JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(4), 148–160
https://doi.org/10.12911/22998993/199823
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Received: 2025.01.04
Accepted: 2025.02.01
Published: 2025.02.17

Assessment of silica-enriched biochar for enhancing soil fertility and mitigating methane emissions in acid-stressed rice fields

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ABSTRACT

Rice cultivation is a source of methane emissions (CH_4), contributing to global warming. Efforts to reduce CH_4 emissions play an important role in sustainable rice production. This study aimed to evaluate the effect of silica-enriched biochar on CH_4 emissions, soil chemical properties, and the growth and yield of rice. A field experiment was conducted using a Complete Randomized Block Design (CRBD) with ten treatments comprising combinations of biochar, silica-enriched biochar, inorganic fertilizers, and control, and each was replicated three times. The MAPAN rice variety was used as the test crop in naturally acidic soils. Scanning Electron Microscopy analysis revealed that silica-enriched biochar contained abundant micropores measuring 9.38 × 5.13 µm. Silica-enriched biochar significantly improved soil chemical properties, including pH, soil organic carbon (SOC), cation exchange capacity (CEC), total nitrogen (TN), total silica (SiO_2), potential and available phosphorus (P), and potential and available potassium (K), compared to the control (without biochar). Moreover, it effectively reduced CH_4 emissions. Applying 2.5 t/ha of biochar combined with 50% NPK fertilizer increased pH, potential P, and potential K by 0.52 units, 28.35%, and 27.22%, respectively. Treatment with 2.5 t/ha of biochar, 50% NPK, and 320 kg/ha SiO_2 enhanced CEC by 28.66% and TN by 37.14%. Meanwhile, 2.5 t/ha biochar, 100% NPK, and 3 L SiO_2 increased SOC by 22.77%. Applying 2.5 t/ha biochar with 3 L SiO_2 raised total SiO_2 by 22.29% and available P by 11.85%, while biochar at 2.5 t/ha reduced CH_4 emissions by 123.63%. However, none of the treatments significantly affected rice tiller numbers, plant height, or grain wet weight. These findings demonstrate that silica-enriched biochar can function as a soil amendment to reduce CH_4 emissions and promote climate-resilient and sustainable rice cultivation by simultaneously addressing soil fertility and greenhouse gas emissions.

Keywords: climate-resilient agriculture, ghg, methane mitigation, soil chemical, sustainable agriculture

INTRODUCTION

Indonesia is a country that uses rice as a staple food, and 95% of the Indonesian population makes rice the staple food (Ani et al., 2024). Under these conditions, Indonesia has become one of the countries with the most extensive rice consumption globally (Connor et al., 2021). The per capita rice consumption of the Indonesian population per week in 2023 will reach 1.6 kg per capita week^{-1} (BPS, 2024a). The large rice consumption in Indonesia will increase the demand for rice, aligning with the population increase. In 2024, the population in Indonesia will reach 281 million and experience an increase of 5.5% compared to 2019 (BPS, 2024b). However, cultivating rice in rice fields that are currently being carried out to increase rice productivity is still traditional. It needs to be more environmentally friendly, thereby contributing to climate change.

Rice cultivation, which many farmers currently carry out, is a source of methane emissions

(CH_4), which is a greenhouse gas (GHG) that contributes to climate change (IPCC, 2022). In 2011, rice farming contributed around 500 MtCO_2eq to global CH_4 emissions and is expected to increase by 7% by 2030 (FAO, 2014). Apart from that, the current practice of rice cultivation also causes soil degradation, reducing agricultural productivity, which can threaten food security in the future (Mallareddy et al., 2023). A sustainable approach to increasing rice production amidst these various threats can be made by utilizing suboptimal land as agricultural cultivation land.

Suboptimal land use is an alternative for increasing national rice production. The suboptimal sour land in Indonesia with the potential for agricultural land reaches 62.64 million ha. This land includes soil of the orders Entisols, Ultisols, Oxsisols, and Inceptisols (DGFC, 2022). Cultivation on suboptimal acid land faces limiting factors such as low soil fertility, organic matter content, and acidic soil reactions (Fitriatin et al., 2021). Nutrient limitation in acid soil occurs due to the replacement of exchangeable base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}) by H^{+}, Al^{3+}, and Fe (Goulding, 2016). This condition causes metal toxicity (Mn, Fe, and Al) and nutritional imbalances such as phosphate (P) (Bojórquez-Quintal et al., 2017). Low availability of nutrients in the growth phase will inhibit several plant metabolic processes, thereby inhibiting flower formation and reducing crop yields (Wei et al., 2017). A practical solution is needed to maintain high crop productivity while reducing emissions, namely by applying biochar to rice fields (Sriphirom et al., 2021).

Biochar is a solid product from biomass pyrolysis at 300–900 °C temperatures in limited air conditions (Weber et al., 2018). Biochar can be used as a soil amendment because it has the characteristics of alkaline pH, high carbon, large surface area, and high porosity (Sriphirom et al., 2021). Applying biochar to acid soil can significantly improve soil properties by increasing acid soil pH by 0.5–1 and nutrient content and increasing the abundance of beneficial microbes (Zhang et al., 2019). This ability can be enhanced to increase plant protection against pests and pathogens and climate stress on plants by enriching biochar using silica (Coskun et al., 2019).

