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Bioremediation of Former Coal Mining Land Using Natural Organic Matter

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Abstract
Background: Post-coal-mining soils are typically characterized by severe edaphic degradation, including acidic pH, low cation exchange capacity (CEC), nutrient deficiencies, and reduced microbial activity.
Methods: This study evaluated the effectiveness of compost, manure, and biochar applied at 0%, 2.5%, 5%, and 10% (w/w) in improving soil properties through a twelve-week ex situ bioremediation process. Measured parameters included pH, CEC, total N, available P and K, organic C, moisture, and microbial dynamics, with Zea mays used as an agronomic indicator.
Results: Biochar produced the largest increases in soil pH and CEC, while compost and manure more effectively enhanced organic carbon and nitrogen mineralization. Soil pH improvement followed first-order kinetics with treatment-specific rate constants. The 10% amendment rate yielded the highest Zea mays growth.
Conclusion: Overall, compost, manure, and biochar effectively improved post-mining soil quality, nutrient availability, and corn growth, with biochar showing the strongest overall effect. These amendments offer economical, environmentally friendly alternatives for sustainable bioremediation, reclamation, and revegetation of former coal mine land.

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INTRODUCTION

Coal mining is a major global economic activity, but large-scale extraction has generated extensive land degradation challenges worldwide. Post-mining landscapes are commonly characterized by disturbed soil structure, nutrient depletion, acid mine drainage risks, and reduced ecological functionality, creating long-term challenges for reclamation and sustainable land use.

Indonesia, including South Kalimantan as one of the major coal-producing regions, faces similar reclamation challenges. Former coal mining areas, such as the research site in Banjar Regency, exhibit severe soil degradation, including acidic conditions, low organic carbon content, limited nutrient availability, and reduced biological activity, all of which restrict vegetation establishment.

Large-scale coal mining activities have had serious impacts on soil quality, particularly its physical, chemical, and biological properties. One of the most critical problems in former mining land is extremely acidic soil, with pH values below 3, low organic matter content, very low cation exchange capacity (CEC), and severely reduced populations and activity of soil microorganisms. These extreme conditions arise from the oxidation of sulfide minerals, particularly pyrite (FeS_2), which produces large amounts of H^+ ions and increases the concentrations of Al^{3+} and Fe^{2+}, both of which can be toxic to plants and microorganisms. As a result, the soil loses much of its capacity to support biological activity and undergoes severe degradation.

Reclamation efforts on former mining land are generally carried out through the addition of ameliorants, particularly organic materials such as compost, manure, and biochar. Organic matter can improve the chemical properties of soil by increasing pH, reducing Al^{3+} toxicity, increasing CEC, and enhancing nutrient availability. In addition, organic matter contributes to improvements in soil structure and increases the activity of soil microorganisms, which is an important indicator of soil health. However, the effectiveness of each ameliorant differs in terms of its mode of action, persistence of soil improvement, and rate of reaction in neutralizing soil acidity (Bandyopadhyay & Maiti, 2019; Guo et al., 2018; Zhou et al., 2026).

An important problem in post-mining land is the low activity and abundance of soil microorganisms caused by extremely acidic pH conditions and a lack of organic carbon. In fact, microorganisms are major components of organic matter decomposition, nutrient cycling, and soil aggregate formation (Mummey et al., 2002; Wang et al., 2025; Wu et al., 2026). Therefore, restoration of soil biological conditions is highly dependent on the successful chemical amelioration of the soil, particularly through an increase in soil pH.

Soil organic matter (SOM) plays an important role in improving soil structure and fertility. High organic matter content is generally correlated with increased soil quality and biological activity (Bandyopadhyay & Maiti, 2019; Zhou et al., 2026). Soil microorganisms are also known to be highly sensitive to changes in soil quality and can therefore be used as indicators of the success of post-mining land reclamation (Doran & Parkin, 2024; Feng et al., 2019).

Soil microorganisms are involved in the decomposition of organic matter and are highly sensitive to changes in soil quality; therefore, they can be used as indicators of the success of post-mining land reclamation (Feng et al., 2019; Mummey et al., 2002; Wang et al., 2025; Wu et al., 2026). In addition, revegetation and the application of organic matter have been demonstrated to improve soil quality and support plant growth on former mining land (Ghosh & Maiti, 2026; Gu et al., 2020; Guo et al., 2018; Kumar et al., 2015) .

Former coal mine land generally has serious problems, such as low soil pH, nutrient deficiencies, and degradation of soil structure. Revegetation can improve soil properties and promote the recovery of soil microorganisms (Ghosh & Maiti, 2026; Gu et al., 2020; Guo et al., 2018; Kumar et al., 2015; Lin et al., 2026; Karmaita et al., 2026).

The purpose of this study is to identify and analyze the chemical, physical, and biological properties of soil, including pH, CEC, N, P, and K, on former coal mine land before and after ex situ treatment with organic matter. This research is expected to help accelerate the restoration of the ecological functions of former mining land so that it can be reused productively by local communities.

Previous studies have demonstrated that organic amendments improve reclaimed mine soils through different mechanisms. Biochar has been reported to increase pH and CEC through its alkaline characteristics and porous structure, whereas compost and manure contribute more strongly to organic carbon accumulation, nutrient cycling, and microbial recovery. However, previous research has generally examined the effects of individual amendments or focused on a limited number of soil indicators. Comparative evaluations integrating chemical, physical, and biological responses under different amendment application rates remain insufficient. Therefore, this study introduces a comprehensive assessment of compost, manure, and biochar at multiple application rates to evaluate their distinct contributions to post-mining soil restoration.

This research is designed to provide a comprehensive overview of strategies for restoring the quality of former coal mining land through the use of natural organic matter as a bioremediation medium. The main focus of the research is directed toward improving soil conditions that have undergone severe degradation due to mining activities, particularly with respect to the chemical, physical, and biological properties of the soil. The main concerns are extremely acidic soil conditions, low nutrient availability, low CEC, and minimal microbial activity, all of which make it difficult for the soil to naturally support vegetation growth. The manuscript explains that post-coal-mining land generally experiences severe edaphic degradation characterized by highly acidic pH, low CEC, nutrient deficiencies, and minimal microbiological activity. This study uses a quantitative experimental approach to evaluate the effectiveness of organic matter treatments in improving the quality of former mining soil in a measurable and systematic manner (Creswell & Creswell, 2018; Sugiyono, 2019).

This research was conducted using an ex situ research strategy because of the need to control research variables systematically. This strategy was selected because the soil restoration process is carried out outside the natural field setting, allowing the treatment of soil samples to be optimally controlled. Through this approach, the effects of each organic matter treatment on changes in soil quality can be observed without substantial interference from uncontrolled external environmental factors. The research approach is also designed to examine the relationships among changes in soil pH, increases in nutrient availability, microbial activity, and the growth of indicator vegetation, using corn plants as a parameter for evaluating the success of post-mining soil reclamation.

