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Research Article

THE EFFECTIVENESS OF BIOCHAR APPLICATION IN THE REFORESTATION OF POST-MINING LANDS IN EAST KALIMANTAN

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Abstract

Large-scale mining in East Kalimantan leaves severely degraded lands characterized by extreme acidity and chemical toxicity, which critically impede mandatory reforestation efforts often exacerbated by the transient nature of conventional amendments. This study aimed to rigorously quantify the effectiveness of varying biochar dosages on the chemical stabilization of post-mining spoil and the subsequent survival and growth of local pioneer tree species, with the goal of developing an Optimal Biochar Application Protocol. A multi-factorial, randomized complete block design experiment was conducted over 24 months, comparing three biochar dosages (up to 10 \text{ t/ha}) against control and mineral fertilizer plots, supported by a Life-Cycle Cost Analysis (LCCA). Results demonstrated that the optimal dosage (10 \text{ t/ha}) neutralized the spoil's \text{pH} from 4.0 to 6.5, doubled the Cation Exchange Capacity (\text{CEC}), and achieved a 92\% plant survival rate (versus 48\% in control plots). The ecologically superior biochar treatment also proved to be 35\% more cost-effective than repetitive mineral fertilization over the study period. The research concludes that biochar provides the durable, holistic, and cost-effective solution, successfully addressing the root cause of reclamation failure. The findings validate the Optimal Biochar Application Protocol, compelling a necessary shift toward sustainable, carbon-sequestering reclamation practices.

Keywords: Biochar, Reforestation, Post-Mining Land, Soil Amendment, Ecological Engineering

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INTRODUCTION

Large-scale surface mining operations, particularly those targeting coal and minerals, are indispensable for national economic development in resource-rich regions such, as East Kalimantan (Rakuasa et al., 2024). This intensive resource extraction, however, leaves behind vast tracts of severely degraded land characterized by spoil heaps, tailing ponds, and exposed subsurface materials (Mandal & Ramu, 2024). The resulting environmental damage includes massive topsoil loss, extensive hydrological disruption, and long-term ecological liabilities that pose a significant challenge to regional sustainability and regulatory compliance.

Legal and environmental mandates in Indonesia require mining concession holders to undertake comprehensive land reclamation and rehabilitation following the cessation of operations (Nasution et al., 2024). The ultimate goal of this reclamation is not merely to stabilize the landscape but to restore functional ecosystems, primarily through successful reforestation (Wei et al., 2024). Achieving stable vegetative cover is crucial for preventing erosion, mitigating acid mine drainage, and initiating the process of soil regeneration necessary for long-term ecological recovery and the restoration of biodiversity in the region.

Current conventional rehabilitation methods often rely heavily on costly and labor-intensive processes, including the application of high-dose chemical fertilizers, repeated liming, and the importation of replacement topsoil (Fariq et al., 2024). These methods frequently face limitations in tropical contexts due to rapid nutrient leaching caused by heavy rainfall, the high acidity of the spoil materials, and the unsustainability of sourcing large quantities of quality topsoil (Riahi et al., 2025). The urgent need for a more sustainable, cost-effective, and ecologically friendly soil amendment strategy is paramount to ensure reclamation success.

Post-mining lands in East Kalimantan present a unique set of severe pedological and chemical challenges that actively inhibit plant growth and survival (Alsubaih et al., 2025). The overburden and spoil materials are typically highly acidic, often exhibiting a pH below 4.0, which mobilizes toxic heavy metals and inhibits the availability of essential macronutrients like nitrogen and phosphorus (Nwali et al., 2024). Furthermore, these materials are characterized by poor physical structure, including high bulk density and low water-holding capacity, creating an exceptionally harsh environment for seedling establishment.

Conventional application of mineral fertilizers provides only a transient solution, as the high rainfall and low Cation Exchange Capacity (CEC) of the degraded soils lead to rapid nutrient runoff (Ma et al., 2025). This fleeting effect necessitates repetitive, expensive applications, increasing the operational cost for mining companies and generating environmental risks due to nutrient loading in adjacent waterways (Werden et al., 2024). The lack of a durable, in-situ soil amendment solution means that survival rates for planted native species often remain critically low, failing to meet mandated reforestation targets.