Applying silica (SiO_2) can increase plant resistance to rice stress against biotic and abiotic stresses (El-Okkiah et al., 2022; Kang et al., 2016; Adrees et al., 2015). The SiO_2 absorbed by plants is bound to the cell walls, thereby increasing the stiffness and elasticity of the cell walls (He et al., 2013). Apart from that, SiO_2 also acts as a buffer for the availability of P elements in the soil because SiO_2 can free P from binding to soil particles (Greger et al., 2018). Si-based crop protection can open new avenues to increase crop yields by overcoming the threat of environmental stress (Li and Delvaux, 2019).

Enriching biochar with SiO_2 can provide dual benefits, namely reducing methane emissions by changing soil microbial activity and improving soil properties that support plant health and yield. However, no have examined the potential of enriching biochar with SiO_2 to reduce methane emissions, improve soil properties, and increase rice growth in paddy fields. This research aims to evaluate the effect of silica-enriched biochar on methane emissions, soil chemical properties, and increasing rice growth in paddy fields. This research seeks to provide insight into the potential of silica-enriched biochar as a sustainable strategy to increase the resilience of rice fields and promote climate-smart agriculture.

MATERIALS AND METHODS

Formulation and characterization of technological components

Rice husk biochar was produced using the pyrolysis technique at 400 °C for 2 hours. This process produces biochar with a stable carbon content of around 40–50% with a material weight loss of 20–30%. Then, SiO_2, which comes from zeolite (SiO_2 powder) and SiO_2 fertilizer (liquid SiO_2), is added. The ratio between SiO_2 and biochar is 3:7. Each formula is characterized by pH, water content (WC), ash content (AC), carbon content (CC), total SiO_2 (TS), cation exchange capacity (CEC), total nitrogen (TN), total phosphate (TP), and total potassium (TK). Then, observations were made using a scanning electron microscope (SEM) on the silica-enriched biochar formula.

Field experiment

The research was conducted in experimental rice fields at the Faculty of Agriculture, Padjadjaran University (6°55’18”S 107°46’28” E). This experimental site is located in a tropical region about 752 meters above sea level. The research location has an annual temperature of around 19–30 °C and a relative humidity level of 39–84%. The land is Inceptisols, which has a pH of 6.29 (slightly acidic), as in Table 1.

This study used a Complete Randomized Block Design (CRBD) with ten treatments (Table 2), each with three replications. The experiment was carried out on a limited-scale experimental plot (semi-demo-plot). Land preparation is carried out by making trial plots and ploughing the land. Application of biochar according to treatment is carried out 2 weeks before planting. Rice seedlings of variety MAPAN P05 are planted at the age of 20 DAS (days after sowing). Fertilization is done by providing NPK fertilizer according to the treatment at planting time, 14 DAS, and 30 DAS. During growth, plant height and number of rice plant shoots were observed. Plant height measured from the base to the tip of the plant is used as a growth parameter.

Data collection

Methane analysis

Methane gas was sampled from rice fields using the close chamber technique. Sampling was carried out every week from 2 to 9 weeks after planting. CH_4 analysis was carried out using gas chromatography with a flame ionization detector (GC-FID) to estimate the amount of CH_4 following the procedure by Pazhanivelan et al. (2024). CH_4 flux calculations are carried out using the following formula:

$$f = (V/A) \times (\Delta C/\Delta t) \tag{1}$$

where: f – level of greenhouse gas emissions (mg m^{-2} h^{-1}), V – the volume of space above ground (m^3), A – cross-section of the room (m^2), ΔC – concentration difference between zero and t times (mg cm^{-3}), Δt – the duration of time between two sampling periods (h).

Soil sampling and analysis

The soil samples were prepared for analysis with air-dried soil and ground to obtain a particle size of 2 mm. The pH of H_2O and KCl were measured using distilled deionized water and 1 M KCl with a soil solution concentration of 1:1 and 1:2.5 using a pH meter (Kome et al., 2018). Soil organic carbon (SOC) was measured using the Walkley and Black method (Tola et al., 2018). TN was determined using the Kjeldahl method (Gautam et al., 2023). CEC was determined using the 1 mol L^{-1} NH_4OAc method (Black, 1965). TS was described using atomic absorption spectrometry (Snyder, 2001) and available phosphate (AP) using the Bray I method (Lumbanraja et al., 2017). Potassium potential (KP) and exchangeable potassium (EK) were described following the procedures performed by Linquist et al. (2022).

Table 1. Initial soil characteristics before treatment with silica-enriched biochar

Parameter	Value	Criteria
pH: H_2O	6.29	Slightly acidic
pH: KCl	4.59	-
Organic-C (%)	3.19	High
N total (%)	0.51	High
C/N	6.65	Low
P_2O_5 HCl 25 % (mg 100 g^{-1})	39.53	Medium
P_2O_5 (Bray I) (ppm)	6.29	Low
K_2O HCl 25 % (mg 100 g^{-1})	33.32	Medium
CEC (cmol kg^{-1})	24.64	Medium
Cation		
Exchangeable K (cmol kg^{-1})	0.67	High
Exchangeable Na (cmol kg^{-1})	0.13	Low
Exchangeable Ca (cmol kg^{-1})	6.59	Medium
Exchangeable Mg (cmol kg^{-1})	3.40	High
Base saturation (%)	51.95	Medium
Exchangeable Al^{3+} (cmol kg^{-1})	0.43	-
Exchangeable H^+ (cmol kg^{-1})	0.23	-
Saturation Al (%)	3.19	Low
Texture		
Sand (%)	2	Sand
Silt (%)	52	Clay
Clay (%)	46	Muddy

Table 2. Experimental treatment design for evaluating silica-enriched biochar in paddy fields

Treatment	Explanation
A	Biochar 2.5 t
B	Biochar 2.5 t + SiO_2 320 kg
C	Biochar 2.5 t + SiO_2 3 L
D	Biochar 2.5 t + 50% NPK
E	Biochar 2.5 t + 50% NPK + SiO_2 320 kg
F	Biochar 2.5 t + 50% NPK + SiO_2 3 L
G	Biochar 2.5 t + 100% NPK
H	Biochar 2.5 t + 100% NPK + SiO_2 320 kg
I	Biochar 2.5 t + 100% NPK + SiO_2 3 L
J	Control

Selection of the best formulation

The selection of the best treatment is conducted by ranking by scoring method based on PHH, SOC, CEC, TN, PP, AP, KP, EP, TS, and CH4 (Ambarita et al., 2024).

