

POLICY FRAMEWORKS FOR BIOCHAR-DRIVEN SOIL REVITALIZATION AND CLIMATE CHANGE MITIGATION IN INDONESIA

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Abstract— Indonesia's agricultural sector faces persistent challenges related to land degradation, declining soil fertility, and increasing climate variability, while large volumes of agricultural biomass residues remain underutilized and contribute to greenhouse gas emissions. This study examines the role of biochar as a nature-based solution that simultaneously supports soil revitalization and climate change mitigation in Indonesia. Using a policy-oriented and qualitative synthesis approach, the study integrates scientific literature, government regulations, market reports, and international benchmarking to assess the biophysical benefits of biochar, existing policy frameworks, and implementation gaps. Evidence from field applications in Central Java indicates that biochar can substantially improve soil properties and increase crop productivity, while its stable carbon structure enables long-term carbon sequestration and reductions in soil-based greenhouse gas emissions. Comparative analysis of international experiences highlights the importance of regulatory standardization, economic incentives, market integration, and capacity-building programs in accelerating biochar adoption. Based on relevance analysis using the THIO framework, this study formulates a phased National Biochar Implementation Roadmap (2025–2029) and proposes policy recommendations structured under the S.M.A.R.T framework. The findings demonstrate that biochar has significant potential to enhance soil health, strengthen sustainable agricultural systems, and contribute to Indonesia's climate mitigation and food security objectives, provided that supportive and integrated policy mechanisms are effectively implemented.

Keywords— biochar, soil revitalization, sustainable agriculture, climate change mitigation, carbon sequestration, policy framework, nature-based solutions

1. INTRODUCTION

Indonesia's agricultural sector faces complex challenges in maintaining national food security amid the pressures of climate change and land resource degradation. Increasingly unpredictable weather patterns—marked by prolonged droughts and flooding—directly threaten production stability and farmers' livelihoods, as experienced by coconut sugar farmers in Kulon Progo (Global Center on Adaptation, 2024). At the same time, the primary foundation of agriculture, soil, is undergoing alarming quality deterioration. More than 60% of Indonesia's agricultural land is reported to be degraded, characterized by poor soil health and low organic matter content, which in turn reduces fertility, water retention capacity, and soil structure (Kamar Dagang dan Industri Indonesia, 2025). This situation creates a paradox in which the demand for higher productivity is confronted by the declining carrying capacity of the land, necessitating innovative interventions capable of addressing both challenges simultaneously.

This large-scale land degradation is further exacerbated by unsustainable conventional farming practices and the limited return of organic matter to the soil. The impacts are not only agronomic but also ecological. Degraded land tends to exhibit low productivity, encouraging excessive use of chemical inputs that may ultimately pollute the environment. In addition, the natural decomposition of millions of tons of unmanaged agricultural biomass waste—estimated to exceed 100 million tons annually—releases greenhouse gases (GHGs), such as carbon dioxide (CO₂) and methane (CH₄), into the atmosphere. The widespread practice of

open burning of agricultural residues further intensifies emissions and air pollution (Sustainability Directory, 2025). Consequently, land degradation and biomass waste management represent two sides of the same problem, both contributing to a cycle of declining productivity and increasing emissions.

Amid these challenges, biochar has emerged as a nature-based solution offering dual benefits: improving soil health while contributing to climate change mitigation. Biochar is a carbon-rich solid material produced through the pyrolysis of biomass—such as rice husks, oil palm shells, or wood—under limited oxygen conditions. When applied to soil, biochar functions as a distinctive soil amendment due to its ability to significantly enhance the physical, chemical, and biological properties of soil (Tuti Ariani Bawamenewi et al., 2025). Studies have demonstrated that biochar can increase cation exchange capacity, improve moisture and nutrient retention, and provide a favorable habitat for beneficial soil microorganisms (Abbey et al., 2025). Moreover, its highly stable carbon structure allows it to persist in the soil for hundreds of years, effectively locking atmospheric carbon (CO_2 absorbed by plants) into the soil over the long term through a process known as carbon sequestration (Adiansyah et al., 2025).

