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PADDY WASTE VALORIZATION THROUGH BIOCHAR PRODUCTION: ENHANCING FARMERS' WILLINGNESS TO PAY BASED ON BEHAVIORAL TREATMENT EFFECT

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Abstract

Climate change has intensified paddy soil degradation, including the accumulation of ferrous iron (Fe^{2+}), evidenced by yellowish-brown irrigation water observed in the study area, which directly suppresses rice yields by 15-30%. Biochar as a soil amendment offers dual potential in mitigating iron toxicity and contributing to carbon sequestration, yet farmers' economic valuation of this technology remains underexplored. As consequence, biochar application remains limited among paddy rice smallholders, though its huge potential for improving soil quality and carbon removal. This study examines smallholder rice farmers' willingness to pay (WTP) for biochar adoption in West Java, Indonesia, using contingent valuation with a double-bounded dichotomous choice format. Through an information framing effect experiment, 201 respondents were assigned to three groups: control, agronomic information treatment (T1), and carbon credit information treatment (T2) which aimed to observed the effect of information treatment on biochar willingness to pay (WTP) among smallholders. Estimation was conducted using interval regression with robust standard errors, validated by ordered probit. Results reveal that information treatments significantly increased WTP. Mean WTP was IDR 103,994 in the control group, rising to IDR 220,502 under T1 and IDR 316,034 under T2, confirmed by a significant joint Wald test ($\chi^2(2) = 14.78$; p-value = 0.001). Key WTP determinants include farmer group participation, household size, carbon credit awareness, and agricultural training. This result confirms that integrating agronomic benefits and carbon credit information into biochar dissemination strategies is critical to accelerating smallholder adoption. Thus, the future adoption of biochar to smallholders is recommended to combine these information treatments to elevate the adoption process among smallholders.
Keywords: Willingness to Pay, Biochar, Carbon Credits, Contingent Valuation, Rice Farmers, Framing Treatment Effect

1. Introduction

Climate change has emerged as a critical challenge threatening both the productivity and sustainability of agricultural systems, particularly rice farming, which is highly dependent on climatic conditions and seasonal patterns. Changes in rainfall distribution, rising temperatures, and the increasing frequency of extreme weather events have accelerated soil degradation and reduced agricultural land productivity. Among the most significant impacts are increasing soil salinity and acidity, which disrupts nutrient balance, induces osmotic stress, and reduces photosynthetic efficiency, ultimately leading to lower crop yields and greater production risks for farmers (Ansari et al., 2023; Wu et al., 2023; Das et al., 2025). These challenges are further exacerbated by unsustainable agricultural residue management practices, particularly the open-field burning of rice straw and rice husks, which remains common in many rice-producing regions. Such practices not only contribute substantially to greenhouse gas (GHG) emissions but also accelerate the loss of soil organic matter and essential nutrients required to maintain soil fertility (Akahoshi et al., 2024; Arunrat et al., 2023).

These issues are particularly relevant in West Java, one of Indonesia's largest rice-producing provinces, contributing approximately 16% of the country's total rice production (BPS West Java, 2025). Sumedang Regency, one of the province's major rice-growing areas, is dominated by smallholder farmers operating on relatively limited landholdings. This characteristic makes farming households particularly vulnerable to climate-related pressures and land degradation. Preliminary observations conducted among rice farmer groups in Sumedang revealed increasing concentrations of reduced iron (Fe^{2+}), indicated by the yellowish-brown discoloration of irrigation water. This condition has led to chlorosis symptoms in rice plants, resulting in yield reduction and a higher risk of crop failure. Ahmed et al. (2023) reported that excessive accumulation of Fe^{2+} ions under flooded soil conditions represents a major environmental stressor limiting rice production in tropical regions. Meanwhile, the continued practice of burning crop residues and inadequate agricultural waste management further deteriorates soil quality while increasing carbon emissions from the agricultural sector.

One promising innovation that addresses these interconnected challenges is biochar. Biochar is a carbon-rich material produced through the pyrolysis of biomass, including agricultural residues such as rice straw and rice husks. In recent years, biochar has been widely recognized as a climate-smart agricultural technology due to its ability to simultaneously improve the physical, chemical, and biological properties of soil (Moragues-Saitua et al., 2023). Numerous studies have demonstrated that biochar application enhances water retention capacity, stabilizes soil pH, improves nutrient availability, and promotes better soil structure, thereby supporting crop growth and productivity (Liang et al., 2024; Frene et al., 2025). In rice cultivation systems, biochar has also been shown to adsorb excessive iron ions, reduce their solubility in soil, and mitigate the risk of iron toxicity in rice plants (Evizal & Fembriarti, 2023). Beyond its agronomic benefits, biochar contributes to improving the resilience of agricultural systems against salinity and drought stresses that are becoming increasingly common under changing climatic conditions.

