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Impact of silicon-rich rice husk biochar on nitrogen use efficiency in nitrogen- deficient soils with contrasting pH

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Article

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Abstract

Silicon (Si) enhances plant resilience under stress, where nitrogen (N) is one of the major essential nutrient elements for improving crop growth and yield. This study aimed to assess the influence of Si-rich rice husk biochar (RHB) on nitrogen use efficiency (NUE) in three N-deficient soils with varying pH by using maize (*Zea mays* L.) as a test crop. A pot experiment was conducted with three N sources (*i.e.*, urea, KNO_3 and NH_4Cl as amide, nitrate and ammonical form, respectively) along with four RHB levels (0, 2, 4 and 8 t ha^{-1}). Compared with other N sources, the application of KNO_3 significantly increased plant height and biomass compared with other N sources. Increasing RHB rates further enhanced these growth parameters across all the soils. However, the combined application of RHB and N sources reduced the plant N concentration, while markedly improving N uptake, Si content and uptake. Pearson's correlation analysis revealed a strong positive relationship between silicon accumulation efficiency (SiAE) and NUE ($r = 0.95–0.99$, $p < 0.05$). These findings indicate that integrating Si-rich RHB with suitable N sources enhances nitrogen utilization and crop performance in N-deficient soils. This approach presents a sustainable strategy for improving soil fertility, nutrient cycling and crop productivity under varying soil pH conditions.

Introduction

Nitrogen (N) is one of the most important essential elements for plant growth and is required in relatively large quantities by plants[1]. It is crucial in enhancing crop productivity. Grass crops, such as rice (*Oryza sativa*), maize (*Zea mays* L.) and wheat (*Triticum aestivum)* consume approximately 50 per cent of all N-based fertilizers produced[2]. In Indian soils, nitrogen deficiency is widespread; 99 per cent of soils respond to N addition[3]. In recent times, due to the application of excessive and less efficient N fertilizers in nitrogen-deficient soils, N losses have become evident[4]. This can result in serious ecological problems such as soil acidification, eutrophication of water bodies and greenhouse gas emissions[5]. The increased application of N fertilizers to soils is also a major cause of groundwater pollution, resulting in severe health problems such as methemoglobinemia (blue baby syndrome). In addition to ecological threats, excessive N application leads to an increase in the cost of production for the farmers. Management practices that improve N use efficiency (NUE) are therefore needed to ensure that crop productivity is maximized while reducing the environmental impacts resulting from excessive N application and by enhancing N fertilizer use efficiency in N-deficient soils.

Silicon (Si) is the second-most abundant element after oxygen. The potential of Si for improving crop yield has been demonstrated in many studies, especially under abiotic (drought, heavy metal and salinity) and biotic stress conditions (pathogens)[6,7]. Si is well known for its ability to reduce the harmful effects of stress on a variety of plant species. Si has significant beneficial effects, particularly when the plant is experiencing biotic and abiotic stress[7,8]. It enhances the plants' resistance to diseases and pest attacks; alleviates lodging, water and climatic stress; and improves water and nutrient use efficiency. It has been reported that few crops (sugarcane, rice, wheat and maize) can absorb Si quickly and in great

quantity[9]. According to previous reports, Si-based fertilizers enhance NUE by increasing plant growth and N absorption in various crops[10,11].

For the last decade, the conversion of crop residues into biochar and its incorporation into agricultural soils have been encouraged to improve soil fertility in the context of mitigating climate change[12]. The quantity of rice husk per kg of harvested paddy ranges from 20 to 30 per cent of the total weight of the crop. Nearly 137 million tonnes of rice husk are produced annually across the world[13] and most of it is burnt as fuel in rice processing mills, which is not an eco-friendly practice. This can be avoided by converting rice husk into biochar. Biochars prepared from rice husk contain nearly 30 per cent silica and can be used as Si-based fertilizer.

The objective of this study was to evaluate how Si-rich RHB regulates uptake and use efficiency of N across contrasting soil pH under N-deprived conditions. To achieve this objective, a pot experiment was conducted with three N-deficient soils varying in pH (acidic, neutral and alkaline) and only 50 per cent of the recommended dose of N was applied to induce stress (N starvation) in the maize plants.

Results and discussion

Effect of Si-rich RHB and different sources of N on plant height and plant dry biomass of maize in different soils

The application of various nitrogen (N) sources had a significant effect on maize plant height across all the soils (Table 1). Application of KNO_3 as an N source recorded higher plant height in all soils and was found to be on par with the application of urea as an N source. This response may be attributed to the higher assimilation efficiency of nitrate-N by maize plants, which promotes vigorous vegetative growth and improved nitrogen use efficiency. Similar results have been reported in previous studies, where nitrate-based fertilizers were found to enhance maize growth and nutrient uptake more effectively than ammonium-based sources[14,15]. In contrast, NH_4Cl application resulted in lower plant height in all three soils, corroborating earlier findings that maize exhibits superior growth with nitrate-based N sources compared to urea or ammonium sulphate[16].