Empirical evidence supporting the effectiveness of biochar continues to grow. Field trials conducted by WasteX in collaboration with the Ministry of Agriculture in Grobogan, Central Java, demonstrated that biochar application increased tomato and long bean yields by up to 52% (WasteX, n.d.). This efficiency is also reflected in the reduced need for chemical fertilizers, which not only lowers production costs but also minimizes the environmental footprint of agricultural activities. From a climate perspective, biochar holds strategic potential as a Carbon Dioxide Removal (CDR) technology. Research cited by Mongabay indicates that global-scale biochar deployment could mitigate greenhouse gas emissions by approximately 0.03 to 11 gigatons of CO_2 equivalent per year (Mongabay Indonesia, 2025)—comparable to emissions from the entire global industrial sector. These emission reductions stem not only from stable carbon storage but also from decreased soil emissions of nitrous oxide (N_2O) and methane (CH_4), as well as the utilization of pyrolysis by-products as renewable energy sources.

Recognizing this substantial potential, the Indonesian government has begun to take strategic steps to promote biochar adoption. The Ministry of Agriculture has established biochar quality standards through Ministerial Decree No. 261/KPTS/SR.310/M/4/2019 and has developed innovative products such as Biotron (biochar enriched with microbes and organic fertilizers). In July 2025, the Indonesian International Biochar Association (Asosiasi Biochar Indonesia Internasional/ABII) was established as a cross-sector collaboration platform, targeting national production of 1.3 million tons by 2025 and 2 million tons by 2029 (Asosiasi Biochar Indonesia Internasional, 2025). Despite these initiatives, adoption at the farmer level remains uneven across regions, and the translation of policy into practical implementation is still limited. Therefore, the effectiveness of these policies in accelerating large-scale biochar adoption still requires comprehensive, evidence-based assessment.

Accordingly, this study aims to examine existing policy frameworks governing biochar utilization for soil revitalization and climate change mitigation in Indonesia, and to propose integrated policy pathways to scale up its adoption through regulatory alignment, research and innovation support, economic incentives, and farmer-centered implementation mechanisms.

2. LITERATURE REVIEW

This section reviews the existing body of literature to establish the scientific and policy foundations of biochar utilization in the context of soil revitalization and climate change mitigation. It first synthesizes evidence on the biophysical mechanisms through which biochar improves soil quality and enhances plant resilience, thereby justifying its strategic relevance for sustainable agricultural systems. Subsequently, it examines international policy experiences and benchmarking studies to identify key policy instruments, governance approaches, and implementation pathways that have supported biochar adoption across different national contexts.

2.1. Biochar for Soil Quality Improvement as a Strategic Solution

Beyond its conventional role as a soil amendment, biochar functions as a strategic intervention that transforms soil into a more resilient living system. Its role as a readily available source of biosilica for plants represents a critical advantage that is often overlooked. Dissolved silica released from biochar strengthens plant cell walls, enhances resistance to pests and diseases, and alleviates abiotic stresses such as drought and metal toxicity (Tuti Ariani Bawamenewi et al., 2025). From a physiological perspective, biosilica improves photosynthetic efficiency and transpiration regulation, enabling plants to utilize water and nutrients more

efficiently (Abbey et al., 2025). Consequently, biochar application not only improves the growing medium but also directly enhances plant health and resilience, thereby promoting sustainable productivity while reducing reliance on external inputs such as pesticides.

The strategic effectiveness of biochar can also be demonstrated quantitatively. A study on the application of rice husk biochar produced through pyrolysis (characterized by a pH of 8.7, organic carbon content of 18.72%, and a cation exchange capacity of 17.57 cmol/kg) on acidic soils reported comprehensive improvements in soil properties. The application significantly increased soil pH, organic carbon content, phosphorus availability, and cation exchange capacity. Simultaneously, detrimental parameters such as bulk density and aluminum and iron toxicity (Tuti Ariani Bawamenewi et al., 2025)—both of which constrain root development—were substantially reduced. This combination of effects creates a markedly improved rhizosphere environment: soils become looser, nutrient-rich, and non-toxic, forming an essential foundation for healthy root systems and efficient nutrient uptake. These findings confirm that biochar operates as a precise soil engineering tool, particularly effective for revitalizing degraded lands such as the extensive acidic soils found across Indonesia. and efficient nutrient uptake. These findings reinforce the role of biochar as a precise soil engineering tool, particularly for revitalizing degraded lands, including the extensive acidic soils found in Indonesia (Abbey et al., 2025).