In addition to its agronomic advantages, biochar possesses significant potential as a climate change mitigation instrument. Its highly stable carbon structure allows long-term carbon storage, making biochar one of the most promising carbon dioxide removal (CDR) technologies. Several studies have reported that biochar application can significantly reduce CO_2, CH_4, and N_2O emissions while simultaneously enhancing soil carbon sequestration capacity (Singh et al., 2023; Salma et al., 2024; Jiang et al., 2025). As a result, biochar has attracted increasing attention within global carbon markets as a source of high-value carbon credits. Verra, one of the world's leading carbon registries, has registered biochar-based agricultural residue projects under the VM0044 methodology, enabling agricultural waste to be converted into biochar while generating additional economic value through carbon credit trading (Verra, 2024). This development highlights the dual role of biochar as both a soil improvement technology and a potential economic instrument capable of enhancing farmers' livelihoods through low-carbon agricultural practices.

Despite its well-documented benefits, the adoption of biochar among smallholder farmers remains relatively limited, particularly in developing countries. Preliminary observations among farmer groups in Sumedang indicate that limited access to information, high initial investment costs, uncertainty regarding long-term benefits, and risk-averse behavior constitute major barriers to adoption. These findings are consistent with previous studies reporting that global biochar adoption remains largely confined to pilot-scale initiatives and has not yet achieved widespread implementation among farming communities (Latawiec et al., 2017; Janiszewska-Latterini et al., 2025; Perrone et al., 2025). Moreover, existing research has predominantly focused on the biophysical performance of biochar, including soil improvement, crop productivity enhancement, and greenhouse gas mitigation, while comparatively little attention has been devoted to understanding the economic feasibility and behavioral dimensions influencing farmers' adoption decisions.

From a behavioral economics perspective, technology adoption decisions are influenced not only by the characteristics of the technology itself but also by how information is presented to potential adopters. The framing effect suggests that individuals may respond differently to identical information depending on how it is communicated. Previous studies have demonstrated that information framing can significantly influence preferences and decision-making processes in environmental and sustainable agriculture contexts (Streletskaya et al., 2020; Ploll et al., 2023; Zou et al., 2025). Therefore, information regarding both the agronomic benefits of biochar and its potential economic value through carbon credits may shape farmers' perceptions and willingness to adopt the technology.

Although extensive research has established the effectiveness of biochar in improving soil quality, enhancing crop productivity, and mitigating carbon emissions, empirical evidence regarding how farmers' economic value this technology remains limited. More specifically, studies examining the influence of information framing related to agronomic benefits and carbon credit opportunities on farmers' willingness to pay (WTP) for biochar adoption remain scarce, particularly among smallholder rice farmers in developing countries. This knowledge gap limits the availability of evidence-based strategies for designing effective dissemination programs and incentive mechanisms to promote biochar adoption at the farm level.

Unlike previous studies that have primarily focused on either the biophysical or economic dimensions of biochar separately, this study integrates three key components: farmers' economic valuation of biochar through willingness-to-pay analysis, information framing treatments considering agronomic and carbon-credit benefits, and the exploration of biochar implementation within agricultural carbon market schemes. This integrated approach is expected to provide a more comprehensive understanding of the factors influencing biochar adoption decisions while expanding opportunities for implementing carbon-credit mechanisms in smallholder rice farming systems in Indonesia.

Based on these research gaps, this study evaluates farmers' willingness to pay for rice straw-based biochar using the Contingent Valuation Method–Double Bounded Dichotomous Choice (CVM-DBDC) approach. Furthermore, the study examines the effects of information framing on farmers' preferences, identifies socioeconomic factors influencing biochar adoption decisions, and explores the potential development of biochar-based carbon credit schemes for smallholder rice farmers in Sumedang Regency, Indonesia.

2. Literature Review

The existing literature has extensively documented the agronomic and environmental benefits of biochar, encompassing improvements in soil fertility (Ansari et al., 2026; Frene et al., 2025; Kapoor et al., 2026), water retention capacity (Demir & Bayrakli, 2026), and greenhouse gas (GHG) emission reduction (Yang et al., 2024; Liu et al., 2024), as well as its potential as a carbon dioxide removal (CDR) technology within carbon market frameworks (Moragues-Saitua et al., 2023). Nevertheless, these two research streams — the agronomic benefits of biochar and carbon credit mechanisms — have largely developed in parallel, particularly within the context of smallholder agriculture. Empirical studies that operationalize the integration of biochar into carbon credit schemes accessible to smallholder farmers remain scarce, and this gap is further pronounced in developing countries such as Indonesia, where carbon credit initiatives remain concentrated in large-scale industrial and forestry sectors with minimal smallholder participation.

