JEK
Journal of Earth Kingdom
JEK 3(2): 149–165
ISSN 3024-9821

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Potential of local *Trichoderma* in bioremediation of degraded soil

Bima Iqbal Ghifari[1], Muhammad Rasyid Ridho[2], Reggina Sonia Putri[3], Syahwa Fitria Maharani Wagino[1], Wahda Zahra Azizah[4], Muhimmatul Husna[1,*], Iffah Izzatuddinillah[3], Rahayu Arraudah[1]

[1] *Department of Agroecotechnology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia;*
[2] *Department of Agricultural Industry Technology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia;*
[3] *Department of Soil Science, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia;*
[4] *Department of Agribusiness, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.*
*Correspondence: mhusna@unib.ac.id

Received Date: December 26, 2025 Revised Date: January 29, 2026 Accepted Date: January 29, 2026

ABSTRACT

Background: Soil degradation in Indonesia is a serious challenge, impacting agricultural productivity and environmental quality. One potential ecological solution is bioremediation using soil microorganisms such as *Trichoderma spp.* This study aims to identify local *Trichoderma* isolates from various regions in Indonesia along with their biological and functional characteristics in the bioremediation process. **Method:** This study uses a narrative literature review to synthesize conceptual and empirical evidence from academic journals, scientific articles, and policy reports. This review focuses on assessing the biological and functional characteristics of local *Trichoderma* isolates and their effectiveness in addressing unsustainable soil management and environmental degradation. **Finding:** The results of the literature study indicate that species such as *Trichoderma harzianum*, *Trichoderma viride*, *Trichoderma asperellum*, and *Trichoderma koningiopsis* can degrade organic and inorganic pollutants, suppressing pathogens, and improving soil fertility. The potential of each isolate is strongly influenced by its environmental origin and type of pollutant, with high effectiveness recorded in ex-mining soil, agricultural land, and pesticide-contaminated areas. Further research and policy support from research institutions or relevant parties are needed so that local *Trichoderma* can be developed as a bioremediation agent in sustainable agricultural systems in Indonesia. **Conclusion:** Local *Trichoderma* species offer a significant and sustainable solution for restoring soil health in Indonesia, provided that challenges related to technology adoption and isolate data can be overcome. Future success depends on cross-sector collaboration to bridge the gap between laboratory research and field application, ensuring that these biological agents are optimized through farmer education and regulatory support. **Novelty/Originality of this article:** This study presents a comprehensive synthesis of native Indonesian *Trichoderma* isolates, identifying a direct relationship between their geographic origin and their specific multifunctional effectiveness.

KEYWORDS: bioremediation; Indonesia; soil degradation; *Trichoderma.*

Cite This Article:
Ghifari, B. I., Ridho, M. R., Putri, R. S., Wagino, S. F. M., Azizah, W. Z., Husna, M., Izzatuddinillah, I., Arraudah, R. (2026). Potential of local *Trichoderma* in bioremediation of degraded soil. *Journal of Earth Kingdom, 3*(2), 149-165. https://doi.org/10.61511/jek.v3i2.2026.2749

1. Introduction

Soil is a primary natural resource that plays a vital role in supporting human life, particularly in the agricultural sector. It provides nutrients, a growing medium for plants, and a habitat for various microorganisms that play a role in the biogeochemical cycles of life. According to the FAO (2021), soil is a natural system composed of minerals, organic matter, air, water, and living organisms, and it plays a vital role in maintaining the balance of the global ecosystem. However, soil conditions in Indonesia currently face significant challenges due to increasing degradation over the years.

Soil degradation is the process of decreasing the quality and productivity of soil due to human activities and natural processes, which is characterized by a reduction in organic matter content, a decrease in the soil's ability to store water and nutrients, and disruption of soil structure and biological function (Dragovic & Vulevic, 2020). According to Ambarwulan et al. (2021), the research on the one of the most degraded drylands in Indonesia was dominated by the potentially degraded land classes (38%), followed by the degraded land classes (21%)—the loss of soil productivity causes direct implications for declining agricultural productivity and national food security. Based on data from the Central Statistics Agency/*Badan Pusat Statistik* (BPS) (2022), it was noted that critical land in Indonesia reached 14 million hectares, spread across various provinces, and was largely caused by intensive agricultural practices, land conversion, and unsustainable exploitation of natural resources.

The effect of land degradation not only affects the land degradation located, but it will spread far and wide. Land degradation will be a source of disasters: droughts, floods, landslides, and fires that can impact the acceleration of global warming. As degraded land continues to expand, both in forest areas and outside forest areas, in drylands as well as in wetlands/marshlands, it will result in increasingly severe environmental damage, which drives the occurrence of natural disasters with higher intensity. In agriculture, land degradation caused the decrease the productivity directly reduces crops yields. In economic effect, that reduce revenue for farmers because agricultural land is smaller. In addition, land scarcity will trigger agricultural conflicts.

Land degradation in Indonesia has reached a critical condition along with the rampant expansion of oil palm plantations, monoculture farming, and environmentally unfriendly mining activities, thus triggering, soil erosion rates in Java range from 6 to 12 tons annually each hectare, and degradation affecting 14.0 million hectares, with natural factors contributing 5.0% of the total impact (Yaseen et al., 2025). Furthermore, FAO (2021) reported that global land degradation has affected more than 33% of the world's land, including tropical regions like Indonesia, necessitating sustainable restoration solutions. Soil degradation also disrupts the soil's microbiological balance, resulting in a reduction in the population of microorganisms that play a crucial role in organic matter decomposition, nitrogen fixation, and plant pathogen control (FAO, 2021). To address these challenges, bioremediation presents itself as an environmentally friendly and sustainable solution.

Bioremediation is an environmental restoration approach that relies on the biological capabilities of living organisms, particularly soil microorganisms, to address pollution problems. Through microbial metabolic activity, various contaminants such as toxic organic compounds and heavy metals can be broken down, immobilized, or converted into more stable forms with lower toxicity levels. This process serves to reduce pollution levels and contributes to improving soil conditions, including chemical balance, nutrient availability, and biological activity that supports the sustainability of soil function. Bioremediation is the process of restoring or improving the quality of damaged soil by utilizing the activity of microorganisms, such as bacteria, fungi, or algae, which can degrade or neutralize organic and inorganic pollutants (Ayilara & Babalola, 2023). In the context of environmental management, bioremediation plays an important role as an environmentally friendly and sustainable technology because it utilizes natural mechanisms without causing further harmful impacts on the ecosystem. The application of bioremediation contributes to the restoration of degraded land, the protection of human health, and the prevention of pollutant accumulation in the food chain. Additionally, the improved soil quality resulting from bioremediation has positive implications for land productivity, particularly in the agricultural sector. Thus, bioremediation can be seen as a strategic solution that can be integrated with other environmental technologies to rehabilitate ecosystems effectively and sustainably.

