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Effect of Silicon based Fertilizer and Biochar from Crop Residues on Dry Matter Accumulation and Si Uptake by Rice Crop in Central Vietnam

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ABSTRACT

Background: Silicon (Si) has been considered a beneficial element for many plants. Si-rich biochar (Sichars) from rice husk or peanut shell have been suggested to be a potential source of bioavailable Si for Si-accumulator plants. Our study aimed to assess the Si-fertilization efficiency from chemical fertilizer and rice husk and peanut shell biochars on rice dry matter and shoot Si uptake.

Methods: Pot trials were conducted in two crop seasons in 2023 (from February to April - spring season and from May to July-summer season) in the close net house. Treatments included 1 treatment with pure soil (control), 4 treatments with Si and N-P-K fertilizers and 6 treatments with biochar amendments and N-P-K fertilizers. These pot experiments were designed in the randomized complete block (RCBD) with 4 replications.

Result: Shoot dry matter increased from 35.6 to 66.7% compared with control in different rates of Si fertilizer application and was also found the highest values in RHB and PSB at 15 g/kg soil application. Different Si and biochar application rates had a significant effect ($P<0.05$) on Si uptake by rice shoot. Therefore, Si-rich biochar considers as potential material for providing available Si to maintain the required level of available Si in soil and plant for healthy and high crop production.

Key words: Biochar, Rice, Pot experiment, Shoot Si, Si rate.

INTRODUCTION

Silicon (Si), the second most abundant element on the earth's crust after oxygen, has been considered advantageous for a wide variety of plants (Deshmukh *et al.*, 2017). Around the world, there has been a rise in the usage of silicon dioxide (SiO_2) as silica to lessen the effects on the environment and there is growing interest in using Si for a variety of crops. Si-rich biochar has been suggested as a possible soil amendment to increase rice productivity (Ratnadass *et al.*, 2024). Si-rich biochars (Sichars) from rice husks or peanut shells have been proposed as a viable source of bioavailable Si for Si-accumulator plants in Vietnam. The amount of this biomass annually is quite big but they have not been utilized well (Hughes *et al.*, 2020). The dissolution of Si from biochar is a key process for providing Si fertilizer to plants. Thus, it is necessary to evaluate available Si release from biochar and assess the continuous Si supply ability of biochar.

Rice is a staple crop consumed by half of the world's population; thus, its sustainable cultivation is essential to billions of people's health. Among agricultural plants, rice is unique in that it accumulates silicon (Si) in quantities higher than other macronutrients in the straw and husk (Limmer *et al.,* 2023). Although silicon is not thought to be necessary for all crops, it does provide resistance to several biotic and abiotic stresses, leading to a more robust rice crop (Abubakar *et al.*, 2023). It has been proposed that Si is a nutrient that limits rice productivity (Cuong *et al.*, 2017). Research has shown that rice husk has a higher Si content (about 50–70 g kg^{-1}) than other soil amendments (Gutekunst *et al.,* 2017; Linam *et al.,* 2023). Similar to rice straw, rice husk can also be burned or pyrolyzed before being applied in the field; however, high temperatures during burning can reduce the amount of silicon that is available because of crystallization or a reduction in surface area (Linam *et al.,* 2023). Even though Si was administered at a high loading rate (5 Mg Si ha^{-1}), rice husk that was either unburned or burned at a moderate temperature enhanced the concentration of Si in rice straw and husk two years after application (Seyfferth *et al.*, 2018). Application of crop residue biochars could directly import both Si and nutrients into croplands, in particular with Si-rich biochars (Li *et al.*, 2019a). There were some researches related to biochar use for rice to indicate that application of biochar for this crop in the first year has increased the plant nutrient uptake (NPK).