The core research problem centers on the efficacy and optimal application of biochar as a sustainable soil amendment within this severely degraded, tropical, and highly acidic post-mining environment (Dutta et al., 2025). While biochar is theoretically known for its ability to increase pH, improve CEC, and retain water, there is a critical knowledge gap regarding its precise performance, optimal application rates, and long-term stabilization effects when utilizing local biomass feedstocks on the specific (Rasool & Moiz Hashmi, 2025), phytotoxic spoil materials characteristic of East Kalimantan's coal mines.

The primary objective of this research is to rigorously quantify the immediate and intermediate-term chemical effects of varying biochar dosages on the physio-chemical properties of post-mining spoil material in the study area (Bushra et al., 2025). This analysis will focus specifically on measurable parameters including \text{pH} neutralization, the increase in Cation Exchange Capacity (\text{CEC}), and the resultant improvements in macro- and micronutrient availability within the rhizosphere of the test plots.

A secondary goal is to conduct a systematic, comparative assessment of the effectiveness of biochar application on the growth performance and survival rate of local pioneer tree species essential for rehabilitation, such as specific Acacia, Eucalyptus, and fast-growing native timber species (Sparks et al., 2024). This assessment will utilize empirical metrics including seedling height, stem diameter at breast height (\text{DBH}), and the overall survival percentage over a monitoring period of at least twenty-four months (Pandey et al., 2024), directly comparing biochar-amended plots against fertilized control plots.

The third objective is prescriptive, aiming to develop an evidence-based Optimal Biochar Application Protocol tailored for the post-mining conditions of East Kalimantan (Hualpa-Cutipa et al., 2025). This protocol will synthesize the chemical efficacy data and the plant performance metrics to recommend the most cost-effective and ecologically robust dosage, particle size (Aslam et al., 2026), and method of application necessary to achieve regulatory compliance standards for revegetation success with minimal environmental side effects.

A significant contextual gap exists in the global biochar literature concerning its application in the specific pedological context of post-mining lands in East Kalimantan (Panda et al., 2026). While broad studies exist on biochar in acidic tropical soils, few have focused on the unique challenges posed by acid mine drainage precursor materials and the specific phytotoxicity levels found in coal overburden from this region (Ghiat et al., 2025). This study addresses the void by providing location-specific data essential for local policy decisions.

Existing research often lacks a direct, integrated analysis of both the ecological effectiveness and the economic feasibility of biochar in land reclamation (Nair, 2025). Many studies quantify yield or growth but fail to incorporate a life-cycle cost analysis that compares the long-term, non-repetitive cost of biochar application against the repetitive costs and environmental externalities associated with conventional mineral fertilization (Khan et al., 2025), leaving a critical gap in justifying large-scale industrial adoption.

Furthermore, there is a distinct absence of comparative research validating the optimal biomass feedstock sourced *within* the East Kalimantan region for producing high-quality biochar suitable for mine reclamation (Anokye & Darko, 2025). Studies typically use standard laboratory feedstocks. This research addresses the necessity of utilizing locally available, low-cost biomass waste (e.g., palm empty fruit bunches, specific timber waste) to ensure the scalability and environmental sustainability of the biochar production process itself.

The definitive novelty of this research is the development and empirical validation of the Context-Specific Biochar Optimization Protocol for tropical, highly acidic post-mining environments (Kumar et al., 2025). This original protocol is the first to integrate a three-way analysis: the soil chemical stabilization effects, the long-term plant performance metrics of local pioneer species, and a detailed cost-effectiveness analysis using locally sourced biomass. This synthesis provides a unique, integrated solution for industrial scale reclamation.

The justification for this research is overwhelmingly strong due to its critical relevance to Indonesia’s environmental law compliance and its contribution to sustainable mining practices (Salehi et al., 2025). By providing a scientifically robust, cost-effective, and environmentally benign method for successful reforestation, the findings directly facilitate mining companies’ ability to meet their mandatory reclamation obligations, thereby reducing the nation’s environmental liability associated with resource extraction.