Trichoderma spp. is one of the soil microorganisms widely known in the fields of agricultural biotechnology and bioremediation. *Trichoderma* is a genus of saprophytic fungi that can act as a biological control agent, decomposing organic matter, stimulating plant growth through the production of various enzymes and plant hormones (Harman et al., 2004), and can increase soil aggregation and help plants absorb micronutrients that were previously not directly available (Mukherjee et al., 2019). In addition, *Trichoderma* can produce various enzymes, such as chitinase, glucanase, and protease, which decompose complex organic matter and control the growth of pathogenic fungi (Kumari, et al. 2025).

Various local studies have identified *Trichoderma* isolates with high potential in various regions of Indonesia. For example, Rosfiansyah & Sopialena (2024) studied some indigenous *Trichoderma* sp. from East Kalimantan that can inhibit *Fusarium oxysporum* in tomato. Meanwhile, Hastuti & Hidayat (2019) noted isolates from ex-tin mining soil in Bangka Belitung, Trichoderma crassum, T. virescentiflavum, and T. aff. tomentosum that were tolerant at Cr a concentration of 2 mM. Although most local Indonesian research focuses more on the role of *Trichoderma* as a biocontrol agent and plant growth stimulant, these findings are scientifically relevant for bioremediation because the underlying mechanisms–such as the production of degradative enzymes, competition against pathogenic microbes, and rhizosphere colonization–are also important biological aspects in the degradation of contaminants in the soil. Internationally, meta-analysis shows that *Trichoderma* has tolerance and transformation capabilities against various contaminants, including heavy metals, pesticides, and complex organic compounds, through biosorption, accumulation, and enzymatic degradation mechanisms. This is supported by a literature review stating that this genus is tolerant to pollutant toxicity and has potential as a bioremediation agent for contaminated environments.

Although dozens of national and international studies have demonstrated the effectiveness of *Trichoderma* in bioremediation and soil fertility improvement, data on specific isolates from various provinces in Indonesia remain scattered across national journals, seminar proceedings, and technical reports, and have not been centralized in a single systematic database. This makes it difficult for researchers, molecular industry players, and policymakers to develop innovative biofertilizers and land rehabilitation programs based on local microbes. Therefore, a systematic literature review mapping local Indonesian *Trichoderma* strains and their biological and functional characteristics is urgently needed as a scientific basis and for sustainable agricultural policies.

Therefore, a literature review related to the isolation, taxonomic identification, and biological characterization of local Indonesian *Trichoderma* strains is crucial. This will enable us to assess the functional potential of each strain in decomposing pollutants, controlling pathogens, and improving soil quality and plant growth. Furthermore, writing a scientific paper based on this literature study will be useful in formulating scientifically based recommendations for the development of local *Trichoderma*-based biofertilizers and bioremediation agents as sustainable agricultural innovations.

2. Methods

This research uses a narrative literature review method to examine and assess various scientific sources related to the issue of unsustainable management in the preparation of this essay. This method was used to develop a comprehensive and narrative understanding from various perspectives of relevant literature. The literature from research that is open access and indexed globally. This scientific paper summarizes and presents conceptual and empirical evidence showing that resource management practices that do not consider environmental, social, and economic aspects in a balanced manner have caused various negative impacts, including resource crises, environmental degradation, and social inequality. The writing in this scientific paper is built on a search of academic journals, scientific articles, and policy reports related to conceptual and empirical evidence. The results of this search indicate that unsustainable management practices are still widely found in various sectors, while emphasizing the urgency of changes towards more environmentally sustainable management patterns.

Fig. 1. Research location in Sumatera Island

3. Results and Discussion

3.1 Degradation problems and the urgency of bioremediation

Agricultural development in Indonesia over the past few decades has improved the economy and public welfare, but in some areas, it has resulted in changes or degradation of land resources (Wahyunto & Dariah, 2014). Agricultural land use has both positive and negative impacts, particularly in Indonesia. One negative impact is the decline in soil function (degradation) on agricultural land. For example, oil palm plantations have been heavily contaminated by chemical compounds ranging from fertilizers to pesticides, which impact the physical, chemical, and biological properties of the soil. The impact of land degradation is not limited to a decline in agricultural productivity but also has far-reaching implications for ecosystem stability and human health. The accumulation of heavy metals and toxic compounds in the soil has the potential to contaminate groundwater and enter the food chain, thereby increasing ecological and health risks. Additionally, land degradation worsens environmental resilience to climate change because of the reduced ability of the soil to store carbon and water.

In this context, bioremediation is becoming an increasingly urgent approach to implement as a solution for restoring degraded land. Bioremediation utilizes the natural abilities of microorganisms to decompose, stabilize, or transform soil contaminants into less harmful substances. This approach is regarded as both effective and sustainable because it not only aims to reduce pollution levels but also enhances the restoration of the soil's biological functions. Thus, bioremediation has strategic urgency as an environmentally friendly technology capable of supporting land rehabilitation, maintaining ecosystem balance, and ensuring the sustainable use of soil resources in the future. The extent of degraded land in Indonesia has reached an alarming level, and indications are that the area is increasing. In 2008, 48.3 million hectares of land were severely degraded, or approximately 25.1 percent of Indonesia's total land area (Putri, 2024). One of the main factors causing land degradation is the change in land use from forest to agricultural land.

Intensive agricultural activities without conservation techniques lead to rapid erosion and decreased soil fertility (Saimah & Sarjan, 2024).

Soil degradation is a major issue in the agricultural and environmental sectors in Indonesia. Activities such as mining, excessive use of pesticides and chemical fertilizers, and uncontrolled industrial waste disposal have led to a drastic decline in soil quality. According to Lubis & Kurniawan (2020), soil degradation not only reduces land productivity but also worsens the balance of the soil microbial ecosystem. Therefore, a rehabilitative approach is needed that not only improves the physical and chemical properties of the soil but also maintains environmental sustainability. One technology that has developed in the last decade is bioremediation, a process of restoring contaminated soil using microorganisms that can naturally decompose pollutants.

3.2 The role of Trichoderma in the soil bioremediation process

Bioremediation is a technique that uses living organisms, such as microbes, bacteria, fungi, and plants, to remove contaminants, pollutants, and toxic substances from soil, water, and other environments (Ma'rifah et al., 2024). Bioremediation consists of two words, namely Bio (living things) and Remediation (freeing, suppressing, holding, converting pollutants into harmless materials). There are two basic methods used: ex-situ bioremediation and in-situ bioremediation. In-situ bioremediation is bioremediation by treating contaminated soil and water in its original location. Ex-situ bioremediation requires excavation of the contaminated area for treatment elsewhere, where microbial activity and other parameters can be controlled (Aznur et al., 2022). The bioremediation method used to improve degraded soil is focused on ex-situ bioremediation, which uses microbes for control. One of the microbes used is *Trichoderma*.