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In comparison with NPK treatment, rice yields were increased by 5.9-22.3% in treatments with biochar and by 26.3- 34.2% in treatments of compost mixed with 5% biochar (Vinh *et al.,* 2014; Huang *et al.,* 2018; Feng *et al.,* 2021; Faridah *et al.,* 2021). A result on silicon recycling through rice residue management from Hughes *et al.* (2020) indicated that returning crop residues to fields in Northern Vietnam is expected to partially close the plant-soil Si cycle and reduce the net export of Si. Consequently, in time, such recycling of Si with crop wastes ought to support the maintenance of suitable concentrations of plant-available Si in farmed soils. Si-rich biochar is a potential source of Si for soils with low Si availability (Rizwan *et al.,* 2019). There have been inconsistent results on the impact of biochar application on plant Si uptake (Huang *et al.*, 2020), causing uncertainties in the effect of biochar application on plant Si uptake. Besides, application of Si-rich biochar to improve rice growth and yield and Si uptake has not been studied much in Vietnam yet. Hence, the objective of this study was to evaluate the impact of Si from biochar made from rice husk and peanut shell on improving rice shoot dry matter and Si uptake.

MATERIALS AND METHODS

Experiment treatment

Pot trials included 11 treatments were conducted in two crop seasons in 2023 (from February to April - spring season and from May to July- summer season) in the closed net house of Faculty of Agronomy (16°28′ 39″ N; 107°34′ 22,3″ E), University of Agriculture and Forestry, Hue University, Hue city, Vietnam. Experiments were arranged in a randomized complete block design (RCBD) with four replications, each treatment had three pots and the total pot in each experiment were 132 pots. Not for its grain output, rice was utilized as a reference crop in pot studies simply as a useful biological extractor throughout the vegetative and panicle initiation stages. The same amounts of nitrogen (N), phosphorus (P) and potassium (K) were added to all treatments. The efficiency of Si-fertilization in pots amended with biochars from rice husk (RHB) and peanut shell (PSB) was compared to pots supplied with different rates of silicon fertilizer. In the topsoil (0-20 cm) of a rice field in Quang Tho commune (16°32′ 19″ N; 107°31′ 29″ E), Quang Dien district, Thua Thien Hue province, around 500 kg of alluvium soil was collected before planting. For pot trials, the soil was air-dried and sieved at a 5 mm mesh size. For analysis, a subsample was sieved at a size of 2 mm using conventional methods (Page *et al.,* 1996). The characteristics of the soil used in this study were the following: sand 40%, silt 26% and clay 26%; pH_{KCl} 5.1 at 1:5 soil-water ratio; organic C 1.1%, total N 0.07%; cation exchange capacity at pH 7 (CEC) 2.6 cmol kg^{-1} soil; Si 7.5%). This soil is typical of the alluvial area in Thua Thien Hue province, Central Vietnam. Biochar characteristics from rice husk and peanut shell were analyzed after preparation as follows (C: 46.3%, 43.7%; N: 0.42, 0.51%; P: 0.10, 0.14%; K: 1.6%, 2,0%; Si: 27.2%, 12.7%, respectively).

Practice management

To grow seedlings for pot transplantation, a rice variety (*Oryza sativa* L., HT1) often utilized in central Vietnam was sown in a nursery. Forty-four samples of 4 kg dry soil (11 treatments in 4 repetitions) were combined with fertilizers and biochar amendments in plastic bags. The following treatments were applied: 1 treatment with pure soil (control), 4 treatments with silicon and N–P–K fertilizers and 6 treatments with biochar amendments and N-P–K fertilizers. Silicon was added as silicamon (20% SiO_2) fertilizer in the treatments at five rates: 0, 30, 60, 90 and 120 mg SiO_2 kg^{-1} soil. The rate of biochar amendments from rice husk and peanut shell in the 6 treatments was 5, 10 and 15 g dry matter per kg soil. In all treatments, N (as urea), P (as superphosphate) and K (as KCl) were added at 100 mg N, 60 mg P_2O_5 (*i.e.*, 26.2 mg P kg^{-1} soil and 70 mg K_2O (*i.e.*, 58.1 mg K kg^{-1} soil). 100% of P, 50% N, 50% K and 100% Si were applied before rice transplanting as basal fertilization and the rest fertilizer was applied 10 days after rice transplanting.

Cylindrical pots 2 dm^2 in section and 20 cm in height with closed bottom (no drainage) distributed the soil–fertilizer amendment mixtures. The bulk soil density in the pots was about 1.5 kg dry soil dm^{-3}. Four hundred mL of water were added to each pot in successive fractions to reach approximate water content at field capacity (around 0.15 m^3 water m^{-3} soil). Before planting, the moistened pots were kept for a week to prevent any potential toxicity from the mineralization flush that occurs after rewetting dry soil and adding organic additives. After that, six 10-day-old rice plants that measured roughly 10 cm in height were moved into each pot and the water level was changed to 3 cm over the soil's surface. Two plants were taken out after seven days so that each container included four healthy, uniform plants. Using demineralized water, the water level was routinely readjusted to be 3 cm above the soil's surface (Sai *et al.*, 2022).

