

A comparative study on the application methods of phosphorus and silicon in finger millet (*Eleusine coracana*) in the acidic soils of Meghalaya, India

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Abstract

A field experiment was conducted at the research farm of the College of Agriculture (CAU), Kyrdemkulai, Ri-Bhoi, Meghalaya, during the Kharif season of 2023 to study the “Comparison of Application Methods of Phosphorus and Silicon in Finger Millet (*Eleusine coracana*).” The experiment was designed in a factorial randomized block design with three replications. Factor-A (phosphorus) consisted of three application methods: broadcasting (BC), band placement (BP), and seedling root dip (SRD). Similarly, Factor-B (silicon) also included three application methods: broadcasting, band placement, and seedling root dip. The results revealed that the different application methods of phosphorus and silicon significantly influenced most of the parameters studied. Yield parameters and soil parameters were all affected. Yield parameters, including biological yield, grain yield, and stover yield, were significantly highest in the A2B2 treatment (phosphorus-band placement and silicon-band placement) at 7632, 2967, and 4665 kg ha⁻¹, respectively, and lowest in A3B1 (phosphorus-seedling root dip and silicon-broadcasting) at 4797, 1789, and 3008 kg ha⁻¹, respectively. Soil parameters such as available nitrogen (N), available phosphorus (P), exchangeable acidity, and exchangeable Al were significantly highest in A3B3 (P-SRD and Si-SRD) at 344 kg ha⁻¹, 25.7 kg ha⁻¹, 1.9 meq 100g⁻¹ soil, and 1.117 meq 100g⁻¹ soil, respectively. Soil available silicon (Si) was significantly highest in A1B2 (P-BC and Si-BP) at 25.63 mg/kg soil. Total phosphorus and silicon nutrient uptake were significantly highest in A2B2 (phosphorus-band placement and silicon-band placement) at 8.14 kg ha⁻¹ and 108.92 kg ha⁻¹, respectively. The results of the experiment indicated that the band placement method for both phosphorus and silicon (P-BP and Si-BP) was superior in terms of yield, while the seedling root dip method (P-SRD and Si-SRD) was more effective for soil fertility in the mid-hills of Meghalaya. This is first time reporting comparison of application methods of phosphorus and silicon in finger millet.

1. Introduction

In the tropical parts of Asia and Africa, millets are the main source of calories and proteins. According to Anthony Ceasar et al. (2018), finger millet, *Eleusine coracana* (L.) Gaertn. (Poaceae), ranks fourth among millets. It makes up over 12% of the total area used for millet cultivation and is mostly grown in 25 nations throughout the African and Asian continents. An estimated 4.5 million tonnes of finger millet are produced annually worldwide. Africa generates 2.5 million tonnes of this each year, while India produces 1.2 million tonnes (Anthony Ceasar et al., 2018).

India is the leading producer of finger millet, with Karnataka topping the production charts in the 2022–2023 agricultural year, yielding an estimated 1,125.73 thousand tonnes. These figures reflect the regional disparities in finger millet production during this period (MoA&FW, 2023). Finger millet is known to thrive on only 28% of the water required for rice cultivation (Triveni *et al.*, 2017). Nutritionally, finger millet is composed of carbohydrates (76.3%), protein (9.2%), fat (1.29%), minerals (2.24%), ash (3.9%), and calcium (0.33%) on average (Devi *et al.*, 2014). Despite its traditional significance in the remote areas of the north eastern hill (NEH) region, productivity remains low due to the use of local varieties and inadequate nutrient management. With the global population projected to reach 9.9 billion by 2050, a