Trichoderma belongs to a genus of fungi commonly found in soil and has beneficial properties for plants. The *Trichoderma* genus is cosmopolitan in soil, on woody materials (Kesuma et al., 2024), and on decaying vegetables. *Trichoderma* species are often dominant components of the soil microflora in highly varied habitats (Lestari, 2021). The morphological characterization of *Trichoderma spp.* is distinguished both macroscopically and microscopically. Morphological characters observed macroscopically include colony color and shape. Meanwhile, morphological characters observed microscopically include the shape of conidiophores, phialids, and conidia (Doo et al., 2023).

The use of *Trichoderma* in agriculture has many positive potentials. *Trichoderma* can help plants absorb nutrients, especially phosphorus. Improved nutrient absorption can impact plant growth and development, including seed production (Lestari, 2021). *Trichoderma spp.* plays a role in bioremediation processes, acting as fungi and biological agents against plant pathogens and can enhance plant growth and development in degraded land (Pradana et al., 2023). *Trichoderma* is a genus of soil fungi that has been extensively studied for its potential to improve the quality of contaminated soil. This fungus has the ability to produce lignolytic enzymes such as laccase and peroxidase, which play a crucial role in degrading toxic compounds such as heavy metals, pesticides, and hydrocarbons. According to Andira (2021), *Trichoderma* sp. can degrade the heavy metal Cd in contaminated soil in South Sumatra. Meanwhile, Wang et al. (2024) reported that *Trichoderma harzianum* increased the content of soil organic carbon (SOC) by 27.39%, indicating that *T. harzianum* could enhance soil enzyme activity and promote the transformation of organic matter. In addition to its biodegradation capabilities, *Trichoderma* is known to act as a biocontrol agent, inhibiting the growth of pathogens such as *Rhizoctonia* and *Fusarium* (Abbas et al., 2022; Pereira et al., 2025). This makes *Trichoderma* not only effective as a soil restorer but also as a natural biofertilizer and bioprotectant in sustainable agricultural systems.

Knowledge of *Trichoderma* has expanded, incorporating integrated multidisciplinary approaches exploring its diverse roles as beneficial fungi for plants. By 2025, Trichoderma species will be talented producers of specialised metabolites, with over 200 isolated compounds reported recently, the potential of Trichoderma with ongoing discoveries driven by advanced genomic sequencing and phylogenetic analyses revealing unprecedented diversity in habitats ranging from forest soils to agricultural fields (Jin & Alberty, 2025). Recently, additions such as *T. cerradensis* sp. nov. and *Trichoderma egyptiacum* sp. nov., identified through metagenomic studies in tropical ecosystems (Peixoto et al., 2025; Rashad et al., 2025). *Trichoderma* is recognized as a crucial biotechnological tool in modern agricultural practices, enabling environmentally friendly innovations such as biofertilizers and microbiome engineering for resilient, low-input farming systems worldwide. *Trichoderma* species exhibit remarkable ecological adaptability, particularly in colonizing the rhizosphere and plant root systems. Their capacity for biological control and antagonism highlights their competitive and aggressive nature in occupying ecological niches. Therefore, it is important to evaluate the potential impact of *Trichoderma* on non-target organisms, including plants and soil microbial communities. It is noteworthy that the presence of *Trichoderma* is often considered an indicator of healthy soil (Ratnawati et al. 2023).

Trichoderma core populations are present across a wide range of plant species worldwide, with endemic plants generally supporting higher abundances of antagonistic strains (Ismaiel et al., 2024). Agricultural practices, including planting methods and cultivation practices, significantly influence soil and fungal characteristics in those soils. Vegetation diversity influences both harmful and beneficial fungi. Typically, microbial diversity peaks in the bulk soil and declines in the rhizosphere and endosphere. However, *Trichoderma* inoculation alters bacterial and fungal populations in all these zones (Saimah & Sarjan, 2024). Its application, either alone or in combination with organic compost, has been shown to support plant growth and restructure rhizosphere microbial communities, particularly by increasing phosphorus solubilization and encouraging beneficial microbial consortia (Guzman et al., 2025).

3.3 Potential of local Trichoderma based on region

3.3.1 Sumatra region

Sumatra has a wide variety of land, ranging from agricultural land to former mining areas. Local isolates from Sumatra are often exposed to hydrocarbon contamination from industrial waste and natural resource extraction, as well as high humidity conditions. Isolates from this region show high effectiveness in degrading aliphatic and aromatic hydrocarbons and tolerance to partial anaerobic conditions. Scientifically, the metabolic ability of Sumatran isolation to break down hydrocarbon compounds is stronger than that of isolates from less exposed regions.

Trichoderma isolates from Sumatra have demonstrated outstanding ability to address heavy metal contamination, particularly in former industrial areas. Andira (2021) reported that *Trichoderma* sp. isolated from South Sumatra significantly reduced cadmium (Cd) levels. Remediation effectiveness increased when *Trichoderma* was combined with nutrient-solubilizing bacteria such as *Azotobacter*, which synergistically improved soil structure and enhanced plant growth. This research reinforces the argument that utilizing local microbes adapted to local environmental conditions is more effective than imported biological agents. Furthermore, the use of native microbes is considered safer and more economical because it does not require re-adaptation to Indonesia's tropical climate.

3.3.2 Java region

The Java region generally has soil laden with industrial and intensive agricultural activity, including heavy metal and pesticide residues. Local isolates from Java tend to exhibit high degradation capabilities toward complex organic compounds and agrochemical residues due to adaptation to high pollution pressure and strict microbial competition. Scientifically, Javanese isolates often show increased production of degradative enzymes like peroxidase and laccase, as well as stronger biosorption capabilities for heavy metals due to repeated exposure to pollutants. This makes isolates from Java superior in scenarios with mixed contaminants.

In Java, research on *Trichoderma* isolates has focused more on organic waste remediation and soil pathogen control. Latief et al. (2022) noted that an isolate *Trichoderma harzianum* from a natural forest, East Java, has the potential for bioremediation Mancozeb fungiside, commonly used in potato fields. The Trichoderma harzianum isolated as a soil fungus from a natural forest could grow in the fungicide Mancozeb and reduce the residue of fungicide Mancozeb in soil. Meanwhile, Purwantisari et al. (2021) studied an indigenous *Trichoderma harzianum* isolate from Magelang, Central Java, which was applied as a biocontrol of blight late disease and a biomodulator in potato. The results showed that the application of this fungus was able to serve as an infectious agent and reduce the intensity of late blight disease. Both studies confirmed that local *Trichoderma* isolates from Java have dual functions: as environmental cleanup agents and as agricultural productivity enhancers.

