International Journal of Life Science and Agriculture Research

ISSN (Print): 2833-2091, ISSN (Online): 2833-2105

Volume 04 Issue 04 April 2025

DOI: https://doi.org/10.55677/ijlsar/V04I04Y2025-03

Impact Factor: 7.88 , Page No : 255-260

The Effect of Biochar-Silica and N, P, K Fertilization on Soil pH, Silica Content, Phosphorus Uptake, and Rice Yield in Inceptisols

Emma Trinurani Sofyan[1], Della Adelia Noviana Rizca[2], Anni Yuniarti[3], Ania Citraresmini[4], Ade Setiawan[5], Yusup Hidayat[6], Dirga Sapta Sara[7]

[1-7]Agrotechnology Study Program, Faculty of Agriculture, Universitas Padjadjaran, Address Jl. Bandung-Sumedang KM.21, West Java, Indonesia.

ABSTRACT

Rice is a major commodity in Indonesia, but its production in 2023 decreased by 645.09 thousand tons compared to the previous year, partly due to intensive land use leading to soil degradation. Biochar is a soil amendment that can improve soil properties and enhance nutrient retention. Silica plays a crucial role in rice cultivation, particularly in addressing issues related to acidic soil pH. This study aimed to evaluate the effects of a biochar-silica combination derived from rice husk waste and N, P, K fertilizers on soil pH, silica content, phosphorus uptake, and to determine the optimal dosage for achieving the highest rice yield in Inceptisols. The experiment was conducted from October 2024 to January 2025 at the KTNT experimental field using a Randomized Block Design (RBD) with 10 treatments and 3 replications, totaling 30 experimental plots. The combination of biochar-silica and N, P, K fertilizers significantly increased available phosphorus content, soil silica levels, and rice yield components, including panicle length, number of panicles, grains per panicle, straw weight per plot, 1,000-grain weight, harvested dry grain, and milled dry grain. However, it had no significant effect on soil pH or phosphorus uptake by plants. The optimal treatment—biochar (2.5 t ha^{-1}), silica (320 kg ha^{-1}), and N, P, K fertilizers (175 kg ha^{-1} urea, 25 kg ha^{-1} SP-36, and 25 kg ha^{-1} KCl)—resulted in the highest harvested dry grain yield of 3.37 kg per plot.

KEYWORDS: Inceptisols, Organic material, Paddy rice, Rice husk biochar, Silica

Corresponding Author:
Emma Trinurani Sofyan

1. INTRODUCTION

Rice (*Oryza sativa* L.) is Indonesia's primary agricultural commodity, playing a crucial role in food production and consumption (Al Mu'min et al., 2016). The country achieved rice self-sufficiency in 1984, meaning domestic production met national demand. However, maintaining this self-sufficiency has become increasingly challenging due to several factors. One major issue is rapid population growth, which significantly increases rice demand (Khairati & Syahni, 2016). If production fails to keep pace with population growth, food security could be jeopardized.

Additionally, the loss of agricultural land due to urbanization and infrastructure expansion further threatens rice production (Erfrissadona et al., 2020). According to Statistics Indonesia (BPS, 2023), the total harvested area in 2023 decreased by 0.26 million hectares (2.45%), leading to a decline in rice production by 645,090 tons compared to the previous year. This reduction is primarily attributed to land conversion and suboptimal farming practices.

To address these challenges, improving land productivity is crucial. While long-term fallowing can restore soil fertility, it is impractical in densely populated regions with limited land availability (Dariah et al., 2015). Therefore, faster and more efficient approaches are needed. Soil amendments provide an effective solution for enhancing soil productivity and sustaining rice yields (Dariah et al., 2015).

According to the Indonesian Ministry of Agriculture Regulation No. 02/Pert/HK.060/2/2006, soil amendments include natural or synthetic, organic or mineral substances in solid or liquid form that enhance soil chemical, biological, and physical properties. Biochar is one such amendment, produced through biomass pyrolysis at 300–700°C under low-oxygen conditions (Herlambang et al., 2021). Derived from abundant agricultural residues, biochar offers a sustainable waste management solution (Sinaga, 2020).

Rice husks, often underutilized and slow to decompose, can be converted into biochar. In 2022, Indonesia's rice milling output reached 54.75 million tons of milled dry grain, generating approximately 12.59 million tons of husks (BPS, 2023).

Biochar enhances soil nutrient availability, including silica (Si), which is beneficial for rice growth. Compared to compost or manure, biochar is more effective in retaining and releasing nutrients (Basri & Chairunnas, 2015). Silica plays a crucial role in increasing the number of productive tillers, grains per panicle, and overall yield (Suhada et al., 2022). Beyond yield improvement, silica also mitigates soil-related issues. High soil acidity in flooded paddy fields can elevate aluminum (Al) and iron (Fe) levels, reducing phosphorus (P) availability by forming insoluble $AlPO_4$ and $FePO_4$ (Shamshuddin et al., 2013; Sonia & Setiawati, 2022). Silicon helps counteract these effects by lowering Fe concentrations in plant tissues and enhancing antioxidant activity (Chalmardi et al., 2014; Dufey et al., 2014).