Data collection

Sixty days after transplanting, entire rice plants were taken out of the ground; at that point, the plants were still in the panicle initiation stage. Cuts were made right below the collar. The plant material was mopped with absorbent paper after the roots and shoot base was quickly shaken in water to remove any remaining dirt particles and the fresh weight was calculated right away. After that, the plants were stored and dried at 70°C to determine their dry biomass before examination. Si content in shoots was determined on finely ground subsamples using silicon-molybdenum blue colorimetry. Si uptake in shoots is calculated as follows:

$$\text{Si uptake} = \text{Si concentration/Plant (mg g}^{-1}) \times \text{above-ground biomass yield (g plant}^{-1}) \times 10$$

(Klotzbücher *et al.*, 2016)

Besides, fresh rice leaves were collected and enclosed in plastic self-sealing bags (28 cm × 20 cm) and then taken back to the laboratory of the University of Agriculture and Forestry, Hue University to measure leaf area by leaf area meter (CIC-202, America). Leaf area index (LAI) is defined as the one-sided green leaf area per unit ground surface area in broadleaf canopies (He *et al.,* 2020).

$$LAI = \frac{\text{Leaf area}}{\text{Ground area } (m^2\ m^{-2})}$$

Data analysis

Data was statistically analysed using Statistix 10.0 software. The software's analysis of variance (ANOVA) process ordered mean values using the Least Significant Difference (LSD) multiple range test, with significant differences being taken into account at $P_{0.05}$ and Standard deviation (SD).

RESULTS AND DISCUSSION

Leaf area and leaf area index

An increase in leaf area and leaf area index was observed with the increase of Si fertilizer, RHB and PSB rates (Table 1). The highest leaf area and leaf area index were found at a rate of 120 mg SiO_2 kg^{-1} soil application (29.57-33.83 cm^2 and 0.59-0.68 m^2 leaf m^{-2} soil, respectively). Among the two biochar types application, the highest leaf area and leaf area index were obtained at a rate of 15 g kg^{-1} soil application at RHB and higher than control from 7-10%. This result was in line with Pati *et al.* (2016) who reported an increase in growth parameters with the addition of Si fertilizer over the control. Cuong *et al.* (2017) mentioned that the deposition of Si in the cell wall can increase rice plant height by making the leaves and stems more erect, resulting in a decrease of mutual shading caused by the high density of the plant, thereby increasing the photosynthetic rate of the plant due to better light interception. The combined application of Si + biochar enhanced the leaf area by 13.78% and cob length by 14.64% (Sattar *et al.*, 2022).