more than 70% increase in food production is necessary (Sarfraz *et al.*, 2023). Phosphorus (P), the 11th most abundant element in the Earth's crust, is crucial for plant growth and development. The Earth's crust contains approximately 0.12% phosphorus. After nitrogen, phosphorus is considered one of the most vital macro-elements needed by plants (Saber *et al.*, 2005). Phosphorus deficiency is a key limiting factor in plant growth as it promotes root development, enhancing the uptake of other essential nutrients (CGIAR, 2005). Phosphorus plays a vital role in energy storage and transport, signal transduction, macromolecular biosynthesis, photosynthesis, and respiration (Havlin *et al.*, 2009). It also contributes to root growth, strengthening stalks and stems, flower and seed production, crop maturity and quality, nitrogen fixation in legumes, and disease resistance. Due to the prevalence of acidic soils (81% of 26.22 million hectares) in North East India, the response to SSP application by various crops is often disappointing (Sharma *et al.*, 2006). This situation calls for a reconsideration of the conventional phosphorus management approach, especially in the acidic soils of the North Eastern Hill States. Silicon (Si) is the eight most abundant element in the universe and the second most abundant in the Earth's crust, making up 27.7% of the lithosphere (Epstein, 1999; Adrees *et al.*, 2015). Although silicon (Si) is abundant in the Earth's crust, its necessity for the growth of higher plants is still a subject of debate (Prakash *et al.*, 2018, 2020; Majumdar and Prakash, 2020a). As a result, despite the occurrence of seven international conferences on silicon in agriculture (USA-1999, Japan-2002, Brazil-2005, South Africa-2008, China-2011, Sweden-2014, and India-2017), silicon has not yet been recognized as an essential nutrient for plant growth (Prakash *et al.*, 2020). Nevertheless, due to its immense potential in alleviating various biotic and abiotic stresses, Si was officially classified as a "beneficial substance" by the Association of American Plant Food Control Officials (AAPFCO) in 2014 and by the International Plant Nutrition Institute (IPNI) in 2015 (Majumdar and Prakash, 2020a). Plants absorb silicon in the form of silicic acid, and it is the only nutrient that is non-toxic even in excess (Mitani *et al.*, 2005). Silicon comprises 0.1–10% of a plant's dry weight (Ma and Yamaji, 2006; Adrees *et al.*, 2015). While considered a non-essential or quasi-essential element, silicon is beneficial for increasing yield in higher plants, particularly during the reproductive stage (Liang *et al.*, 2015). Information on silicon availability in Indian soils is limited and fragmented (Prakash *et al.*, 2018). Savant *et al.* (1997) found that silicon (Si) uptake in rice surpasses that of nitrogen (N) and potassium (K) in the plant's above-ground biomass. Additionally, phosphorus-use efficiency (PUE) increased from 24–34% when phosphorus (P) was applied alongside silicon, largely due to reduced phosphorus retention and enhanced availability of water-soluble P in the soil (Singh *et al.*, 2005). Numerous studies have shown that Si application has a positive impact on crop yields (Alovisi *et al.*, 2014). This complementary effect of Si can improve nutrient use efficiency (NUE), thereby boosting rice productivity. Halder and Mandal (1981) also observed a significant rise in rice dry matter accumulation (DMA) from phosphorus application. Similarly, Si not only enhances nutrient translocation within the rice plant but also increases water productivity by reducing transpiration losses (Wang *et al.*, 2019). Kapoor V. *et al.*, (2008) recorded that deep placed N–P briquettes gave significantly higher grain yield, straw biomass, total P and K uptake, apparent P recovery, and agronomic N and P use efficiencies, when plant spacing was reduced from 20 x 20 cm to 20 x 10 cm. Closer plant spacing led to better utilization of P and K and provided opportunities for deep placement of N–P or N–P–K briquettes in soils with low available P. Methods of application have a major impact on plant height,

plant number ha^{-1} , and grain yield (Maqbool *et al.*, 2012). At the beginning of plant growth, standard broadcast fertilization does not always ensure proper plant nutrition because, depending on soil properties, part of the component introduced into the soil in the form of fertilizer will land in places that are beyond the range of crop roots (Grant *et al.*, 2001). Consequently, band placement not only prompts yield growth but also increases the values of NUE indices (Ma *et al.*, 2013; Szulc *et al.*, 2020). Kalidas Singh and Thakuria (2018) identified the critical phosphorus dose (112.5 mg kg^{-1} soil) for dipping rice seedling roots (for 10 hours) in SSP-amended soil slurry before transplanting, particularly in acid Inceptisol soils using the rice cultivar Ranjit. Devi (2018) investigated the optimal silicon (Si) levels in soil-water slurry for rice seedlings using two dominant rice soils (sandy clay loam and clay loam) and three rice types (traditional, high-yielding, and hybrid). The goal was to standardize the seedling root-dip method for Si nutrition in rice. The study found that the critical Si doses varied by soil type and rice variety. In sandy clay loam soil, hybrid rice required the highest Si dose (275 mg/kg soil).