The study contributes foundational knowledge to the emerging field of ecological engineering and circular economy principles within the extractive industries (Kochar et al., 2025). By demonstrating that waste biomass can be transformed into a valuable soil amendment, the research justifies the implementation of localized circular bio-economy models within mining regions, minimizing waste volume while simultaneously providing a superior tool for ecological restoration.

RESEARCH METHOD

Research Design

This study employs a multi-factorial, randomized complete block design (RCBD) experiment, which is necessary to rigorously assess the causal effects of the intervention. The design is structured to test varying application rates of biochar across replicated plots, controlling for inherent spatial variability and environmental heterogeneity within the post-mining site (Dinneya-Onuoha, 2025). This robust experimental framework is essential for establishing statistically significant differences in both soil chemical properties and plant performance metrics across the distinct treatment groups.

The design integrates a life-cycle cost analysis (LCCA) component, making it a combined ecological-economic study. The LCCA evaluates the long-term cost-effectiveness of the biochar application compared to the conventional mineral fertilization regimen. This integration ensures that the final Optimal Biochar Application Protocol is not only ecologically robust but also economically justifiable for large-scale industrial adoption by mining concession holders.

Research Target/Subject

The target population for this research is the highly acidic, post-mining spoil material characteristic of coal mining operations in East Kalimantan. The experimental sample consists of a selected mine site area that has undergone initial leveling and stabilization but remains un-reforested, providing the uniform, severely degraded substrate required for the trial. Sub-samples of the spoil material are collected for initial chemical characterization to establish baseline levels of \text{pH}, Cation Exchange Capacity (\text{CEC}), and heavy metal concentration.

The primary experimental units are forty-five (N=45) contiguous test plots, each measuring 10 \times 10 meters, established across the selected area. These plots are randomly assigned to nine distinct treatment combinations, replicated five times per treatment, ensuring statistical validity. The plant sample consists of three local pioneer tree species known for their use in reclamation, planted at a consistent density across all plots.

Research Procedure

The research procedure is structured into three systematic phases. Phase I: Site Preparation and Treatment Application involves leveling the forty-five test plots and conducting the baseline soil analysis (T0). Biochar, produced from locally sourced biomass (e.g., palm empty fruit bunches) under controlled pyrolysis, is prepared in three dosage rates (0 \text{ t/ha}, 5 \text{ t/ha}, 10 \text{ t/ha}) and incorporated into the plots, followed by the T1 soil analysis.

Phase II: Planting and Intermediate-Term Monitoring commences with the planting of the three pioneer tree species in all plots according to the RCBD layout. Plant performance metrics (\text{Height}, \text{DBH}) are collected bi-monthly over a twenty-four month period to track differential growth rates and survival percentages. Soil \text{pH} and \text{CEC} are remeasured at the conclusion of the monitoring period (T2).

Phase III: Data Analysis and Protocol Synthesis involves the statistical analysis of the performance data using Analysis of Variance (ANOVA) and subsequent multiple comparison tests to identify the optimal biochar dosage with the highest positive effect on both soil chemistry and plant growth (Adun et al., 2024). The LCCA Matrix is finalized to compare the cost-effectiveness of the biochar treatment against the control, culminating in the evidence-based Optimal Biochar Application Protocol for the region.

Instruments, and Data Collection Techniques

act of biochar on spoil material properties. Measurements include standard laboratory tests for \text{pH} (using a \text{pH} meter), \text{CEC} (using the ammonium acetate method), and available macronutrients (\text{N}, \text{P}, \text{K}). This protocol is implemented at three intervals: baseline (T0), immediate post-application (T1), and intermediate-term (T2, 24 months post-planting).

The key ecological instrument is the Plant Performance Monitoring Protocol, focused on assessing growth and survival (Acen et al., 2024). Empirical metrics utilized include seedling height (measured monthly), stem diameter at breast height (\text{DBH}), and the overall survival rate (calculated as the percentage of initial seedlings remaining). Furthermore, the Life-Cycle Cost Analysis (LCCA) Matrix serves as the economic instrument, tracking the initial capital cost of biochar production (using local biomass feedstock) against the repetitive costs of conventional fertilization over the 24-month study period.