3.3.3 Sulawesi region

Research on local *Trichoderma* from Sulawesi shows high potential for improving nutrient-poor post-mining soil. Rosmana et al*.* (2019) examined a *Trichoderma asperellum* isolate from Sulawesi tested on ex-nickel mining soil. The results showed that this fungus was able to increase the availability of nitrogen and phosphorus in the soil and improve the texture of soil that was previously compact and poor in organic matter. This occurs because the fungus's enzymatic activity can dissolve heavy metal compounds, making nutrients more easily absorbed by plants. Furthermore, *Trichoderma* also acts as a growth promoter for test crops such as corn and soybeans. This finding demonstrates that local Sulawesi microbes are not only capable of rehabilitating damaged land but also strengthening plant resilience to environmental stress. *Trichoderma* sp., indigenous to Gorontalo, is a local isolate originating from agricultural soil in the Gorontalo region and exhibits better environmental adaptation than foreign isolates. The specific advantages of this local *Trichoderma* lie in its efficient decomposition of organic matter, rapid colony growth, and potential antagonism against plant disease-causing pathogens commonly found in local agricultural lands (Pulogu et al. 2025).

In Sulawesi, the potential use of local microbes for soil restoration is further strengthened by the discovery of *Trichoderma* sp. isolates in the rhizosphere of plantation crops. According to Mirta & Rasyid (2023), the presence of this genus in Bulukumba agroforestry land indicates that *Trichoderma* is an integral part of the soil fungal community, capable of surviving on various land cover types. The presence of these native Sulawesi isolates offers significant opportunities for the development of more effective bioremediation technologies, as these fungi have naturally adapted to the physical and chemical characteristics of the region's soil.

The use of *Trichoderma* isolates native to Sulawesi is a strategic, sustainable solution for restoring degraded soil conditions. According to a study by Santillan-Culquimboz et al. (2025), this genus acts as a vital component in cocoa agroecosystems due to its ability to improve soil nutrient availability. Furthermore, the use of these local strains has proven effective in increasing plant resistance to various stresses, both biotic and abiotic. In the context of bioremediation, the success of using local *Trichoderma* is largely determined by its adaptability in modulating plant defense systems according to local environmental characteristics. By optimizing nutrient cycling in specific soil types in Sulawesi, these fungi sustainably support the natural process of soil fertility restoration.

3.3.4 Kalimantan region

Kalimantan, a region experiencing extensive deforestation and coal mining exploitation, has also become a research site for local *Trichoderma*. According to Rosfiansyah & Sopialena (2024), *Trichoderma harzianum*, *T. koningii,* and *T. hamatum* isolates from East Kalimantan can suppress the growth of *Fusarium oxysporum*. T. harzoium potential to reduce the toxicity of heavy metals such as mercury (Hg) in post-mining soil and abiotic stress tolerance, remediation, and degradation potential (Tripathi *et al.* 2013). These isolates exhibit high laccase activity, which plays a crucial role in the degradation of hazardous compounds. When tested on peanut and lemongrass plants, the results showed increased root and stem growth compared to untreated controls (Kamaruzzaman et al., 2016). Another advantage of the Kalimantan isolates is their tolerance to extreme pH conditions and high metal levels, which are major challenges in the bioremediation process of mined land. This research demonstrates that local fungi from Kalimantan have great potential to support ecological and economic land restoration.

Research on more than 58 genera and 35 plant families in various habitats of Kalimantan, Malaysia, has succeeded in isolating various *Trichoderma* species from surface-sterilized root tissue. Based on partial sequence analysis of translation elongation factor-1α (tef1), the identified species include *Trichoderma afroharzianum*, *Trichoderma asperelloides*, *Trichoderma asperellum*, *Trichoderma guizhouense*, *Trichoderma reesei*, Tri*choderma strigosum,* and *Trichoderma virens*. Among all these findings, the taxa *Trichoderma asperellum*/*Trichoderma asperelloides*, *Trichoderma harzianum sl*, and *Trichoderma virens* were recorded as the most dominant or most frequently isolated groups (Cummings et al. 2016).

Local *Trichoderma* isolates obtained from the Sarawak region of Kalimantan exhibit superior physiological characteristics in the form of highly aggressive mycelial growth rates. According to research by Wilson et al. (2022), these isolates were able to fill the entire surface of the agar medium within three days of incubation, with an average daily growth rate ranging from 22.2 to 28.8 mm. In the context of remediating degraded soil (bioremediation), this rapid colonization ability is an important indicator. This allows the fungus to quickly dominate the ecological space, accelerate the decomposition process of organic matter, and suppress the growth of pathogenic microorganisms in critical lands of Kalimantan that experience extreme environmental pressures.

The use of local *Trichoderma* species from Kalimantan has strategic potential as a bioremediation agent due to its ability to rapidly and massively colonize degraded soils. Based on research by Saragih et al. (2022), a variety of isolates, such as T. hamatum and T. viride, demonstrated functional effectiveness in improving soil biological quality through enzymatic activity that decomposes complex organic matter. This mechanism is crucial in Kalimantan because these fungi can increase the availability of bound soil nutrients while simultaneously improving soil structure damaged by intensive agricultural or plantation practices. Furthermore, the potential of local *Trichoderma* lies in its ability to produce abundant conidia, thus ensuring the sustainability of the nutrient recovery process through the formation of a stable fungal biomass in the subsoil. With aggressive growth characteristics and adaptability to the local tropical climate, the use of these native Kalimantan strains is key to accelerating the restoration of soil ecosystems that have lost their natural carrying capacity.

3.4 Comparison of the effectiveness of local isolates between regions

The effectiveness of local microbial isolates in soil bioremediation is influenced by local environmental conditions, contaminant characteristics, and the genetic adaptation of microbes to local ecosystem conditions. Each region in Indonesia has different soil profiles, climates, and pollution loads, so local isolates from each region also show different responses to the bioremediation process. Comparison of *Trichoderma* in Table 1. Although Trichoderma isolates from various regions in Indonesia have bioremediation capabilities, their native environmental conditions greatly influence their effectiveness.

According to a study by Tansengco et al. (2018), *Trichoderma virens, T. harzianum, T. gamsii, T. saturnisporum* can tolerate high levels of Cr and Pb. Which indigenuos isolates from mining areas in Kalimantan and Sulawesi (. That is more adaptable to heavy metals, while isolates from agricultural areas such as Java are superior in pathogen control and organic waste processing. This effectiveness is also related to the ability of each isolate to produce specific enzymes. For example, Trichoderma sp. produces peroxidase enzymes, which are efficient in degrading biotic stress (Hazimah et al., 2025), while *Trichoderma asperellum* produces chitinase, which is useful in attacking the cell walls of plant pathogens (Rosyida et al., 2022). In other words, the use of Trichoderma in bioremediation must consider the compatibility between the isolate's characteristics and the type of pollutant in a particular region.

