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The Role of Biochar in Improving Soil Quality and Rice Yields in Indonesia: A Narrative Review

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ABSTRACT
Biochar is a carbon-rich material produced through the pyrolysis of organic biomass, offering promising benefits for improving soil quality and rice productivity in tropical regions. In Indonesian paddy fields, biochar has been shown to enhance soil structure, water retention, nutrient availability, and microbial activity. These improvements contribute to increased plant growth, grain yield, and nutrient use efficiency, especially when biochar is combined with chemical or organic fertilizers. Local agricultural residues provide sustainable feedstocks for biochar production. However, widespread adoption in Indonesia faces challenges, including limited access to pyrolysis technology, inconsistent product quality, and lack of national guidelines. This review emphasizes the need for integrated efforts across research, policy, and farmer training to optimize biochar application for sustainable rice farming in Indonesia.

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INTRODUCTION

Rice is Indonesia's primary staple crop, supporting food security for over 270 million people and sustaining the livelihoods of millions of farmers. As the world's third-largest rice producer, Indonesia relies on rice agriculture for economic stability and cultural significance (BPS, 2023). However, maintaining high productivity is critical to meet rising food demand amidst environmental and agricultural constraints. The harvested area for rice in Indonesia has decreased from 10.45 million hectares in 2022 to 10.21 million hectares in 2023, a 2.45% reduction, resulting in a decline in rice production from 54.75 million tons of dry unhusked rice (GKG) to 53.98 million tons (BPS, 2024). This reduction, equivalent to 31.10 million tons of consumable rice, is driven by land conversion, urbanization, and climate variability, which collectively threaten national rice output.

Soil degradation further exacerbates these challenges in Indonesian agricultural landscapes. Low nutrient availability, poor water retention, and soil compaction, compounded by intensive farming and excessive chemical fertilizer use, reduce soil fertility and limit rice yields (Surmaini et al., 2015). Climate-induced stressors, such as erratic rainfall and flooding, intensify these constraints, undermining agricultural sustainability. Biochar offers a viable solutions. Biochar is a carbon-rich material made by heating organic waste—like crop residues or wood—in a low-oxygen environment, through a process called pyrolysis. In recent years, researchers have explored biochar's many benefits for soil and crops.

Physically, biochar helps loosen compacted soil and increases its porosity, allowing water and air to move more freely. This is especially useful in dry or degraded soils where plants often struggle to grow (Luo et al., 2025). Chemically, biochar can raise the pH of acidic soils and improve the soil's ability to hold on to important nutrients like nitrogen, potassium, and magnesium making them more available for plants to absorb (Qi et al., 2024). Biochar also helps prevent nutrients from washing away during heavy rains, so plants can benefit from them over a longer period (Jatuwong et al., 2025). Biologically, biochar provides a safe and stable habitat for beneficial soil microbes, such as nitrogen-fixing bacteria and phosphate-solubilizing organisms. These microbes play a key role in breaking down organic matter and helping plants access essential nutrients (Jatuwong et al., 2025). With healthier roots and a more active microbial environment, plants tend to grow stronger and produce higher yields (Shyam et al., 2025).

In addition to supporting plant growth, biochar also plays a role in protecting the environment. It helps trap carbon in the soil and reduces emissions of harmful greenhouse gases like methane and nitrous oxide. This makes biochar not only good for agriculture but also an important tool in the fight against climate change (Antonangelo et al., 2025). According to research by Lucky et al. (2021) in the regions of Java and Sumatra, biochar can improve soil structure, nutrient retention, and enhance microbial activity, thereby improving soil quality and increasing rice yields by 10–20%. This narrative review synthesizes research on biochar's potential to mitigate soil degradation and enhance rice production in Indonesia, addressing benefits, challenges, and opportunities for sustainable agriculture.