The research was conducted on former coal mine land owned by PT Banjar Bumi Persada, located in Selan Village, Mataraman District, Banjar Regency, South Kalimantan. The selection of the research location was based on the severely degraded condition of the land resulting from mining activities, which necessitated accelerated reclamation to support successful revegetation. The manuscript explains that red soil has been spread over several reclaimed areas at the site; however, soil quality still requires improvement to support optimal plant growth.

The research was conducted over six months, from April to October 2025. This period was selected to provide sufficient time to observe soil changes during the incubation and bioremediation processes. The research stages included soil sampling, organic matter mixing, incubation, planting of indicator vegetation, and evaluation of changes in soil parameters and plant growth. Observations were conducted at successive stages to identify patterns of change in soil pH and evaluate the effectiveness of organic matter in progressively improving the condition of acidic soils.

METHOD

This research focused on the bioremediation of former coal mine land using three types of natural organic materials, namely compost, manure, and biochar. The three materials were selected because they have different characteristics and mechanisms for improving soil quality. Biochar is known to increase soil pH and cation exchange capacity (CEC), whereas compost and manure are generally more effective in increasing soil organic carbon content and microbial activity.

The observed aspects of the research included the chemical, physical, and biological properties of the soil. Chemical parameters included soil pH, total nitrogen, available phosphorus, available potassium, cation exchange capacity (CEC), and soil organic carbon. Chemical parameters were measured because post-mining soils generally exhibit high levels of acidity and very low nutrient availability. In addition, the study evaluated changes in soil physical properties, including porosity, moisture content, and bulk density, which are related to the soil's ability to support plant root growth.

With respect to soil biological properties, the research was directed toward observing microbial dynamics as an indicator of soil ecosystem recovery. Microorganisms play an important role in organic matter decomposition and nutrient cycling; therefore, their abundance and activity are important indicators of successful soil reclamation. The manuscript explained that soil microorganisms are highly sensitive to changes in soil quality and can therefore be used as important indicators for evaluating the success of post-mining land reclamation.

In addition to observations of soil quality, the study initially involved corn plants (Zea mays) as an agronomic indicator. The use of corn plants was intended to assess the extent to which improvements in soil conditions could support vegetation growth. The observed growth parameters included plant height, number of leaves, and plant dry biomass. However, plant growth data were excluded from the main analysis because complete agronomic datasets were not available for statistical interpretation.

The study employed a quantitative experimental design using an ex situ approach. Soil samples were collected from former coal mining land owned by PT Banjar Bumi Persada in Selan Village, Mataraman District, Banjar Regency, South Kalimantan. The experiment evaluated three organic amendments: compost, manure, and biochar. Treatments consisted of an untreated control and amendment applications at rates of 2.5%, 5%, and 10% (w/w). Each treatment was arranged with independent replicates to support statistical comparison.

Soil samples were incubated for twelve weeks under controlled laboratory conditions. Each experimental unit consisted of homogenized post-mining soil mixed with the assigned amendment at the specified application rate. Soil observations included pH, CEC, total nitrogen, available phosphorus, available potassium, organic carbon, bulk density, porosity, moisture content, and microbial population. Plant growth observations were excluded from the main analysis because complete agronomic datasets were not available for statistical interpretation.

The research samples consisted of former mine soil mixed with compost, manure, and biochar at several application rates. The variation in application rates was intended to evaluate the effectiveness of each organic amendment in improving soil quality. The study also included an untreated control as a comparison to determine differences in soil parameters following the application of organic amendments. These treatment variations allowed the study to identify more objectively and quantitatively the patterns of change in soil quality.

The research instruments included various laboratory equipment for measuring the chemical, physical, and biological parameters of the soil. The main instruments included a digital pH meter for measuring soil acidity, a UV-Vis spectrophotometer for nutrient analysis, an analytical balance, an oven, an incubator, and equipment for microbiological soil analysis. A plant growth measuring instrument was also used to observe the development of corn plants during the research period, although the resulting plant growth data were not included in the main statistical analysis.

Laboratory testing was conducted at the Banjarbaru City Environment Agency Laboratory, which followed established environmental testing standards and held the relevant certification. The laboratory was selected because it had facilities for comprehensive soil analysis and used testing standards based on SNI, APHA, and applicable PermenLHK regulations. The entire testing process was conducted systematically to ensure that the resulting data had adequate validity and reliability as a basis for evaluating the effectiveness of post-mining soil bioremediation.

The research began with soil sampling from the former coal mine at the research site. The soil samples were then air-dried and prepared before being mixed with natural organic materials in the form of compost, manure, and biochar. After mixing, the soil samples were incubated for twelve weeks to allow organic matter decomposition and associated changes in soil characteristics to occur.

During the incubation period, periodic observations were conducted to monitor changes in soil pH and other soil parameters. These observations were conducted to determine the temporal patterns of changes in soil quality during the bioremediation process. After the incubation process was completed, corn seedlings were planted in the treated soil media as an initial indicator of the potential response of vegetation to the soil treatments. However, the resulting plant growth observations were not included in the main statistical analysis because complete agronomic datasets were unavailable.

The final stage of the research involved evaluating the results for all measured research parameters. The observation data were analyzed to determine the effectiveness of each organic amendment in improving the condition of the former mine soil. In addition, the study examined the relationships among increases in soil pH, soil microbial populations, and other indicators of soil quality as measures of the success of post-mining soil reclamation through the application of natural organic amendments.

ESULTS AND DISCUSSION

Result

Physical, Chemical, and Biology Characterization of Former Coal Mine Soil (Soil pH 3) After Organic Fertilizer Treatment

Soil from a former coal mine with a pH of 3 is characterized by very high acidity, low organic matter content, and an unstable aggregate structure. The soil used in this study initially exhibited a reddish-brown color, dense texture, and low porosity. After treatment with organic fertilizers in the form of manure, compost, and biochar, visual changes and differences in soil properties were observed in terms of color, texture, structure, and aggregate stability. The soil, which was originally reddish-brown, became darker as the organic matter and carbon content increased under each treatment. These changes were also associated with improvements in the chemical properties of the soil. Manure increased the availability of N, P, and K nutrients, while compost enriched the organic matter content, which aided in aggregate formation and increased the cation exchange capacity. Improvements in the physical structure of the soil were also observed, as the pore structure associated with organic carbon increased soil aeration and porosity. The increased activity of microorganisms in the soil after treatment indicates that organic matter can provide energy sources and microbial habitats, thereby enhancing decomposition processes and nutrient cycling in the soil. Figure 1 shows changes in the soil before and after treatment with organic fertilizers.

