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Research Article

Influence of Rice Husk Biochar and Its Application Methods on Silicon Dynamics and Rice Yield in Sandy-Loam Soil

John S. Olanrewaju[1,2] **Kuniaki Sato,**[1] **Sadahiro Yamamoto,**[3] **and Tsugiyuki Masunaga**[1]

[1]*Faculty of Life and Environmental Sciences, Shimane University, Matsue, Japan*
[2]*Department of Processing, Storage and Environmental Engineering, National Centre for Agricultural Mechanization, (NCAM), Ilorin, Nigeria*
[3]*Faculty of Agriculture, Tottori University, Tottori, Japan*

Correspondence should be addressed to Tsugiyuki Masunaga; masunaga@life.shimane-u.ac.jp

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Rice husk biochar (RHB) is a potential source of available silicon in paddy soil and an ecologically responsive soil amendment for sustainable rice production. The study tested the influence of RHB application methods on rice growth, rice yield, and silicon dynamics in sandy loam soil in a pot experiment. RHB was applied at 5 tons ha^{-1} as a localized-spot-application (LSA) or top-mixed-application (TMA) with the soil at the upper 7 cm or whole-mixed-application (WMA) within 20 cm of the soil column and at 10 tons ha^{-1} in the TMA and WMA methods and was compared with a control (CTRL) without biochar. Seedlings of the *Koshihikari* rice variety were transplanted in each pot, and all treatments were replicated thrice. Compared to the CTRL, the LSA and TMA methods did not influence the mean porewater silicon concentration at the vegetative and reproductive stages. However, the WMA method applied at 5 tons ha^{-1} increased ($p < 0.05$) the mean porewater silicon concentration by 12.3 and 39.5% at the vegetative and reproductive stages, respectively, while at 10 tons ha^{-1}, the respective increase was by 26.1 and 32.7%. All biochar application methods at the 5 tons ha^{-1} rate increased the rice grain yield ($p < 0.05$) by 21.2% (LSA), 11.3% (TMA), and 47.2% (WMA) compared to the CTRL. Conversely, at 10 tons ha^{-1}, the yield was reduced by 18% in the TMA method, attributable to the immobilization of nitrogen and adsorption of nutrients to biochar surfaces. Our results proved that the choice of biochar application method and rate of application significantly influenced the dissolution of silicon in the porewater, leading to a higher silicon uptake and consequently a higher grain yield. This study provides valuable insights for agricultural practices aiming to enhance silicon dynamics in paddy soil and sustainable rice yield using RHB.

1. Introduction

Rice holds significant importance in various aspects such as agriculture, economics, and food security. Rice is indeed a crucial staple food for a significant portion of the global population, with over half of the world's population relying on it as a primary food source, as recounted by Asad et al. [1]. The production of rice is highly dependent on climatic factors such as precipitation, temperature, and sunshine, indicating the vulnerability of rice cultivation to climate change [2, 3]. The availability of silicon has been identified as a key to sustainable rice production, as reported by Nwite et al. [4], in the face of uncertain and unfavourable environmental conditions. Repeated shreds of evidence have indicated the beneficial effects of Si on rice by playing a "quasi-essential" role in response to diverse biotic and abiotic environmental stresses [5]. Silicon is widely accepted for its beneficial effects on plants, particularly in stress conditions including drought stress, cold stress, flooding, and disease [6, 7]. Other Si-derived benefits include an increase in photosynthetic rate, lower transpiration rates, and an increase in the yield of various crops. The relevance of silicon (Si) to plants has become a subject of increasing interest in the last two decades; however, the availability of Si and the exploration of easily soluble supplies of Si are an overwhelming challenge [8, 9].

Most highly weathered agricultural soils are deficient in available Si [10]. Therefore, the use of Si fertilizer is the most rapid potential method to increase the availability of Si in silicon-deficient fields. The most common traditional Si fertilizers are silicate slags which are available in limited supply, expensive, bulky, constitute logistic problems, and are not readily available to farmers, especially in developing countries [11, 12].

Rice husk biochar (RHB) has been proposed as one of the most readily accessible organic sources of plant-available silicon for rice production. RHB, also known as "*momigara kuntan*" in Japanese, is recognized for its high Si availability in comparison with other kinds of biochar produced through the pyrolytic conversion of agricultural residues in inert conditions [13]. RHB is also a very cost-effective biochar used in Japanese rice-based farming systems [14]. Globally, about 220 million tons of RH are produced per year as agro-industrial waste [15]. The application of RHB and other biochar has a positive influence on enhancing soil carbon (C) sequestration, alleviating greenhouse gas emissions, reducing heavy metal toxicity from paddy fields, and improving rice productivity [16–18]. The potential of rice husk biochar as a silicon source has not been fully utilized in developing and tropical countries where desilication is high and available silicon is low [19, 20].