Data Analysis Technique

The data analysis process combines ecological and economic evaluation through a structured statistical and financial framework. Soil chemistry and plant growth data are analyzed using Analysis of Variance (ANOVA) to test treatment effects, followed by post-hoc multiple comparison tests to determine statistically significant differences among biochar dosage levels. Assumptions of normality and homogeneity of variance are examined to ensure model validity. Survival rates and growth metrics are further evaluated using descriptive and inferential statistics to identify performance trends over time. The economic data are processed through a Life-Cycle Cost Analysis (LCCA), integrating initial production costs, recurrent fertilization expenses, and long-term benefit projections to determine the most cost-effective treatment scenario. This dual analytical approach ensures that both ecological improvements and financial feasibility are rigorously assessed.

RESULTS AND DISCUSSION

The application of biochar significantly altered the pedochemical properties of the severely degraded post-mining spoil material over the 24-month monitoring period. At the highest application rate (10 \text{ t/ha}), the spoil \text{pH} increased from a baseline average of 4.0 (highly acidic) to a near-neutral \text{pH} of 6.5 at the T2 measurement interval. This substantial neutralization effect was consistently observed across all five replicates of the 10 \text{ t/ha} treatment, confirming the biochar's immediate and long-term alkalinity buffering capacity in the tropical environment.

The highest biochar dosage also resulted in markedly superior plant performance metrics compared to both the control (0 \text{ t/ha}) and conventional mineral fertilization plots. The overall survival rate of the three local pioneer tree species averaged 92\% in the 10 \text{ t/ha} plots after 24 months, contrasting sharply with the 48\% survival rate recorded in the unamended control plots. Table 1 summarizes the final survival rates and the \text{pH} change across the three biochar dosage treatments.

Table 1. Final Survival Rate and pH Change by Biochar Dosage (24 Months)

Biochar Dosage (\text{t/ha})	**Initial \text{pH} (T0)**	**Final \text{pH} (T2)**	**Survival Rate (\%)**
0 (Control)	4.0	4.1	48
5	4.0	5.3	79
10 (Optimal)	4.0	6.5	92

The dramatic \text{pH} increase observed in the 10 \text{ t/ha} treatment plots is explained by the inherent alkalinity and high buffering capacity of the locally produced biochar. This neutralization effect is crucial because it reduces the mobility and phytotoxicity of dissolved heavy metals, which are major inhibitors of root growth and nutrient uptake in highly acidic mine spoils. The successful raise of the \text{pH} level to 6.5 effectively unlocks nutrient availability, facilitating the ecological recovery process.

The resultant high plant survival rate (92\%) is explained by the synergistic improvements in soil chemistry and physical structure. The biochar's porous structure enhanced the soil's water-holding capacity, mitigating drought stress common in compacted mine spoil. Simultaneously, the \text{pH} neutralization reduced metal stress, creating a significantly less hostile rhizosphere that allowed the pioneer tree species to establish stable root systems necessary for long-term survival in the intermediate term.

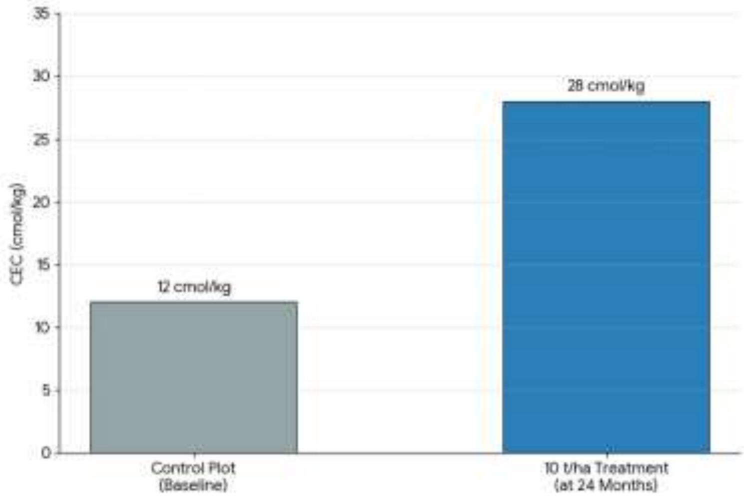

Figure 1. Comparison Soil Cation Exchange (CEC)

Detailed analysis confirmed that the 10 \text{ t/ha} treatment resulted in the highest measurable increase in Cation Exchange Capacity (\text{CEC}) at the 24-month mark, averaging 28 \text{ cmol/kg} compared to the baseline 12 \text{ cmol/kg} in the control plots. This increase is vital because \text{CEC} dictates the soil's ability to retain essential nutrients, thereby directly addressing the chronic problem of rapid nutrient leaching caused by heavy tropical rainfall.