Table 1. Comparison of *Trichoderma*

Region	Species of *Trichoderma*	Types of Contamination	Remediation Potential	Refferences
Sumatra	*Trichoderma sp.*	Heavy metal (Cd)	Decreasing the rate of Cd to 63%	Putri (2024)
East Java	*Trichoderma harzianum*	Bioremediation	Bioremediation in fungicide soil	Latief et al. (2022)
Central Java	*Trichoderma harzianum*	Biomodulator and biocontrol	Infectious agent	Purwantisari et al. (2021)
Sulawesi	*Trichoderma sp.*	biofungicide against Colletotrichum	Inhibit pathogen	Gusnawaty et al. (2014)
Kalimantan	*Trichoderma viride T. harzianum, T. koningii*	Bioremediation	P uptake	Savira et al. (2024)

3.5 Innovation in Trichoderma application in bioremediation technology

Trichoderma has various functions in its application, including biopesticide and bioremediation. One innovation that has utilized *Trichoderma* as a biopesticide is nano-bioformulation. Nano-bioformulations prepared using biological sources of nanoparticles are potential organic pesticides, which could be an important component of organic agriculture. This opens up the possibility of reduced use of synthetic pesticides, ultimately reducing pesticidal pressure on the environment (Nandini et al. 2024).

Table 2. Innovation of *Trichoderma*

Innovation	Potential	Refferences
nano-bio formulation	Organic pesticide	Nandini et al. (2024)
Trichoma + Biochar	Bioremediation	Martins et al. (2025)
Trichoma + T-mix	Bioremediation and Biofungisida	Anandan et al. (2026)
Biological Mecanism/ Fitobial	Bioremediation	Tripathi et al. (2013); Abbas et al. (2014)
Bioabsorption	Bioremediation	Awasthi et al. (2017)
Intregated system	Bioremediation	Pastor et al. (2023)

Trichoderma plays a dominant role as a bioremediation agent for soil contaminated with heavy metals or residues detrimental to soil biological sustainability. As environmental technology advances, various *Trichoderma*-based innovations are being developed to increase bioremediation efficiency. One approach currently being implemented is the use of Trichoderma sp. mixed with organic materials such as biochar, which can improve the root architecture, rhizosphere, soil chemical and biological properties in a regenerating area (Martins et al., 2025; Anandan et al. 2026).

From a biological mechanism perspective, *Trichoderma* is also very useful as a biological or phytobial remediation tool for environmental contaminants (Tripathi et al. 2013; Abbas et al. 2014). This innovation aims to extend the lifespan of fungi in the soil and increase their enzymatic activity. Furthermore, *Trichoderma* plays a role in bioabsorption:

the *Trichoderma* sp. was found to be an excellent fungal agent for Cd^{2+} absorption. It is an innovative tool for the bioremediation of metal-contaminated municipal solid waste leachate (Awasthi et al. 2017).

From a system integration perspective, *Trichoderma* can play an optimal role when combined with other microorganisms. Research by Pastor et al. (2023) shows that combining *Trichoderma* with other microbes, such as *Pseudomonas fluorescens* or *Bacillus subtilis*, can accelerate the remediation process of hydrocarbon-contaminated soil. Drone-based applications and soil sensors to map contaminated areas and regulate inoculum distribution are also being tested in several industrial areas. This breakthrough demonstrates that the use of *Trichoderma* is no longer limited to conventional methods but can be integrated with precision technology.

3.6 Challenges and prospects for local Trichoderma development in bioremediation

Trichoderma is soilborne and associated with plant roots and is commonly considered for its potential to control plant diseases, with many aspects of its endophytic association characteristic (Haryadi et al. 2019). These fungi colonize the root epidermis and outer cortical layers and also release bioactive compounds that cause walling off of the *Trichoderma* thallus. Alma'sum et al. (2025) found that *Trichoderma* sp. is relatively abundant in nature, especially in soils with high organic matter content. *Trichoderma* sp. is known as a natural antagonist capable of suppressing the growth of various pathogens that cause plant diseases, such as *Fusarium oxysporum*, *Rhizoctonia solani*, and *Phytophthora palmivora*.

The use of fungi that has an antagonistic role is expected to be an effort to protect plants, soil and save harvests while increasing productivity and production quality. *Trichoderma spp.* functions as a decomposer to produce organic fertilizer (Darotin et al., 2023). The use of local biological agents in the form of Indigenous *Trichoderma spp.* that have adapted to their native environment can be an effective biological control in their area. Biological control is locally specific, that is, antagonistic microorganisms found in an area will only produce good results in their area of origin (Berlian et al., 2016).

Although the potential of local *Trichoderma* species in soil bioremediation is very promising, several challenges remain in its application in the field. One major challenge is the limited data on the physiological and genetic characteristics of local isolates from various regions in Indonesia. According to Moreno et al. (2025), the widespread application of the most studied Trichoderma strains has been limited by discrepancies between their potential results observed in controlled environments and the outcomes in greenhouses and field conditions. This means that laboratory successes may not necessarily translate into practical solutions applicable on a large scale.

Furthermore, the availability of formulation technology and isolate storage remains a challenge, especially in areas lacking adequate research facilities. Other challenges arise from social and policy perspectives. Trichoderma-based inoculants as crop amendments are promising, considering the multipurpose use of these fungal strains in agricultural systems and also the wide range of pathogenic biocontrol and their capability of the strains of this genus to establish symbiotic relationships with almost all kinds of plant crops, thus contributing to the development of sustainable agrosystems (Ramírez-Cariño et al., 2025). Education, training, and regulatory support are needed to ensure that the use of local microbes becomes part of the national sustainable land management program.

However, the prospects for developing local *Trichoderma* are very promising. Support from environmentally friendly agricultural programs, government initiatives on critical land restoration, and the trend of regenerative agriculture present significant opportunities for the development of biological microbial applications. Research based on molecular technology has also begun to identify bioremediation genes, such as Metagenomic analysis, which opened new frontiers to analyze microbial communities, their genetic diversity, and metabolic pathways. It has provided opportunities to discover microbial consortia and genes involved in the bioremediation of xenobiotic compounds (Chandran et al. (2020).

The prospects for developing local *Trichoderma* are very promising. Support from environmentally friendly agricultural programs, government initiatives on critical land restoration, and the trend of regenerative agriculture present significant opportunities for the development of biological microbial applications. Research based on molecular technology and bioinformatics has also begun to identify genes.

4. Conclusions

Soil degradation in Indonesia is a serious challenge impacting agricultural productivity and environmental sustainability. This study demonstrates that local *Trichoderma* species have significant potential as bioremediation agents, capable of degrading pollutants, improving soil structure, and suppressing pathogen growth. Each isolate from different regions exhibits unique biological and functional characteristics, relevant to the pollution conditions in their respective regions.

Despite its promising potential, the utilization of local *Trichoderma* species still faces challenges, such as limited isolate data, limited technology adoption in the field, and a lack of regulatory support. Therefore, cross-sector collaboration is needed to encourage applied research, biofertilizer product development, and farmer education so that local *Trichoderma* can be optimized as a sustainable agricultural solution in Indonesia.

The application of this technology needs to be integrated into the national soil restoration program and supported by community-based initiatives that utilize local microbes. Policy support, evidence-based technical implementation, and strengthening advanced research are key to improving the effectiveness and sustainability of bioremediation in future soil management.