Data analysis

The impacts of various treatments on the measured variables were assessed using ANOVA with SPSS (Statistical Package for the Social Sciences) software. Significant differences were identified through Duncan's test, with significance established at $P < 0.05$. Data visualization of the research findings was accomplished using Prism 9 software.

Table 3. Physicochemical properties of biochar and silica-enriched biochar

Parameter	Biochar	Biochar + 320 kg ha^{-1} SiO_2	Biochar + 3 L ha^{-1} SiO_2
pH	8.28	8.43	8.31
WC (%)	0.10	0.12	0.11
AC (%)	36.72	36.86	34.21
CC (%)	32.44	34.76	33.81
TS (%)	43	83.08	79.13
CEC (cmol kg^{-1})	36.05	38.94	38.15
N (%)	0.12	0.08	0.10
TPh (%)	0.37	0.42	0.40
TP (%)	1.15	0.93	0.90

Note: WC, water content; AC, ash content; CC, carbon content; TS, total SiO_2; CEC, cation exchange capacity; TN, total nitrogen; TP; total phosphate; TK, total potassium.

RESULTS

Characterization of silica-enriched biochar

Based on the characterization results in Table 3 show that the addition of SiO_2 to biochar affects the characteristics of each biochar formula. Each biochar formula has an alkaline pH of around 8.28–8.43. Adding SiO_2 to biochar increases the total SiO_2 content to 93% (powdered SiO_2) and 84% (liquid SiO_2). Apart from that, the addition of SiO_2 also affected increasing CC (4.22–7.15%), CEC (5.83–8.02%), and TP (8.1–13.51%). Observation of the biochar surface in Figure 1 shows that the silica–enriched biochar formula has many micropores. The size of the micropores is 9.38 × 5.13 µm (horizontal and vertical tangents).

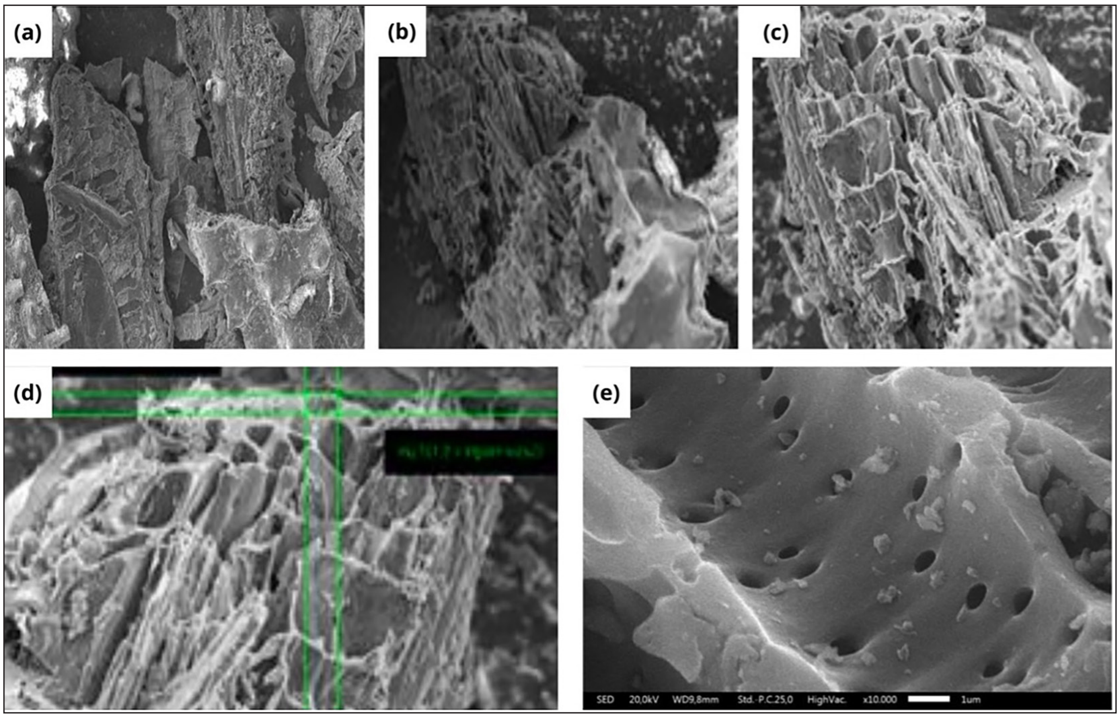

Figure 1. Surface morphology of silica-enriched biochar observed under scanning electron microscopy (SEM). 100x magnification (a), 250x magnification (b), 500x magnification (c), micropore size at 500x magnification (d), and the insi de of the micropore space at 10.000x magnification (e)

Table 4. The two-way ANOVA on the effect of silica-enriched biochar on rice growth, yield, and soil properties