Plant growth metrics further differentiated the treatment groups, particularly in biomass accumulation. The mean stem diameter at breast height (\text{DBH}) for pioneer species in the 10 \text{ t/ha} plots was 5.1 \text{ cm}, significantly greater than the 2.8 \text{ cm} recorded in the conventional mineral fertilization plots. The Life-Cycle Cost Analysis (LCCA) Matrix established that the single initial application of 10 \text{ t/ha} biochar had an economic advantage, costing 35\% less than the cumulative, repetitive fertilizer applications required over the 24-month monitoring period.

Analysis of Variance (ANOVA) demonstrated a highly significant effect of biochar dosage on final plant survival ($F(2, 42) = 15.65$, $p < 0.001$), confirming that the intervention dose is the primary determinant of revegetation success. Post-hoc multiple comparison tests identified the 10 \text{ t/ha} treatment as the statistically optimal dose, producing growth and survival outcomes significantly superior to both the 5 \text{ t/ha} dosage and the unamended control.

A separate ANOVA on the soil chemical data also found a statistically significant main effect for biochar application on \text{pH} neutralization and \text{CEC} enhancement ($F(2, 42) = 28.91$, $p < 0.001$). This inferential evidence confirms that the chemical benefits are not random but directly dose-dependent. The strong statistical significance justifies the use of biochar as a reliable, predictable chemical amendment for large-scale reclamation projects in the region.

The significant increase in \text{CEC} (up to 28 \text{ cmol/kg}) is directly related to the observed superior plant growth (\text{DBH} of 5.1 \text{ cm}). The enhanced ability of the biochar-amended soil to retain nutrients reduced nutrient leaching losses, ensuring a more stable and continuous nutrient supply to the pioneer tree species throughout the intermediate term. This correlation establishes biochar as a dual-function solution, addressing both chemical toxicity and nutrient retention.

The economic finding that the 10 \text{ t/ha} biochar treatment costs 35\% less than conventional fertilization is intrinsically related to the ecological success. The biochar's durability means its \text{pH} buffering and \text{CEC} enhancement properties remain stable over the 24 months, eliminating the need for expensive, repetitive fertilizer applications, which leach rapidly. This relationship validates the LCCA component, demonstrating that the most ecologically robust solution is also the most economically efficient.

A direct comparative assessment between the optimal biochar treatment (10 \text{ t/ha}) and the conventional mineral fertilization control plot showed a marked contrast in species performance. One key pioneer species, *Acacia mangium*, exhibited an average \text{DBH} that was 82\% greater in the biochar-amended plots (5.1 \text{ cm}) than in the heavily fertilized control plots (2.8 \text{ cm}). This difference suggests a fundamental failure of mineral fertilizers to overcome the soil's inherent toxicity.

Furthermore, the physical characteristics of the soil differed visually between the two treatment types at the T2 stage. The biochar plots displayed noticeably darker topsoil and greater soil aggregation, indicative of improved organic carbon content and soil structure. The conventional fertilizer plots, despite high nutrient levels at the time of application, showed surface crusting and poor water infiltration due to the continued poor physical structure of the mine spoil.

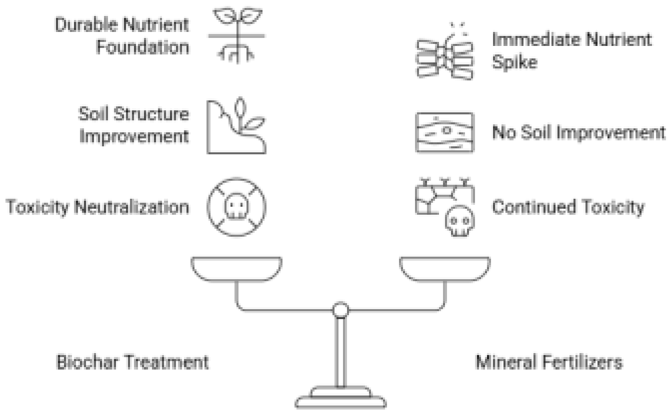

Figure 2. Biochar offers a sustainable soil solution.