MATERIALS AND METHOD

This study employs a narrative review approach to synthesize current knowledge and scientific findings on the application of biochar to enhance soil quality and rice productivity in Indonesia. The narrative review method was chosen for its flexibility in integrating findings from diverse study designs, allowing a comprehensive understanding of biochar's multifaceted roles in tropical agroecosystems. A literature search was conducted using scientific databases such as ScienceDirect, Scopus, Google Scholar, and PubMed. The search was limited to peer-reviewed journal articles published between 2015 and 2025, in English and Bahasa Indonesia, to ensure relevance and recency of information. Studies were selected based on their relevance to the following thematic areas: (1) the effects of biochar on physical, chemical, and biological soil properties; (2) the impact of biochar on rice plant growth and yield; (3) opportunities and challenges in utilizing biochar within Indonesian rice farming systems. The selection process was carried out manually by reviewing the titles, abstracts, and full texts to ensure relevance to the review topic. Irrelevant, duplicate, or inaccessible articles were excluded.

DISCUSSION

Characteristics and Potential of Biochar

Biochar is a stable, carbon-rich substance produced through the pyrolysis of organic materials under low-oxygen conditions, typically at 300–700 °C. Its effectiveness depends heavily on the source material and production parameters (Pyrolysis conditions vary widely, impacting its final properties) (Gamage et al., 2016; Kuryntseva et al., 2023). Agricultural residues like rice husks, coconut shells, and crop straw all prevalent in Indonesia are ideal feedstocks, offering both sustainability and waste management benefits.

Characteristics Biochar from a physical standpoint, biochar exhibits a highly porous microstructure and large surface area developed during pyrolysis. This enhances soil aeration, water infiltration, and retention—especially critical in compacted or coarse-textured tropical soils. Interestingly, the moisture content of the starting biomass influences these characteristics; lower moisture often leads to biochars with more optimal pore formation and reduced energy consumption during pyrolysis (Tomczyk et al., 2020).

Chemically characterictics, biochar's composition depends on feedstock and processing temperature. High-lignin feedstocks, such as rice husks, generate biochar with greater carbon stability and ash content, increasing its capacity to bind nutrients. Higher pyrolysis temperatures typically concentrate nutrients like phosphorus, potassium, calcium, and magnesium, thereby enhancing its fertilizer potential (Ippolito et al., 2020). Moreover, biochar often exhibits a high cation exchange capacity (CEC) a measure of its ability to retain positively charged nutrients. Studies have shown that adding biochar can dramatically raise CEC in weathered tropical soils, sometimes by several-fold (Domingues et al., 2020).

Environmentally, biochar offers long-term carbon sequestration, with stable carbon persisting in soils for decades to centuries. This makes it not only a soil enhancer but also a valuable tool for climate mitigation (Kuryntseva et al., 2023). Indonesia's widespread availability of rice husks and agricultural by-products provides ample potential for locally produced biochar. When produced with appropriate technologies, this biochar can be tailored to provide optimal physical, chemical, and environmental benefits in paddy soil systems.

Table 1. Summary of Biochar Characteristics and Its Agricultural Potential in Indonesia

Aspect	Description	Relevant Findings / Sources
Feedstock Sources	Rice husks, coconut shells, sawdust, corn cobs — widely available in Indonesian agriculture	Luo et al., 2025; Antonangelo et al., 2025
Production Method	Pyrolysis under limited oxygen conditions; temperature and feedstock affect quality	Jatuwong et al., 2025

Aspect	Description	Relevant Findings / Sources
Physical Properties	High porosity and surface area; improves soil aeration, water retention, and reduces compaction	Shyam et al., 2025
Chemical Properties	High pH, rich in nutrients (K, Ca, P); increases cation exchange capacity (CEC)	Qi et al., 2024
Carbon Content	High carbon stability; suitable for long-term carbon sequestration	Luo et al., 2025; Jatuwong et al., 2025
Environmental Benefits	Reduces nutrient leaching, mitigates greenhouse gas emissions, supports sustainable farming	Shyam et al., 2025; Antonangelo et al., 2025
Local Potential	Availability of biomass and increasing access to small-scale pyrolysis units in rural areas	Luo et al., 2025
Implementation Considerations	Effectiveness depends on soil type, crop needs, and appropriate application rates	Qi et al., 2024