2.2. Policy Analysis and International Benchmarking

The adoption of biochar across countries is shaped by diverse policy frameworks, ranging from market-based incentives to structured research and education programs. At the global level, biochar-related policies remain fragmented and are often embedded indirectly within broader agricultural or climate policy frameworks, such as the European Union's Common Agricultural Policy. Common challenges include the need for product standardization to ensure quality and safety, the development of credible markets—particularly for carbon credits—and the design of policy instruments capable of delivering clear economic benefits to farmers as the primary end users. Lessons from international experiences indicate that successful biochar adoption depends on a holistic approach that integrates scientific research, economic incentives, practical education, and cross-sectoral policy coordination.

The following section reviews key research findings and policy initiatives from various countries that may serve as important benchmarks for strengthening and developing biochar policies in Indonesia.

Table 1. Global Biochar Policy Benchmark

Country	Title, Author(s) and Year of Publication	Main Focus/Key Findings	Benchmark Results Relevant to Policy Development
China, India, Pakistan, and Global	"A review of biochar's sustainability in climate-smart agriculture: Recent advances, emerging trends, and future directions" (Abbey et al., 2025)	This study presents a bibliometric and systematic analysis of 180 publications published between 2010 and 2023. The findings indicate that biochar significantly improves soil fertility and crop yields, with reported increases of up to 340% for potato production. In addition, the study estimates a global carbon mitigation potential of 2.56×10^9 tons CO ₂ -eq per year, equivalent to approximately 4.7% of global greenhouse gas emissions in 2023.	The study positions biochar as a "motor theme" in climate-smart agriculture and highlights the importance of policy incentives—such as carbon credit schemes, production technology subsidies, and integrated extension programs—to accelerate adoption, particularly among smallholder farmers.
India	Asia Pacific Biochar Market Report (Grand View Research, 2024)	The report highlights rapid growth of the Asia-Pacific biochar industry (CAGR 16.1%), driven by demand for organic products and soil improvement needs. The Indian government established a task force to explore biochar utilization in the steel industry (2023).	Government Incentive Model: Proactive government policies, such as establishing task forces, can stimulate innovation and adoption of biochar beyond agriculture, create new markets, and support national emission reduction targets.
Australia	Asia Pacific Biochar Market Report (Grand View Research, 2024)	Australia leads the biochar market share in the Asia-Pacific region. Growth is supported by agricultural benefits, climate mitigation potential, financial incentives such as carbon credits, and sustained government and research support.	Carbon Market Integration: Policies linking biochar use with carbon credit schemes (e.g., cap-and-trade programs) have proven effective in creating additional economic value and encouraging commercial-scale adoption.
Thailand	Biochar Learning and Collaboration in South East	Report on the Biochar Academy that trained 70 practitioners from 18	Human Capacity Investment: Immersive, location-based peer-

Asia (International Biochar Initiative, 2024)	Biochar countries. The curriculum covered small-scale production, agricultural applications, and carbon removal market navigation. 100% of participants reported the training as highly beneficial for their careers.	to-peer training programs are effective in building practitioner networks, transferring technical knowledge, and accelerating grassroots adoption while strengthening trust.
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As summarized in Table 1, a growing body of international evidence demonstrates how different countries have operationalized such approaches through distinct but complementary policy instruments. The reviewed studies and policy initiatives provide valuable benchmarks for Indonesia’s biochar policy development. For example, bibliometric and systematic analyses covering China, India, Pakistan, and global contexts highlight biochar as a “motor theme” within climate-smart agriculture, underscoring the importance of policy incentives such as carbon credit schemes, production subsidies, and integrated extension programs to accelerate adoption, particularly among smallholder farmers(Abbey et al., 2025).

Market-oriented policy signals are further illustrated by the Asia Pacific Biochar Market Report, which documents rapid industry growth in India and Australia driven by proactive government involvement, including task force formation, carbon market integration, and sustained research support. These cases demonstrate how policy alignment between agricultural productivity goals and climate mitigation mechanisms can create new markets and enhance the economic viability of biochar utilization. In parallel, capacity-building initiatives in Thailand, such as the Biochar Academy documented by the International Biochar Initiative, emphasize the role of targeted education and peer-to-peer training in strengthening human capital, fostering practitioner networks, and accelerating grassroots-level adoption.