Source of variance	TNR 14	TNR 28	TNR 42	TNR 56	PH 14	PH 28	PH 42	PH 56	GWW	
T × R	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	
T	0.827	0.658	0.582	0.057	0.348	0.661	0.570	0.976	0.228	
R	0.353	0.161	0.213	0.294	0.100	0.331	0.284	0.837	0.120	
Source of variance	PHH	PHK	SOC	CEC	TN	PP	AP	KP	EK	TS
T × R	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
T	< 0.001	0.137	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
R	0.728	0.142	0.870	0.201	0.886	0.147	0.354	0.302	0.785	0.171

Note: TNR, tiller number; PH, plant height; GWW, grain wet weight; PHH, pH H_2O, PHK, pH KCl; SOC, soil organic carbon; CEC, cation exchange capacity; TN, total nitrogen; PP; phosphate potential; AP, available phosphate; KP, potassium potential; EK, exchangeable potassium; TS, total silica.

Effect of silica-enriched biochar on rice growth and yield

The analysis showed that all treatments on rice plants had no significant effect on the number of rice tillers aged 14, 28, 42, and 52 DAP (Figure 2). All treatments did not significantly affect plant height at 14, 28, 42, and 52 DAP (Figure 3). Apart from that, they also had no natural effect on the wet weight of rice per hectare (Figure 4).

Effect of silica-enriched biochar on soil chemical properties after harvesting

pH H_2O dan pH KCl

The results of the two-way ANOVA analysis showed that the application of silica-enriched biochar significantly affected the pH of H_2O but had no significant effect on the pH of KCl (Table 4). The addition of biochar and 100% NPK (G) produced the lowest pH (5.95), while biochar and 50% NPK (D) produced the highest pH (6.46), as in Figure 5a. Adding silica-enriched biochar can maintain soil pH conditions suitable for rice plant growth.

SOC and CEC

Application of silica-enriched biochar showed a significant effect ($p < 0.001$) on increasing SOC after harvest (Table 4). Applying A, E, F, G, and I resulted in the highest increase in SOC, namely around 22.50–22.77% compared to the control (Figure 5c). However, the application rate

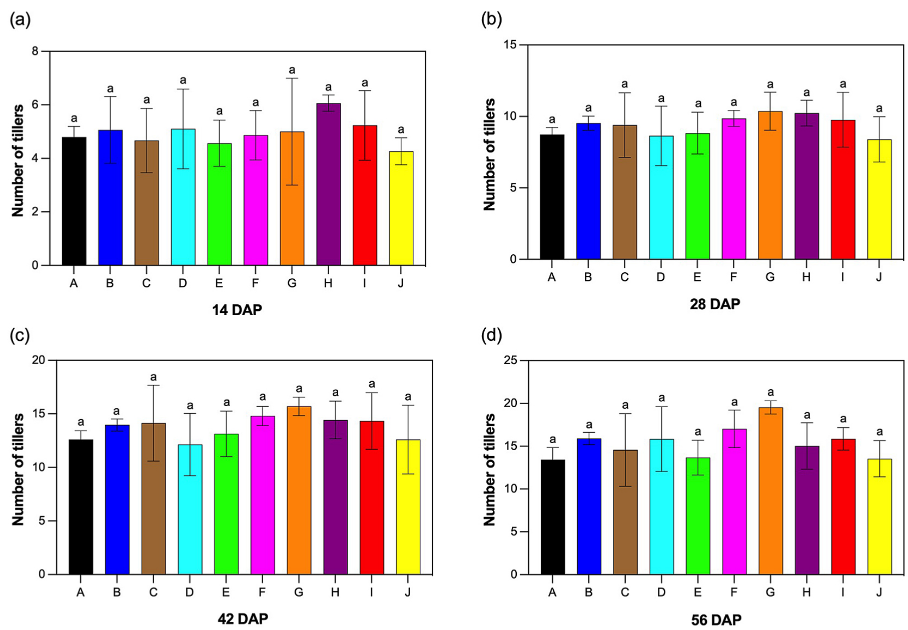

Figure 2. Effect of silica-enriched biochar application on tiller number in rice plants. 14 days after planting (DAP) (a), 28 DAP (b), 42 DAP (c), and 56 DAP (d)

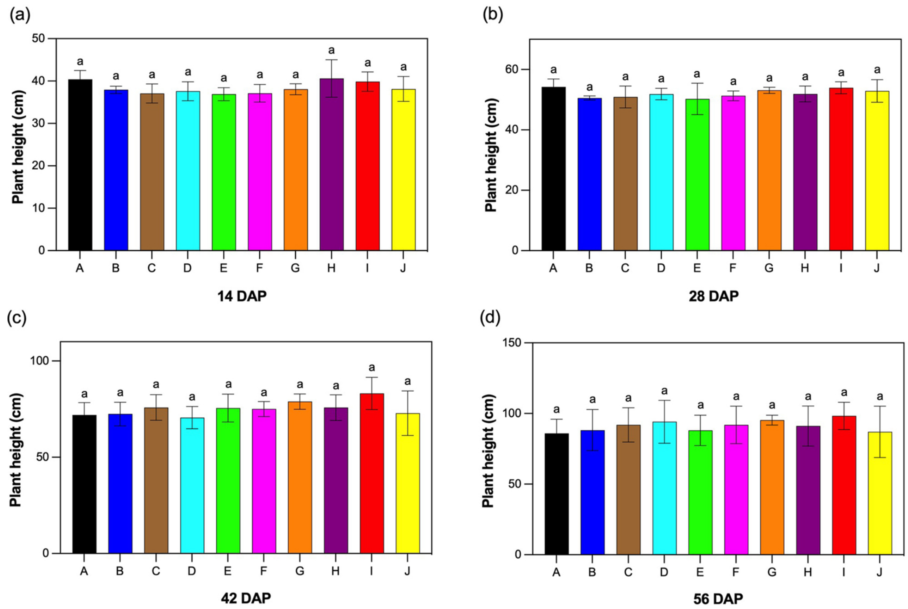

Figure 3. Effect of silica-enriched biochar application on rice plant height. 14 DAP (a), 28 DAP (b), 42 DAP (c), and 56 DAP (d)