Table 1

Effect of rice husk biochar (RHB) and different sources of N on maize plant height and plant dry biomass in different soils. Values represent means of three replications ± standard error. Mean values marked with same letters do not differ significantly according to the Fisher's LSD test at $p \leq 0.05$.

Treatments	Plant height (cm)			Plant dry biomass (g pot^{-1})		
	Acidic soil	Neutral soil	Alkaline soil	Acidic soil	Neutral soil	Alkaline soil
Nitrogen sources						
Urea	51.27 ± 1.25^{a}	63.40 ± 0.99^{a}	54.63 ± 1.51^{a}	7.17 ± 0.32^{a}	8.90 ± 0.26^{b}	7.71 ± 0.26^{b}
KNO_3	51.53 ± 1.23^{a}	64.17 ± 0.85^{a}	54.78 ± 1.14^{a}	7.48 ± 0.21^{a}	9.69 ± 0.22^{a}	8.65 ± 0.24^{a}
NH_4Cl	47.64 ± 1.04^{b}	60.74 ± 0.87^{b}	43.38 ± 1.52^{b}	6.80 ± 0.27^{a}	8.18 ± 0.27^{c}	7.90 ± 0.26^{b}
Biochar levels						
0 t ha^{-1}	48.32 ± 1.35^{b}	61.59 ± 1.00^{b}	50.64 ± 1.62^{a}	6.64 ± 0.27^{b}	8.54 ± 0.37^{b}	7.21 ± 0.25^{b}
2 t ha^{-1}	49.50 ± 1.83^{ab}	63.19 ± 0.71^{ab}	51.20 ± 2.27^{a}	7.26 ± 0.32^{ab}	8.72 ± 0.28^{b}	8.09 ± 0.30^{a}
4 t ha^{-1}	52.20 ± 1.12^{a}	65.32 ± 1.04^{a}	55.08 ± 2.31^{a}	7.75 ± 0.36^{a}	9.77 ± 0.31^{a}	8.77 ± 0.29^{a}
8 t ha^{-1}	50.57 ± 1.23^{ab}	60.98 ± 1.26^{b}	52.12 ± 1.49^{a}	6.94 ± 0.21^{ab}	8.67 ± 0.31^{b}	8.25 ± 0.25^{a}

Increasing the application rate of RHB enhanced plant height significantly in neutral soil and marginally in acidic and alkaline soils. Regardless of the soil type, application of RHB @ 4 t ha^{-1} recorded higher plant height. Furthermore, the application of RHB @ 8 t ha^{-1} decreased the plant height in all the soils. The positive response at moderate rates (2–4 t ha^{-1}) may be due to the silicon-rich nature of RHB, which can improve plant growth and yield through enhanced nutrient availability and stress mitigation[17,18,19].

Plant dry biomass followed a similar pattern (Table 1). KNO_3 application resulted in higher shoot biomass in neutral soil, followed by alkaline and acidic soils. Biochar application significantly increased biomass in neutral and alkaline soils, with 4 t ha^{-1} RHB resulting in higher biomass. The improvement in shoot biomass following biochar addition can be attributed to several concurrent mechanisms, including a reduction in soluble aluminium and iron toxicity, an increase in soil pH, balanced and slow nutrient release, increased availability of plant-available water and stimulation of beneficial microbial activity.

Such improvements in soil physicochemical and biological properties in biochar-amended systems have been widely reported[20,21].

Although the interaction effect between N sources and RHB application rates was statistically insignificant for plant height in acidic soil (Supplementary Table S1), a significant interaction effect was observed for plant biomass. This suggests that, compared with the individual treatments, the combined application consistently enhanced plant height and biomass, indicating a synergistic effect between Si-rich RHB and N fertilization[22,23].

Effect of Si-rich RHB and different sources of N on total plant N content and N uptake

A significant effect of N sources on both total plant N concentration and uptake was observed across all soils (Table 2). Among the N sources, application of KNO_3 consistently resulted in higher N content in all soils compared to other N sources. Nitrogen uptake was also higher under KNO_3 compared with urea or NH_4Cl, especially under Si-amended conditions, indicating preferential nitrate acquisition in maize. Nitrate from KNO_3 is readily available, efficiently absorbed via inducible transporters and acts as a signal promoting root growth and nutrient uptake[24,25]. Silicon further enhances nitrate assimilation by improving nitrate reductase activity, photosynthesis, redox balance and transcriptional up-regulation of genes involved in N uptake[25]. In a similar study, addition of Si resulted in up-regulation of nitrate transporter genes (BnaNTR2.1 and BnaNTR1.1) in rapeseed (*Brassica napus*) to cope with nitrogen-limited condition[26]. In contrast, urea requires microbial transformation, causing delays and losses, while NH_4Cl can induce rhizosphere acidification and metabolic stress due to the high energy cost of ammonium assimilation[27].