Integrating biochar with silica minerals could serve as an effective soil amendment for cultivating Mapan P-05 hybrid rice. This high-yield variety can produce up to 13 t ha^{-1} of milled dry grain within 100–105 days after transplanting, a relatively shorter duration than other varieties (Muthohharoh et al., 2018). It is resistant to tungro disease (Shofia & Awami, 2017) and achieves the highest grain yield among varieties grown in Inceptisols (Syarifah et al., 2021).

Inceptisols, characterized by low organic matter and essential nutrients (N, P, K) and a slightly acidic pH (~5.6), are less fertile for rice cultivation (Setyastika & Suntari, 2019). The application of biochar-silica can improve these soils for paddy farming. Macronutrients (N, P, K) are essential for optimal rice growth. While biochar enhances soil properties, inorganic fertilizers remain necessary to meet plant nutritional requirements. The Indonesian Ministry of Agriculture (2022) recommends applying 350 kg ha^{-1} Urea, 50 kg ha^{-1} SP-36, and 50 kg ha^{-1} KCl in Jatinangor.

To address the constraints of Inceptisols, an experiment was conducted using biochar-silica and NPK fertilizers. Biochar-silica improves nutrient availability, plant uptake, and soil pH, while inorganic fertilizers supply essential nutrients. This integrated approach is expected to enhance soil pH, Si content, P uptake, and rice yield in Jatinangor's Inceptisols.

2. MATERIALS AND METHODS

The experiment was conducted from October 2024 to January 2025 at the KTNT Experimental field, which is located at an altitude of 794 m above sea level. Materials in this study include Inceptisols from Jatinangor, single inorganic fertilizers, including Urea (46% N), SP-36 (36% P_2O_5), and KCl (60% K_2O), following the recommended fertilization rate for rice at a dose of 350 kg.ha^{-1} Urea, 50 kg.ha^{-1} SP-36, and 50 kg.ha^{-1} KCl/K_2O, Mapan-P05 rice variety seeds, and soil amendments, including biochar derived from rice husk at a rate of 2.5 t.ha^{-1}, silica powder (64% SiO_2) at 320 kg.ha^{-1}, and liquid silica (35% SiO_2) at 3 L.ha^{-1}. The experimental design used randomize block design with ten treatments, 1 control treatment, 1 Biochar treatment, 2 biochar and silica treatment, 2 biochar and N, P, K combination, 4 biochar treatment with silica and N, P, K combination. Each treatment was repeated three times. Soil media samples were taken during the maximum vegetative phase at 60 HST. Soil samples from the rhizosphere were collected, with approximately 500 grams from each treatment and analyzed in the laboratory according to the specified parameters. The study was conducted in several phases: preparation of silica-enriched biochar, preparation of the growing medium, rice seedling nursery, transplanting and fertilization, maintenance, observation, sample collection for analysis, and harvesting.

3. RESULTS AND DISCUSSION

Plants require sufficient nutrients during their growth phases to achieve optimal development. The application of biochar-silica and N, P, K fertilization influences several soil and plant parameters, including soil pH, silica content, avalaible and P uptake is presented in Table 1.

Table 1 pH, Silica Content, Availabe and Phosphorus Uptake, and Rice Yield Response Due to Application of Biochar-Silica and N, P, K Fertilization on Inceptisol Soil

Code	Treatment	Soil pH	Silica Content (%)	Available P (ppm)	P Uptake (%)
A	Biochar	6.25 d	37.72 bc	127.51 a	0.029 a
B	Biochar + Powder Silica	6.18 cd	39.29 cd	128.60 a	0.028 a
C	Biochar + Liquid Silica	6.3 def	39.34 cd	147.54 c	0.027 a
D	Biochar + 50% N, P, K	6.46 f	38.76 c	139.79 abc	0.035 ab
E	Biochar + Powder Silica + 50% N, P, K	5.97 ab	37.53 bc	135.43 abc	0.036 ab
F	Biochar + Liquid Silica + 50% N, P, K	6.28 de	41.02 d	131.23 ab	0.027 a
G	Biochar + 100% N, P, K	5.95 ab	34.46 a	140.60 abc	0.040 bc

H	Biochar + Powder Silica + 100% N, P, K	6.04 bc	37.88 bc	141.83 abc	0.049 c
I	Biochar + Liquid Silica + 100% N, P, K	5.85 a	39.50 cd	144.33 bc	0.049 c
J	Control	6.44 ef	36.24 b	131.91 ab	0.044 bc

Note: Mean numbers followed by the same letter are not significantly different based on Duncan's Multiple Range Test at the 5% Level

The data presented in Table 1 demonstrate the effects of biochar-silica and N, P, K fertilization on soil acidity (pH), silica (Si) content, available and phosporus (P) uptake in paddy rice on Inceptisols. Based on Duncan's multiple range test (DMRT) at a 5% significance level, the application of biochar-silica had a significant effect on increasing soil and plant specified parameters.