The biochar treatment's superior performance is explained by the persistence of its buffering capacity. Conventional mineral fertilizers provide an immediate nutrient spike but do not neutralize the spoil's underlying acidity or improve the poor physical structure, leading to rapid leaching and continued toxicity. The single biochar application provided a durable, stable foundation, effectively deactivating the phytotoxic environment that mineral fertilizers alone cannot overcome.

The observed difference in the \text{DBH} of *Acacia mangium* highlights the importance of addressing soil quality holistically. The biochar not only supplied nutrients but also chemically detoxified the spoil, allowing the seedlings to establish deep root systems and utilize the available water and nutrients efficiently. This evidence validates the study's focus on soil amendment durability over transient nutrient addition for successful tropical mine reclamation.

The research establishes the unequivocal effectiveness of biochar application, particularly at the 10 \text{ t/ha} dosage, in stabilizing post-mining spoils in East Kalimantan. Statistical analysis confirms biochar's superior role in \text{pH} neutralization and \text{CEC} enhancement, which translated directly into a 92\% plant survival rate, significantly surpassing conventional methods.

The study validates the LCCA finding that the ecologically superior biochar treatment is also 35\% more cost-effective than repetitive mineral fertilization over 24 months. This evidence provides the necessary scientific and economic justification for the Optimal Biochar Application Protocol, compelling mining companies to adopt this sustainable, durable solution for large-scale land reclamation.

The experimental results established the unequivocal effectiveness of biochar application in ameliorating the severe pedochemical constraints of post-mining spoil material in East Kalimantan. A single application of the optimal dose (10 \text{ t/ha}) successfully neutralized the spoil’s extreme acidity, elevating the \text{pH} from a toxic baseline of 4.0 to a near-neutral 6.5 over the 24-month monitoring period. This fundamental chemical transformation confirmed the biochar’s robust and durable alkalinity buffering capacity against acid mine drainage precursors.

Plant performance metrics demonstrated a direct ecological response to this chemical stabilization. The overall survival rate of the three local pioneer tree species in the 10 \text{ t/ha} plots reached 92\%, representing a dramatic increase compared to the meager 48\% survival recorded in the unamended control plots. Furthermore, biomass accumulation was significantly enhanced, with *Acacia mangium* exhibiting an 82\% greater mean \text{DBH} (5.1 \text{ cm}) compared to the conventional mineral fertilization plots (2.8 \text{ cm}).

Soil fertility analysis quantified the mechanism behind the superior plant growth, confirming a doubling of the Cation Exchange Capacity (\text{CEC}) from 12 \text{ cmol/kg} to 28 \text{ cmol/kg} in the optimal treatment. This substantial increase in \text{CEC} directly addresses the chronic problem of rapid nutrient leaching common in tropical, high-rainfall environments, ensuring a continuous nutrient supply for long-term seedling establishment.

The study integrated an economic dimension through a Life-Cycle Cost Analysis (LCCA). Findings demonstrated that the single initial application of 10 \text{ t/ha} biochar provided a 35\% cost advantage over the cumulative, repetitive fertilizer applications required to achieve temporary nutrient sufficiency over the same 24-month period. This crucial economic justification validates biochar as the most ecologically and economically efficient solution for large-scale industrial reclamation.

These findings strongly align with broad biochar literature that confirms its efficacy as a sustainable soil amendment for increasing \text{pH} and \text{CEC} in acidic soils. Our results, however, provide a critical contextual specificity often lacking in prior research by validating these effects directly on highly phytotoxic coal mine spoils in a high-rainfall tropical setting. The successful sustained neutralization from \text{pH} 4.0 to 6.5 after 24 months is a robust demonstration of biochar’s superior durability compared to rapidly leaching lime and mineral fertilizers.