Full maximization of these potentials of RHB as a sustainable silicon source requires improved processing and application methods. The biochar application method is a major controlling component in the dynamics and conservation of soil nutrients [21]. Generally, biochar applied to the soil surface through broadcasting could increase water retention and decrease fertilizer evaporation [22]. However, this application method is unsuitable because the wind may blow away the applied biochar, thereby polluting the air around the farm. It is also not suitable for areas with high precipitation or irrigated paddy fields because surface runoff could easily wash away the applied biochar. Another biochar application method to improve growth and nutrients is generally achieved by mixing it with the soil. However, the optimum level (rate and depth) of incorporation of biochar into the soil is unknown. In a report by Li et al. [23], it was found that biochar could optimally decrease nitrate leaching by 8.3–17.0% and improve the soil's hydraulic conductivity (K_{sat}) by 20.9% by mixing with soil at 10–20 cm depth. To the best of our knowledge, the mode of application of RHB has not been tested to elucidate the effect of RHB application on silicon dynamics and its influence on rice growth and yield. Thus, the mode of application is important to obtain maximum benefits from the application of RHB as a source of silicon.

We, therefore, examined the influence of three biochar application methods, namely, "top-mixed application" (TMA), "whole-mixed application" (WMA), "localized spot application" (LSA) and control (CTRL) without biochar, and two rates of application (5- and 10 tons ha^{-1}) on the rice plant growth, yield, Si dynamics, and uptake in rice plant using a column-like pot experiment.

2. Materials and Methods

2.1. Rice Husk Biochar Preparation. A programmable electric furnace (model FO810, Yamato, Japan) equipped with a digital temperature controller was used for the pyrolysis. The rice husk biomass was put in stainless vessels and pyrolyzed in the electric furnace at a heating rate of 5°C min^{-1} until the temperature of 600°C was reached, and then kept at this temperature for 2 hours before the pyrolyzed samples were cooled down. The pyrolysis was carried out in an inert atmosphere by supplying N_2 gas at a rate of 5 L min^{-1}.

2.2. Soil Preparation. The soil used in the experiment was obtained from the ploughed layer (0–15 cm) of the experimental rice field at Shimane University, Japan. The soil was air-dried in the greenhouse, crushed, and sieved to a uniform size using a 2 mm mesh size sieve.

2.3. Biochar and Soil Analysis

2.3.1. Biochar Characterization. The biochar's electrical conductivity (EC) and pH were determined in a 1 : 20 w/v biochar-water mixture with EC and pH meters (Horiba models D-24 and D-15, Horiba, Kyoto, Japan, respectively) [24]. Total carbon and nitrogen were measured in a 0.03 g portion by the dry combustion method with an automatic high-sensitive NC-analyzer (Model Sumigraph NC-22 Analyzer, Tokyo, Japan). Available phosphorus was extracted by 0.5 M $NaHCO_3$ in a ratio of 1 : 30 w/v after shaking for 30 minutes at 120 rpm, and the P in the supernatant was determined by the molybdenum blue method [25]. Extractable base cations (Ca, K, Mg, and Na) were extracted by 1 : 100 w/v of 1 M CH_3COONH_4 at a pH of 7.0 and quantitatively determined by inductively coupled plasma spectroscopy (model ICPE-9000, Shimadzu, Kyoto, Japan). Available Si was extracted by the following two methods (1) sodium acetate buffer (pH 4.0) with a ratio of 1 : 30 w/v, intermittently shaken for 5 h at 40°C [26], and (2) 0.01 M $CaCl_2$ with a ratio of 1 : 30 w/v and continuously shaken for 16 h [27]. Silicon concentrations in the extracts were determined by colourimetry with the molybdenum blue method at a wavelength of 810 nm [28] using a UV-probe spectrophotometer (Model UV-1800, Shimadzu, Kyoto, Japan).

2.3.2. Soil Properties. For the soil analysis, the air-dried soil samples were digested with hydrogen peroxide, and the textural analysis was done using the pipette method [29]. The pH and EC were measured in a 1 : 5 w/v soil-water mixture with EC and pH meters (Horiba models D-24 and D-15, Horiba, Kyoto, Japan. The soil's total C and N were determined in a 0.02 g portion with the same method for biochar, and their ratio was calculated. Available phosphorus was extracted by the Bray-II method [30] because of the soil's slightly acidic nature, and the P in the supernatant was determined by the molybdenum blue method. The exchangeable cations were extracted with 1 M ammonium acetate in a ratio of 1 : 20 w/v and then determined by inductively coupled plasma spectroscopy (Model ICPE-9000, Shimadzu, Kyoto, Japan). Available Si was extracted by the same methods for biochar but with a ratio of 1 : 10 w/v soil-extractant, and the silicon concentration was similarly determined.