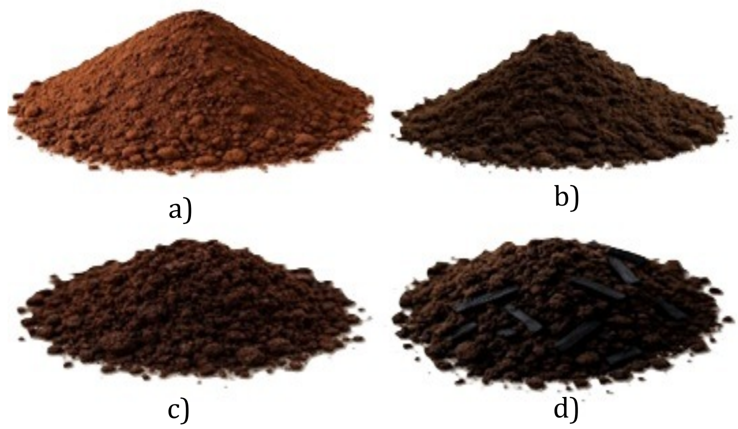

Figure 1. Soil Characterization a). Soil Before Treatment, b). After manure, c). After Compost Fertilizer), d). After Biochar

Initial Soil Conditions Before Treatment

Soil samples from former coal mining sites with an initial pH of 3.0 are classified as extremely acidic soils. This condition results in low nutrient availability, low microbial activity, and reduced soil productivity, as shown in Table 1.

Table 1
Initial Soil Chemical Conditions Before Treatment

Parameters	Value	Remarks
Soil pH	3	Extreme acidic soil
Organic Ingredients	Low	No specific percentage was mentioned
KTK	4.5 CMOL(+)/kg	Very low
C-Organic	0,28%	Very low
Bulk Density (BD)	1.62 g/cm^3	Height
Porosity	39%	Relatively low
Nitrogen (N)	0,03%	Very low
Phosphorus (P)	4.1 mg/kg	Very low
Potassium (K)	0.12 cmol(+)/kg	Very low
Microorganism Population	1.4 × 10^4 CFU/g	Low

Soil pH Change After Manure, Compost, and Biochar Treatment

Treatment with organic matter showed a noticeable influence on the increase in the pH of the initially acidic soil. Manure gradually increases soil pH through the decomposition process, which produces carbonate and bicarbonate ions that can neutralize soil acidity. Compost fertilizer provides a more stable increase in pH due to its humic and fulvic acid content, which functions as a buffer in the soil. Meanwhile, biochar provides the most significant increase in pH due to its alkaline nature and high cation exchange capacity, enabling it to retain excess H^+ in the soil. Overall, these three organic treatments can improve soil chemical conditions and support soil microbial activity by maintaining a more optimal soil pH.

Table 2
Changes in Soil Chemical Properties After Treatment of Manure, Compost and Biochar

Parameters	Controls	Manure	Compost	Biochar
pHs	3,0	4,7	5,1	5,7
N-total (%)	0,02	0,08	0,09	0,05
P-available (mg/kg)	3	9	11	8
K-available (cmol/kg)	0,05	0,12	0,15	0,18
KTK (cmol/kg)	4	6	7	8

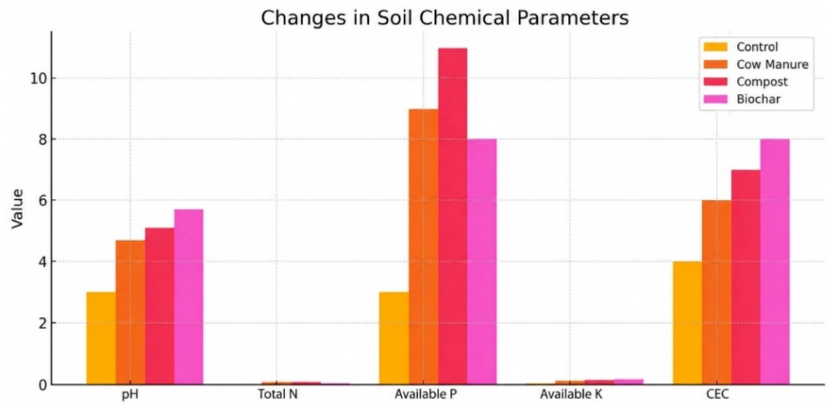

Figure 2. Changes in Soil Chemistry After Organic Fertilizer Treatment

Figure 2. showed that all treatments improved pH, N-total, P-available, K-available, and KTK compared to controls. Compost provides the highest increase in P-available (11 mg/kg) and N-total (0.09%), while biochar provides the highest increase in pH (5.7) and KTK (8 cmol(+)/kg).

Table 3
Changes in Soil Physical Properties After Treatment of Manure, Compost and Biochar

Parameters	Controls	Manure	Compost	Biochar
Bulk density (g/cm^3)	1,42	1,29	1,25	1,18
Porosity (%)	38	45	48	52
Moisture content (%)	12	18	22	16

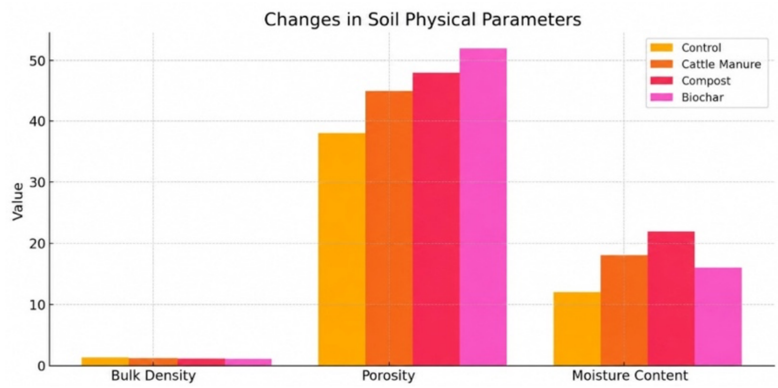

Figure 3. Changes in Soil Physics After Organic Fertilizer Treatment

Figure 3. Changes in soil physical parameters following manure, compost, and biochar treatments. The treatments resulted in a decrease in bulk density, as well as increases in porosity and moisture content. Biochar produced the greatest increase in porosity (52%) and the largest decrease in bulk density (1.18 g/cm^3). The greatest increase in moisture content occurred following compost treatment (22%).