This situation is compounded by the widespread practice of open burning of crop residues on paddy fields, which not only exacerbates GHG emissions and soil degradation but also impedes the integration of paddy waste into sustainable circular agricultural systems. Departing from this gap, the present study develops an integrated framework that combines farmer preference-based economic valuation, biochar carbon credit mechanisms, and behavioral intervention through information framing, specifically nudge information treatment — to promote biochar adoption among smallholder paddy farmers in Sumedang Regency. By linking the environmental benefits of biochar to measurable economic incentives, this study contributes to the development of climate-smart agricultural solutions that are practically applicable and support the operationalization of carbon economic instruments within Indonesia's smallholder rice farming systems, as mandated under Presidential Regulation No. 110 of 2025.

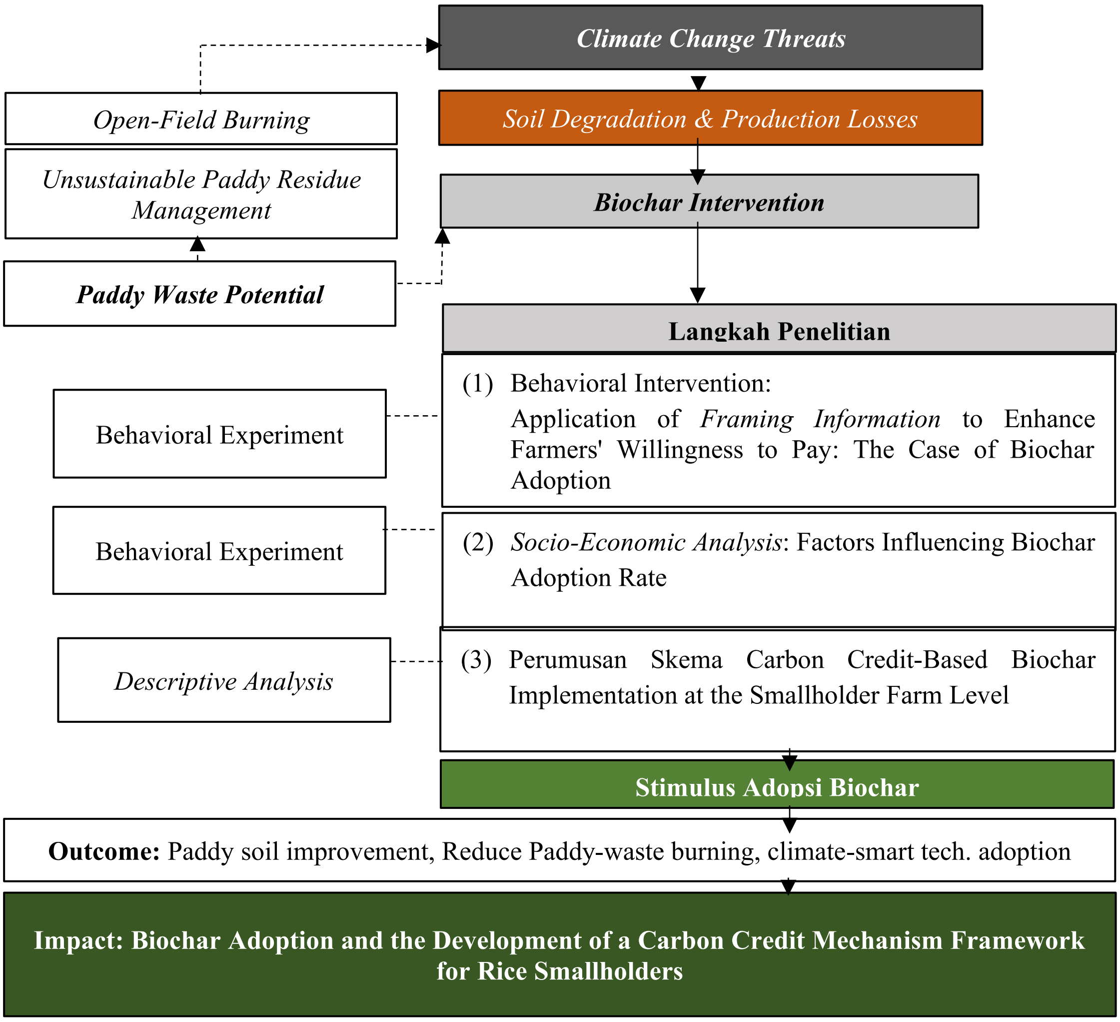

Figure 1. State of the Art Penelitian dan *Research Framework*

Table 1. Research Variable Description

No.	Variable	Definition	Measurement
Farmer Socio-Economic Characteristics			
1.	Age	Farmer's age	Tahun
2.	Gender	Farmer's gender	Dummy
3.	Education Level	Farmer's level of formal education	Ordinal scale
4.	Household Size	Number of members in farmer's household	Count
5.	Income	Monthly income [farmer selects income range]	Ordinal scale
Farm Characteristics			
6.	Farming Experience	Years of experience in paddy farming	Years
7.	Paddy Field Area	Total cultivated land area	Hectares
8.	Rice Productivity	Rice productivity per hectare	*Ton/Hectare*
9.	Paddy Waste Management	How does the farmer manage paddy waste after harvest?	Option choice
10.	Organic Fertilizer	Does the farmer use organic fertilizer?	Kilogram/Ha
Innovation Adoption			
11.	Field Trial Participation	Field Trial ParticipationHas the farmer ever participated in a demonstration plot (demplot) trial?	Dummy
12.	Training Frequency	Frequency of training related to paddy cultivation innovations	Count