Selected initial properties of the soil and RHB are presented in Table 1.

2.4. Treatment and Management Practices. To mimic a typical paddy environment in the soil profile, a column-like pot experiment was conducted to determine the influence of RHB application depth and rate on silicon dynamics in paddy cultivation and its effect on the growth, yield, and Si uptake in rice plants. Dried soil of 4.5 kg was added to each 1/5000 "*a*" Wagner pot (internal diameter = 16 cm; height = 30 cm) (Fujiwara Seisakusho Ltd, Tokyo, Japan). The pots have drainage holes at the base which were sealed with silicone rubber stoppers equipped with draining points at the centre.

Six treatments, namely, control (CTRL: without biochar), "Localized Spot Application" (LSA) at 5 tons ha^{-1}; "Top-Mixed Application" (TMA) at 5 tons ha^{-1}; TMA at 10 tons ha^{-1}; "Whole-Mixed Application" (WMA) at 5 tons ha^{-1}, and WMA at 10 tons ha^{-1} were replicated three times and laid out in a completely randomized manner. These application methods and rates were selected from practical point of view and based on the economic feasibility of biochar application on a large scale. The biochar application methods are shown in Figure 1.

Koshihikari rice variety was used for the experiment. One day before rice seedlings were transplanted, all pots were fertilized using 4.71 g of $(NH_4)_2SO_4$ as a nitrogen source and 4.39 g of KH_2PO_4 as potassium and phosphorus source which is equivalent to 1.0 g N and 1.0 g P per pot as the recommended rate for the *Koshihikari* rice cultivar. There was no supplementary fertilization throughout the rice growth period. The RHB material was also applied to the biochar-treated pots. One seedling was transplanted into each pot. Continuous flooding with a water depth of 3–10 cm was maintained by regular watering.

2.5. Porewater Sampling and Analysis. The porewater of the soil column was sampled every week after transplanting by collecting the water from each pot into 50 ml centrifuge tubes. The porewater was collected through the draining point at the centre of the rubber stoppers. The collected samples were used for pH measurement (with a calibrated probe), and a portion was used for mono-silicic acid determination using colorimetry with the molybdenum blue method as previously described above. The remaining portion was centrifuged at 10,000 rpm for 5 minutes. The supernatant was decanted and acidified with drops of 2 M HCl to prohibit iron oxide deposition, and the elemental composition was determined by ICPE-9000.

2.6. Plant Analysis. The rice plants were harvested at 118 days after transplanting and separated into roots, straw (leaves and stem), and grains. The soil was carefully removed from the roots and thoroughly washed and air-dried. The grains were also air-dried and properly separated into filled and unfilled grains, while the straw and air-dried roots were oven-dried at 60°C for 48 hours. All dried biomasses were weighed to determine the total biomass yield per pot.

A manual, hand-held rice dehusker was used to dehusk the filled rice grains. The silicon content from the rice plant parts (root, flag leaf, and husk) was extracted by a diluted hydrogen fluoride solution as described by Saito et al. [31] after grinding into a fine powder with a mill ball grinder (MM 200, Retsch GmbH, Haan, Germany). The Si in the extract was measured by the molybdenum yellow method at a wavelength of 400 nm [32].

The total plant nutrient was determined by ICPE-9000 after the digestion of a 0.05 g portion of the plant part with concentrated HNO_3 in Teflon vessels using a programmable graphite block sample acid digestion system (ODLAB, Geumcheon-gu, South Korea).

The nutrient uptake was calculated using the formula as previously described by Nwajiaku et al. [33] in the following equation:

$$\text{Nutrient Uptake}\left(\text{g pot}^{-1}\right) = \text{Nutrient content in plant}\left(\left(\text{g kg}^{-1}\right)\right) \times \text{Plant dry weight}\left(\text{kg pot}^{-1}\right). \quad (1)$$

2.7. Statistical Analysis. A repeated measure (mixed) analysis of variance (ANOVA) was used to test the influence of biochar application methods and rate (the between-subject factors at 6 levels) on the porewater silicon concentration (a continuous dependent variable) spanning the three stages of rice growth, namely the vegetative, reproductive, and maturity stages. This method was deemed appropriate because the basic assumptions of the method were not violated by the data as reported in the result section. The differences in biomass yield (Grain, straw, and roots), silicon contents in the different parts of the rice (flag leaf, husk, and root) and silicon uptake at harvest were analysed using a one-way ANOVA and accepted after Tukey's honestly significant difference (Tukey's HSD) post hoc test at the 0.05 significant level. Except otherwise stated, all data presented in the tables are means of the parameters ± standard deviation (SD). The statistical analyses were conducted using the IBM® SPSS® Statistics package (Version 28) (IBM, SPSS Inc.).

Table 1: Physico-chemical properties of the soil and biochar used in the experiment.