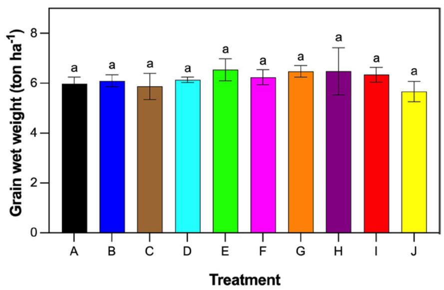

Figure 4. Effect of silica-enriched biochar application on grain wet weight

of B and D did not significantly differ from the controls. Soil CEC was significantly ($p < 0.001$) different as a result of the application of silica-enriched biochar (Table 4). Treatment E (Biochar 2.5 t + 50% NPK + SiO_2 320 kg) significantly produced the highest CEC of 48.21 cmol 100 g^{-1}, and J (Control) produced the lowest CEC (37.47 cmol 100 g^{-1}). Adding biochar and silica-enriched biochar can increase soil CEC by around 11.13 to 28.73% compared to the control (Figure 5d).

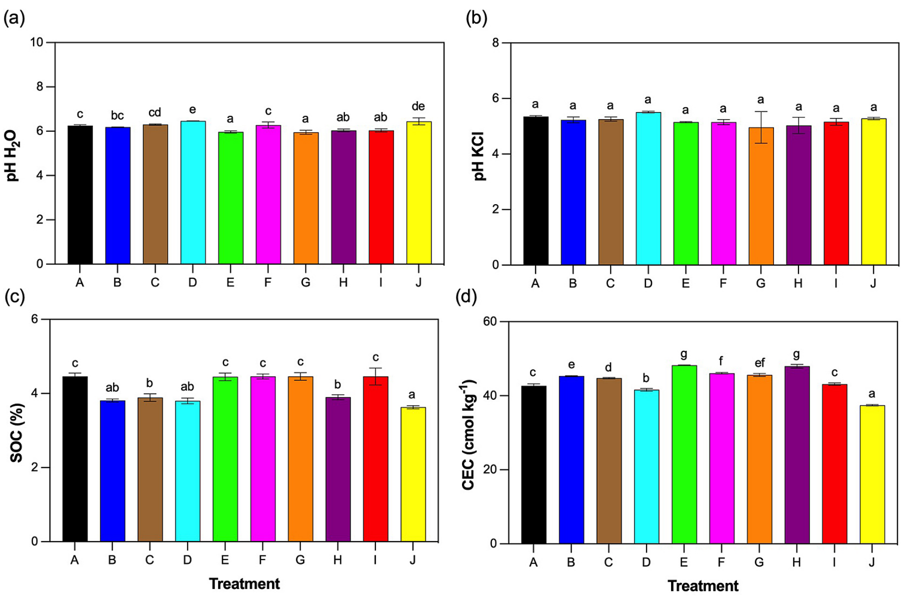

Figure 5. pH H_2O (a), pH KCl (b), soil organic carbon (c), and cation exchange capacity (d) as influenced by silica-enriched biochar application after rice harvest. Distinct letters on the bars in each figure designated significant differences in the data points

Total N and SiO_2

After field experiments, the presence of soil TN was significantly influenced by adding biochar and silica-enriched biochar (Table 4). Figure 6a shows that the highest average soil TN was 0.48% obtained from treatment E (Biochar 2.5 t + 50% NPK + SiO_2 320 kg). Adding biochar and silica-enriched biochar can increase soil TN by around 11.43 to 37.14% compared to control. Figure 6b shows that the addition of biochar and silica-enriched biochar has a significant effect on soil TS (Table 4). Treatment C (Biochar 2.5 t + SiO_2 3 L) can increase the highest TS, 22.29%. The increase in soil TS was around 17.59–22.29% compared to the control. However, treatments H (Biochar 2.5 t + 100% NPK + SiO_2 320 kg) and I (Biochar 2.5 t + 100% NPK + SiO_2 3 L) were not significantly different from the control (Figure 6b).

Potential P and available P

The addition of biochar and silica-enriched biochar had a significant effect ($p < 0.001$) on the average soil PP (Table 4). Treatments C (Biochar 2.5 t + SiO_2 3 L) and D (Biochar 2.5 t + 50% NPK) significantly ($p < 0.001$) increased soil PP by 8.94% and 28.35%, respectively, compared to the control (Figure 6c). However, applying treatments B, E, F, H, and I reduced soil PP by around -42.86 to -11.90% compared to the control. The two-way ANOVA analysis showed that silica-enriched biochar application significantly affected the AP (Table 4). The presence of soil AP increased significantly by around 2.67–11.85% compared to the control due to treatments C, D, E, G, H, and I. The decrease in AP was around -3.34 to -2.51% due to treatments A and B, while treatment F did not have a significant effect compared to the control.