13.	Farmer Group Activeness	How active is the farmer in their farmer group?	Scale [1–5]
Risk Attitude			
14.	Farmer Risk Attitude	Farmer's risk attitude scale toward innovation adoption in agricultural programs	Scale [1–10]
Future Orientation			
15.	Future Cost Preference	Is the farmer willing to incur costs for future economic benefits?	Scale [1–5]
16.	Future Benefit Preference	Does the farmer prefer larger benefits in the future or smaller benefits received immediately?	Scale [1–5]
Carbon Credit Awareness			
17.	Carbon Credit Knowledge	Does the farmer have prior knowledge of carbon credits?	Dummy
18.	Carbon Credit Economic Benefit	Farmer's perception of the future economic benefits of carbon credits	Scale [1-5]
Climate Change Perception			
19.	Climate Change Impact	Has climate change affected the farmer's rice production?	Scale [1-5]
20.	Extreme Weather Frequency	Farmer's perception of the frequency of extreme weather events	Scale [1-5]
Environmental Attitude			
21.	Straw Burning Perception	Should straw burning after harvest be reduced due to its environmental impact?	Scale [1-5]
Willingness to Pay (WTP)			
22.	1st Bid	[Rp 200.000,-]	Dummy
	2nd Bid	[Rp 300.000,-], [Rp 100.000,-]	Dummy

3. Research Methods

3.1. Object, time and Place

The study was conducted in June 2026 in Sumedang Regency, West Java Province, Indonesia. The research site was selected purposively based on its characteristics as one of the main rice-producing areas in West Java, dominated by smallholder farmers and facing various challenges related to soil quality degradation and the impacts of climate change. Data collection was carried out in two active farmer groups, namely the Gandasari Farmer Group and the Sri Jati Farmer Group, which were recommended by local agricultural extension officers due to their high level of participation in agricultural innovation development activities.

3.2. Data Collection Techniques

This study employed a quantitative approach with a survey experiment design combined with the Contingent Valuation Method–Double Bounded Dichotomous Choice (CVM-DBDC) to estimate farmers' willingness to pay (WTP) for the adoption of rice straw-based biochar. This approach was chosen because it enables the measurement of farmers' economic preferences for a technology that is not yet fully traded in the market, while also identifying the effect of information treatment on adoption decisions. The study population consisted of all active members of the farmer groups in the selected research locations. A total of 201 respondents were selected using simple random sampling based on the membership lists of the farmer groups. The sample size was determined through an a priori statistical power analysis, resulting in a power value greater than 0.85, thus meeting the minimum standard for experimental and quantitative survey research (Cohen, 1988). Primary data were collected through structured interviews using a questionnaire covering farmers' socio-economic characteristics, farming information, perceptions of biochar, and willingness-to-pay questions. Prior to the main survey, the instrument was pre-tested to ensure clarity of the questions and consistency in respondents' understanding of the valuation scenarios provided.

3.3. Data Analysis Techniques

To examine the effect of information on farmers' preferences, the study applied an information framing treatment through a three-group randomized experimental design. The control group received basic information regarding the definition of biochar and its production process from rice straw without additional benefit-related information. The first treatment group (T1) received additional information on the agronomic benefits of biochar, including improvements in soil quality, increased water retention capacity, enhanced fertilizer use efficiency, and potential increases in farm productivity. The second treatment group (T2) received additional information on the environmental and economic benefits of biochar, particularly its potential as a carbon sequestration technology that can generate economic value through carbon credit trading mechanisms. This design allows comparison of the effects of agronomic information and carbon credit-related information on biochar adoption decisions.

Willingness to pay was elicited using the Double-Bounded Dichotomous Choice (DBDC) format, in which respondents were asked two sequential dichotomous questions. If respondents accepted the initial bid, they were given a higher follow-up bid; conversely, if they rejected the initial bid, they were offered a lower follow-up bid. This approach was chosen because it provides more efficient WTP estimates compared to the single-bounded dichotomous choice method (Hanemann et al., 1991; Cameron & Quiggin, 1994).