Taken together, the comparative insights presented in Table 1. suggest that effective biochar policy frameworks combine regulatory clarity, economic incentives, market integration, and sustained investments in knowledge transfer. These international experiences provide a concrete reference for designing integrated and context-sensitive policy pathways to scale up biochar-driven soil revitalization and climate change mitigation in Indonesia.

3. METHODS

To address the research objectives and ensure analytical rigor, this study employs a structured methodological framework that integrates qualitative synthesis, relevance analysis, and policy-oriented assessment. The methodological approach is designed to systematically link the research questions with the analytical tools and data sources used to derive evidence-based policy recommendations.

3.1. Research Approach and Data Sources

This study adopts a policy-oriented and recommendation-based research approach aimed at formulating evidence-informed strategies to accelerate the adoption of biochar in Indonesia. Rather than generating new experimental data, the research emphasizes the systematic synthesis and qualitative analysis of existing knowledge, an approach well suited to addressing complex environmental and governance challenges.

Data were collected through a desk-based study encompassing peer-reviewed scientific literature, official government regulations, policy reports, market analyses, and documentation from international biochar initiatives. These sources were selected to capture both the biophysical foundations of biochar application and the institutional, economic, and governance factors influencing its implementation. All materials were analyzed qualitatively to identify enabling conditions, key constraints, and strategic leverage points for national-scale adoption.

3.2. Relevance Analysis

A relevance analysis was conducted to assess the suitability and feasibility of biochar implementation within the Indonesian context. This analysis employed the THIO framework (Technoware, Humanware, Infoware, Orgaware, and Environment) to systematically evaluate technological readiness, human resource capacity, information systems, institutional coordination, and environmental considerations. Each THIO dimension was examined to identify the roles and interactions of key stakeholders, including academic institutions, private-sector actors, and government agencies, across the biochar value chain. The analysis focused on how these dimensions interact to support or constrain large-scale biochar adoption.

While international experiences with biochar are reviewed in the literature review to establish the state

of knowledge and global trends, international benchmarking is applied in this study as an analytical tool to assess policy relevance and contextual suitability for Indonesia. Benchmarking draws on selected cases from China, India, Australia, and Thailand, with attention to product standardization, economic incentive schemes, capacity-building programs, and integration with carbon markets. These comparative insights are used to inform the relevance analysis rather than to replicate policy models directly.

3.3. Legal, Social, and Economic Framework Analysis

To complement the relevance analysis, the study assessed the legal, social, and economic frameworks shaping biochar adoption in Indonesia. The legal analysis reviewed existing national regulations related to biochar to identify regulatory gaps and opportunities for policy integration across sectors. The social analysis examined farmer adoption dynamics, emphasizing participatory extension approaches, demonstration-based learning, and trust-building mechanisms. The economic analysis evaluated potential value creation along the biochar value chain, including productivity gains, input cost reductions, and opportunities arising from carbon market mechanisms.

Collectively, these analyses provide the analytical foundation for formulating policy recommendations that are feasible, context-specific, and aligned with national development and climate objectives.

4. RESULT AND DISCUSSION

This section presents and discusses the main analytical findings of the study by synthesizing insights from the literature review, policy analysis, and relevance assessment conducted in the Indonesian context. The discussion focuses on translating scientific evidence and international policy benchmarks into actionable and context-specific policy pathways. Particular attention is given to the identification of strategic priorities, institutional roles, and implementation mechanisms required to scale up biochar utilization for soil revitalization and climate change mitigation in Indonesia.

4.1. National Biochar Implementation Roadmap (2025–2029)

Based on the relevance analysis, a phased National Biochar Implementation Roadmap for 2025–2029 was formulated to provide a structured pathway for scaling up biochar adoption in Indonesia. The roadmap outlines sequential policy, technical, and institutional interventions, progressing from preparatory actions to large-scale adoption and long-term institutionalization, as summarized in Table 2.