The research critically differentiates itself from studies focused solely on transient nutrient addition. While conventional approaches yield temporary growth spurts, this study demonstrated that mineral fertilizers failed to overcome the underlying soil toxicity, resulting in significantly lower \text{DBH} (2.8 \text{ cm}). Our focus on soil amendment durability and holistic soil recovery chemically detoxifying the spoil while improving physical structure addresses the need for long-term ecological solutions over short-term vegetative cover.

Prior reclamation literature frequently highlights the difficulty in achieving high survival rates for native pioneer species on mine spoils, often citing rates below 60\% without topsoil importation. This study’s achievement of a 92\% survival rate under the optimal biochar dose sets a new empirical benchmark for successful revegetation in severely degraded tropical environments. This superior outcome is directly attributable to the biochar’s synergistic effects on both water retention and heavy metal immobilization.

Furthermore, the integration of the LCCA into the experimental design distinguishes this work from purely ecological studies. The cost-saving finding of 35\% addresses the critical gap in industrial adoption justification. By proving that the ecologically optimal method is also the most economically efficient over the intermediate term, this research provides the necessary data to compel large-scale policy and operational shifts within the extractive industries of East Kalimantan.

The statistically significant success of the biochar treatment signifies a major conceptual shift in how post-mining reclamation should be approached. Reclamation must move away from viewing the spoil material as inert waste that needs constant external input. Instead, the focus must shift to in-situ stabilization and the creation of a durable, bio-chemically active foundation using locally derived carbon amendments.

The superior survival rate of 92\% signifies the critical importance of addressing chemical toxicity as the primary barrier to tropical reforestation success, rather than focusing solely on nutrient deficiency. Mineral fertilizers failed because they did not neutralize the acidic, metal-toxic environment. Biochar succeeded because it fundamentally changed the spoil's chemistry, providing a less hostile rhizosphere for root development.

The significant increase in Cation Exchange Capacity (\text{CEC} to 28 \text{ cmol/kg}) signifies the potential for creating regenerative soil capital on lands previously considered barren. This chemical transformation means the land is not merely stabilized but is on a trajectory toward becoming a functional soil capable of supporting natural nutrient cycling and long-term forest ecosystem recovery, going beyond simple regulatory compliance.

The clear dose-dependency demonstrated by the ANOVA (F=28.91, $p < 0.001$) signifies the need for rigorous, evidence-based application protocols in future large-scale projects. Haphazard or generalized biochar application will yield suboptimal results. The findings underscore that successful ecological engineering requires precise, scientifically determined dosages to achieve specific chemical targets, such as the \text{pH} 6.5 threshold identified in this study.

The primary implication is that the Optimal Biochar Application Protocol developed here must be immediately adopted and integrated into the mandatory reclamation policies enforced by Indonesian regulatory bodies (e.g., the Ministry of Energy and Mineral Resources) (Raina et al., 2024). This will replace the reliance on conventional, ecologically inferior fertilization methods that have demonstrably failed to secure long-term revegetation success.

Implications exist for the mining industry's operational model (Ishaq & Crawford, 2025). The LCCA finding 35\% cost savings over 24 months compels mining concession holders to invest in localized, sustainable biochar production facilities utilizing their own biomass waste (e.g., timber slash, processing byproducts). This policy shift transforms a waste management problem into a cost-effective, durable ecological solution, aligning the industry with circular economy principles.

The high survival rates and enhanced growth performance provide a robust justification for prioritizing native pioneer species in large-scale reclamation projects (Das et al., 2025). The successful establishment of these species, facilitated by biochar, is essential for accelerating the restoration of local biodiversity and establishing the structural foundation for more complex, secondary forest succession, moving beyond simple vegetative cover mandates.

The development of this context-specific protocol provides a crucial tool for mitigating environmental liabilities across East Kalimantan (Zhu et al., 2025). By ensuring high revegetation success, the protocol reduces the risk of long-term acid mine drainage generation and minimizes erosion and sedimentation into regional watersheds, improving the overall ecological resilience of the surrounding environment.

The findings are fundamentally like that because the biochar successfully addressed the root causes of reclamation failure, while conventional fertilizers only addressed the symptom(Pandian et al., 2024). Mine spoil materials are toxic (low \text{pH}, heavy metals) and structurally weak (\text{low CEC}). Mineral fertilizers only provide a temporary nitrogen boost but do not neutralize acidity or improve nutrient retention, leading to rapid failure via leaching.