Acknowledgement

The authors sincerely thank the reviewers for their constructive feedback that significantly enhanced the manuscript and expresses to colleagues and mentors for their guidance and support during the research.

Author Contribution

The authors were involved in formulating the research idea, designing the study, collecting and analyzing the data, and preparing the manuscript. All authors took part in writing, revising, and giving final approval for the manuscript to be published.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

The author declares that no generative artificial intelligence tools were used in the preparation, writing, analysis, or editing of this manuscript. All contents were produced entirely through the authors’ own reasoning, interpretation, and analysis based on existing data and published literature.

Open Access

References

Abbas, A., Mubeen, M., Zheng, H., Aamir, M. S., Shakeel, Q., Kumar, M. S., Iftikhar, Y., Sharma, S., Kumar, B. K., Hussain, S., del Carmen, M. Z. R., Moya- Elizondo, E. A., Zhou L. (2022). Trichoderma spp. Genes involved in the biocontrol activity againts Rhizoctonia solani. *Frontiers in Microbiology, 13*, 884469. https://doi.org/10.3389/fmicb.2022.884469

Alma'sum, M. L., Ramadhan, R. Arif, Malik., & Dewi, S. M. (2025). Isolasi, Pemurnian, dan Identifikasi *Trichoderma* sp. dari Rhizosfer Bambu. *Jurnal Pertanian Cemara, 22*(2). https://ejournal.wiraraja.ac.id/index.php/FP/article/view/4783

Ambarwulan, W., Nahib, I., Widiatmaka, W., Suryanta, J., Munajati, S., Suwarno, Y., Turmudi, Darmawan, M. & Sutrisno, D. (2021). Using Geographic Information Systems and the Analytical Hierarchy Process for Delineating Erosion-Induced Land Degradation in the Middle Citarum Sub-Watershed, Indonesia. *Frontiers in Environmental Science, 9*. https://doi.org/10.3389/fenvs.2021.710570

Anandan, S., Ali, A., Selvarajoo, A., Supramaniam, V. C. (2026). Trichoderma combined with palm kernel shell biochar promotes root health and rhizosphere biodiversity in young oil palm seedlings infected with Ganoderma boninense. *Frontiers in Microbiology, 13*(5). https://doi.org/10.3389/frmbi.2026.1742803

Andira, P. (2021). *Utilization of Trichoderma sp. and Azotobacter in bioremediation of soil contaminated with heavy metal Cd in South Sumatra.* UIN Syarif Hidayatullah Jakarta.

Ayilara, M. S. & Babalola O. O. (2023). Bioremediation of environmental waste: the role of microorganisms. *Frontiers in Agronomy, 5*. https://doi.org/10.3389/fagro.2023.1183691

Aznur, B. S., Nisa, S. K., & Septriono, W. A. (2022). Potential Biological Agents for Heavy Metal Bioremediation. *Maiyah Journal*, *1*(4), 186–198. https://doi.org/10.20884/1.maiyah.2022.1.4.7442

Awasthi, A. K., Pandey, A. K. & Khan, J. (2017). Biosorption an innovative tool for bioremediation of metal-contaminated municipal solid waste leachate: optimization and mechanisms exploration. *International journal of Environmental Science and Technology, 14*(4), 729–742. https://doi.org/10.1007/s13762-016-1173-2

Berlian, I., Anarqi, S., & Pudjihartati, E. (2016). Isolasi, Identifikasi dan Antagonisme *in Vitro* Isolat *Trichoderma Spp.* Asal Kebun Karet Blimbing, Pekalongan, Jawa Tengah. *Jurnal Penelitian Karet, 34*(2), 201-212. https://doi.org/10.22302/ppk.jpk.v34i2.231

BPS. (2022). *Indonesia's Critical Land Statistics 2022*. Badan Pusat Statistik Indonesia.

Chandran, H., Meena, M. & Sharma, K. (2020). Microbial Biodiversity and Bioremediation Assessment Through Omics Approaches. *Frontiers in Environmental Chemistry, 1,* 570326. https://doi.org/10.3389/fenvc.2020.570326

Cummings, N. J., Ambrose, A., Braithwaite, M., Bissett, J., Roslan, H. A., Abdullah, J., Stewart, A., Agbayani, F. V., & Hill, R. A. (2016). Diversity of root-endophytic *Trichoderma* from Malaysian Borneo. *Mycological Progress*, *15*(5), 50. https://doi.org/10.1007/s11557-016-1192-x

Darotin, T., Agustiani, R. D., & Ekawandani, N. (2024). Perbanyakan Agen Pengendali Hayati pada Media Jagung dan Beras untuk Pertumbuhan *Trichoderma Spp.* di UPTD Balai Perlindungan Perkebunan Dinas Perkebunan Provinsi Jawa Barat. *Jurnal Biosains Medika,* *2*(1), 1-7. https://ejournal.iwu.ac.id/index.php/biosains_medika/article/view/95

Doo, S. R. P., Meitiniarti, V. I., Kasmiyati, S., Betty, E., & Kristiani, E. (2023). *Trichoderma spp.*, The Multi-Function Mushroom *Trichoderma*. *Tropical Microbiome Journal*, *1*(1), 73–89. https://ejournal.uksw.edu/jtm/article/view/10659

Dragovic, N., & Vulevic, T. (2020). Soil Degradation Processes, causes and Assessment Approaches. In W. Leal Filho, A. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Life on land. Encyclopedia of the UN Sustainable Development Goals.* Springer.

FAO. (2021). *Status of the World's Soil Resources 2021.* Food and Agriculture Organization.

Gusnawaty, H. S., Taufik, M., & Herman. (2014). Efektifitas *Trichoderma* Indigenus Sulawesi Tenggara Sebagai Biofungisida Terhadap Colletotrichum Sp. Secara In- Vitro. *Jurnal Agroteknos*, *4*(1), 38-43. http://dx.doi.org/10.56189/ja.v4i1.204

Guzman, P., Etesami, H. & Santoyo, G. (2025). *Trichoderma:* a multifunctional agent in plant health and microbiome interactions. *BMC Microbiology, 25*, 434. https://doi.org/10.1186/s12866-025-04158-2

Hastuti, A. & Hidayat, I. (2019). Screening and molecular identification of Cr(VI)-resistant Trichoderma isolated from ex-tin mining soil in Bangka Belitung Province, Indonesia. IOP Conf. *Series: Earth and Environmental Science, 308*, 012011. https://doi.org/10.1088/1755-1315/308/1/012011

Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). *Trichoderma* species—opportunistic, avirulent plant symbionts. *Nature Reviews Microbiology, 2*(1), 43–56. https://doi.org/10.1038/nrmicro797