Table 2
Effect of rice husk biochar (RHB) and different sources of N on total plant nitrogen content and N uptake in different soils. Values represent means of three replications ± standard error. Mean values marked with same letters do not differ significantly according to the Fisher's LSD test at $p \leq 0.05$.

Treatments	N content (%)			N uptake (mg pot^{-1})		
	Acidic soil	Neutral soil	Alkaline soil	Acidic soil	Neutral soil	Alkaline soil
Nitrogen sources						
Urea	1.42 ± 0.03^{b}	1.78 ± 0.02^{b}	1.48 ± 0.03^{a}	101.96 ± 5.27^{a}	162.81 ± 4.71^{a}	117.58 ± 3.59^{b}
KNO_3	1.45 ± 0.02^{a}	1.91 ± 0.02^{a}	1.50 ± 0.04^{a}	108.16 ± 2.78^{a}	169.73 ± 4.18^{a}	129.25 ± 3.64^{a}
NH_4Cl	1.01 ± 0.02^{c}	1.68 ± 0.03^{c}	1.44 ± 0.03^{a}	68.52 ± 2.77^{b}	145.33 ± 4.72^{b}	113.29 ± 3.32^{b}
Biochar levels						
0 t ha^{-1}	1.40 ± 0.08^{a}	1.88 ± 0.03^{a}	1.62 ± 0.02^{a}	93.49 ± 7.28^{b}	146.93 ± 6.97^{a}	116.94 ± 4.82^{a}
2 t ha^{-1}	1.33 ± 0.07^{b}	1.82 ± 0.03^{b}	1.54 ± 0.01^{b}	96.67 ± 6.68^{a}	158.39 ± 4.56^{ab}	124.46 ± 5.08^{a}
4 t ha^{-1}	1.29 ± 0.07^{c}	1.76 ± 0.04^{c}	1.42 ± 0.02^{c}	100.02 ± 8.17^{a}	171.29 ± 4.65^{a}	124.91 ± 3.99^{a}
8 t ha^{-1}	1.16 ± 0.07^{d}	1.69 ± 0.04^{d}	1.32 ± 0.04^{c}	81.35 ± 6.45^{a}	160.54 ± 6.14^{a}	113.85 ± 3.28^{a}

The application of RHB markedly impacted both N concentration and uptake across all soils. Irrespective of soils, higher N content was recorded in the treatments receiving 2 t ha^{-1} of RHB. However, higher uptake of N was observed with 4 t ha^{-1} of RHB. Increasing RHB application rates led to a progressive decline in total plant nitrogen content. This decline may be associated with reduced inorganic N availability due to enhanced N immobilization and adsorption by biochar[28], a process further intensified by the elevated soil C:N ratio following biochar addition[29]. Additionally, the dilution of N concentration resulting from greater biomass accumulation under biochar treatments might have contributed to the observed reduction in tissue N levels[30].

Conversely, N uptake exhibited a different response pattern to biochar addition (Table 2). Application of RHB (2–4 t ha^{-1}) significantly increased N uptake across the soils. This positive response could be attributed to improved soil properties such as enhanced moisture retention, pH stabilization and increased N mineralization and nitrification, all of which facilitate N availability and uptake by plants[31,32].

Furthermore, biochar's capacity to decrease N leaching losses enhances N retention and contributes to greater plant N assimilation[33]. Silicon also enhances the N uptake by improving N availability through up-regulation of nitrate transport genes[25,26]. Enhanced N uptake under limited or low N availability with Si supplementation has been reported in rice[34], cowpea[35] and maize[36]. However, a further increase in RHB rate (8 t ha^{-1}) reduced N uptake in all soils, which could be correlated to the reduction in biomass production with the higher dose of RHB.

The interaction between N sources and RHB rates significantly influenced the nitrogen content and uptake in all the soils (*Supplementary Table S2*). This demonstrates the synergistic effect of N sources and optimal RHB levels. This synergism can also be linked to improved yield performance and nutrient utilization efficiency under varying soil conditions. The silicon-rich nature of RHB (30.16% Si) may have further contributed to enhanced N acquisition, as silicon supplementation is known to stimulate root activity and improve N uptake efficiency in plants. Similar synergistic effects between silicon-rich biochar and N fertilization have been reported in maize and other cereal systems[37,38], underscoring the importance of integrated nutrient management strategies for optimizing crop performance.