Dry matter accumulation in rice shoots and roots

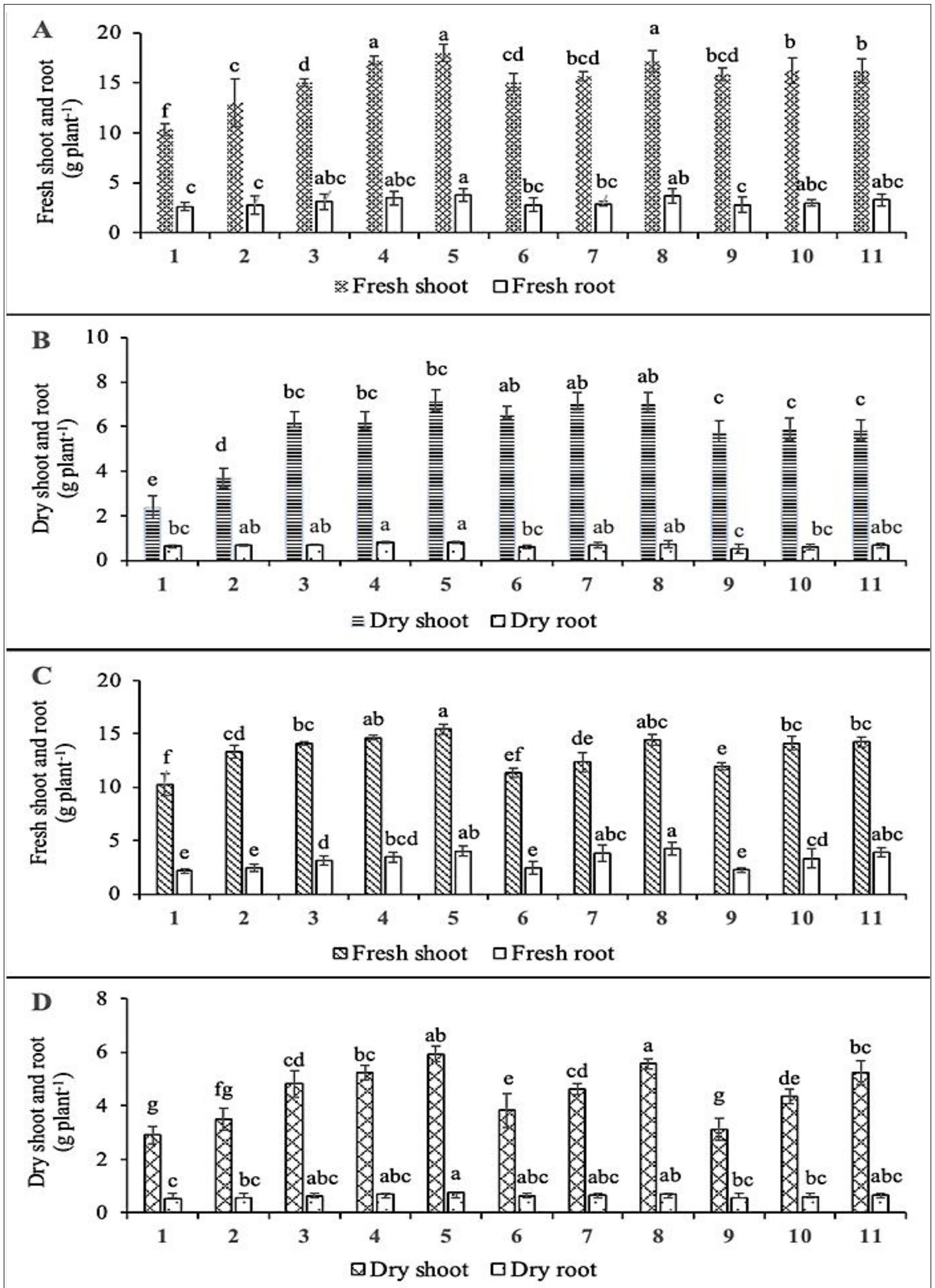
Fresh and dry matter in rice shoot and root were significantly affected by Si application both in fertilizer and biochar application (Fig 1). In the spring season, fresh shoot and root matter were increased by almost 42.5 and 30.5% under 120 mg SiO_2 kg^{-1} soil compared with the control. At 15 g kg^{-1} RHB and PSB application, fresh shoot and root matter obtained the highest values and increased 39.8 and 28.4% (RHB) and 36.2 and 20.1% (PSB) in comparison with control. Similarly, shoot dry matter increased from 35.6 to 66.7% compared with control in different rates of silicon fertilizer application. Shoot dry matter was also found the highest values in 15 g kg^{-1} application of RHB and PSB. In the dry season, fresh shoots and root matter ranged from 10.21 to 15.42 g kg^{-1} and 2.15 to 4.24 g kg^{-1}, respectively. Dry shoot matter was found to increase from 17.1 to 51.0% as compared with control. The highest dry shoot matter was also observed at a rate of 120 mg SiO_2 kg^{-1} soil application (5.94 g $plant^{-1}$), followed by a rate of 15 g kg^{-1} RHB application (5.57 g $plant^{-1}$). Numerous studies have demonstrated how Si can enhance plant growth and output (Farooq and Dietz, 2015; Cuong *et al.*, 2017; Swe *et al.*, 2021). According to Li *et al.* (2020), using Si could enhance rice straw's dry weight and vegetative growth parameter. Application of Si raised rice grain and straw dry weights by 24 and 30% above unamended soil at the rice reproductive stage (Limmer *et al.*, 2023). Silicon is an important nutrient that alleviates abiotic stress in plants by improving the physiochemical processes of the plant. In the current study, the interactive effect of Si and biochar improved crop productivity relative to the sole application of either Si or biochar. This interactive effect is attributed to improve in bioavailability of Si (Li *et al.,* 2019b) and are beneficial for crop productivity, thus increasing productivity.