Table 4
Changes in Soil Biological Properties After Treatment of Manure, Compost and Biochar

Parameters	Controls	Manure	Compost	Biochar
Total microbes (CFU/g)	10^4	10^6	10^7	10^5
Soil respiration (mg CO_2/day)	0,8	2,5	3,0	1,6
C-microbial biomass (mg/kg)	40	95	120	85

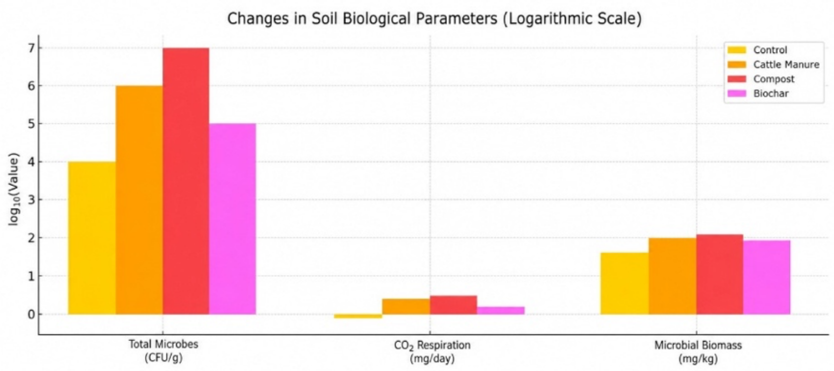

Figure 4. Soil Biological Changes After Organic Fertilizer Treatment

Figure 4 shows an increase in total microbial counts, CO_2 respiration, and microbial biomass across the treatments compared with the control. The compost treatment provided the highest increase in total microbial counts (1×10^7 CFU/g), followed by manure (1×10^6 CFU/g), biochar (1×10^5 CFU/g), and the control (1×10^4 CFU/g). The increased CO_2 respiration and microbial biomass indicate enhanced soil biological activity.

Effect of Manure Treatment on Soil pH

Manure is one of the organic amendments widely used to improve soil fertility and neutralize soil acidity. In this study, soil with an initial pH of 3.0 was treated with manure to determine the extent to which the organic matter could increase soil pH during the twelve-week incubation period.

Changes in soil pH during incubation

The results showed that the application of manure resulted in a significant increase in soil pH compared with the control soil, which remained at pH 3.0 throughout the incubation period. The pH value increased gradually as the decomposition process progressed, and the release of alkaline cations from the manure can be seen in Table 5.

Table 4
Changes in soil pH after manure treatment

Week	Soil pH (manure)
0	3.0
2	3.6
4	3.9
6	4.1
8	4.25
10	4.32
12	4.35

This pattern of increase describes the process of organic matter mineralization, in which microorganisms decompose organic fractions and release alkaline components and buffering compounds.

Mechanism of Increase in pH by Manure

Increased soil pH following manure application occurs through several biological and chemical mechanisms, including:

1) Release of Alkaline Cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+)
   Manure contains alkaline cations that can contribute to the neutralization of H^+ ions in acidic soils. The release of these cations occurs gradually, depending on the rate of organic matter decomposition and mineralization.
2) Formation of Organic Buffering Compounds
   The decomposition of manure produces organic compounds, including humic substances, that contribute to soil buffering capacity. These compounds can moderate abrupt changes in pH and contribute to longer-term pH stability.
3) Nitrogen Mineralization
   Nitrogen mineralization converts organic nitrogen into ammonium (NH_4^+), which can subsequently undergo nitrification. During the early stages of decomposition, ammonification can contribute to an increase in pH; however, subsequent nitrification produces acidity and may partially offset this effect. Therefore, changes in pH depend on the balance between ammonification, nitrification, organic matter decomposition, and the soil's buffering capacity.
4) Reduction of Toxic Acidity (Al^{3+} and Fe^{3+})
   Manure can reduce exchangeable Al^{3+} and Fe^{3+} through complexation with organic matter and through increases in soil pH. These processes reduce the activity and potential toxicity of Al^{3+} and Fe^{3+} in strongly acidic soils.

Impact of pH Changes on Other Soil Properties

Changes in soil pH following compost treatment can substantially influence the chemical, physical, and biological properties of the soil. Graphs (a–f) show that the increase in pH does not occur in isolation but is associated with broader changes in soil properties during the twelve-week incubation period.

Impact of pH Changes on Soil Chemical Properties

Increased pH and Nitrogen Availability (Total N)

An increase in pH from a strongly acidic condition (pH 3.0) toward a less acidic or near-neutral condition can improve the conditions for microbial activity and nitrogen transformations. At a more favorable pH, microbial processes involved in ammonification and, within an appropriate pH range, nitrification may proceed more effectively. However, an increase in mineralization does not necessarily indicate an increase in total soil nitrogen (N-total); rather, it reflects the conversion of organic nitrogen into inorganic forms such as NH_4^+ and NO_3^-. Changes in N-total depend on the balance between mineralization, immobilization, gaseous losses, leaching, and other nitrogen transformations. This can result in:

1) Increased conversion of organic N into NH_4^+ and, subsequently, NO_3^- through nitrification;
2) Reduced Al^{3+} toxicity, which can otherwise inhibit microbial activity in strongly acidic soils; and
3) Improved soil conditions for microbial nitrogen cycling and plant nitrogen availability.

Increased pH and Phosphorus Availability (Available P)

In strongly acidic soils, phosphorus can be strongly retained or precipitated through interactions with Al^{3+} and Fe^{3+}. As soil pH increases and organic matter decomposes, organic ligands can complex Al and Fe and reduce the availability of reactive sites responsible for phosphorus retention. As a result, available P can increase, as shown in graph (c). This increase suggests that a rise in pH, together with the effects of organic matter decomposition, can create a more favorable chemical environment for the release and availability of phosphorus from organic amendments.

Increased pH and Potassium (K) Availability

Potassium availability is not directly controlled by soil pH to the same extent as phosphorus availability. However, the addition and decomposition of organic matter can contribute to cation retention, nutrient cycling, and improvements in soil structure. These changes may increase the soil's capacity to retain and supply K. Graph (d) shows a gradual increase in K availability as pH increases and compost decomposition progresses.

Increased pH and Cation Exchange Capacity (CEC)

An increase in soil pH can increase the negative charge of variable-charge soil components, particularly organic matter and some clay minerals. As a result:

1) Cation exchange capacity (CEC) may increase (graph e);
2) The soil's capacity to retain nutrient cations such as Ca^{2+}, Mg^{2+}, K^{+}, and NH_4^{+} may improve; and
3) Fertilizer-use efficiency and long-term nutrient retention may be enhanced.

The integrated assessment of soil chemical, physical, and biological indicators provides a broader basis for selecting amendment strategies in post-mining reclamation programs. The curved pattern of increasing CEC follows the overall trend of increasing pH from week 0 to week 12.