Effect of Si-rich RHB and different sources of N on total plant Si content and Si uptake

Application of various N sources exerted a significant influence on total plant Si content and its uptake across all the soils (Table 3). Among the N sources, application of KNO_3 recorded significantly higher total plant Si content. This suggests that the form of nitrogen markedly affects Si accumulation in plants. The enhancement under KNO_3 application may be attributed to the alkalinizing effect of nitrate ions in the rhizosphere, which promotes Si mobilization and solubility, thereby promoting greater availability of Si. Similar findings have been reported in previous studies demonstrating that nitrate-based fertilizers can influence rhizosphere pH and enhance the availability of silicic acid for plant absorption[39,40].

Table 3
Effect of RHB and different sources of N on silicon (Si) content and uptake by maize in three different soils. Values represent means of three replications ± standard error. Mean values marked with same letters do not differ significantly according to the Fisher's LSD test at $p \leq 0.05$.

Treatments	Si content (%)			Si uptake (mg pot^{-1})		
	Acidic soil	Neutral soil	Alkaline soil	Acidic soil	Neutral soil	Alkaline soil
Nitrogen sources						
Urea	1.11 ± 0.01[b]	1.49 ± 0.05[b]	1.61 ± 0.04[b]	79.31 ± 3.70[b]	130.45 ± 7.44[b]	127.54 ± 7.42[b]
KNO_3	1.26 ± 0.03[a]	1.57 ± 0.04[a]	1.80 ± 0.04[a]	94.40 ± 4.26[a]	152.25 ± 4.69[a]	152.46 ± 6.79[a]
NH_4Cl	1.01 ± 0.04[c]	1.46 ± 0.06[b]	1.39 ± 0.07[c]	69.07 ± 4.29[c]	118.90 ± 6.19[c]	110.99 ± 7.70[c]
Biochar levels						
0 t ha^{-1}	1.01 ± 0.04[d]	1.27 ± 0.03[c]	1.36 ± 0.08[d]	67.22 ± 4.74[b]	109.26 ± 6.73[c]	99.42 ± 7.82[c]
2 t ha^{-1}	1.06 ± 0.03[c]	1.51 ± 0.02[b]	1.57 ± 0.07[c]	77.16 ± 4.55[b]	129.13 ± 5.98[b]	123.55 ± 7.34[b]
4 t ha^{-1}	1.18 ± 0.04[b]	1.58 ± 0.05[b]	1.68 ± 0.03[b]	91.66 ± 5.19[a]	152.39 ± 7.14[a]	146.96 ± 7.25[a]
8 t ha^{-1}	1.26 ± 0.04[a]	1.67 ± 0.02[a]	1.79 ± 0.06[a]	87.66 ± 5.55[a]	144.69 ± 6.31[a]	151.39 ± 7.54[a]

The addition of RHB progressively improved the total Si content across the soils. This improvement can be linked to the higher release of soluble Si from the Si-rich RHB addition[41]. Across all treatments, plants grown in alkaline soil resulted in higher total Si content, consistent with the higher solubility of monosilicic acid and enhanced Si bioavailability at elevated pH levels[19,42]. Notably, the interaction between N source and RHB rate was significant in all the soils, indicating a synergistic response of Si uptake to both N form and soil pH. This finding implies that soil chemical environment and nutrient form collectively regulate Si dynamics and plant accumulation[43].

Application of KNO_3 resulted in higher Si uptake by maize plants across the soils (Table 3). This enhanced Si uptake may be attributed to increased plant biomass associated with KNO_3 application. Increasing RHB rates significantly enhanced Si uptake by maize plants across the soils studied. This is likely due to the increased pool of plant-available Si released from RHB[19,42]. The interaction between N sources and RHB levels was found to be statistically significant for Si uptake (*Supplementary Table S3*).

The overall Si acquisition remained consistently greater in alkaline soils, underscoring the pivotal role of soil pH in regulating Si solubility and bioavailability.