Table 1: Rice leaf area and leaf area index in different crop seasons.

No.	Treatment	Spring season		Summer season	
	(mg SiO_2 kg^{-1} soil)	Leaf area (cm^2)	LAI (m^2 leaf m^{-2} soil)	Leaf area (cm^2)	LAI (m^2 leaf m^{-2} soil)
1	0 (control)	30.30^{d}±2.23	0.60^{d}±0.06	27.15^{b}±1.21	0.55^{b}±0.05
2	30	31.91^{bcd}±3.12	0.64^{bcd}±0.05	28.65^{ab}±1.32	0.57^{ab}±0.06
3	60	32.35^{bc}±2.45	0.65^{bc}±0.07	28.70^{ab}±1.38	0.57^{ab}±0.04
4	90	32.83^{ab}±2.89	0.65^{ab}±0.04	29.42^{ab}±1.45	0.59^{ab}±0.08
5	120	33.83^{a}±3.32	0.68^{a}±0.08	29.57^{a}±1.24	0.59^{a}±0.06
6	5 (RHB, g kg^{-1} soil)	31.52^{bcd}±1.87	0.61^{bcd}±0.04	29.41^{ab}±1.28	0.57^{ab}±0.05
7	10	31.91^{bcd}±1.54	0.64^{bcd}±0.05	29.29^{ab}±1.30	0.58^{ab}±0.04
8	15	32.70^{abc}±2.12	0.65^{abc}±0.05	29.78^{ab}±0.99	0.59^{ab}±0.07
9	5 (PSB, g kg^{-1} soil)	30.65^{d}±1.98	0.61^{d}±0.05	28.35^{ab}±0.87	0.57^{ab}±0.04
10	10	30.71^{d}±2.01	0.61^{d}±0.03	29.00^{ab}±1.02	0.58^{ab}±0.08
11	15	31.55^{bcd}±2.13	0.63^{bcd}±0.04	29.41^{ab}±1.19	0.58^{ab}±0.07
$LSD_{0.05}$		1.46	0.03	1.55	0.04

Different letters in a column indicate significant LSD differences between Si and biochar rates at α = 5%.

Data after ± indicates SD values.



A, B - spring season and C, D - summer season. Different letters in a column indicate significant LSD differences between Si and biochar rates at α = 5%, Bars are SD values.

Fig 1: Fresh and dry matter in rice shoot and root in different crop seasons.