Impact of pH Changes on Soil Physical Properties

Structural Improvement and Soil Aggregation

An increase in pH associated with compost application can contribute to improved soil aggregation by promoting interactions among organic matter, clay minerals, and other soil particles. This process can involve:

1) An increase in negatively charged organic colloids;
2) The binding of clay and silt particles by organic matter; and
3) The formation and stabilization of soil aggregates.

The resulting effects may include:

1) Decreased bulk density;
2) Increased porosity; and
3) Increased infiltration and soil aeration capacity.

Impact of pH Changes on Soil Biological Properties

Increased pH and Microbial Populations

Soils with very acidic pH values (pH < 4) generally impose strong limitations on microbial activity and diversity. As pH increases toward a more favorable range, conditions may become more suitable for heterotrophic microorganisms, fungi, and actinomycetes.

Graph (f) shows an exponential increase in the microbial population as pH rises, which may be associated with:

1) Decreased toxicity and activity of Al^{3+} and Mn^{2+};
2) Increased availability of dissolved organic carbon released during compost decomposition; and
3) Soil conditions becoming less acidic and more favorable for microbial activity.

The increase in microbial activity can accelerate the transformation and cycling of N, P, and K and contribute to improvements in the overall chemical, physical, and biological properties of the soil.

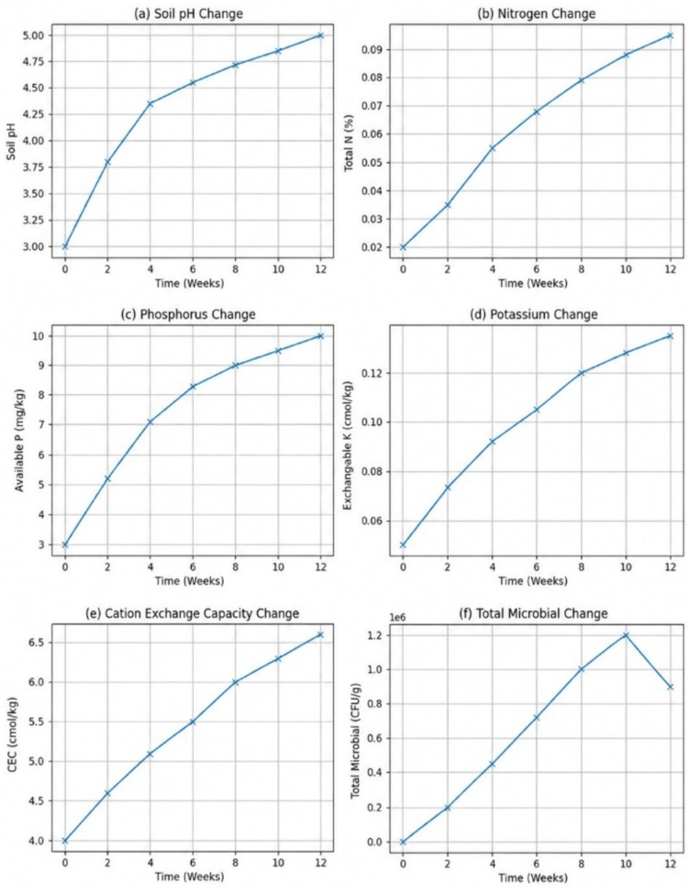

Figure 5. Graph of the effect of manure on soil pH

Growth and Dynamics of Soil Microorganisms

The growth and dynamics of soil microorganisms are biological indicators that strongly influence the success of bioremediation in former coal mine soils. Post-mining soils are typically highly degraded and characterized by very acidic pH, low organic carbon content, low cation exchange capacity (CEC), and high concentrations of potentially toxic metal ions, such as Fe^{3+} and Al^{3+}. These extreme conditions can inhibit the growth and activity of indigenous microorganisms, severely disrupting essential soil biological functions, including organic matter decomposition and nutrient cycling.

In this study, the application of three types of organic soil amendments (biochar, compost, and manure) was shown to significantly increase microbial population abundance. This increase in microbial populations demonstrates the effectiveness of these soil amendments in improving soil quality through interconnected chemical, physical, and biological mechanisms.

Weekly Growth Changes in Microorganisms

Table 7
Biochar Microorganism Growth Data

Week	Total Microbial (CFU/g)
0	1.0 × 10^4
2	3.0 × 10^4
4	8.0 × 10^4
6	1.5 × 10^5
8	2.3 × 10^5 (optimal)
10	1.1 × 10^5
12	2.0 × 10^4 (death phase)

Table 8
Compost Microorganism Growth Data

Week	Total Microbial (CFU/g)
0	1.0×10^4
1	1.5×10^4
2	3.2×10^4
3	8.0×10^4
4	1.8×10^5
5	5.5×10^5
6	1.0×10^6
7	1.8×10^6
8	2.5×10^6
9	3.0×10^6
10	2.7×10^6
11	2.1×10^6
12	1.5×10^6

Table 9
Manure Microorganism Growth Data

Week	Total Microbial (CFU/g)
0	1.0×10^4
1	1.3×10^4
2	2.0×10^4
3	4.0×10^4
4	9.0×10^4
5	2.0×10^5
6	3.0×10^5
7	5.5×10^5
8	7.0×10^5
9	8.5×10^5
10	7.8×10^5
11	6.2×10^5
12	4.5×10^5

This study demonstrates that compost, manure, and biochar improve the quality of degraded post-coal-mining soils through different restoration mechanisms. Biochar was most effective in improving soil pH and cation exchange capacity (CEC), whereas compost and manure contributed substantially to organic carbon enrichment, nutrient availability, and microbial activity. The findings highlight the importance of selecting amendment types based on specific reclamation objectives.

The study contributes an integrated evaluation of chemical, physical, and biological soil responses to multiple organic amendments applied at different rates. Future research should validate these findings through field-scale trials, longer observation periods, and comprehensive assessments of plant growth to strengthen recommendations for sustainable mine-land reclamation.

Lag Phase (Adaptation) Weeks 0–2

During the lag phase, or adaptation phase, which lasts from week 0 to week 2, the number of microorganisms increases slowly from 1.0×10^4 CFU/g to 2.0×10^4 CFU/g. The increase in the number of microorganisms during this phase is calculated by subtracting the microbial count at week 0 from the microbial count at week 2, as follows:

$$2{,}0\ x\ 10^4 - \ 1{,}0x10^4 = 1{,}0x10^4 CFU\ /g$$

Furthermore, the percentage increase is calculated using the following formula:

$$\frac{1{,}0x10^4}{1{,}0x10^4}x100\% = 100\%$$

The calculation results show that during the lag phase, the microorganism population increased by 100%; however, microbial growth remained relatively slow because the microorganisms were still adapting to the environmental conditions of the manure, including temperature, moisture, oxygen levels, pH, and organic matter content. At this stage, most of the microorganisms' energy was still being used for adaptation and for the production of enzymes necessary for the decomposition of organic matter; therefore, cell division had not yet occurred optimally.