Effect of Si-rich RHB and different sources of N on NAE, SiAE and NUE

Application of various N sources had a significant effect on nitrogen accumulation efficiency (NAE) in all three soils (Fig. 1). Higher NAE was recorded with the application of KNO_3 as an N source in acidic soil, neutral soil and alkaline soils. This enhancement can be attributed to the rapid uptake and higher mobility of NO_3^-–N within the plant–soil system, facilitated by mass flow transport processes. Similar findings have been reported previously, indicating that nitrate-based fertilizers enhance N transport efficiency and assimilation in maize compared with ammonium-based sources[15]. Even Si addition also favours N uptake in the form of NO_3^--N through the up-regulation of nitrate transport genes[24,25,26]. SiAE also greatly varied with the application of various N sources (Fig. 2). Among the N sources, addition of KNO_3 as an N source recorded higher SiAE in alkaline soil, followed by neutral and acidic soil. The improvement observed with KNO_3 application can be attributed to the alkalinizing effect of nitrate ions in the rhizosphere, which enhances Si mobilization and solubility, leading to increased Si uptake by plant roots[39,40]. Application of increasing rates of RHB, significantly increased the SiAE in the all soils. In contrast, NAE decreased with the application of graded levels of RHB. This reduction may be due to the immobilization of N within biochar-amended soils[28,29] and the physiological trade-off between Si uptake and N accumulation[44].

Nitrogen use efficiency varied with soil pH and N form (Fig. 3). Among the three N sources, the application of NH_4Cl recorded higher NUE in acidic soil followed by alkaline and neutral soils. However, application KNO_3 as N source, resulted higher NUE in neutral soil. In low pH soils, ammonium nutrition improves NUE due to lower energetic costs of direct assimilation and reduced N losses. Whereas in neutral soil, optimal nitrification, stable rhizosphere pH and efficient nitrate reduction favour nitrate-based nutrition. Consequently, KNO_3 optimizes both N uptake and utilization under neutral soil pH, while NH_4Cl enhances NUE primarily under acidic and alkaline soil pH[45,24,25]. On the other hand, the addition of increasing rates of RHB, significantly increased the NUE in acidic, neutral and alkaline soils. This could be attributed to the enhanced biomass production with application of RHB[18,19].

Correlation analysis (Table 4) revealed a strong negative correlation between SiAE and NAE ($r = -0.92$ to -0.99, $p < 0.05$) and a positive correlation between SiAE and NUE ($r = 0.95$ to 0.99, $p < 0.05$) across the soils. The inverse relationship between NAE and SiAE suggests that enhanced Si uptake reduced N accumulation in maize plants[44]. Since RHB is inherently rich in bioavailable silicon, its application likely increased Si uptake, thereby lowering NAE[46,47].

Table 4

Pearson correlation coefficients between silicon agronomic efficiency (SiAE), nitrogen agronomic efficiency (NAE) and nitrogen use efficiency (NUE) in maize under different nitrogen sources across soils. Significant correlations ($p \leq 0.05$) indicate strong interrelationships among SiAE, NAE and NUE in response to varying soil conditions and nitrogen sources. SiAE – Silicon accumulation efficiency, NAE – Nitrogen accumulation efficiency, NUE – Nitrogen use efficiency.

Soil Type	N source	SiAE vs NAE		SiAE vs NUE	
		Pearson's r value	p value	Pearson's r value	p value
Acidic soil	Without N	-0.962	0.038	0.954	0.046
	Urea	-0.983	0.017	0.973	0.027
	KNO_3	-0.971	0.029	0.960	0.040
	NH_4Cl	-0.917	0.083	0.902	0.098
Neutral soil	Without N	-0.962	0.038	0.952	0.048
	Urea	-0.954	0.046	0.954	0.046
	KNO_3	-0.962	0.038	0.939	0.061
	NH_4Cl	-0.918	0.082	0.894	0.106
Alkaline soil	Without N	-0.998	0.002	0.999	0.001
	Urea	-0.779	0.221	0.761	0.239
	KNO_3	-0.985	0.015	0.989	0.011
	NH_4Cl	-0.930	0.070	0.902	0.098

The positive correlation between SiAE and NUE (Table 4) indicates that increased Si accumulation in maize plants upon the addition of RHB might have increased the plant biomass by reducing the nitrogen demand (reduced NAE) by maize[48,49]. Reduced N demand by maize upon addition of Si-rich biochar indicates the enhancement in bioavailability (higher NUE) of N for maize[50]. This reveals that the application of Si-rich RHB improved the nitrogen use efficiency in nitrogen-deficient soils by enhancing the growth and yield of the maize crop.

Conclusions

The combined application of silicon-rich RHB with different N sources significantly improved maize growth, as reflected in increased plant height and biomass. Among the N sources, KNO_3 recorded the highest growth performance, while RHB at 4 t ha^{-1} consistently enhanced growth parameters. Although

plant N concentration and NAE slightly declined, combined application of RHB and N sources markedly increased N uptake, Si content, Si uptake, SiAE and NUE, indicating improved N acquisition and physiological efficiency. NH_4Cl resulted in the highest NUE across soil types, demonstrating strong compatibility with RHB for efficient N management. Notably, acidic soil with lower N availability exhibited the greatest NUE, highlighting the benefits of RHB under N-deficient conditions. This study confirms the effectiveness of Si-rich RHB in enhancing nutrient efficiency and crop productivity, offering a sustainable strategy for improving soil fertility and reducing N losses in diverse soil conditions.