Properties	Soil	RH biochar
Soil texture (%)		
Clay	19	—
Sand	75	—
Silt	6	—
pH (H_2O)	6.20 ± 0.06	10.60 ± 0.04
EC (dS m^{-1})	0.08 ± 0.03	0.14 ± 0.14
Total C (g kg^{-1})	29.78 ± 0.21	498.91 ± 2.69
Total N (g kg^{-1})	2.49 ± 0.16	4.71 ± 0.11
C/N Ratio	11.96 ± 0.23	106.15 ± 2.40
Available P (g kg^{-1})	0.12 ± 0.01	0.11 ± 0.02
Exchangeable/extractable base cations (cmol $_c$ kg^{-1})		
Ca	10.22 ± 0.13	1.89 ± 0.04
K	4.02 ± 0.02	19.91 ± 1.16
Mg	0.26 ± 0.06	1.48 ± 0.06
Na	0.37 ± 0.07	0.98 ± 0.07
Available Si (g kg $^{-1}$)		
Ac. buffer-extracted	0.48 ± 0.12	0.15 ± 0.06
$CaCl_2$-extracted	0.10 ± 0.01	1.92 ± 0.15

(Reported values are means ± standard deviations).

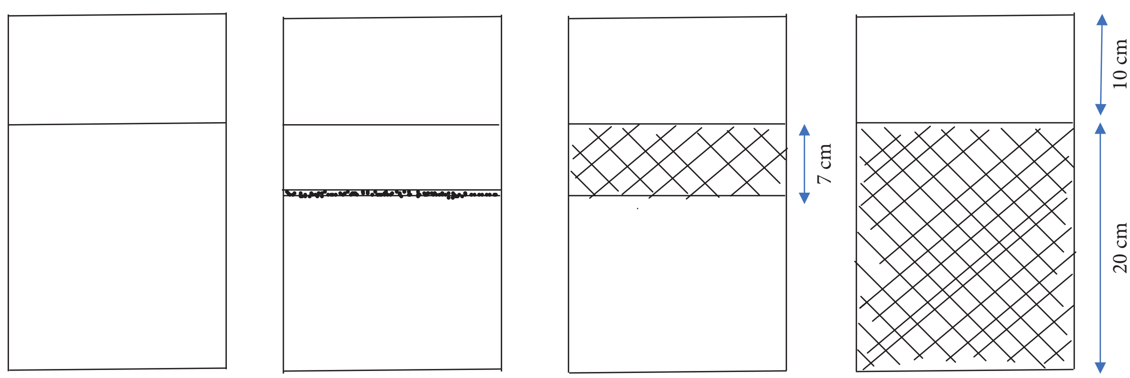

Figure 1: Biochar application methods. *Note*. CTRL (control, no biochar), LSA (localized spot application; RH biochar was placed at 7 cm soil depth and not mixed with the soil), TMA (top-mixed application; RH biochar was mixed within the top 7 cm of the soil column), and WMA (whole-mixed application; RH biochar was mixed with the whole 20 cm of the soil column).

3. Results

3.1. Change in Porewater Si Concentration. The porewater silicon concentration during the rice growing periods for all the treatments was divided into three rice growing stages namely vegetative (before 35 days after transplanting (DAT)), reproductive (35–70 DAT), and maturity (70–118 DAT) stages. Table 2 shows the results of the repeated measures ANOVA for the RHB application methods and the rate of application for the change in the porewater silicon concentration. There were no outliers, as evaluated by boxplot. The data were normally distributed, as measured by Shapiro-Wilk's test of normality (p = 0.15). There was homogeneity of variance (p > 0.26) and covariance (p = 0.144), as assessed by Levene's test of homogeneity of variance and Box's M test, respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the two-way interaction, $\chi^2(2) = 11.381$, p = 0.003, so we adopted the Greenhouse-Geisser's calculated Epsilon (ε) value of 0.755 to correct the degree of freedom reported in Table 2.

The mean porewater silicon concentration is presented in Table 3. The silicon dynamics were significantly affected by the RHB application method at the different stages of rice. The effect of the application method was significant at $p < 0.001$ ($R^2 = 0.576$).

The effect of the application method of RHB showed that the WMA method at 10 tons ha^{-1} has significantly higher ($p < 0.001$) porewater Si concentration. The mean differences above the corresponding treatments were 2.5 mg L^{-1} (CTRL), 2.3 mg L^{-1} (LSA, 5 tons ha^{-1}), 2.4 mg L^{-1} (TMA, 5 tons ha^{-1}), and 2.8 mg L^{-1} (TMA, 10 tons ha^{-1}). The within-subject effect of the growth stage showed higher silicon concentration in the vegetative and reproductive stages more than the maturity stage (Table 3).

Table 2: Summary ANOVA table for the main and interaction effects of application methods and rice growth stage on the porewater silicon concentration.