Effects of Biochar on Soil Quality

Biochar enhances physical, chemical, and biological aspects of paddy soils, thereby improving conditions essential for rice cultivation. One of the most immediate impacts of biochar in paddy soils is the improvement of soil structure, particularly in poorly drained or compacted rice fields. Biochar's high porosity, low bulk density, and large surface area help to reduce compaction and enhance water movement. Biochar significantly improves soil structure by reducing bulk density and increasing porosity especially in the upper 0–50 cm layers. In a six-year study on saline alkali paddy soils, a single biochar application led to a reduction in bulk density by 11–26%, while total porosity increased by 19–27%, and saturated hydraulic conductivity skyrocketed by over 3,2% enabling better root growth and water movement (Jin et al., 2024). Similarly, research in double-rice fields found enhanced macroporosity and connectivity in topsoil (0–50 mm), although deeper layers responded differently (Wang et al., 2018).

Biochar also significantly alters the chemical characteristics of paddy soils. Due to its alkaline nature and mineral content, biochar helps neutralize soil acidity common in many tropical rice-growing regions and increases nutrient retention by improving the cation exchange capacity (CEC). Biochar boosts soil fertility by increasing the availability of carbon, nitrogen, and phosphorus. In subtropical paddy soils, application rates of 10–40 t/ha raised soil C and N concentrations by 23–117%, while bulk density dropped by 7.4% (Jin et al., 2023). In a three-year field trial, biochar enhanced available phosphorus and potassium levels and activated key soil enzymes like phosphatase and catalase—though pH and total nutrient contents remained stable (Lv et al., 2023).

Biochar also exerts profound influence on soil microbial communities, which are essential for decomposition, nitrogen fixation, and overall soil fertility. The porous matrix of biochar provides microhabitats for soil microorganisms, buffering them against environmental fluctuations and promoting colonization. Biochar shifts microbial communities and stimulates enzyme activity. One study reported that biochar increased soil bacterial richness and altered the relative abundance of key phyla, indicating enhanced microbial habitat and activity.

Table 2. Effects of Biochar on Soil Properties (Indonesian Field Studies)

Soil Aspect	Biochar Effect	Study Location	Reference
Physical	- Increases available water capacity and total soil porosity	Madura	Supriyadi et al. (2022)
	- Reduces bulk density and enhances soil aggregation	Bogor	Rahmat et al. (2025)
Chemical	- Raises soil pH and improves availability of nitrogen (N), phosphorus (P), and potassium (K)	South Kalimantan	Maftuah & Indrayati (2014)
	- Increases soil organic carbon and cation exchange capacity (CEC)	East Lampung	Muhtar et al. (2021)
Biological	- Enhances soil respiration, microbial population, and enzyme activities	Lampung	Syaifudin et al. (2022)
	- Accelerates decomposition of organic matter when combined with compost	Bali	Soniari et al. (2023)

Impact of Biochar on Rice Growth and Yield

The application of biochar has been widely reported to enhance vegetative growth and yield components of rice, particularly in degraded or nutrient-poor paddy soils. Biochar improves plant height, number of tillers, leaf area, and root development by enhancing soil water retention, reducing bulk density, and increasing nutrient availability. These physical and chemical improvements lead to better plant vigor and biomass accumulation during the vegetative stage. By enhancing soil water retention, reducing compaction, and improving nutrient availability, biochar promotes plant height, tiller number, leaf area, and root biomass leading to stronger, more vigorous crops. Yield benefits include increased numbers of panicles, improved grain filling, higher thousand-grain weight, and greater overall grain yield (Mahyudi et al., 2025)

