favorable porosity, and slow decomposition rate make it an effective organic amendment for soil rehabilitation (Tuckeldoe et al. 2023). Recent studies also highlight that coconut coir improves soil structure, reduces surface erosion, and supports beneficial microbial communities, further contributing to the success of plant establishment on restored Land (Gomes et al. 2023). Improving soil health through organic amendments is essential for restoring degraded ecosystems and enhancing microbial activity (Lehmann et al. 2020).

In conclusion, the coconut fiber mats play an important role in supporting early biological recovery in degraded volcanic soils in Mount Batur. The presence of coconut fiber mats was associated with higher culturable microbial abundance, AMF presence in the root zone, and initial vegetation establishment, suggesting that these materials may contribute to more favorable conditions for ecosystem recovery. However, this study was exploratory with limited replication and without baseline soil data, and seedlings were pre-treated with a commercial mycorrhizal inoculant. Therefore, the findings should be interpreted as preliminary associative field evidence. Future studies with longer monitoring periods, additional biological indicators, and improved experimental designs will be essential to confirm long term restoration effects.

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