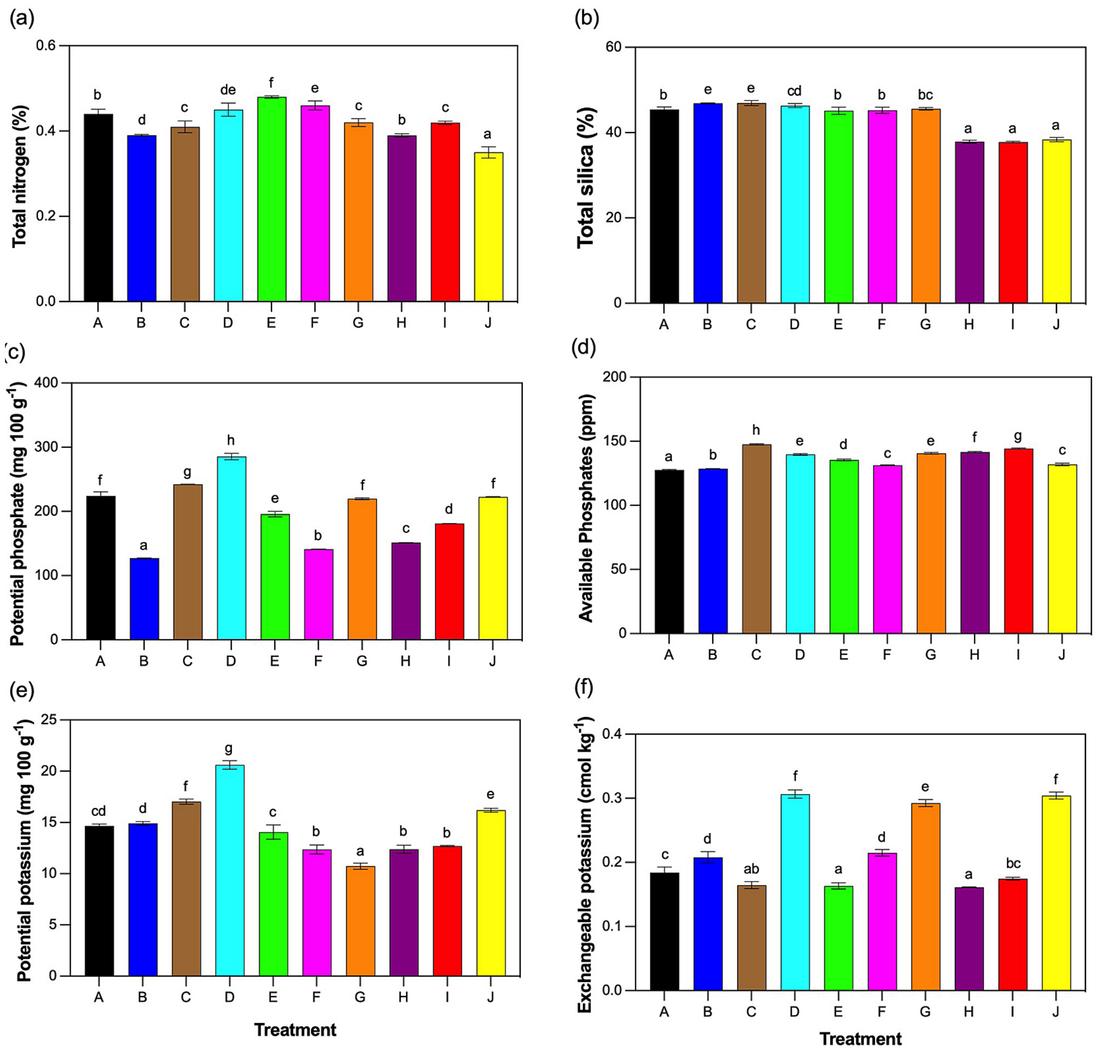

Figure 6. Total nitrogen (a), total silica (b), potential phosphate (c), available phosphate (d), potential potassium (e), and exchangeable potassium (f) as influenced by silica-enriched biochar application after rice harvest. Distinct letters on the bars in each figure designated significant differences in the data points

Potential K and exchangeable K

The KP concentration showed a significant difference ($p < 0.001$) due to the addition of biochar and silica-enriched biochar (Table 4). The application of C (Biochar 2.5 t + SiO_2 3 L) and D (Biochar 2.5 t + 50% NPK) significantly increased the KP content in the soil by 5.12% and 27.22%, respectively, compared with the control (Figure 6e). However, other treatments significantly reduced soil KP by around -33.77 to -7.96% compared to the control. The results of the ANOVA test (Table 2) also showed that the soil EP concentration significantly ($p < 0.001$) decreased as a result of the application of biochar and silica-enriched biochar by around -46.97 to -3.79% compared to the control. However, treatment D (Biochar 2.5 t + 50% NPK) had no significant effect on soil EP concentration compared to the control.

Methane

Figure 7 shows the accumulation of CH_4 during rice cultivation based on the application of biochar and silica-enriched biochar. CH_4 accumulation decreased due to biochar and silica-enriched biochar administration by around 23.1–123.63% compared to the control. Treatments A (Biochar 2.5 t), E (Biochar + 320 kg/ha SiO_2 + 50% NPK), C (Biochar + 3 L ha^{-1} SiO_2), and B (Biochar + 320 kg ha^{-1} SiO_2) were the best treatments, respectively can reduce CH_4 by 123.63%, 97.40%, 46.45%, and 44.00%. However, treatment D (Biochar 2.5 t + 50% NPK) was not significantly different from the control.