Materials and methods

Soils

Three distinct soils differing in soil reaction were collected from Hassan, Mandya and Chamarajanagara, representing the Southern Dry Zone of Karnataka, India. The soil from Hassan was characterized as acidic (pH 4.62) with a sandy clay loam texture and an average annual rainfall of 806 mm. The Mandya soil was neutral (pH 7.25), also with a sandy clay loam texture and received an average annual rainfall of 713 mm. The soil from Chamarajanagara was alkaline (pH 8.32) with a sandy clay texture and an average annual rainfall of 812 mm. All soil samples were air-dried, gently ground and sieved through a 2 mm mesh. The physicochemical properties of these soils are presented in Table 5.

Table 5
Physico-chemical properties of acidic, neutral and alkaline soil. Each value represents the mean value of three replications.

Parameters		**Acidic soil**	**Neutral soil**	**Alkaline soil**
Location		Hassan	Mandya	Chamarajnagara
pH (1: 2.5)		4.62	7.25	8.32
EC (dS m^{-1}) (1: 2.5)		0.21	0.34	3.09
Organic matter (g kg^{-1})		8.30	11.30	10.90
CEC [cmol (p^+) kg^{-1}]		7.83	15.70	31.34
Particle size distribution	Sand (%)	65.42	53.83	47.34
	Silt (%)	8.79	16.92	6.48
	Clay (%)	25.79	29.25	46.17
Textural class		Sandy clay loam	Sandy clay loam	Sandy clay
MWHC (%)		37.60	50.37	55.26
Available N (kg ha^{-1})		188.53	171.73	152.8
NH_4^+-N (mg kg^{-1})		32.6	27.0	20.5
NO_3^--N (mg kg^{-1})		27.0	12.1	9.33
Available P_2O_5 (kg ha^{-1})		199.32	171.02	229.18
Available K_2O (kg ha^{-1})		171.07	408.92	682.17
Exch. Ca [cmol (p^+) kg^{-1}]		2.32	5.63	12.57
Exch. Mg [cmol (p^+) kg^{-1}]		1.48	2.28	11.39
Available sulphur (mg kg^{-1})		35.25	58.00	61.32
0.5 M Acetic acid Si (mg kg^{-1})		5.01	93.34	82.81
0.01 M $CaCl_2$ Si (mg kg^{-1})		15.53	36.32	34.05
DTPA extractable Fe (mg kg^{-1})		13.32	10.54	39.25
DTPA extractable Mn (mg kg^{-1})		12.76	8.68	21.38
DTPA extractable Zn (mg kg^{-1})		0.48	0.87	2.76

Parameters	Acidic soil	Neutral soil	Alkaline soil
DTPA extractable Cu (mg kg^{-1})	1.41	0.51	4.27

Production and Characterization of rice husk biochar (RHB)

Rice husk biochar (RHB) used in this study was produced at a relatively lower temperature (around 400°C) using a hallow-drum pyrolizer[18]. RHB was processed by sieving it through a 0.2 mm sieve. RHB was finely powdered and sieved using a 0.2 mm sieve and three replicate samples were combusted at about 950°C in CNS analyser for estimation of total contents of N, C and sulphur (S) (Dry Combustion, CNS, LECO). Acid-digested biochar samples were used to quantify the total nutrient content using atomic absorption spectrophotometer (Perkin-Elmer AAnalyst 700 AAS)[51]. The physicochemical properties and nutrient composition of RHB were measured and presented in Table 6.

Table 6
Physico-chemical properties and nutrient content of rice husk biochar. Each value represents the mean value of three replications.

	Rice husk biochar
Physical properties	
Bulk density (g cm^{-3})	0.49
Particle density (g cm^{-3})	1.80
Porosity (%)	72.68
MWHC (%)	125.67
Chemical properties	
pH (1:5)	7.44
Eelectrical conductivity (1:5) (dS m^{-1})	1.86
Cation exchange capacity [cmol (p^{+}) kg^{-1}]	41.24
Calcium carbonate equivalent (%)	30.12
Nutrient content	
Carbon (%)	39.83
Nitrogen (%)	0.63
Phosphorus (%)	0.22
Potassium (%)	0.89
Calcium (%)	0.34
Magnesium (%)	0.30
Sulphur (%)	0.05
Sodium (%)	0.05
Zinc (mg kg^{-1})	63.10
Copper (mg kg^{-1})	31.23
Manganese (mg kg^{-1})	557.34
Iron (mg kg^{-1})	773.30
Boron (mg kg^{-1})	8.13