Haryadi, D., Sidhu, M. S., Panjaitan, T., Hendra, H., & Chong Khim Phin. (2019). The Potencial of Endophytic *Trichoderma* from Oil Palm (*Elaeis guineensis* Jacq.) Roots of North Sumatra, Indonesia Against. *Journal of Oil Palm Research, 31*(4), 592- 603. https://doi.org/10.21894/jopr.2019.0049

Hazimah, N., Taufikurahman, T., & Iriawati. (2025). Application of Trichoderma sp. for Enhancing Growth and Defence Mechanism of Red Chilli (*Capsicum annuum* L.) Cultivated Under Aluminum Stress. *Current Research on Biosciences and Biotechnology, 6*(2), 28-35. https://doi.org/10.5614/crbb.2025.6.2/JQU3BSWW

Ismaiel, A., Lakshman, D. K., Jambhulkar, P. P., & Roberts, D.P. (2024). *Trichoderma*: Population Structure and Genetic Diversity of Species with High Potential for Biocontrol and Biofertilizer Applications. *Applied Microbiology, 4,* 875 – 893. https://doi.org/10.3390/applmicrobiol4020060

Kamaruzzaman, M., Rahman., M. M., Islam., M. S., & Ahmad., M. U. (2016). Efficacy of four selective Trichodermaisolates as plant growth promoters in two peanut varieties. *International Journal of Biological Research,* *42*(2),152-156. https://doi.org/10.14419/ijbr.v4i2.6468

Kesuma, L. R., Mayasari, U., & Nasution, R. A. (2024). The Potential of *Trichoderma* sp. as a Bioremediation Agent for Palm Oil Liquid Waste. Spizaetus: *Journal of Biology and Biology Education*, *5*(2), 238. https://doi.org/10.55241/spibio.v5i2.419

Kumari, R., Koul, B., Kumar, V., Kumar, A., Kaur, M., & Kumar, R. S. (2025). Protease and chitinase activity of Trichoderma isolates and their synergy with biochar in enhancing chickpea defense related enzymes. *Frontiers in Microbiology, 16.* https://doi.org/10.3389/fmicb.2025.1699251

Latief, A. A., Abdul, F. C., Oktavianita, M., Arinata, N., Syamsul, M. H., & Setiawan, Y. (2022). Screening of soil fungi as bioremediation fungicide and its effect on growth of potato plants. *Biodiversitas, 23*(3). https://doi.org/10.13057/biodiv/d230351

Lestari, N. K. P. P. (2021). Uji Efektivitas Biofungisida Trichoderma sp. dan Media Tanam Terhadap Karakter Agronomi Bibit Kakao (*Theobroma cacao L.).* Politik Negeri Lampung.

Martins, E., Martins, A. P., Costa, D. P., Felix, R. F., Luiz, E. L., Conceicao, M. S., Alves, J. B., Alberto, C. F., Romualdo, J. S., Pereira, G.D., Hammecker, C., Valente, E. M. (2025). Potential of biochar inoculated with Trichoderma to improve soil chemical and biological properties in a regenerating area. *Journal of Arid Environments, 230*. https://doi.org/10.1016/j.jaridenv.2025.105430

Mirta, B., & Rasyid, B. (2023). Exploration of mahogany and cocoa rhizosphere fungi as agroforestry land cover in Herlang District, Bulukumba Regency. In *IOP Conference Series: Earth and Environmental Science*, *1230*(1), 012073. https://doi.org/10.1088/1755-1315/1230/1/012073

Ma'rifah, A. U., Anggraito, Y. U., & Setiati, N. (2024). Literature Review: Metallothionein As a Metal-Binding Protein for Heavy Metal Bioremediation. *BIOPENDIX: Journal of Biology, Education and Applied Sciences*, *10*(2), 186–193. https://doi.org/10.30598/biopendixvol10issue2page186-193

Moreno, K. G., Olguin-Martinez, A. I., Montoya-Matinez, A. C., & Santos Villalobos, S. (2025). Trichoderma in Sustainable Agriculture and the Challenges Related to Its Effectiveness. *Diversity, 17,* 734 https://doi.org/10.3390/d17100734

Mukherjee, P. K., Horwitz, B. A., Herrera-Estrella, A., Schmoll, M., & Kenerley, C. M. (2019). *Trichoderma* research in the genome era: new perspectives. *Annual Review of Phytopathology, 57*, 123–142. https://doi.org/10.1146/annurev-phyto-082712-102353

Nandini, M. L. N., Ruth, C. H., Maheswari, T. U. (2024). Development of next-gen nano-bio formulation of *Trichoderma asperellum* against soil borne pathogens. *International Journal of Research in agronomy*. https://doi.org/10.33545/2618060X.2024.v7.i4i.620

Pastor, N., Palacios, S. & Torres, A. M. (2023). Microbial consortia containing fungal biocontrol agents, with emphasis on Trichoderma spp.: current applications for plant protection and effects on soil microbial communities. *European Journal of Plant Pathology*, *167*, 593-620. https://doi.org/10.1007/s10658-023-02773-1

Peixoto, G. H. S., da Silva, R. A. F., Zacaroni, A. B., Silva, T. F., Chaverri, P., Pinho, D. B., & de Mello, S.C.M. 2025. Trichoderma collection from Brazilian Soil Reveals a New Species: T. ceradensis sp. Nov. *Frontiers in Microbiology*. https://doi.org/10.3389/fmicb.2025.1279142

Pereira, L. S., Luccrecia, A. S., Alina, V. C. B., Pablo, S. R. (2025). Bioactive proteins from *Trichoderma* for the control of *Fusarium*: Evaluation of antagonist efficacy and potential for agronomic application. *Biocatalysis and Agricultural Biotechnology, 67,*103628. https://doi.org/10.1016/j.bcab.2025.103628

Pradana, A. P., Astuti, D. F., Kurniawan, I., Lestari, A. P., Regar, D. A. H. B., Istiqomah, T. F. N., Damayanti, D. I., Putra, A. T., Dellasyah, B. L., Sholikhin, M. I., Niswah, A., Wafa, A., & Prastowo, S. (2023). Bioremediation Technology Using *Trichoderma* Sp. to Increase Agricultural Productivity on Former Sand Mining Land in Mrawan Village, Jember. Selaparang. *Journal of Progressive Community Service, 7*(2), 912. https://doi.org/10.31764/jpmb.v7i2.14144

Pulogu, Siska, I., Iswati, R., & Idrus, T. (2025). Edukasi Pemanfaatan *Trichoderma* sp. Indigenus Gorontalo dalam Mendukung Pertanian Organik di Desa Tunggulo Kabupaten Bone Bolango. *Journal of Community Service, 5* (2). https://jurnal.umsrappang.ac.id/mallomo/article/view/2049

Purwantisari, S., Sitepu, H., Rukmi, I., Lunggani, A. T. & Budihardjo, K. (2021). Ingenous Trichoderma arzianum as Biocontrol toward Blight Late Disease and Biomodulator in Potato Plant Productivity. *Journal of Biology & Biology Education, 13*(1), 26-33. http://dx.doi.org/10.15294/biosaintifika.v13i1.26706