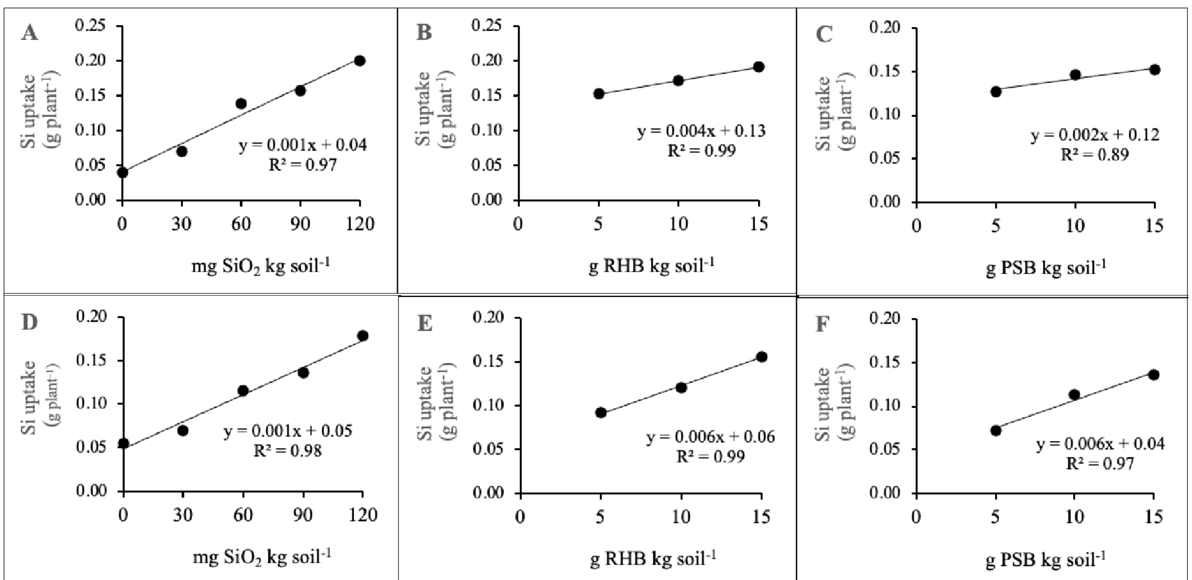
Si uptake

Different Si and biochar rates had a significant effect (*P*<0.05) on Si uptake by rice shoots (Table 2). The absorption and accumulation of Si in rice shoots rose with a higher rate of Si and biochar, which in turn increased total biomass. All rates of Si and biochar treatment had a substantial impact on rice shoot Si uptake when compared to the control; however, there was no statistically significant difference between the various forms of biochar application. Greater uptake of Si (0.18–0.20 g plant^{-1}) when the highest rate of Si fertilizer was applied as opposed to the control and the other lower rates of additional Si. Si accumulations in the shoot differed considerably (P<0.05) from the control at all biochar dosages. In both seasons, a strong positive linear connection (R^2 = 0.89 - 0.99) between Si uptake and varying rates of Si fertilizer and biochar treatment was seen (Fig 2 A-F). It has been suggested that monocotyledons in general

Table 2: Shoot Si concentration and Si uptake in rice at different crop seasons.

No.	Treatment ($mg\ SiO_2\ kg^{-1}$ soil)	Spring season			Summer season		
		Shoot DM ($g\ plant^{-1}$)	Shoot Si content ($mg\ g^{-1}$)	Shoot Si uptake ($g\ plant^{-1}$)	Shoot DM ($g\ plant^{-1}$)	Shoot Si content ($mg\ g^{-1}$)	Shoot Si uptake ($g\ plant^{-1}$)
1	0 (control)	2.39^{e}±0.32	17.1^{f}±1.0	0.04^{e}±0.01	2.91^{g}±0.51	19.2^{e}±1.7	0.06^{e}±0.01
2	30	3.71^{d}±0.41	19.3^{ef}±1.0	0.07^{e}±0.02	3.51^{fg}±0.42	20.4^{de}±3.6	0.07^{e}±0.01
3	60	6.32^{bc}±0.50	22.4^{de}±1.7	0.14^{cd}±0.03	4.82^{cd}±0.36	24.4^{c}±1.7	0.12^{c}±0.03
4	90	6.29^{bc}±0.28	25.2^{a-d}±2.0	0.16^{bc}±0.05	5.24^{bc}±0.38	26.5^{bc}±2.5	0.14^{b}±0.02
5	120	7.18^{bc}±0.28	22.8^{a}±1.7	0.20^{ab}±0.04	5.94^{ab}±0.48	30.3^{a}±4.1	0.18^{a}±0.05
6	5 (RHB, $g\ kg^{-1}$ soil)	6.64^{ab}±0.63	23.5^{cd}±1.7	0.12^{bcd}±0.02	3.83^{ef}±0.27	24.7^{c}±0.4	0.09^{d}±0.02
7	10	7.13^{a}±0.21	24.8^{bcd}±1.0	0.17^{ab}±0.03	4.62^{cd}±0.39	26.5^{bc}±1.1	0.13^{bc}±0.04
8	15	7.11^{a}±0.20	27.1^{ab}±1.0	0.19^{a}±0.04	5.57^{a}±0.42	28.4^{ab}±2.2	0.14^{b}±0.03
9	5 (PSB, $g\ kg^{-1}$ soil)	5.79^{c}±0.40	22.4^{de}±2.0	0.13^{d}±0.02	3.12^{g}±0.47	23.7^{cd}±2.1	0.07^{e}±0.01
10	10	5.88^{c}±0.27	25,6^{a-d}±	0.15^{bcd}±0.04	4.35^{de}±0.49	26.4^{bc}±2.9	0.11^{c}±0.02
11	15	5.84^{c}±0.44	26.3^{abc}±	0.16^{bcd}±0.02	5.24^{bc}±0.45	26.6^{bc}±1.2	0.12^{b}±0.03
	$LSD_{0.05}$	0.67	3.51	0.03	0.68	0.32	0.02