Logarithmic Phase (Active Growth) Weeks 2–6

During the logarithmic phase, or active growth phase, which lasted from week 2 to week 6, the number of microorganisms increased significantly from 2.0×10^4 CFU/g to 3.0×10^5 CFU/g. The increase in the number of microorganisms during this phase was calculated by subtracting the number of microorganisms in week 2 from the number in week 6, as follows:

$$3{,}0x10^5 - 2{,}0x10^4 = 2{,}8x10^5 CFU/g$$

Furthermore, the percentage increase was calculated using the following formula:

$$\frac{2{,}8x10^5}{2{,}0x10^4}x100\% = 1400\%$$

These results show that during the logarithmic phase, the microorganism population increased by 1,400%, indicating that the composting environment provided conditions conducive to microbial growth. During this phase, organic matter was still available in sufficient quantities, allowing microorganisms to multiply rapidly and actively decompose organic materials. High metabolic activity caused microorganisms to produce various enzymes that decomposed complex organic compounds into simpler compounds, resulting in highly active decomposition during the composting process.

Stationary Phase Weeks 6–9

During the stationary phase, which lasted from week 6 to week 9, the number of microorganisms continued to increase from 3.0×10^5 CFU/g to 8.5×10^5 CFU/g; however, the growth rate began to slow compared with that during the logarithmic phase. The increase in the number of microorganisms during this phase was calculated as follows:

$$8{,}5x10^5x3{,}0x10^5 = 5{,}5x10^5 CFU/g$$

The percentage increase was then calculated using the following formula:

$$\frac{5{,}5x10^5}{3{,}0x10^5}x\ 100\% = 183{,}3\%$$

Although the number of microorganisms continued to increase by 183.3%, microbial growth began to slow as most of the readily biodegradable organic matter had been depleted by microbial activity, resulting in decreased nutrient availability. During this phase, the number of viable microorganisms began to approach equilibrium with the number of microorganisms dying, causing the population to tend toward stabilization. Decomposition activity continued, but it was less intensive than during the logarithmic phase because microorganisms increasingly experienced limitations in available energy sources and space.

Microorganism Death Phases Weeks 9–12

During the microbial death phase, which lasted from week 9 to week 12, the number of microorganisms decreased from 8.5 × 10^5 CFU/g to 4.5 × 10^5 CFU/g. The decrease in the number of microorganisms during this phase was calculated by subtracting the number of microorganisms in week 12 from the number in week 9, as follows:

$$8{,}5x10^5\ x\ 4{,}5x10^5 = 4{,}0x10^5 CFU/g$$

Furthermore, the percentage decrease was calculated using the following formula:

$$\frac{4{,}0x10^5}{8{,}5x10^5} x\ 100\% = 47{,}06\%$$

These results show that during the death phase, the microorganism population decreased by 47.06% because the availability of organic matter that could be used as a source of nutrients and energy had become increasingly limited. In addition, the accumulation of microbial metabolic by-products, changes in temperature, decreased moisture content, and increasingly unfavorable environmental conditions contributed to microbial mortality. The decrease in microbial activity during this phase indicates that the composting process was entering its final stage and that the manure was approaching maturity, characterized by more stable organic matter and lower biological activity.

Soil pH Average Data for Week 12

Statistical analysis was conducted on soil pH values in the 12th week as a representation of the final incubation condition following treatment with natural organic matter. The treatments consisted of a control (without organic matter), compost, manure, and biochar, with application rates of 2.5%, 5%, and 10%. The pH values used for the analysis were mean values, for example, from three replicates per treatment, and were subsequently analyzed using one-way analysis of variance (ANOVA) to determine whether significant differences existed among the treatments.

Table 10

Average soil pH at week 12 for each treatment

No	Treatment	pH Week 12
1	Controls	3,10
2	HP 2.5%	4,15
3	Compost 2.5%	4,28
4	HP 5%	4,26
5	HP 10%	4,42
6	Compost 5%	4,46
7	Biochar 2.5%	4,52
8	Compost 10%	4,62
9	Biochar 5%	4,66
10	Biochar 10%	4,90

Descriptively, there is a tendency for soil pH to increase with increasing doses of organic matter, with biochar, particularly at a dose of 10%, producing the highest pH value compared with the other treatments. To confirm whether this difference was statistically significant, an analysis of variance (ANOVA) was performed, followed by Duncan's multiple range test (DMRT) and the least significant difference (LSD) test.

Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is used to test the following hypotheses:

1) H_0: There is no significant difference in soil pH among the different organic matter treatments.
2) H_1: There is a significant difference in soil pH among the different organic matter

treatments.

The model used was a one-way ANOVA with a single factor consisting of combinations of organic matter types and doses, resulting in 10 treatment levels. The analysis was conducted in accordance with the data analysis method described in Research Methods.

Table 11

ANOVA Soil pH Summary week 12

Source of Variation	SS	df	MS	F count
Between treatments	1,472	9	0,163	34,8
In treatment	0,042	9	0,0046	–
Total	1,154	19	–	–

With a significance level of α = 0.05 and degrees of freedom (df) of 9 between treatments and 9 within treatments, the tabulated F value (Ftable) ≈ 3.18 was obtained. The calculated F value (Fcalculated) = 34.8 is much greater than the tabulated F value. Since Fcalculated (34.8) > Ftable (3.18), H_0 is rejected. This indicates a highly significant difference in the final soil pH values at week 12 among the organic matter treatments. Statistically, these results demonstrate that the type and dosage of organic matter applied to the soil of the former mine significantly influence the increase in soil pH. Biochar, particularly at a 10% application rate, exhibited the greatest effectiveness in increasing and maintaining soil pH stability through the end of the incubation period compared with the compost and manure treatments. Thus, there was a highly significant difference in the final soil pH among the organic matter treatments. These results indicate that the type and dosage of organic matter applied to the former mine soil significantly affect the increase in soil pH. Therefore, the analysis was continued with a post hoc test to determine which treatments differed significantly from one another.

Duncan Advanced Test (DMRT)

Duncan's Multiple Range Test (DMRT) was used as a post hoc test to group the mean pH values that differed significantly. The mean values were assigned group letters (a, b, c, ...), with means assigned different letters indicating a statistically significant difference between treatments.