The dependent variable in this study is farmers' willingness to pay for biochar adoption. The independent variables consist of agronomic information treatment (T1) and carbon credit information treatment (T2), while control variables include farmers' socio-economic characteristics such as age, education level, farming experience, farm size, household income, farmer group membership, and other variables relevant to agricultural technology adoption decisions.

The data were analyzed using an interval regression model appropriate for estimating interval-censored WTP data generated from the Double-Bounded Dichotomous Choice format. The empirical model is specified as follows:

$$WTP i^* = \alpha + \beta_1 T_1 i + \beta_2 T_2 i + \gamma X i + \varepsilon i$$

Where WTPi* represents farmers' latent willingness to pay, T1i and T2i are dummy variables for information treatments with the control group as the reference category, Xi is a vector of farmers' socio-economic characteristics, and εi is the error term. The mean willingness to pay was calculated based on the estimated parameters from the interval regression model. The effect of information framing was tested using a Wald test on the treatment coefficients to evaluate differences in willingness to pay between treatment and control groups at the 5% significance level.

4. Results and Discussion

4.1. Willingness to Pay (WTP) Model Specifications

The estimation of farmers' willingness to pay (WTP) for biochar adoption was conducted using the interval regression (intreg) method developed by Cameron and Quiggin (1994). This model is appropriate for double-bounded dichotomous choice (DBDC) data structures, in which each respondent answers two sequential bid questions (initial bid of IDR 200,000 and follow-up bid of IDR 300,000). Under this framework, WTP is not directly observed but lies within an interval range. The initial bid of IDR 200,000 was determined based on the scenario of constructing a simple biochar reactor at the farmer group level, representing the initial contribution cost per farmer member. Meanwhile, the follow-up bid of IDR 300,000 represents an upper bound estimate (1.5 times the initial bid) used to assess farmers' maximum willingness to pay for the initial investment in a simple biochar reactor. Table 2 presents the distribution of observation types in the dataset.

Table 2. Distribution of WTP Observation Types

Observation Type	Amount	Percentage (%)
Interval-censored	144	71.6
Right-censored	57	28.4
Total	201	100.0

Source: Primary data (processed)

A total of 144 observations (71.6%) are interval-censored, indicating that farmers' WTP lies between the two bid values, while 57 observations (28.4%) are right-censored, indicating that WTP exceeds the highest bid offered. The relatively high proportion of right-censored observations suggests that the bid design is conservative relative to farmers' actual valuation, thus strengthening the justification for using interval regression rather than a bivariate probit model, which requires correlation assumptions between response equations.

4.1.1 Estimation Results of the Model

The interval regression model was estimated using robust standard errors to address potential heteroskedasticity. The results indicate that the model is statistically significant overall (Wald test $\chi^2(21) = 205.13$; $p < 0.001$), with a log-pseudolikelihood value of -258.34. Table 3 presents the estimated coefficients of the relevant variables. Overall, both treatment variables (T1 and T2) significantly influence farmers' willingness to pay for biochar adoption. The control variables further explain variations in WTP at the farmer level, as presented in Table 3 below.

Table 3. Interval Regression Results of WTP for Biochar Adoption

Variable	Coefficient	Robust SE	z	*p*-value
T1: Agronomic Information	84,088.62***	26,315.96	3.20	0.001
T2: Carbon Credit Information	133,413.80***	32,725.98	4.08	0.000
Household Size	16,567.49**	7,217.95	2.30	0.022
Active in Farmer Group	22,320.66**	9,083.27	2.46	0.014
Carbon Credit Knowledge	61,376.34**	28,214.06	2.18	0.030
Training Participation	20,149.75*	12,079.02	1.67	0.095

Note: ***p<0.01; **p<0.05; *p<0.10. Source: Primary data (processed)

4.1.2 Effect of Information Treatment on WTP

The estimation results show that both treatment groups (T1 and T2) have a positive and statistically significant effect on farmers' willingness to pay for biochar adoption. Farmers in the T1 group, who received agronomic benefit information, exhibit a significantly higher WTP compared to the control group, with an average increase of IDR 84,089 ($\chi^2(1) = 9.20$; $p = 0.002$). Meanwhile, the T2 group, which received additional information regarding carbon credit mechanisms, shows an even larger increase in WTP of IDR 133,414 compared to the control group ($\chi^2(1) = 14.72$; $p < 0.001$). The joint Wald test for both treatment coefficients is statistically significant ($\chi^2(2) = 14.78$; $p = 0.001$), confirming that information framing as a whole significantly influences WTP. Furthermore, the difference between T1 and T2 is marginally significant ($\chi^2(1) = 3.81$; $p = 0.051$), indicating that WTP in the T2 group is higher than in T1 at the 90% confidence level. Detailed hypothesis testing results are presented in Table 4.