Source	SS	df	MS	F ratio	p value	Sig	Estimate of effect size
Application methods	105.56	5.00	21.11	8.17	<0.001	***	0.576
Growth stages	1962.00	1.51	1299.44	321.28	<0.001	***	0.915
Application method X growth stages	76.93	7.55	10.19	2.52	0.025	*	0.296
Error (application methods)	77.56	30.00	2.59				
Error (growth stages)	183.21	45.30	4.05				

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 3: Effect of RHB application methods on the mean porewater Si concentration.

Application method	Rate (t ha^{-1})	Si concentration (mg L^{-1}) Vegetative	Reproductive	Maturity
Control	0	9.20 ± 1.16b	10.74 ± 1.26b	1.55 ± 0.72b
LSA	5	9.11 ± 1.92b	10.22 ± 1.22b	2.71 ± 0.81a
TMA	5	10.05 ± 1.41b	10.48 ± 1.41b	1.31 ± 0.61b
TMA	10	9.60 ± 0.96b	9.31 ± 2.39b	1.63 ± 0.63b
WMA	5	10.33 ± 1.60ab	13.55 ± 1.67a	1.84 ± 1.02b
WMA	10	12.83 ± 2.53a	14.25 ± 4.22a	1.92 ± 0.87b

Note. Means in the same column and growth stage in the same row followed by the same letters are not significantly different from each other at $p < 0.05$. LSA: localized spot application, TMA: top-mixed application, and WMA: whole-mixed application.

The interactive effect of the application methods and the rice growth stages shows no significant differences in the mean Si concentration between the vegetative and reproductive stages, with the WMA treatments having higher Si released into the porewater. However, the two stages significantly differ in the mean Si concentration at the maturity stage. Specifically, in the reproductive stage, the amount of Si in the porewater was significantly higher in the WMA application method compared to the CTRL with a mean difference of 2.81 ± 0.81 mg L^{-1} ($p = 0.015$); LSA, 3.33 ± 0.80 mg L^{-1} ($p = 0.003$), and a mean difference of 3.07 ± 0.81 mg L^{-1} for the TMA application method.

At the maturity stage, only the LSA treatment had a significantly higher Si in the porewater than the TMA treatment with a mean difference of 1.395 ± 0.465 mg L^{-1} ($p = 0.042$).

3.2. Rice Growth Parameters and Biomass Yield. Table 4 presents the different biomass yields and yield components as influenced by the RHB application methods and rates of application. The grain yield ranged between 31.53 g pot^{-1} in the CTRL treatment to 46.4 g pot^{-1} in the WMA treatment at 5 tons ha^{-1} rate of application.

At the 5 tons ha^{-1} rate of application, there were higher grain yields with the RHB treatment at different application methods compared to the CTRL. Specifically, the differences ($p < 0.05$) were 21.2, 11.3, and 47.2% in the LSA, TMA, and WMA, respectively. However, at the 10 tons ha^{-1} application rate in which only the TMA and WMA treatments were applied, the TMA gave a reduction of 18% in the grain yield compared to the CTRL while the WMA increased the grain yield by 19.3% ($p < 0.05$). The percentage of filled rice grain also varied with the different application methods with the highest percentage in the WMA at 5 tons ha^{-1} with a value of 94.6% and significantly different ($p < 0.05$) from that of the TMA at 10 tons ha^{-1} with a value of 79.2%.

There were no significant root and straw biomass differences between the RHB application methods, the rate of application, and the CTRL.

3.3. Distribution of Si Concentrations in Different Parts of Rice Plant. The distribution patterns of Si concentrations in the different parts of the rice plants (Flag leaf, husk, and Roots) as shown in Table 5, significantly varied among the different treatments ($p < 0.05$). In the flag leaf, the mixed RHB application methods (TMA and WMA) have significantly higher Si content compared to the CTRL, but there were no significant differences in the rate of application. The banded application method (LSA) was not significantly different in the Si accumulation in the flag leaf.

The Si accumulation in the husk was higher in the WMA application method at both rates (5 and 10 tons ha^{-1}) of application compared to all other treatments. The rate of application was also statistically significant ($p < 0.05$) in the WMA. All other application methods have similar patterns of Si accumulation in the husk.

However, in the root, the Si content differs between treatments (application methods and rate of application). All biochar treatments increased the Si Concentration in the root with WMA at 10 tons ha^{-1} having the highest concentration of 33.11 g kg^{-1}, while the CTRL has a root's-Si content of 15.79 g kg^{-1}. There was a marked reduction in the root's Si content in the 10 tons ha^{-1} rate of application of the TMA method compared with the 5 tons ha^{-1}. A higher amount of 26.53 g kg^{-1} was obtained for the TMA treatment at 5 tons ha^{-1} compared to 23.59 g kg^{-1} obtained with the TMA method at 10 tons ha^{-1}.