	Rice husk biochar
Physical properties	
Silicon (%)	30.16

Pot culture experiment with maize plants

A pot culture experiment was conducted with maize as a test crop in three different soils (acidic, neutral and alkaline). Two kilograms of different soils were filled in separate plastic pots with graded levels of biochar (0, 2, 4, 8 t ha^{-1}). Phosphorus (P) and potassium (K) were applied as per RDF (*i.e.*, 75 kg each of P_2O_5 & K_2O ha^{-1}) and 50 per cent of the RDF nitrogen (*i.e.*, 75 kg N ha^{-1}) was applied through urea, KNO_3 and NH_4Cl as per the treatments. P and K were applied through KH_2PO_4 and KCl. After thorough mixing of all the inputs in the pot, distilled water was added to maintain 60 per cent of the maximum water holding capacity (MWHC) of the soil and left in the greenhouse conditions for one week. After that, four seeds of maize (DKC-9053) were sown in all the pots and later thinned to two seedlings per pot. The experiment consisted of 16 treatments replicated thrice. Moisture content was maintained at 60 per cent of MWHC by weighing the pots periodically and weight loss due to evaporation was taken care with adding distilled water. After 6 weeks of sowing, shoot parts were harvested.

Plant sampling and analysis

After harvesting the crop, plant samples were collected from each pot and oven dried at 60°C until attaining a constant weight. After drying, plant samples were powdered and used for analysis. Powdered plant sample (0.5 g) was predigested with 10 ml H_2SO_4 and digestion mixture in Kjeldahl tubes and later digested using Gerhardt digestion unit. Digested plant samples were analyzed for total N content by using Kjeldahl distillation unit. For silicon, plant shoot samples were pre-digested with 7 ml HNO_3 (70%), 2 ml H_2O_2 (30%) and 1 ml HF (40%) and later digested using a microwave digester and digested samples diluted to 50 ml using 4% boric acid. Content of silicon in digested plant shoot samples was determined by the colorimetric molybdenum blue method at 600 nm[52] using UV-Visible spectrophotometer (SHIMADZU Pharma spec, UV-1700 series) with auto sample changer (ASC-5). Nitrogen and silicon uptake by maize plants were calculated using the formula,

$$Nutrient\ uptake\ \left(mg\,pot^{-1}\right) = \frac{\text{Nutrient concentration}\ (\%)\ \times\ \text{Biomass}\ \left(\text{mg}\,pot^{-1}\right)}{100}$$

Nitrogen accumulation efficiency (NAE), Silicon accumulation efficiency (SiAE) and nitrogen use efficiency (NUE) were calculated using the below-given formula to evaluate the bioavailability of N[50].

$$NAE\ \left(g\,g^{-1}\right) = \frac{N\ uptake}{Weight\ of\ dry\ biomass}$$

$$SiAE\ \left(g\,g^{-1}\right) = \frac{Si\ uptake}{Weight\ of\ dry\ biomass}$$

$$NUE\ \left(g\,g^{-1}\right) = \frac{Weight\ of\ dry\ biomass}{N\ uptake}$$

Statistical analysis

All data were subjected to analysis of variance (ANOVA) under a factorial CRD using OriginPro 2025b (OriginLab Corp., Northampton, USA). Treatment means were compared using the Fisher's least significant difference (LSD) test at $p \leq 0.05$. Pearson's correlation analysis was performed to assess relationships among SiAE, NAE and NUE. Graphical visualization and Pearson's correlation analysis were done in OriginPro 2025b.

Declarations

Competing interests

The authors declare no competing interests.

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Author Contribution

P. N. B. and S.V. planned and designed the study. S.V. carried out the investigation through pot culture experiment under the supervision of P. N. B. S.V. analyzed the data and wrote the manuscript. All the authors approved the final version of the manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. All relevant data supporting the findings of this study are included within the article and its Supplementary Information files.