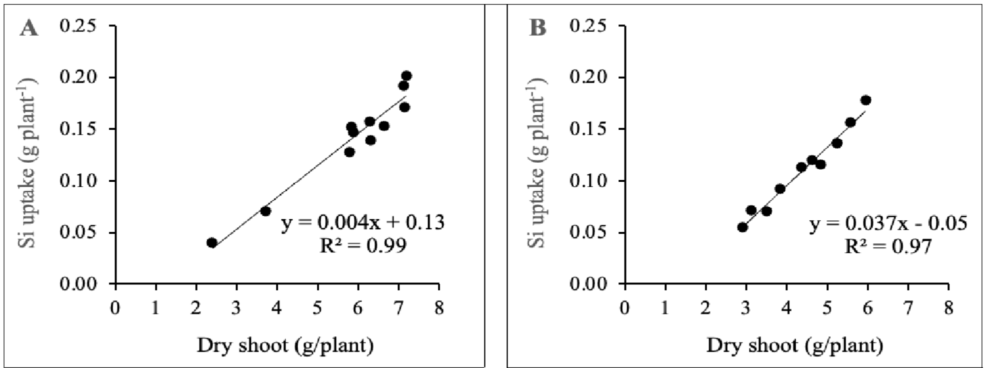
Different letters in a column indicate significant LSD differences between Si and biochar rates at α = 5%. Data after ± indicates SD values, (DM: Dry matter; RHB: Rice husk biochar; PSB: Peanut shell biochar).



A, B, C - Spring season; D, E, F- Summer season.

Fig 2: Relationship between different rate of Si fertilizer and biochar application and shoot Si uptake.

and Poaceae plants like rice in particular benefit from an increased supply of Si (Wang *et al.*, 2020). Si can be absorbed by rice both actively and passively, although the uptake can be greatly inhibited by low temperatures or metabolic inhibitors (Sun *et al.*, 2016). The present findings are consistent with prior investigations since there was a significant positive linear correlation (P<0.05) between the quantity of Si applied and the amount of Si absorption in above-ground (R^2 = 0.97 - 0.98) (Fig 2A, D). Moreover, the interaction of biochar with Si is also important as biochar increases the pH of the soil (Kim *et al.*, 2018) and higher pH facilitates the uptake of Si (Sirisuntornlak *et al.*, 2021). Applying Si fertilizer may increase the amount of silicon available in the soil and strengthen the root system, which may encourage the plant to take up more silicon from the soil solution (Pati *et al.*, 2016). This study was also found that there was very high correlation between shoot dry matter and shoot Si uptake in rice crop (R^2 = 0.97 - 0.99) (Fig 3A-B). The overall uptake of Si was much enhanced by the administration of silicon fertilizer (Swe *et al.*, 2021). Biochar prepared from Si-accumulator crops, such as rice and wheat straws, may contain higher concentrations of phytolith Si that might be a potential source of available Si for plants (Rizwan *et al.*, 2019). The content of Si in wheat shoots was elevated by rice straw biochar (Abbas *et al.*, 2017).



A- Spring season; B- Summer season.

Fig 3: Relationship between shoot dry matter and shoot Si uptake.

Si concentrations in rice were raised by applying biochar made from wheat straw and rice husks (Patil *et al.*, 2018) and biomass differed ($P<0.05$) from the control values. Silicon-enriched biochar is more effective than medium and low Si biochar in increasing the availability of Si in soil, which translated to increased Si uptake by rice and improved yield and biomass of rice (Ratnadass *et al.*, 2024).

CONCLUSION

The accumulation of dry matter and Si uptake in rice shoots were impacted by the application of Si fertilizer and biochar from crop residues. The highest dry matter and Si uptake in rice shoot was obtained at the rate of 120 mg SiO_2 kg^{-1} soil and 15 g kg^{-1} soil of RHB and PSB. Therefore, RHB and PSB are considered as sources for providing potential available Si for rice crop. The optimal Si rates from fertilizer and Si-rich biochar can be included in the general fertilizer recommendation for paddy rice cultivation. Further research will be conducted in real field conditions.

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Conflict of interest

All authors declared that there is no conflict of interest.

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