Table 2. National Biochar Implementation Roadmap (2025–2029)

Phase	Period (Year)	Key Focus and Activities	Expected Outcomes
Phase 1: Policy and Capacity Preparation	2025	1. Regulation and Standards: Finalizing and issuing a Ministerial Regulation on biochar quality standards, production, and application. 2. Preliminary Research: Mapping local biomass potential and developing site-specific application guidelines (mineral soils, peatlands, drylands). 3. Network Formation: Strengthening the International Indonesian Biochar Association (ABII) as a national coordination and knowledge hub. 4. Training of Trainers: Developing training modules and certifying agricultural extension officers and provincial agricultural technicians as master trainers.	1. National biochar quality standards officially enacted. 2. A national database on biomass potential and application recommendations for three major agroecosystems established. 3. One active national biochar association serving as a focal point. 4. At least 100 certified master trainers prepared for nationwide dissemination.
Phase 2: Demonstration and Validation	2026	1. Pilot Projects: Implementing 50–100 demonstration plots in major food production regions (Java, Sumatra, Sulawesi) focusing on strategic commodities (rice, maize, horticulture). 2. Intensive Assistance: Master trainers providing hands-on support to farmer groups for small-scale biochar production and application. 3. Proof-of-Concept Studies: Quantitatively assessing the impacts of biochar on crop productivity, soil health, and farm-level economics. 4. Early Market Development: Registering pilot projects under voluntary carbon standards (e.g., Verra) to test biochar-based carbon credit mechanisms.	1. One hundred well-documented demonstration plots accessible for learning and replication. 2. Five hundred pioneer farmers trained and capable of independently producing and applying biochar. 3. Validation reports indicating an average productivity increase of >15% and improved soil organic carbon in pilot sites. 4. One nationally validated methodology for biochar-based carbon projects.

Phase 3: Scale-Up and Market Incentives	2027 – 2028	1. Policy Integration: Incorporating biochar into national subsidy schemes (e.g., bundled with subsidized fertilizers or land rehabilitation programs). 2. Fiscal Incentives: Providing value-added tax (VAT) reductions or income tax incentives for certified biochar processing enterprises. 3. Industrial Strengthening: Delivering technical assistance and financial support to establish cooperative- or MSME-scale biochar production units. 4. National Campaigns: Conducting large-scale outreach through media and field days to stimulate demand (demand-pull).	1. Biochar included in at least one national agricultural subsidy program (e.g., rice production enhancement programs). 2. Ten to twenty cooperative/MSME-scale biochar production units operating with local government support. 3. Adoption by more than 5,000 farmers beyond the initial pilot sites. 4. The emergence of a domestic carbon credit market with initial transactions from biochar projects.
		1. Policy Review and Evaluation: Assessing roadmap effectiveness and revising regulations based on evidence and field-level challenges. 2. Value Chain Strengthening: Developing downstream industries such as enriched biochar or biochar-based organic fertilizers. 3. NDC Integration: Incorporating carbon sequestration contributions from the national biochar program into Indonesia's updated Nationally Determined Contribution (NDC). 4. Functional Expansion: Promoting biochar applications in other sectors, including mine land remediation and waste management.	1. A Phase II Roadmap (2030–2034) developed based on comprehensive evaluation. 2. A self-sustaining biochar industrial value chain involving MSMEs and corporate actors established. 3. Mitigation contributions from biochar formally included in Indonesia's NDC reporting. 4. Initial cross-sectoral adoption (mining, forestry) piloted and evaluated.
Phase 4: Institutionalization and Sustainability	2029		

As shown in Table 2, each implementation phase is defined by specific timeframes, priority activities, and expected outcomes. This phased structure reflects the need to align regulatory readiness, capacity development, market formation, and governance consolidation to ensure the effective and sustainable integration of biochar into national agricultural and climate strategies.

4.2. THIO Analysis and Multi-Actor Roles

The national implementation of biochar requires a systemic approach that integrates technological, human, informational, institutional, and environmental dimensions. Accordingly, this study applies the THIO framework (Technoware, Humanware, Infoware, Orgaware, and Environment) to ensure that all enabling elements supporting biochar adoption are coherently aligned. The effectiveness of this approach is highly dependent on synergy and collaboration among key stakeholders, including academic institutions, private-sector actors, and government agencies, as summarized in Table 3.