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Figures

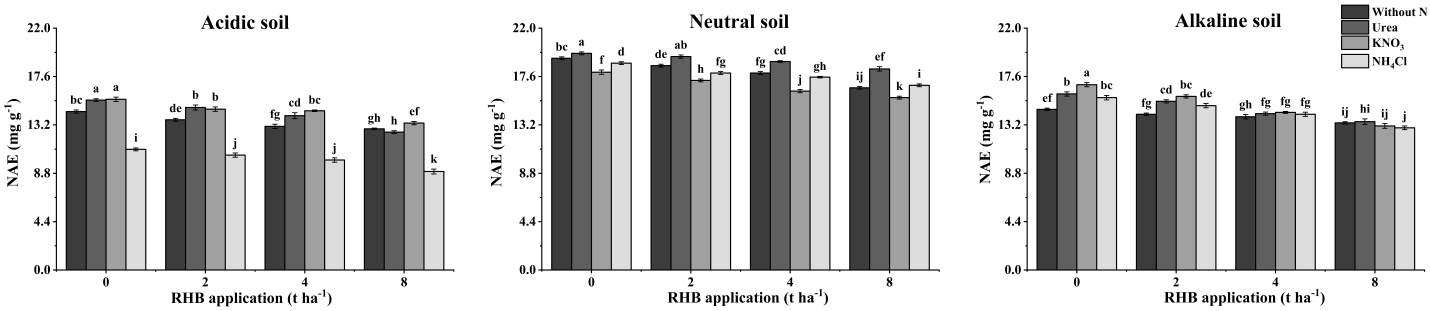


Figure 1

Effect of graded levels of Si-rich RHB and different sources of N on NAE in acidic, neutral and alkaline soils. Error bars indicate standard error of mean (n = 3). Different letters denote significant differences at $p \leq 0.05$. NAE – Nitrogen accumulation efficiency.

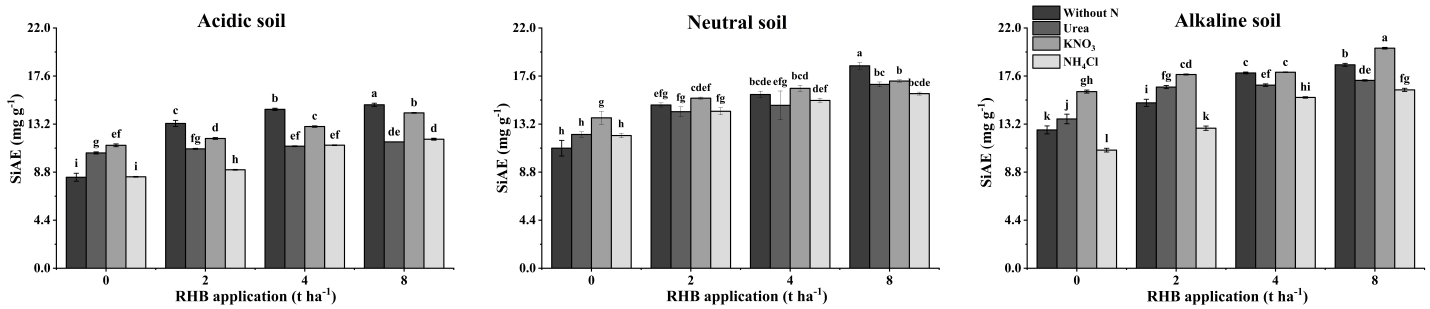


Figure 2

Effect of graded levels of Si-rich RHB and different sources of N on SiAE in acidic, neutral and alkaline soils. Error bars indicate standard error of mean (n = 3). Different letters denote significant differences at $p \leq 0.05$. SiAE – Silicon accumulation efficiency.

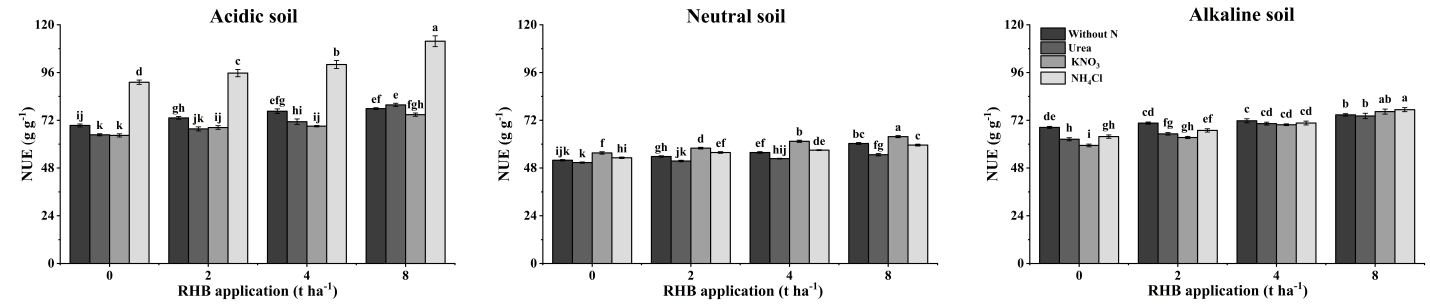


Figure 3

Effect of graded levels of Si-rich RHB and different sources of N on NUE in acidic, neutral and alkaline soils. Error bars indicate standard error of mean (n = 3). Different letters denote significant differences at $p \leq 0.05$. NUE – Nitrogen accumulation efficiency.

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