Table 4: Effect of biochar application methods and rates on rice dry biomass and grain yield.

Application method	Rate (t ha^{-1})	Biomass yield (g pot^{-1})			Filled grain %
		Grain	Root	Straw	
Control	0	31.5 ± 1.3c	68.6 ± 6.7	122.7 ± 13.7	86.8ab
LSA	5	38.2 ± 2.1b	54.0 ± 5.9	110.0 ± 12.2	88.9ab
TMA	5	35.1 ± 1.3b	53.4 ± 7.4	125.3 ± 8.0	87.6ab
TMA	10	25.8 ± 2.2d	50.8 ± 9.0	129.3 ± 10.2	79.2b
WMA	5	46.4 ± 1.3a	51.9 ± 3.4	118.0 ± 14	94.6a
WMA	10	37.6 ± 2.4b	66.9 ± 9.8	129.3 ± 7.6	89.7ab

Note. Means in the same column followed by the same letters are not significantly different from each other at $p < 0.05$. LSA: localized spot application, TMA: top-mixed application, and WMA: whole-mixed application.

Table 5: Silicon content in different parts of rice as influenced by biochar application methods and rates.

Application method	Rate (t ha^{-1})	Si content (g kg^{-1})		
		Flag leaf	Husk	Root
Control	0	22.15 ± 0.54c	44.18 ± 0.82cd	15.79 ± 0.29d
LSA	5	23.06 ± 0.99c	46.65 ± 1.23c	22.57 ± 0.39c
TMA	5	25.07 ± 0.64b	40.61 ± 2.0d	26.53 ± 0.78b
TMA	10	26.57 ± 0.19b	43.15 ± 0.51cd	23.59 ± 0.46c
WMA	5	28.69 ± 0.61a	56.61 ± 1.64b	27.78 ± 1.36b
WMA	10	29.24 ± 0.44a	61.35 ± 1.93a	33.11 ± 0.50a

Note. Means in the same column followed by the same letters are not significantly different from each other at $p < 0.05$. LSA: localized spot application, TMA: top-mixed application, and WMA: whole-mixed application.

3.4. Plant Nutrient Uptake. The Si uptake presented in Table 6 shows that it ranges from 2.53 to 3.78 g pot^{-1}. The banded application method (LSA) has the lowest uptake while pots amended with the WMA method at 10 tons ha^{-1} have the highest Si uptake. Except for the LSA method, both mixed methods, TMA, and WMA, at the two application rates, have significantly ($p < 0.05$) higher Si uptake than the CTRL treatment. The effect of the rate of application was also significantly different from each other in which the higher rate has the higher Si uptake.

The K and P uptake did not show any significant differences in the uptake patterns, but the biochar amended pots have higher P uptake than the CTRL.

4. Discussion

4.1. Silicon Dynamics and Release Pattern in the Porewater. In this study, the banded application of RHB with the LSA method numerically but not statistically decreased the Si concentration in the porewater compared to the CTRL in both the vegetative and reproductive stages while it showed a significant increase in the Si concentration at the maturity stage (Table 3). This pattern could be traced to a time-dependent release of Si from this banded application method. In a biochar incubation experiment in which RHB was applied to coarse-textured Ultisol, Ebido et al. [34] reported that RHB-induced effects on carbon mineralization and nutrient release were a function of time. Our results on the LSA method agrees with this observation. Biochar undergoes an aging process during which silicon release occurs, impacting soil properties [35]. The characteristics of silicon in biochar significantly influence soil, and the release of silicon from biochar affects soil silicon dissolution kinetics [36, 37].

Similarly, the LSA method is like the deep placement of conventional fertilizers or the application of slow-release fertilizer which slowly dissolves in the soil to provide a continuous supply of nutrients during the plant's growing period, [38]. Thus, for this method of biochar application to be effective and beneficial to the plant, the timing of the application of the biochar is essential for the first crop and for the subsequent crops on the same soil as it could have the ability to continually supply silicon in its residual form after the first harvest.

Unlike the LSA, the TMA method applied at both 5 and 10 tons ha^{-1} showed a numerical but not significant increase in the porewater Si concentration in the vegetative stage compared to the CTRL, while there was a numerical decrease in the reproductive stage. Though we cannot clearly explain the reason for this phenomenon now, it could be due to the heterogeneous nature of the soil-biochar mixture.