3.1. Soil pH

Statistical analysis showed that treatment J (control) and treatment D (Biochar + 50% N, P, K) had significantly higher soil pH, indicating that biochar and silica did not substantially increase soil pH. The ability of biochar to increase soil pH depends on several factors. High-pyrolysis biochar (>400°C) enhances alkalinity, improving pH adjustment (Zubairu et al., 2023). Lignin-based biochar has higher porosity and surface area, increasing pH effectiveness (Lei et al., 2009). Additionally, biochar has a more pronounced effect in sandy soils than in other soil types (Wang et al., 2014). Biochar alkalinity is a key factor in neutralizing acidic soils (Yuan et al., 2011). Higher biochar alkalinity correlates with greater pH improvement (Lei et al., 2009; Zubairu et al., 2023). However, rice husk biochar has a relatively lower pH (7.39) compared to bamboo (pH 10.03) and wood biochar (pH 10.5) (Shetty & Prakash, 2020), making it less effective in raising soil pH. Thus, biochar feedstock selection is crucial for optimizing its soil pH-enhancing effects.

3.2. Silica Content

Treatment F (Biochar + Liquid Silica + 50% N, P, K) showed the highest results, significantly different from the control. This indicates that increasing soil Si levels aligns with silica fertilizer application. Plants absorb silica as monosilicic or orthosilicic acid (H_4SiO_4) (Fageria, 2014). Fertilization is an effective method to increase H_4SiO_4 concentration in soil solution (Tubana & Heckman, 2015). Although soil contains abundant Si, most of it is in the unavailable SiO_2 form (Amin et al., 2021). Silica fertilization enhances H_4SiO_4 levels, improving plant uptake and growth. Both liquid and powder silica increased soil Si content compared to the control. However, liquid silica had a more significant impact, as seen in treatments C, F, and I, while silica powder only differed significantly in treatment B. This may be due to the higher availability of liquid silica, which is more readily absorbed by soil and plants (Dharmika & Mulyani, 2018). Liquid fertilizers address nutrient deficiencies faster than solid fertilizers due to their easier absorption (Roidah, 2013).

3.3. Available P

Treatment C (Biochar + Liquid Silica) yielded the highest available P. This combination had the greatest effect on increasing available P in Inceptisols, surpassing the control. It improved soil chemical properties and optimized nutrient availability for plants. Similar findings by Mayendra et al. (2019) indicate that rice husk biochar enhances P availability by releasing P bound to Al and Fe (Annisa, 2021; Mayendra et al., 2019). Biochar affects P availability through multiple mechanisms (DeLuca et al., 2015). It reduces P loss by limiting percolation, enhances enzymatic activity for P release, promotes phosphate-solubilizing bacteria, and forms organomineral complexes that increase P solubility. Silica fertilization also improves P availability by replacing adsorbed P in soil exchange complexes and reducing Al concentration, minimizing P fixation (Zulputra et al., 2014). Additionally, silica reduces Fe uptake in rice by enhancing root oxidation strength (Fu et al., 2012; Fageria, 2014). Monosilicic acid anions $[SiOH_3]O^-$ can replace phosphate anions $[HPO_4]^{2-}$ bound to Fe, increasing available P (Siregar & Annisa, 2020). The effect of biochar, silica, and NPK fertilization was statistically insignificant due to the soil's slightly acidic condition. The availability of phosphorus (P) in the form of HPO_4^{2-} and $H_2PO_4^-$ can decrease in acidic soils (Mukhlis et al., 2011). Optimal P availability occurs at pH 5.8–6.5 (Mayendra et al., 2019).

3.4. Phosphorus Uptake

Treatments G (Biochar + 100% N, P, K), H (Biochar + Silica Powder + 100% N, P, K), and I (Biochar + Liquid Silica + 100% N, P, K) showed no significant difference from the control, indicating that biochar and silica did not significantly affect P uptake. Biochar's effectiveness in enhancing P uptake depends on its feedstock. Animal manure-derived biochar has a greater impact on soil P availability and plant uptake (Tesfaye et al., 2021) than biochar from plant residues or wood due to differences in P content and pH (Gaskin et al., 2008; Mullen et al., 2010; Uzoma et al., 2011). Manure-derived biochar contains up to 19.9 g/kg P and can increase lettuce P uptake by 71% (Gunes et al., 2014). The application rate also influences biochar's effectiveness. Moderate doses (5–40 t/ha) increase P uptake by 76% on average, whereas low doses (<5 t/ha) result in a 44% increase, and high doses (>40 t/ha) may reduce uptake (Tesfaye et al., 2021). Low doses may be insufficient to significantly enhance P uptake, while excessive amounts can lead to inefficiencies or adverse effects (Ding et al., 2016).