In terms of yield, biochar has demonstrated significant positive impacts, including increases in the number of panicles per plant, grain filling, and thousand-grain weight. This is often attributed to improved nitrogen and phosphorus uptake, enhanced microbial activity, and stabilization of soil pH. Furthermore, biochar's high cation exchange capacity (CEC) allows for better retention of essential nutrients like potassium (K^+), ammonium (NH_4^+), and magnesium (Mg^{2+}), reducing nutrient leaching and enhancing fertilizer use efficiency. iochar also improves nutrient use. A meta-analysis covering global paddy soils (including Indonesia) showed that biochar increases rice yield by 10.7% and nitrogen use efficiency (NUE) by 12.0%—with optimal effects at > 20 t/ha biochar combined with 150–250 kg/ha Nitrogen (Liu et al., 2022). In a pot experiment, combining biochar and reduced nitrogen fertilizer increased NUE by 54–142%, grain yield by up to 18%, and reduced ammonia volatilization and N_2O emissions significantly (Ning et al., 2022). Research of Mahyudi et al., (2024) with bamboo biochar plus N and P fertilizers in Central Java resulted in higher shoot and root biomass, improved grain weight, and stronger yield compared to fertilized controls.

Opportunities and Challenges in Indonesia

Indonesia generates vast amounts of agricultural residues—rice husks, coconut shells, corn cobs—making it ideal for producing local biochar. Smallholder farmers can potentially convert this waste into valuable soil amendments through low-cost pyrolysis, supporting both soil fertility and sustainability. However, reaching wide-scale adoption faces hurdles. Producing high-quality biochar requires precise control over pyrolysis temperature and duration, which many small rural producers lack. Farmers in remote areas may also struggle with the cost of biochar production or purchase. Additionally, there are no clear national standards for biochar quality, recommended application rates, or guidelines for integrating biochar into soil fertility programs leading to uncertainty.

Table 3. Estimated Agricultural Waste and Its Potential as a Biochar Raw Material

Agricultural Biomass	Total (t/year)	Assumed Conversion Rate (%)	Potential Biomass Converted (t/year)	Biochar/ Ratio	Biomass	Biochar Potential (t/year)
Rice husk	13,612,343	50%	6,806,172	0.26		1,769,605
Coconut shell	539,644	50%	269,822	0.25		67,456
Oil palm shell	6,400,000	30%	1,920,000	0.50		960,000
Cocoa pods	1,208,553	50%	604,277	0.33		199,411
Corn cobs	3,652,372	30%	1,095,712	0.13		142,443
Total	25,412,912	—	10,695,982	—		3,138,914

Source: Sarwani, (2013)

Institutional support remains limited. Few extension services actively promote biochar, and there is no integration into national agricultural or climate resilience plans. To overcome these gaps, it's essential for researchers, policymakers, and extension agents to collaborate. Suggested actions include developing farmer-friendly pyrolysis units, quality certification systems, standardized guidelines, and incentive schemes (e.g., subsidies, carbon credits) to encourage adoption. Successful scaling will require coordinated efforts to build farmer capacity, ensure supply chains, and integrate biochar into climate-smart agriculture initiatives.

Table 4. Challenges in Biochar Utilization in Indonesia

Challenge Category	Description	Implications
Technical	Minimally developed pyrolysis technology for smallholders	Difficulties in consistent quality and efficiency of biochar production
	Variation in feedstock and production conditions affects biochar properties	Inconsistent results in soil improvement and crop response
Economic	High initial investment for pyrolysis units and biochar processing	Low adoption by small-scale farmers
	Limited financial incentives and market access	Biochar remains economically unattractive for rural users
Social / Institutional	Low awareness and technical capacity among farmers	Misuse or underutilization of biochar
	Lack of extension services and education on biochar benefits	Delayed diffusion of technology
Policy / Regulatory	Absence of national standards or guidelines for biochar quality and application	Hinders integration into formal agricultural practices
	Weak coordination between sectors (agriculture, energy, environment)	Fragmented efforts and limited long-term support

CONCLUSION

Biochar is a promising solution for improving soil quality and rice productivity in Indonesia. It enhances soil structure, water retention, nutrient availability, and microbial activity—factors that support healthier plant growth and higher yields. When combined with fertilizers, biochar also improves nutrient use efficiency and reduces environmental losses.

Indonesia's abundant agricultural waste provides great potential for local biochar production. However, widespread adoption is still limited by technical challenges, production costs, and a lack of clear guidelines and policy support. To maximize biochar's benefits, future efforts should focus on developing accessible technologies, setting national standards, and expanding farmer training and institutional support.

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