Table 3. THIO Framework Analysis and Roles of Key Stakeholders

THIO Dimension	Roles and Contributions of Academia / Researchers	Roles and Contributions of Corporations / Private Sector	Roles and Contributions of Regulators / Government
Technoware (Technical Devices and Technologies)	Developing and testing efficient, affordable, and safe pyrolysis reactor prototypes for small- to medium-scale applications (e.g., farmer cooperatives). Conducting research to optimize site-specific biochar formulations (biomass type, pyrolysis temperature) for acidic soils, peatlands, and other conditions.	Investing in and operating industrial-scale pyrolysis facilities for mass production of standardized, high-quality biochar. Developing value-added downstream products, such as enriched biochar combined with fertilizers or microbial inoculants.	Establishing and enforcing national standards (SNI) for biochar quality (stable carbon content, moisture levels, contaminant thresholds). Providing fiscal incentives (grants, tax reductions) to support the acquisition and development of pyrolysis technologies.
Humanware (Human Capacity and Skills)	Designing evidence-based technical training curricula and modules for farmers, extension officers, and technicians. Serving as resource persons and facilitators in programs such as “Biochar Academy” or farmer field schools to develop pioneer farmer groups (master trainers).	Delivering technical training and mentoring programs for partner farmers or biomass suppliers. Creating new employment opportunities in biochar production, distribution, and application (e.g., technicians, agronomists, sales personnel).	Leading and funding national training programs for public agricultural extension officers as key dissemination agents. Integrating biochar-related content into vocational and agricultural polytechnic curricula.
Infoware	Generating scientific data and publications on biochar performance under diverse agroclimatic	Developing blockchain-based platforms to track biomass origin, production processes, and biochar distribution,	Establishing and managing an integrated National Biochar Information System containing

(Data, Knowledge, and Information Systems)	conditions. Developing interactive digital guidelines and decision support systems for biochar application recommendations.	supporting certification and carbon trading. Conducting marketing and consumer education campaigns on the benefits of biochar-based products.	data on biomass potential, certified producers, application guidelines, and adoption monitoring. Disseminating biochar-related policies and benefits through official communication channels.
Orgaware (Institutions, Networks, and Coordination)	Facilitating scientific forums and multi-stakeholder dialogues to align research agendas with market needs and policy priorities. Acting as independent technical advisors to government bodies and industry associations.	Collaborating within industrial clusters or biochar consortia (e.g., under chambers of commerce) for industry standardization, policy advocacy, and joint research initiatives. Building business partnerships with farmer cooperatives for biomass supply chains and biochar distribution.	Strengthening the role and capacity of the Indonesian Biochar Association as a national coordination platform. Leading inter-ministerial task forces or working groups (Agriculture, Environment, Industry, National Planning) to harmonize biochar-related policies.
Environment (Environmental Compliance and Impacts)	Conducting Life Cycle Assessment (LCA) studies to evaluate the holistic environmental impacts of biochar from production to application, including long-term effects on soil health and carbon stocks.	Applying circular economy principles by utilizing in-house biomass waste (e.g., from palm oil, sugar, or timber industries) as feedstock. Adopting low-emission production systems and proper management of pyrolysis by-products.	Designing and overseeing green certification and carbon credit schemes for biochar projects. Ensuring compliance with environmental impact assessment (AMDAL) regulations and waste management standards. Integrating biochar mitigation contributions into Indonesia's Nationally Determined Contribution (NDC) reporting.

As summarized in Table 3, the THIO analysis maps the specific roles and contributions of Academia, Industry, and Government across each dimension of the framework. This mapping is designed to directly support the phased actions outlined in the National Biochar Implementation Roadmap, highlighting how coordinated multi-actor engagement can address technical readiness, capacity development, information management, institutional coordination, and environmental compliance.

4.3. Legal, Social, and Economic Frameworks

This subsection examines the broader legal, social, and economic conditions that shape the feasibility and sustainability of biochar implementation beyond technical and institutional considerations. These dimensions influence regulatory certainty, stakeholder acceptance, and economic viability, and therefore play a critical role in determining whether the proposed roadmap and governance mechanisms can be effectively operationalized in practice.

4.3.1. Legal Framework

The legal framework for biochar in Indonesia has an initial foundation in the issuance of Ministerial Decree No. 261/KPTS/SR.310/M/4/2019 on Biochar as a Soil Amendment. However, this regulation remains limited to product quality standards and has yet to evolve into a comprehensive legal framework governing biochar deployment. Further regulatory development is required in the form of a Ministerial Regulation that not only specifies technical standards but also regulates safe production practices (including the control of pyrolysis emissions), producer certification systems, incentive schemes, and integration with broader national agricultural programs. In addition, harmonization with existing environmental protection legislation and alignment with national carbon trading mechanisms are essential to ensure legal certainty, reduce investment risks, and foster private-sector participation.