However, in comparison to the CTRL and other treatments, the WMA method significantly ($p < 0.05$) increased the Si concentration in the porewater (Table 3) in both the vegetative and reproductive stages. This could be traced to the fact that the RHB from the WMA had better contact with the soil and enhanced Si concentration in the pore water at the reproductive stage (Table 2). This agrees with the findings of Linam et al. [39] and other literatures that the mixing of biochar into the soil increases Si concentration in porewater and performs a vital role in the Si cycle in rice plants and paddies. In a similar study on the effects of application methods of carbonized organic materials on carbon and nitrogen retention, Oraegbunam et al. [40] reported that higher amount of leached total organic carbon was leached in the mixed application method which was attributed to a higher carbon solubilization. Our results

Table 6: Effect of biochar application methods and rate on Si, K, and P uptake.

Application method	Rate (t ha^{-1})	Nutrient uptake (g pot^{-1})		
		Si	K	P
Control	0	2.72 ± 0.03d	1.23 ± 0.14	0.37 ± 0.10
LSA	5	2.53 ± 0.22d	1.20 ± 0.10	0.48 ± 0.02
TMA	5	3.14 ± 0.09c	1.21 ± 0.26	0.46 ± 0.05
TMA	10	3.43 ± 0.05b	1.55 ± 0.26	0.49 ± 0.17
WMA	5	3.39 ± 0.09b	1.48 ± 0.31	0.52 ± 0.09
WMA	10	3.78 ± 0.19a	1.33 ± 0.26	0.39 ± 0.09

Note. Means in the same column followed by the same letters are not significantly different from each other at $p < 0.05$. LSA: localized spot application, TMA: top-mixed application, and WMA: whole-mixed application.

showed that besides the higher contact of the RHB, it also led to a higher silicon solubilization from both the soil and the biochar materials.

The high concentration of Si from the WMA method at the reproductive stage could also be termed as an excess supply of Si which could easily be leached out in an open environment, especially with the sandy loam texture of the soil giving rise to a highly permeable paddy soil which could in turn influence the effect of this method of application.

4.2. Effect of the RHB Application Methods on Rice Dry Biomass and Grain Yield. In this column-like pot experiment, the application of RHB significantly increased the grain yield but not the biomass (Table 4). This contrasts with the report by [41] that the significant impact of biochar application is much larger for plant biomass than for crop yield.

In a report by Yin et al. [42], it was found that short-term biochar application increased biomass production but decreased harvest index in rice, resulting in unchanged grain yield when applying biochar short-term, indicating a potential trade-off between biomass and grain yield with biochar application. Moreover, Si et al. [43] reported that notable effects of biochar on rice yield and biomass production were not detected, suggesting that the impact of biochar on rice biomass and grain yield may vary depending on specific conditions [43].

The reported 21.2, 11.3, and 47.2% increases in grain yield above the CTRL from the LSA, TMA, and WMA, respectively, at 5 tons ha^{-1}, explains the fact that RH biochar application improves the soil fertility, or it enhances the release of bioavailable nutrients from the soil and consequent supply of nutrients to the plant. This is also evident from the lower root-shoot ratios calculated from Table 4 of all biochar-amended pots compared to the CTRL.

Concerning the application method, the highest grain yield increase (47.2%) obtained from the WMA method could be traced to the better contact between the soil and biochar particles because of the homogeneity of the mixing throughout the soil column. This homogeneity of mixing reduces the intra- and interparticle distances between the biochar-biochar and biochar-soil layers and as well as a reduction in the free energy required for nutrient accumulation [44], thus, it enhances nutrient supply which in turn leads to an increase in the grain yield more than the other methods. Additionally, higher dissolution of Si from the biochar in the WMA method as depicted in the porewater Si concentration positively correlated with the observed grain yield, which could be traced to the positive effect of RHB-Si in rice plants by promoting effective photosynthesis [45].

The banded application method of LSA has low contact with the soil, but it has a higher concentration of biochar at the banded area, which is the root zone of the rice since most of the plant-soil interaction occurs at the root zone, [39] and thus also leads to an increase in the grain yield. Similarly, in an open system where it is possible for the applied nutrients to leach down the soil profile, this method could help in preventing nutrient leaching by adsorbing nitrate and ammonium in the porous surfaces of the biochar produced at a temperature of 600°C [46] which could be gradually made available to the plant over a longer period.

Conversely, the application rates of RHB at the 10 tons ha^{-1} level have different effects on the grain yield between the TMA and WMA compared to the CTRL. While the TMA decreased the grain yield by 18% (Table 4), the WMA increased the grain yield by 19.3% (lower than that of 5 tons ha^{-1}) over the CTRL. This result could be one of the negative impacts of excessive biochar addition, especially at the root zones of the crop. It was reported by Reibe et al. [47] that there was a reduction in crop yield in a short timeframe after biochar application. The observed reduction in rice yield at the higher application rate of 10 tons ha^{-1} in the top-mixed application (TMA) method could be attributed to several factors. Firstly, it may be due to nutritional imbalance caused by the immobilization of soil nitrogen [48], leading to an increase in the carbon-to-nitrogen (C/N) ratio. This imbalance can negatively impact crop development and productivity. Additionally, the adsorption of nutrients such as phosphorus on biochar surfaces could also contribute to hindering crop development and productivity [49]. These factors may have collectively contributed to the reduction in rice yield observed in the TMA method at the higher application rate. This nitrogen immobilization or adsorption is reflected in the significantly lower percentage of filled grains exhibited by the TMA method at 10 tons ha^{-1} (Table 4).