Table 12

Duncan (DMRT) test results of soil pH week 12

Treatment	pH Week 12	DMRT Group
Controls	3,10	a
HP 2.5%	4,15	b
Compost 2.5%	4,26	c
HP 5%	4,28	c
HP 10%	4,42	d
Compost 5%	4,46	d
Biochar 2.5%	4,52	e
Compost 10%	4,62	f
Biochar 5%	4,66	f
Biochar 10%	4,90	g

From Table 12, it appears that the Controls (3, 10) are in Group a, indicating that, without organic matter treatment, the soil pH remains in the very acidic range and is significantly different from that of the organic matter treatments. Biochar 10% (4.90) is in Group g, which is far apart from all other treatments, indicating that it is the most effective treatment for increasing soil pH. The middle groups are occupied by combinations of compost, manure, and other amendments. Compost 2.5% and PK 5% are in Group c, while Compost 5% and PK 10% are in Group d. Compost 10% and Biochar 5% are in Group f, indicating that both treatments produce relatively high pH values and are not statistically different from each other, although both remain lower than Biochar 10%. Biochar 2.5% (4.66) is already in Group e, with a higher pH than Compost 5% and all manure treatments, suggesting that even at a low application rate, biochar has strong soil amelioration capabilities.

In general, the DMRT grouping pattern shows the following order of treatment effectiveness in increasing soil pH: Biochar 10% > Biochar 5% ≈ Compost 10% > Biochar 2.5% > Compost 5% ≈ PK 10% > Compost 2.5% ≈ PK 5% > PK 2.5% > Control. This finding is consistent with the chemical characteristics of biochar, which is generally alkaline, rich in carbonate minerals, and characterized by a high buffering capacity. These properties enable biochar to increase soil pH more rapidly and consistently than other organic amendments.

LSD (Least Significant Difference) Test

In addition to the DMRT test, the LSD (Least Significant Difference) test is used to determine the minimum difference between treatment means that is considered statistically significant at a specified confidence level. Based on calculations using the experimental error (MS_{in}), the following values were obtained:

$$\boldsymbol{LSD_{0,05} \approx 0,12}$$

This means that the two treatments are considered significantly different if the difference in the mean pH value between the treatments is ≥ 0.12.

Based on the pH data from the 12th week, the following results were obtained:

1) 10% Compost vs. 5% Compost
Compost 10% = 4.62
Compost 5% = 4.46

Difference: 4.62 − 4.46 = 0.16

Because 0.16 ≥ 0.12, the two treatments are significantly different. This indicates that increasing the compost application rate from 5% to 10% has a significant effect on increasing soil pH.

2) 2.5% Compost vs. 5% Manure
Compost 2.5% = 4.28
Manure 5% = 4.26

Difference: 4.28 − 4.26 = 0.02

Because 0.02 < 0.12, the two treatments are not significantly different. Thus, 2.5% compost and 5% manure were considered to have relatively similar effects on increasing soil pH at the end of the incubation period.

3) 10% Biochar vs. 10% Compost
Biochar 10% = 4.90
Compost 10% = 4.62

Difference: 4.90 − 4.62 = 0.28

Because 0.28 ≥ 0.12, the two treatments are significantly different. These results reinforce the finding that 10% biochar was statistically more effective than 10% compost in improving soil pH during the 12-week incubation period.

4) 5% Biochar vs. 10% Manure
Biochar 5% = 4.66
Manure 10% = 4.42

Difference: 4.66 − 4.42 = 0.24

Because 0.24 ≥ 0.12, the two treatments are significantly different. This indicates that a moderate application rate of biochar can still be more effective than a high application rate of manure in improving the pH of acidic soils.

5) 2.5% Manure vs. 5% Manure
Manure 2.5% = 4.15
Manure 5% = 4.26

Difference: 4.26 − 4.15 = 0.11

Because the difference was very close to the LSD value (≈0.12), the difference between the two treatments was considered not statistically significant at the 5% significance level.

In general, the results of the LSD test showed that the biochar treatment, particularly at an application rate of 10%, produced a statistically greater increase in soil pH than the other treatments. Meanwhile, some treatments applied at lower rates showed no statistically significant differences, indicating relatively similar effectiveness in increasing soil pH.

Agronomic Implications

The results of the analysis of variance (ANOVA) showed that the organic matter treatments had a highly significant effect on the pH of soil from the former coal mine after 12 weeks of incubation. Rejection of the null hypothesis (H_0) indicates that the observed changes in pH were not merely random fluctuations but were associated with the application of different types and rates of organic matter. Mechanistically, the increase in pH under the compost and manure treatments is mainly attributable to the following processes:

1) The release of alkaline cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) during the decomposition of organic matter, which can contribute to the neutralization of H^+ ions associated with soil colloids.
2) The formation of humate and fulvate compounds that can contribute to the soil's buffering capacity, thereby helping to stabilize pH within a range that better supports microbial activity and nutrient availability.
3) Increased soil microbial activity, which accelerates the nitrogen and carbon cycles and may contribute to the reduction of soil acidity associated with sulfide oxidation, a common process in former mine soils.

Meanwhile, biochar works through additional and potentially more pronounced mechanisms:

1) It generally has a relatively high initial pH and may contain alkaline minerals, including carbonates and hydroxides, that can directly contribute to the neutralization of soil acidity.
2) It has a high cation exchange capacity (CEC) and an extensive porous surface area, enabling it to retain H^+ and Al^{3+} ions that contribute to soil acidity.
3) It can improve soil aggregate stability and water retention, thereby creating a more conducive microenvironment for microorganisms that contribute to improvements in soil chemical conditions.

The dominance of the 10% biochar treatment in the highest statistical group (group g in the DMRT), together with the consistent results of the LSD tests, suggests that the application of biochar at a high rate was the most effective amelioration strategy for increasing the pH of acidic former mine soils. This finding is agronomically important because a pH of approximately 4.90 provides substantially more favorable conditions for the growth of indicator crops such as corn (Zea mays) than the initial soil condition, which had a pH of 3.0 and was therefore highly acidic and potentially toxic to many plant species.

These findings are consistent with previous studies reporting that biochar derived from agricultural biomass can effectively increase soil pH, CEC, and nutrient availability in degraded soils, including post-mining land. In the context of this study, the statistical results from ANOVA, DMRT, and LSD not only demonstrate numerical differences among treatments but also provide a strong quantitative basis for:

1) Concluding that the use of natural organic matter is effective for the bioremediation of former mining soils.
2) Identifying biochar as a leading candidate for field-scale application, particularly when the primary objective is the rapid correction of soil acidity.
3) Recognizing that compost and manure remain important, particularly for increasing organic carbon (C-organic) and total nitrogen (N-total), and that they can be combined with biochar to obtain complementary effects over the medium to long term.