Table 4. Summary of Hypothesis Testing on Treatment Effects

Hypothesis	chi^2	*p*-value	Significance
T1 = 0 (T1 vs Control)	9.20	0.002	***
T2 = 0 (T2 vs Control)	14.72	0.000	***
T1 = T2 = 0 (Joint Test)	14.78	0.001	***
T1 = T2	3.81	0.051	*

Note: *** p < 0.01; * p < 0.10. Source: Primary data (processed)

3.1.3 Average WTP Value per Treatment Group

Based on the model's predicted values, the average WTP for the control group was recorded at Rp103,994 per planting season. Group T1 had an average WTP of Rp220,502, a 112% increase compared to the control group, while group T2 reached Rp316,034, a 204% increase compared to the control group. A comparison of WTP values between treatments is presented in Table 5.

Table 5. Average WTP for Biochar Adoption per Treatment Group

Group	Average WTP	*Std. Dev.*	% vs Control
Control	103,993.80	31,202.34	-
T1: Agronomy	220,502.00	40,963.38	+112%
T2: Carbon Credits	316,034.30	54,842.39	+204%

Source: Primary data (processed)

4.2. Discussion

4.2.1 Determinants of Farmers' WTP for Biochar Adoption

In addition to treatment variables, several farmer characteristics significantly influence willingness to pay. Household size has a positive and significant effect on WTP (coef. = IDR 16.567; p = 0.022), which may reflect greater availability of family labor, thereby reducing the relative cost of technology adoption. This finding is consistent with the argument that households with larger labor resources have greater capacity to implement agricultural technologies (Teklewold et al., 2013; Mariano et al., 2012). Active participation in farmer groups also significantly increases WTP (coef. = IDR 22.321; *p*-value = 0.014), indicating that socially engaged farmers have better access to information, peer learning, and collective knowledge-sharing processes that reduce uncertainty regarding biochar benefits. Social networks and learning processes have been widely shown to accelerate agricultural innovation diffusion, as farmers tend to observe and imitate peers before adopting new technologies (Genius et al., 2014; Rodríguez et al., 2017).

Carbon credit knowledge has a positive and significant coefficient (coef. = IDR 61.376; *p*-value = 0.030), suggesting that understanding environmental incentive mechanisms enhances farmers' perception of the economic benefits of biochar. This finding aligns with literature showing that awareness of payment for environmental services (PES) schemes increases farmers' willingness to participate in market-based environmental programs (Ma et al., 2012). Moreover, higher knowledge of biochar and its environmental benefits enhance farmers' willingness to adopt the technology when both economic and environmental advantages are clearly understood (Latawiec et al., 2017).

Training participation shows a positive but marginally significant effect (p = 0.095), indicating that agricultural training may increase farmers' willingness to pay for biochar innovation, although the statistical evidence is weak at the 95% confidence level. This is consistent with studies suggest that information access and knowledge enhancement through training can increase farmers' valuation of new agricultural technologies, although the magnitude of the effect depends on the quality of information delivery and farmer characteristics (Channa et al., 2019). Recent biochar studies also show that participatory training and field demonstrations can substantially improve farmers' acceptance of biochar, suggesting that effectiveness depends not only on frequency but also on experiential learning approaches (Frimpong et al., 2026).

In contrast, socio-demographic variables such as age, gender, education, income, and land size do not show statistically significant effects on WTP. This indicates that farmers' economic valuation of biochar is more strongly influenced by social capacity, information access, and technology-specific knowledge rather than demographic characteristics alone. This finding is consistent with systematic reviews showing that socio-demographic effects on willingness to pay are often inconsistent and highly context-dependent (Olum et al., 2020). Furthermore, studies on biochar adoption emphasize that knowledge and familiarity with the technology are more important determinants than individual characteristics such as age, education, or farm size in explaining adoption behavior (Latawiec et al., 2017).

4.2.2 Biochar Development Model at the Rice Farmer Level

The following outlines the concept of biochar development at the farmer group level. However, for a detailed explanation of the development mechanism.