Putri, F. A. (2024). The Impact of Land Degradation on the Sustainability of Rice Farming in Indonesia: Results of an Integrated Agricultural Survey (SITASI) 2021. *Seminar Nasional Official Statistics, 2024*(1), 111–116. https://doi.org/10.34123/semnasoffstat.v2024i1.2024

Ramírez-Cariño, H. F., Guadarrama-Mendoza, P. C., Romero-Cortes, T., Cuervo-Parra, J. A., Valadez-Blanco, R. (2025). Exploring the potential benefits of *Trichoderma* species in agro-industrial crop production. In K. A. Abd-Elsalam & A. H. Hashem (Eds.), *Fungal endophytes: Volume II.* Springer. https://doi.org/10.1007/978-981-97-8804-0_9

Rashad, Y. M., Shabana, Y. M., & Deng J. X. (2025). Trichoderma biodiversity from Egypt and a new Trichoderma species, Trichoderma egyptiacum sp. nov. (Hypocreaceae, Hypocreales). *Mycological Progress, 24*(33). https://doi.org/10.1007/s11557-025-02052-9

Ratnawati, Arfan, Jaya, K., & Mufida. (2023). Storage Capacity and Growth Rate of *Trichoderma asperellum* TR3 in Various Packaging. *Agrotech Journal, 13*(1), 34–39. https://doi.org/10.31970/agrotech.v13i1.112

Rosfiansyah & Sopialena. (2024). Identifikasi dan Uji Antagonis *Trichoderma* spp. Indigenus Beberapa Daerah Kalimantan Timur Terhadap Penyebab Penyakit Layu Tomat (*Fusarium oxysporum*). *Jurnal Agroekoteknologi Tropika Lembab, 7*(1), 26-34. http://dx.doi.org/10.30872/jatl.7.1.2024.15630.26-34

Rosmana, A., Sakrabani, R., Sjam, S., Nasaruddin, N., Asman, A., & Pandin, B. Y. S. (2019). Plant residue based-composts applied in combination with trichoderma asperellum improve cacao seedling growth in soil derived from nickel mine area. *Journal of Animal and Plant Sciences, 29*(1), 291-298. https://dspace.lib.cranfield.ac.uk/bitstreams/406de4d6-f08d-498e-8e41-38281d8e0cfc/download

Rosyida, R., Martosudiro, M., & Muhibuddin, A. (2022). Analysis of Chitinase Enzyme Trichoderma sp. in Degrading *Fusarium oxysporum*. *Research Journal of Life Science*. *9*(3),131-145. https://doi.org/10.21776/ub.rjls.2022.009.03.5

Saimah, W., & Sarjan, M. (2024). The Balance Between Land Use and Conservation: Land Degradation in Sekaroh Village, Jerowaru District, East Lombok. *Lambda: Journal of Mathematics and Natural Sciences Education and Its Applications, "Bale Literasi" Institute*, 4(3), 2809–4409. https://doi.org/10.58218/lambda.v4i3.1006

Santillan-Culquimboz, H. W., Leiva, S. T., Munoz-Salas, M. N., Meza-Maicelo, W., Lozano-Isla, F., Oliva-Cruz, M., & Balcázar-Zumaeta, C. R. (2025). Ecology and functions of *Trichoderma* in coffee and cocoa agroecosystems: bibliometric and systematic insights for sustainable agriculture. *Frontiers in Mictrobiology*, *16*, 1717484. https://doi.org/10.3389/fmicb.2025.1717484

Saragih, R., Simanjorang, M., Angrelina, I., Irvanto, D., Retnosari, E., Murgianto, F., & Ardianto, A. (2022, February). Exploration, identification, and in vitro antagonism test of *Trichoderma spp.* against Ganoderma *spp.* at PT Bumitama Gunajaya Agro palm oil plantation, Central Kalimantan. *IOP Conference Series: Earth and Environmental Science, 976*(1). https://doi.org/10.1088/1755-1315/976/1/012043

Savira, V., Suci, U. Y. & Sulakhudin. (2024). Ability of several types of trichoderma isolates on ultisol and peat soil against p uptake and soybean plant growth (*Glycine max* L.). *Jurnal Pertanian Agros, 26*(1), 5690-5698. http://dx.doi.org/10.37159/jpa.v26i1.4237

Tripathi, P., Singh P. C., Mishra, A., Chauhan., P. S., Dwivedi, S., Bais., R. T., & Tripathi R.D. (2013). *Trichoderma*: A Potential Bioremediator for Environmental Clean-up. *Clean Techn Environ Policy, 15*, 541–550. https://doi.org/10.1007/s10098-012-0553-7

Wahyunto, & Dariah, A. (2014). Land Degradation in Indonesia: Existing Conditions, Characteristics, and Standardized Definitions to Support the Movement Toward a Single Map. *Journal of Land Resources,* 8(2), 81–93. https://doi.org/10.2018/jsdl.v8i2.6470

Wang, J., Mu, H., Liu, S., Qi, S., & Mou S. (2024). Effects of *Trichoderma harzianum* on Growth and Rhizosphere microbial Community of Continuous Cropping *Lagenaria siceraria*. *Microorganism, 12*(10), 1987. 10.3390/microorganisms12101987

Wilson, J. F., Zuki, A. A., & Kwan, Y. (2022). Characterisation of *Trichoderma spp.* and Assessment as Biocontrol Using Dual Culture Assay Against Fungi Associated with

Black Pepper (Piper nigrum L.) Diseases in Sarawak. *Borneo Journal of Resource Science and Technology*, *12*(1), 60–72. https://doi.org/10.33736/bjrst.4358.2022

Yaseen, U., Denita, R., Nurbaity, A., Natalie, B.F., Yudha, S.S. & Zaviera R.D. (2025). Soil erosion and food security in Asia's most populous nations: a systematic review from China, India, and Indonesia. *Discover Soil, 2*(60). https://doi.org/10.1007/s44378-025-00091-y

Biographies of Authors

Bima Iqbal Ghifari, Department of Agroecotechnology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: khalidbilalhamzah@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Muhammad Rasyid Ridho, Department of Agricultural Industry Technology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: mrasyidridho1406@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Reggina Sonia Putri, Department of Soil Science, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: spreggina@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Syahwa Fitria Maharani Wagino, Department of Agroecotechnology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: syahwafm@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Wahda Zahra Azizah, Department of Agribusiness, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: wahda.zahra.a.05@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Muhimmatul Husna, Department of Agroecotechnology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: mhusna@unib.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Iffah Izzatuddinillah, Department of Soil Science, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: iffah.izzatuddinillah@unib.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Rahayu Arraudah, Department of Agroecotechnology, Faculty of Agriculture, Universitas Bengkulu, Bengkulu City, Bengkulu 38122, Indonesia.

- Email: rahayuarraudah@unib.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A