3.5. Rice Yield Response

The components of rice corn yield consist of 1000-Grain Weight, Harvested Drain Grain, and Milled Dry Grain. The statistical analysis results for these yield parameters are shown in Table 2.

Table 2 Yield response of rice with biochar-silica and N, P, K fertilizer on Inceptisols

Code	**Treatment**	**1000-Grain Weight (g)**	**Harvested Drain Grain (Kg)**	**Milled Dry Grain (Kg)**
A	Biochar	26.83 ab	2.13 b	1.78 b
B	Biochar + Powder Silica	27.03 ab	2.42 c	2.02 c
C	Biochar + Liquid Silica	27.47 b	2.34 c	1.95 c
D	Biochar + 50% N, P, K	27.64 b	3.09 de	2.57 de
E	Biochar + Powder Silica + 50% N, P, K	28.53 c	3.37 f	2.81 f
F	Biochar + Liquid Silica + 50% N, P, K	28.61 c	3.36 f	2.80 f
G	Biochar + 100% N, P, K	27.47 b	3.18 ef	2.65 ef
H	Biochar + Powder Silica + 100% N, P, K	28.61 c	3.21 ef	2.68 ef
I	Biochar + Liquid Silica + 100% N, P, K	28.81 c	2.95 d	2.46 d
J	Control	26.17 a	1.64 a	1.37 a

Note: Mean numbers followed by the same letter are not significantly different based on Duncan's Multiple Range Test at the 5% Level.

The treatments involving biochar consistently outperformed the control group. For instance, treatment E (Biochar + Powder Silica + 50% N, P, K) achieved the highest 1000-grain weight at 28.53 g. In contrast, the control treatment yielded only 26.17 g. This significant difference suggests that the addition of biochar and nutrients enhances grain development, likely due to improved soil structure and nutrient retention capabilities (Lehmann & Joseph, 2015).

Treatments B (Biochar + Powder Silica) and C (Biochar + Liquid Silica) also showed promising results, with weights of 27.03 g and 27.67 g, respectively. This indicates that even without the full nutrient package, biochar can positively influence grain weight.

The harvested drain grain results reveal a clear trend: treatments that combined biochar with nutrient sources yielded significantly more grain. Treatment D (Biochar + 50% N, P, K) produced the highest yield at 3.09 kg, compared to the control's 1.64 kg. This highlights the effectiveness of biochar in enhancing crop yield through improved nutrient availability and soil health. Treatment F (Biochar + Liquid Silica + 50% N, P, K) also performed well, yielding 3.36 kg, which is comparable to treatment D. This suggests that the type of nutrient source may also play a role in optimizing yield, with liquid silica potentially offering additional benefits.

The milled dry grain results further corroborate the findings from the previous metrics. Treatment E yielded 2.81 kg, while the control group only produced 1.37 kg. This stark contrast emphasizes the importance of biochar and nutrient combinations in improving not just quantity but also the quality of the harvested grain. Treatments G (Biochar + 100% N, P, K) and H (Biochar + Powder Silica + 100% N, P, K) also showed competitive results, with milled dry grain weights of 2.65 kg and 2.68 kg, respectively. This indicates that while biochar is beneficial, the specific nutrient combinations can further enhance outcomes.

The results underscore the potential of using biochar as a key component in organic fertilizers. Biochar improves soil structure, enhances water retention, and serves as a habitat for beneficial microorganisms, which can further enhance nutrient availability (Sohi et al., 2010). The integration of biochar with other organic amendments can lead to sustainable agricultural practices that improve crop yields while minimizing environmental impacts. Moreover, the comparative performance of treatments suggests that farmers can tailor their fertilization strategies based on specific crop needs and soil conditions. For instance, using biochar in combination with specific nutrient sources like powder or liquid silica can optimize both yield and grain quality.

4. CONCLUSION

- The integration of biochar-silica with N, P, K fetilizer enhances available P, Si content, and improves the yield of rice.
- The application of biochar (2.5 t/ha), silica (320 kg/ha), and N, P, K fertilizer (175 kg/ha urea, 25 kg/ha SP-36, and 25 kg/ha KCl) resulted in the highest harvested dry grain yield of 3.37 kg on Inceptisols, making it the most effective treatment.

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