4.3. Application Methods Influence Si Concentration in Different Rice Parts and Si Uptake. The distribution of Si content in the different parts of rice as influenced by the application methods (Table 5) reveals that RHB addition supplies Si to the soil and the plant. All RHB-amended pots have significantly higher ($p < 0.05$) Si content in all parts of the rice compared to the CTRL.

The application of biochar has been shown to have significant effects on plant nutrient uptake and overall health. Several studies have demonstrated that biochar application can enhance nutrient availability and uptake by plants, leading to improved growth and productivity. For instance, Uzoma et al. [50] found that biochar application significantly increased plant nitrogen (N) uptake, while Zheng et al. [51] attributed enhanced plant growth to the improved nutrient availability from biochar-amended soil. Additionally, Solaiman et al. [52] reported that biochar can positively influence nutrient concentrations in plant leaves through enhanced nutrient uptake. Biochar application has been linked to improvements in root traits, such as increased root length and number of root tips, which can contribute to better nutrient and water uptake by plants [53].

Chew et al. [44] reported that root hairs and microbes can reside in the pores of biochar particles and thus increase the availability of nutrients thereby reducing the energy plants must expend to uptake nutrients. Our result also agrees with the report by Wang et al. [36] that the application of Si-rich biochar such as RHB significantly increases the silicon content in various tissues such as roots, straw, and grains of rice. This increase in the Si content of rice tissues and higher Si uptake is more pronounced in the WMA method because of the homogeneity of the biochar-soil mixture, which has a greater effect on the amount of silica deposited in the rice tissues and on Si uptake (Table 6). Additionally, the WMA provided a uniform medium for root elongation. The elongated root zone enhances Si dissolution when root exudates can easily diffuse into the homogenous biochar layer and thus favours enhanced Si release and uptake.

4.4. Significances for Practical Si-Rich Biochar Field Management. Generally, the WMA method applied at a rate of 5 tons ha^{-1} generated a win-win condition by concurrently increasing rice yield, Si concentration in the porewater or soil solution, and uptake by the rice plants thereby improving the resistance of the plant to adverse environmental stresses [54, 55]. The adoption of an appropriate RHB application method in addition to other field management practices such as tillage practices, fertilizer management, water management, etc. may further optimize the potential benefits of RHB.

The WMA method is applicable in paddy fields where rotary tillage is widely practised. This will ensure an even mixing of the biochar with the soil because deep rotary tilling inverts the soil profile [56]. This deep rotary tillage and homogenous mixing of RH biochar could also facilitate the improvement in the soil's physical properties suitable for the growth of rice [57] and improve the uptake of subsoil nutrient resources [56].

The practical implementation of this WMA is limited to mechanized paddy field preparation. Farmers in developing countries, like Sub-Saharan Africa, with limited access to agricultural machineries might not be able to fully implement this method of biochar application. Manual mixing of the biochar into the soil might be advised but this could be laborious and time consuming.

5. Conclusion

In this study, we demonstrated that the choice of RHB placement method and the rate of application significantly influenced the dissolution and concentration of Si in the porewater of sandy loam paddy soil. The higher dissolution of Si in the porewater corresponds to a higher Si uptake and consequently a higher rice grain yield. Irrespective of the application method, all biochar-amended pots at 5 tons ha^{-1} significantly increased the grain yield compared to the CTRL. Conversely, a negative effect of excessive biochar application was observed at the application rate of 10 tons ha^{-1}, which led to a reduction in the grain yield by 18% in the TMA method compared to the CTRL and only a slight increase of 19.2% in the WMA method compared to the CTRL. Thus, the adoption of appropriate RHB application method such as the WMA used in this study at an economically feasible rate of 5 tons ha^{-1} in addition to other field management practices may further optimize the potential benefits of rice husk biochar in similar soil types. Our results clearly demonstrated that the use of RHB as a waste management technique serves as an affordable and sustainable soil amendment for replenishing low or deficient soil available silicon for a sustainable rice production. Further study is needed to understand long-term soil impacts of RHB application methods across different soil types.

Data Availability

All datasets used in this study are obtainable from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

This work was carried out in collaboration between all authors. JSO performed the pot experiment, plant analysis, and statistical analysis, and wrote the draft of the manuscript. KS managed rice husk biochar preparation and analyses. SY contributed to the preparation of rice husk biochar and contributed to pot experiment design. TM made overall study design, data analysis and wrote the manuscript with the author JSO.

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