Scoring results for optimal treatment selection

The best treatment is selected using scoring for each observation variable. The results of the score analysis in Table 5 show that treatment C (Biochar 2.5 t + SiO_2 3 L) is the best treatment for improving soil properties so that they can support plant growth. Treatment H (Biochar 2.5 t + 100% NPK + SiO_2 320 kg) was the treatment with the lowest points, namely 44 points. This result was lower than the control, with an endpoint of 55 points.

DISCUSSION

The characteristics of each formula in Table 3 show that the silica-enriched biochar formula can improve the soil conditions of rice fields that are used intensively. The paddy soil is acidic due to inorganic fertilizers in high doses and intensity. The alkaline pH value in enriched biochar will help release nutrients easily absorbed by metals that characterize acid soil, such as Al and Fe. The presence of SiO_2 in the enriched biochar formula will maintain the presence of phosphorus elements, which become available due to an increase in the pH value (Cornelissen et al., 2018). Adding SiO_2 to biochar can increase the SiO_2 content in the soil. The presence of SiO_2 plays a role in maintaining oxidative conditions in the root environment, thereby reducing the reduction potential of Fe_2O_3 and suppressing the release of electrons into the soil. These electrons are a food source for

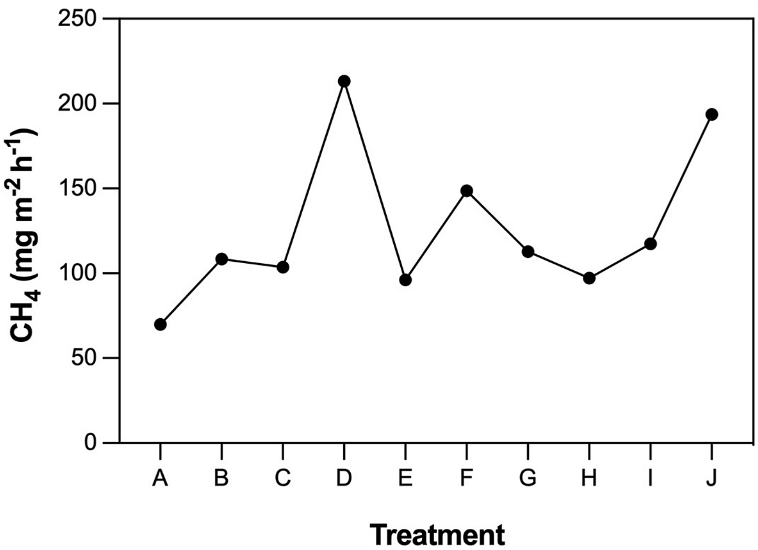

Figure 7. Accumulation CH_4 influenced by silica-enriched biochar application on rice field

Table 5. Scoring-based ranking of biochar and silica-enriched biochar for best performance evaluation

Treatment	PHH	SOC	CEC	TN	PP	AP	KP	EP	TS	CH_4	Total	Rank
A	6	8	3	7	8	1	6	5	6	10	60	3
B	5	3	6	3	1	2	7	6	9	6	48	7
C	8	4	5	4	9	10	9	3	10	7	69	1
D	10	2	2	8	10	6	10	10	8	1	67	2
E	2	6	10	10	5	5	5	2	4	9	58	4
F	7	7	8	9	2	3	2	7	5	3	53	6
G	1	9	7	6	6	7	1	8	7	5	57	5
H	3	5	9	2	3	8	3	1	2	8	44	10
I	4	9	4	5	4	9	4	4	1	4	48	7
J	9	1	1	1	7	4	8	9	3	2	45	9

Note: PHH, pH H_2O; SOC, soil organic carbon; CEC, cation exchange capacity; TN, total nitrogen; PP, potential phosphate; AP, available phosphate; KP, potential potassium; EP, exchangeable potassium; TS, total silica; PH, plant height; TNR, tiller number; GWW, grain wet weight.

methanogenic bacteria, so using Si-enriched biochar will increase the function of biochar in reducing CH_4 emissions (Kunchariyakun et al., 2013).

Figure 1 shows the micropores in biochar produced at 400 °C for 1.5 hours. This condition is formed due to the pyrolysis process at a temperature of 300–500 °C so that the volatile material content is broken down and forms many micropores (Claoston et al., 2014). The presence of micropores in the pore structure of biochar produces more than 80% of the pore volume (Yadav et al., 2023). These micropores' presence can change paddy soil's structure to become more porous. The use of biochar with high micropores can increase the surface cross-sectional area so that it can increase water holding capacity and cation exchange capacity, which can affect the availability of nutrients for plants (Briggs et al., 2012) and help the absorption of dissolved nutrients by plants (Sriphirom et al., 2021). In addition, the high carbon content of up to 34.76% can function as a soil improver and reduce the possibility of environmental degradation and pollution (Ulusal et al., 2021).

This research found that the application of biochar and silica-enriched biochar did not significantly affect the number of tillers, plant height and rice yield. This condition is likely due to the slow working mechanism of biochar's nutrient release, potentially causing a delayed effect that may not align with the peak period of nutrient uptake in rice plants. This is in line with research by Tan et al., (2024), which shows that the development of rice husk biochar-based fertilizer has a slower nutrient release mechanism in the soil compared to conventional fertilizer. This mechanism provides advantages in reducing nutrient loss in the soil and extending the efficiency of fertilizer for plant absorption (Wang et al., 2022). The research results of Selvarajh et al., (2024) show that applying rice husk biochar can increase soil nutrition by reducing NH_3 loss in the soil.