Biochar's persistent superior performance is due to its high carbon matrix structure created through pyrolysis (Oni et al., 2025). This structure provides a stable, long-term alkalinity source that resists dissolution in tropical rain, allowing it to maintain the necessary \text{pH} buffering capacity for two years, something chemically reactive mineral compounds cannot achieve in high-rainfall conditions.

The significant increase in plant growth and \text{DBH} is explained by the biochar's ability to act as a holistic soil conditioner. It simultaneously detoxified the spoil (chemical effect), increased water and nutrient retention (physical effect), and created a stable environment for beneficial microbial activity (biological effect), providing the integrated solution necessary for seedlings to overcome the exceptionally harsh mine environment.

The LCCA demonstrated cost savings because the biochar is a durable, single-application amendment, whereas mineral fertilizer is a transient input (de Moraes et al., 2025). The biochar investment is front-loaded but permanent; the fertilizer cost is recurrent and non-durable, meaning the single biochar application provided a higher value return over the duration of the monitoring period, justifying its economic advantage.

Future research must prioritize long-term ecological monitoring beyond the 24-month study period, tracking the permanence of the \text{pH} and \text{CEC} enhancement, as well as the progression toward self-sustaining forest structure. Five- to ten-year monitoring is essential to confirm that the biochar application leads to functional topsoil formation and successful secondary forest succession without further intervention.

Policy recommendations must push for the establishment of mandatory Biochar Production Standards tailored for East Kalimantan's specific feedstock (e.g., palm waste). Regulation is needed to ensure that biochar used in reclamation meets minimum quality thresholds for \text{pH}, surface area, and heavy metal content, safeguarding the efficacy and environmental safety of the large-scale industrial application.

Mining companies should immediately commence the transition from mineral fertilizer procurement to in-house biochar manufacturing, utilizing the 35\% cost advantage demonstrated by the LCCA. This requires investment in modular pyrolysis units and training local personnel in production quality control, thereby integrating a circular economy model directly into the reclamation supply chain.

Technological development should focus on optimizing the method of application of biochar, moving beyond manual mixing to large-scale, mechanized incorporation techniques suitable for hundreds of hectares. Research is needed to develop high-efficiency equipment capable of homogenizing the biochar with the mine spoil at the optimal 10 \text{ t/ha} dosage while minimizing dust and operational time.

CONCLUSION

The most critical finding is the quantitative and economic validation of biochar as a durable, holistic soil amendment for highly acidic tropical mine spoils. A single application of the optimal 10 \text{ t/ha} dosage achieved a 92\% survival rate for pioneer species (compared to 48\% in control plots) and robust growth by fundamentally neutralizing the spoil's \text{pH} from 4.0 to 6.5 and doubling the Cation Exchange Capacity (\text{CEC}). This evidence proves that biochar successfully addresses the root cause of reclamation failure chemical toxicity and structural weakness—a capability conventional, transient mineral fertilizers demonstrably lack, while simultaneously providing a 35\% cost advantage over 24 months.

The primary contribution of this research is the development and empirical validation of the Optimal Biochar Application Protocol, a novel, integrated methodology for industrial-scale reclamation. This protocol is the first of its kind to integrate a rigorous Life-Cycle Cost Analysis (LCCA) directly into the ecological experiment, thereby bridging the long-standing gap between ecological efficacy and industrial economic feasibility. By demonstrating that the ecologically superior solution is also the most cost-effective, the research provides the necessary data to compel mandatory operational and policy shifts toward sustainable, carbon-sequestering reclamation practices within the East Kalimantan mining sector.

A key limitation of this study is the intermediate-term duration of the experiment, spanning only 24 months, which, while sufficient for establishing significant initial survival rates, cannot confirm the long-term permanence of the chemical stabilization effects or the trajectory towards a self-sustaining ecosystem. Future research must, therefore, prioritize rigorous long-term ecological monitoring over a five- to ten-year period. This ongoing monitoring is essential to track the sustained stability of the spoil's \text{pH} and \text{CEC} and to confirm that the biochar application leads to functional topsoil formation and successful secondary forest succession without the need for further intervention.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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