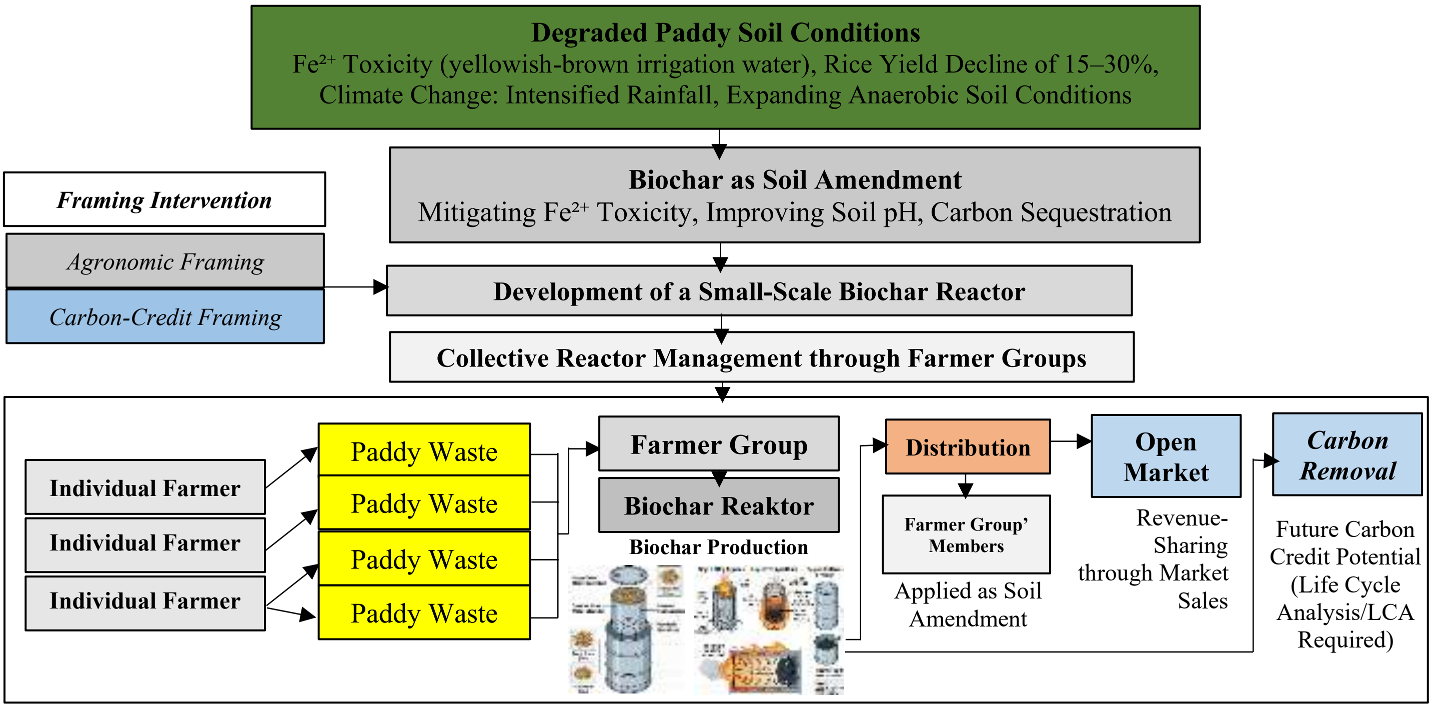

Figure 2. Farmer Group-Based Biochar Development Scheme for Paddy Farming

a. Degraded Paddy Soil Conditions
Paddy fields in West Java face a dual pressure from climate change and soil quality degradation. Waterlogged anaerobic soil conditions trigger the reduction of Fe^{3+} to toxic Fe^{2+} ions, visually manifested as yellowish-brown irrigation water. Methane production in paddy soils begins when Fe^{3+} is reduced to Fe^{2+}, occurring near neutral pH levels and further exacerbated by suboptimal land management practices. These conditions directly suppress rice productivity, making Fe^{2+} toxicity one of the most agronomically detrimental constraints in tropical lowland paddy farming systems.

b. Biochar as a Technological Solution
Biochar derived from paddy waste (straw) represents a technically and economically relevant solution. The conversion of rice straw into biochar constitutes an effective strategy for sustainable rice production, whereby biochar application significantly reduces carbon footprint while enhancing soil organic carbon sequestration. With respect to iron toxicity mitigation, the combined application of biochar and chemical fertilizers has been shown to significantly reduce cumulative CH_4 and CO_2 emissions, net global warming potential (GWP), and greenhouse gas emission intensity by 42.9%, 37.4%, 39.5%, and 67.8%, respectively, compared to chemical fertilizers applied without biochar.

c. Development of a Small-Scale Biochar Reactor
Biochar production at the farmer level requires technology that is affordable, portable, and operable without advanced technical expertise. Given farmers' limited technical knowledge, capital, and time, energy-efficient small-scale pyrolysis reactors that can be operated for in-situ biochar production are essential to address these constraints. Portable reactor technology innovations have demonstrated feasibility across various developing country contexts. Portable reactors utilizing auto-thermal processes, requiring no external fuel, can be operated directly in the field, overcoming the biomass logistics paradox, wherein the costs of biomass collection and transportation frequently exceed its market value.

d. Farmer Group-Based Reactor Governance
A collective governance model through farmer groups represents the most realistic technology diffusion mechanism in the context of smallholder farmers. Smallholder farmers constitute a large proportion of national paddy farming, with substantial biomass waste potential, yet face significant constraints in individually accessing biochar production technology. Group-based

reactor management enables the collective sharing of investment costs, risks, and labor, while simultaneously reinforcing social learning mechanisms that have been demonstrated to accelerate agricultural innovation adoption in a more rapid and sustainable manner.