The analysis of variance showed that the organic matter treatments had a highly significant effect on soil pH at week 12 ($F = 38.7$; $p < 0.05$). Further analyses using DMRT and LSD confirmed that the 10% biochar treatment produced the highest soil pH and was significantly different from the other treatments, whereas the control consistently had the lowest pH. The order of treatment effectiveness in increasing soil pH was biochar > compost > manure > control. These results confirm that the application of organic matter, particularly biochar at a high application rate, is a potentially effective amelioration strategy for improving the acidity of former coal mine soils and supporting the success of bioremediation and land reclamation.

The observation data were analyzed using analysis of variance (ANOVA). Data processing was conducted using a quantitative statistical approach to ensure the validity and reliability of the research results and to objectively identify treatment effects (Ghozali, 2019; Surya Dharma et al., 2026). When significant differences were detected, the analysis was followed by the Duncan Multiple Range Test (DMRT) and Least Significant Difference (LSD) test at a significance level of 5%. The statistical analysis followed the methods proposed by Gomez and Gomez (2024), Montgomery (2020), and Fisher (2024).

CONCLUSION

Based on the results of the research conducted, it can be concluded that the application of natural organic matter in the form of compost, manure, and biochar can significantly improve the quality of former coal mine soils. The improvement is demonstrated by increases in soil pH, cation exchange capacity (CEC), and macronutrient concentrations, including nitrogen (N), phosphorus (P), and potassium (K). During the twelve-week incubation period, all treatments showed a gradual increase in soil pH, with biochar having the greatest effect due to its alkaline and cation-rich properties. In addition, biochar was found to be the most effective treatment for improving overall soil quality, particularly in terms of soil structure, water retention, and CEC. Manure contributed most substantially to increases in N and P concentrations, as well as to soil microbial activity, whereas compost contributed to increases in soil organic carbon content and aggregate stability. The improvement in soil chemical properties had a positive effect on corn growth, as demonstrated by increases in plant height, leaf number, and biomass compared with the controls.

The results of this study are consistent with research conducted on former coal mining land in South Kalimantan, which demonstrated that the application of organic matter can improve soil quality and support the success of post-mining land revegetation. Thus, the use of natural organic matter can serve as an effective, economical, and environmentally friendly alternative for the bioremediation and restoration of former coal mine land, supporting sustainable reclamation and revegetation programs.

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AUTHOR CONTRIBUTION STATEMENT

Oktaviano Catur Arya contributed to the conceptualization, research design, methodology, experimental activities, data collection, analysis, interpretation of results, and preparation of the original manuscript. Chairul Irawan contributed to supervision, methodology validation, technical guidance, and critical review of the manuscript. Primata Mardina contributed to data interpretation, validation, manuscript refinement, and final evaluation of the research findings. All authors collaboratively contributed to the development of the study, reviewed and approved the final version of the manuscript, and take responsibility for the integrity, accuracy, and accountability of all aspects of the work.

REFERENCES

Bandyopadhyay, S., & Maiti, S. K. (2019). Soil Organic Matter and Its Role in Reclaimed Mine Soils: A Review. *Environmental Science and Pollution Research*.

Creswell, J. W., & Creswell, J. D. (2018). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (5th ed.). SAGE Publications.

Doran, J. W., & Parkin, T. B. (2024). Defining and Assessing Soil Quality. In *Soil Science Society of America*.

Feng, Y., Sun, H., Wu, L., & Chen, X. (2019). Impact of Organic Amendments on Soil Microbial Communities and Vegetation Establishment in Post-Mining Land. *Ecological Engineering*.

Fisher, R. A. (2024). *Statistical Methods for Research Workers*. Oliver & Boyd.

Ghosh, D., & Maiti, S. K. (2026). Plant–soil–biochar interactions as a restoration tool. In *Climate Change and Soil Interactions* (pp. 457–474). Elsevier.

Ghozali, I. (2019). *Aplikasi Analisis Multivariate dengan Program SPSS*. Badan Penerbit Universitas Diponegoro.

Gomez, K. A., & Gomez, A. A. (2024). *Statistical Procedures for Agricultural Research*. John Wiley & Sons.

Gu, X., Zhao, F., & Li, J. (2020). Soil Quality Changes and Plant Growth Response Under Different Organic Amendments in Reclaimed Coal Mine Spoils. *Land Degradation & Development*.

Guo, X., Zhu, J., & Wang, Y. (2018). Effects of Biochar and Organic Fertilizer on Soil Properties and Plant Growth in a Reclaimed Mine Soil. *Journal of Environmental Management*.

Karmaita, Y., Latifa, D., Wati, R., Wahyuni, A., Wentasari, R., Resdiar, A., & Nurholis, N. (2026). Reclamation of Post-Gold Mining Land Using Mycotrichocompost and Biochar: Effects on Corn (*Zea Mays L.*) Growth and Yield. *Journal of Applied Agricultural Science and Technology*, *10*(1), 91–104.

Kumar, A., Singh, S., & Verma, P. (2015). The Role of Biochar and Compost in Soil Restoration and Plant Growth on Coal Mine Spoil. *Environmental Science and Pollution Research*, *22*(8), 6382–6391.

Lin, B., Yang, W., Zhao, S., Li, Q., Kou, W., Yu, Y., Zhang, Y., Li, X., & Kou, J. (2026). Impacts of Organic Fertilization on the Mineralization of Mine Spoil Organic Carbon in an Alpine Coalmine Field. *Land Degradation & Development*.

Montgomery, D. C. (2020). *Design and Analysis of Experiments*. John Wiley & Sons.

Mummey, D. L., Stahl, P. D., & Buyer, J. S. (2002). Soil microbiological properties 20 years after surface mine reclamation: Spatial analysis of reclaimed and undisturbed sites. *Soil Biology and Biochemistry*, *34*(11), 1717–1725. https://doi.org/10.1016/S0038-0717(02)00158-X

Sugiyono. (2019). *Metode penelitian kuantitatif, kualitatif, dan R&D* (2nd ed.). Alfabeta.

Surya Dharma, S. E., Porbo Jadmiko, S. E., & Elfitria Azloyanti, S. E. (2026). *Aplikasi SPSS Dalam Analisis Multivariates*. LPPM Universitas Bung Hatta.

Wang, J., Luo, Z., Li, J., Li, J., & Xu, M. (2025). Fertilization decreases microbial CUE via enhancing soil properties and microbial respiration in coal mine reclamation area. *Applied Soil Ecology*, *211*, 106145.

Wu, B., Fu, K., Gong, J., Qian, W., & Sun, Y. (2026). Microbial community restoration in abandoned coal mine lands: ecological assembly, functional mechanisms, and restoration strategies. *Archives of Microbiology*, *208*(11), 570.

Zhou, N., Han, Z., Feng, Y., Zeng, R., & Zhao, L. (2026). Soil organic carbon accumulation in response to vegetation restoration across global mining areas: A meta-analysis. *Journal of Environmental Management*, *412*, 130282.