The application of silica-enriched biochar affects the chemical properties of post-harvest soil. Applying biochar and silica-enriched biochar has been proven to increase soil pH significantly. The increase in soil pH is caused by the alkaline nature of biochar, which can quickly release basic cations in the form of Ca_2^+, Mg_2^+, and K^+ into the soil solution (Al-Sayed et al., 2022). These cations are embedded in biochar as oxides, carbonates and hydroxides, which are hydrolyzed to form hydroxide ions, which increase soil pH (Arwenyo et al., 2023). It can also occur due to the small fraction of ash in biochar, which can cause the dissolution of hydroxides and carbonates, thereby reducing soil acidity (Ndoung et al., 2021).

The SOC and CEC values in the soil have increased due to the application of biochar and silica-enriched biochar (Figure 5), which can be caused by the high organic carbon content in biochar (Acharya et al., 2022). In addition, biochar has a stable carbon structure, so it plays a role in increasing the organic carbon content in the soil by increasing SOC stability (Ma et al., 2023). Application of biochar, on average, can increase SOC by 29% (Gross et al., 2021). SOC can be used as an energy source for soil microorganisms, which play a role in the decomposition and mineralization processes (Billings et al., 2021). Increasing SOC stocks means silica-enriched biochar can increase soil fertility (Paustian et al., 2019). The significant effect of biochar and silica-enriched biochar on CEC shows an increase in the soil's ability to retain and provide essential cations for plants. The research results of Antonangelo at al., (2024) show that biochar can increase CEC by 91%.

The use of silica-enriched biochar as a soil amendment in paddy fields can significantly increase nutrient availability for plants such as total N, potential P, available P, potential K, available K, and total SiO_2 compared to controls. This is reinforced by previous findings where biochar application can significantly increase nutrients in the soil compared to soil without biochar (Dahal et al., 2021). The increase in total N in the soil due to adding biochar occurs because biochar has a very porous structure and many functional groups on its surface. This condition has an impact on reducing N leaching. It is used for microbial growth, increasing soil biological processes such as mineralization, nitrification and other mineral dissolution activities (Acharya et al., 2022). The increase in P availability aligns with the increase in soil pH due to biochar application. In acidic soils, PO_4^- is bound in the soil by Al and Fe, with an increase in pH towards neutral. More P is available in the soil solution (Hale et al., 2013). The high surface area of biochar encourages an increase in K availability in the soil. This is because biochar absorbs K strongly and reduces K loss due to leaching in the soil (Martinsen et al., 2014). In addition, high K concentrations in the soil can be caused by low exchangeable acidity due to Al precipitation when hydroxyl releases cations into the soil (Rasuli et al., 2022). Increasing silica in the soil is used to increase plant tolerance against pathogen attack and abiotic stress and increase growth and plant yield (Zargar et al., 2019).

Figure 7 shows that silica-enriched biochar can reduce CH_4 emissions in rice fields. This aligns with previous research that shows that applying mangrove-based biochar combined with inorganic fertilizer in rice fields can reduce methane emissions by up to 24.9% (Sriphirom et al., 2021). The decrease in CH_4 emissions is related to the decrease in the ratio of methanogens to methanotrophs (Wang et al., 2019). Biochar can stimulate methanotroph activity, thereby increasing CH_4 oxidation in the soil (Han et al., 2016). The presence of biochar in the soil can encourage the growth of bacteria, especially aerobic bacteria, through porous structures that provide habitat and oxygen availability (Chen et al., 2017). CH_4 oxidation is usually active in the rhizosphere, where oxygen is available, so increased rice growth under biochar conditions can also provide more oxygen for this process. Applying biochar negatively impacts methanogens' growth, while methanotrophs' growth is encouraged (Sriphirom et al., 2021).

Ranking of treatments based on scores, as presented in Table 5, provides a systematic comparison of the effectiveness of each biochar treatment on reducing methane gas, increasing soil fertility, and rice growth. Treatment C (Biochar 2.5 t + SiO_2 3 L) was the best treatment in improving soil properties and reducing CH_4 emissions. This shows that silica-enriched biochar has a more significant effect on increasing soil fertility and changing soil microbial processes, which reduce CH_4 emissions. Silica-enriched biochar aligns with climate-smart agricultural practices by reducing methane emissions and addresses the need to improve soil health and plant resilience.

CONCLUSIONS

The findings of this research indicate that the application of silica-enriched biochar has a significant impact on improving soil properties and reducing greenhouse gas (CH_4) emissions in rice fields. Applying silica-enriched biochar can improve soil conditions by increasing pH, SOC, CEC total N, total Si, potential P, available P, potential K, and available K compared to the control (without adding biochar). Adding Biochar 2.5 t and SiO_2 3 L (treatment C) was the best treatment for improving soil chemical properties and reducing CH4 emissions. Silica-enriched biochar primarily provides additional benefits by increasing the SiO_2 content, which can increase plant resistance and improve soil quality for long-term resilience. Applying silica-enriched biochar can be part of a sustainable agricultural strategy that increases productivity and plant resilience and reduces the negative impact of agricultural activities on the environment. Long-term research at different locations would be useful to assess the sustainable impact of silica-enriched biochar over multiple cropping cycles and its economic feasibility for large-scale adoption in rice farming systems.

Acknowledgments

The author would like to express his appreciation to the National Research and Innovation Agency, which has supported research activities through the Research and Innovation Program for Advanced Indonesia with agreement numbers B-840/II.7.5/FR.06/5/2023 and B- 977/III.5/FR.06.00/5/2023 and the Padjadjaran University for their valuable support and funding of the publication of this article.

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