4.3.2. Social Framework

The social dimension of biochar implementation centers on farmer acceptance and adoption, as farmers constitute the primary end users. A major challenge lies in shifting entrenched farming practices by introducing innovations that may initially be perceived as complex or unfamiliar. Consequently, successful adoption depends on participatory communication and dissemination approaches rather than top-down instruction. Demonstrating tangible benefits through farmer-managed demonstration plots, particularly those led by trusted local farmer groups or “champion farmers,” has proven to be an effective strategy. Moreover, practical training combined with narratives that emphasize direct household-level economic benefits—such as reduced fertilizer costs and yield improvements—rather than abstract long-term climate benefits, is critical

for building motivation, trust, and local ownership.

4.3.3. Economic Framework

For biochar adoption to be sustainable, it must generate clear and tangible economic value. At the farm level, this value can be realized through productivity gains, reduced input costs, and potential additional income from carbon credit revenues where appropriate schemes are available. For business actors, fiscal incentives such as tax allowances for reactor investments, subsidies or concessional financing schemes for equipment acquisition, and guaranteed government procurement (e.g., for land rehabilitation programs) can significantly stimulate industry growth. In this context, the government plays a catalytic role by creating early-stage markets and facilitating the development of an integrated business ecosystem that links biomass feedstock suppliers, biochar producers, distributors, financial institutions, and carbon market actors.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

The conclusions of this study are articulated in the form of policy recommendations structured under the S.M.A.R.T framework, translating analytical findings into concrete, measurable, and time-bound actions. The proposed recommendations aim to accelerate biochar adoption while ensuring regulatory credibility, economic feasibility, and social inclusiveness, as summarized in Table 4.

Table 4. Policy Recommendations Based on the S.M.A.R.T Framework

Policy Recommendation	National Roadmap and Mandatory Certification-Based Standards	Targeted Fiscal Incentives and Dedicated Financing for Biochar Value Chain Development	Integrated “Biochar Desa” Program Linked to Extension Services and Carbon Markets
Specific	Strengthen and integrate the Indonesian National Standard (SNI) for biochar by enforcing mandatory certification for all commercial producers and government program participants.	Establish incentive packages including subsidized loans for certified pyrolysis reactors, tax incentives for MSME producers, and matching grants for industry-academia applied research.	Develop a village-level circular business model by training farmer groups to convert local biomass into biochar and generate income from agricultural production and verified carbon credits.
Measurable	At least 50 certified producers within the first 3 years; 100% compliance in government procurement; zero cases of soil contamination from certified biochar.	Creation of at least 200 new production units within 5 years; IDR 500 billion in dedicated financing disbursed within 3 years; minimum 5 applied research collaborations per year.	Participation of 500 villages or farmer groups within 5 years; average 15% increase in farmer income; verified sequestration of 1 million tCO ₂ e.
Achievable	Builds upon existing regulations (Ministerial Decree No. 261/2019) and collaboration with IBI and BSN; certification implemented gradually starting from medium-large producers.	Utilizes existing financing instruments (e.g., public credit schemes) with biochar-specific windows; funding sourced from subsidy reallocation or future carbon market revenues.	Built upon existing demonstration plots and extension service infrastructure; partnerships with carbon verification platforms and corporate buyers.
Relevant	Addresses quality assurance and trust gaps identified in the THIO analysis and international benchmarking; enables integration with high-credibility carbon markets.	Directly addresses high upfront capital costs identified as the main economic barrier; accelerates upstream-downstream industry growth and improves farmer affordability.	Empowers farmers as active agents, strengthens rural economies, and delivers measurable climate mitigation; aligns with food security and rural development agendas.
Time-bound	Comprehensive SNI revision completed within 12 months; mandatory certification for government partners within 24 months; full enforcement within 36 months.	Incentive scheme designed and launched within 18 months; effectiveness evaluated annually during the scale-up phase.	Pilot 50 villages in Year 1; national rollout of 100 villages per year starting Year 2; comprehensive impact evaluation at Year 5.

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