e. Production Flow: Individual Farmer → Paddy Waste → Biochar Reactor
Each farmer group member contributes paddy waste (straw) as feedstock for biochar production. For every 1 kg of rice straw, the carbonization process yields 320 grams of biochar with sufficient calorific value to sustain autonomous pyrolysis. This scheme simultaneously addresses the problem of agricultural residue management, which is conventionally disposed of through open burning — a practice contributing to local air pollution and significant GHG emissions. Redirecting rice straw from open burning to biochar production represents an effective residue management strategy while contributing to agricultural carbon neutrality.

f. Biochar Distribution to Farmer Members
Collectively produced biochar is subsequently redistributed to farmer group members for application on their respective paddy fields. The co-application of biochar and NPK fertilizers yield higher rice productivity and improved soil quality indices, with a significant positive relationship between soil quality and crop yield, indicating that soil quality plays a crucial role in enhancing rice productivity.

g. Market Access: Open Market and Carbon Removal
This model extends beyond agronomic application alone, opening two additional income streams for farmers. The first pathway, Open Market: Biochar produced in excess of internal requirements can be sold in commercial markets as a soil amendment product. Governments and private entities globally are increasingly promoting biochar application in agriculture, particularly for its potential to generate additional revenue streams through carbon credits, as exemplified by the Carbon Incubator Facility initiative in India, which empowers Farmer Producer Organizations to integrate biochar projects. The second pathway, Carbon Removal: Biochar qualifies as a carbon dioxide removal (CDR) instrument tradeable in both voluntary and compliance carbon markets. The Biochar Carbon Removal (BCR) market has experienced remarkable growth, with a CAGR of 131.6%, expanding from USD 14.6 million in 2022 to USD 181.5 million in 2024, making it the most purchased CDR method with 290 unique buyers (CDR.fyi, 2024), nearly five times more than the next most popular CDR method. Smallholder farmers in low- and lower-middle-income countries have a genuine opportunity to participate in carbon markets through biochar production, given that carbon credits are traded on a one-to-one basis per tonne of CO_2 sequestered.

5. Robustness Test: Ordered Probit Model

As a robustness check, the estimation was replicated using an ordered probit model with the DBDC response category as the dependent variable. Results demonstrate full consistency with the primary estimation: T1 (coef. = 0.878; *p*-val = 0.002) and T2 (coef. = 1.333; *p*-val < 0.001) remain positive and statistically significant, with T2 yielding a larger coefficient than T1. Variables found significant in the interval regression model, namely household size, farmer group activeness, carbon credit knowledge, and agricultural training, also exhibit consistent directional effects and significance levels in the ordered probit model. The consistency of results across both approaches indicates that the findings of this study are robust to model specification choices.

Tabel 6. Perbandingan *Robustness Test* antar *treatment effect*

Variable	Coef.	*z*	*p*-value
T1: Agronomic benefit	0.878	3.03	0.002***
T2: Carbon Credit benefit	1.333	3.84	0.000***

Tabel 7. Comparison accross *control variable*

Variabel	*Interval Regression*	*Ordered Probit*	Consistency
Household Size	*p*=0.022**	*p*=0.023**	✓
Farmer Group Activeness	*p*=0.014**	*p*=0.012**	✓
Carbon Credit Knowledge	*p*=0.030**	*p*=0.030**	✓
Agricultural Training	*p*=0.095*	*p*=0.059*	✓
Other Control Variables	Not Sig.	Not. Sig	✓

6. Conclusion

This study shows that the provision of information has a positive effect on farmers' willingness to pay (WTP) to adopt biochar. Information on carbon credits resulted in a greater increase in WTP than information on agronomic benefits, indicating that potential economic incentives are important considerations in biochar adoption decisions. Furthermore, active participation in farmer groups, family size, knowledge of carbon credits, and agricultural training experience were shown to increase farmers' WTP. Conversely, sociodemographic characteristics such as age, education, income, and land area did not have a significant effect. Overall, the results indicate that increasing farmers' social capacity and knowledge are more important factors in encouraging biochar adoption than farmers' demographic characteristics.

7. Recommendation

Based on the findings, biochar promotion programs should integrate information on both agronomic benefits and the economic incentive potential of carbon credits, as such information has been demonstrated to significantly increase farmers' willingness to invest in biochar technology. Furthermore, farmer groups should be positioned as the primary channel for technology dissemination, given their critical role in information diffusion, social learning, and the strengthening of trust among smallholders. The quality of agricultural training programs also warrants attention, particularly through enriching curriculum content related to biochar, its environmental benefits, and the economic opportunities arising from carbon markets. For future research, it is recommended to evaluate farmers' WTP under more realistic implementation conditions, including scenarios that incorporate existing carbon incentive schemes, so that the resulting estimates more accurately reflect actual farmer adoption behavior.

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