2 Materials and methods

2.1 Location of the field experiment

The field experiment was conducted at the Agriculture Farm of the College of Agriculture, Kyrdemkulai, CAU (Imphal), Meghalaya, India. Kyrdemkulai is a village in the Umsning Block in the Ri-Bhoi District of Meghalaya, India (Fig. 1). It is located 28 km south of the Ri-Bhoi district headquarters in Nongpoh and lies between $25^{\circ}44'4.9''$ N latitude and $91^{\circ}49'13.5''$ E longitude. Kyrdemkulai falls in the subtropical hill zone with an annual rainfall of 400–1200 mm and a temperature range of 12–32°C. The soil physico-chemical properties were analysed at the laboratory of the Department of Soil Science and Agricultural Chemistry, College of Post-Graduate Studies in Agricultural Sciences, Umiam, Barapani, India.

2.2 Climate and weather at the experimental site

The Northeastern Hill Region of India experiences a humid subtropical climate with high rainfall and cold winters. The monsoon season generally begins in the first fortnight of June and withdraws by October, with rainfall decreasing from September onward. Average weekly data on total rainfall, average maximum and minimum temperatures (°C), average relative humidity (%), and wind direction during the crop-growing period were recorded at the meteorological station of the College of Agriculture, Kyrdemkulai, CAU (Imphal), Meghalaya, India as shown in Fig. 2. During the field experiment, the experimental crop (Finger millet) received a total rainfall of 1043.6 mm. Maximum and minimum temperatures ranged from 30.14°C to 34.43°C and 27.00°C to 30.86°C, respectively. Relative humidity ranged from 66.49–85.60% during the crop-growing period.

2.3 Field experimental details

The field experiment was conducted using a sandy clay loam having an acidic reaction, pH 5.24 and the other initial physico-chemical soil parameters are presented in Table 1. The field experiment was conducted by taking Finger millet as a test crop in a factorial randomized block design (FRBD). Three

application methods viz., broadcasting (BC), band placement (BP) and seedling root dip (SRD) were chosen for application of phosphorus (factor-1) and silicon (factor-2) fertilizers. Single superphosphate (SSP) and calcium silicate (Ca_2SiO_3) were used as sources of phosphorus (P) and silicon (Si), respectively. The details of the experiments are briefly presented in Table 2. Altogether, there were 9 treatment combinations and they were replicated thrice. Hence, the total number of plots were 27. The details of treatments used in this experiment are presented in Table 3. Seedlings of finger millet (variety: GPU-28) were raised on a nursery bed for 24 days. 24 days old seedlings of finger millet were transplanted in the main field on 20th August, 2023 and upon maturity, harvested on 19th November, 2023.

Table 1. Initial properties of soil used in the field experiment.

Chemical properties

S. No.	Parameters	Experiment Farm Soil	Method of Estimation	Reference
1.	pH	5.24	Glass electrode pH meter	(Jackson, 1973)
2.	EC (dS m ⁻¹)	0.07	EC meter {Soil: water (1:2.5)}	(Jackson, 1973)
3.	Organic Carbon (%)	1.33	Rapid dichromate wet digestion method	(Walkley and Black, 1934)
4.	Available N (kg ha ⁻¹)	112.90	Alkaline potassium permanganate method	(Subbiah and Asija, 1956)
5.	Available P ₂ O ₅ (kg ha ⁻¹)	13.79	Ammonium molybdate stannous chloride blue colour method	(Bray and Kurtz, 1945)
6.	Available K (kg ha ⁻¹)	104.49	Neutral normal ammonium acetate extraction method followed by flame photometer	(Hanway and Heidel, 1952)
7.	Zinc (mg kg ⁻¹)	3.31	DTPA –CaCl ₂ -TEA extraction method	Lindsay and Norvell, 1978
8.	Copper (mg kg ⁻¹)	0.36	DTPA –CaCl ₂ -TEA extraction method	Lindsay and Norvell, 1978
9.	Manganese (mg kg ⁻¹)	5.77	DTPA –CaCl ₂ -TEA extraction method	Lindsay and Norvell, 1978
10.	Iron (mg kg ⁻¹)	19.35	DTPA –CaCl ₂ -TEA extraction method	Lindsay and Norvell, 1978
11.	Dissolved Si (mg kg ⁻¹)	15.29	0.01 M CaCl ₂ extractable	Haysom and Chapman (1975)
12.	Adsorbed Si (mg kg ⁻¹)	17.63	0.5 M Acetic acid	Korndorfer <i>et al.</i> (2001).

	kg ⁻¹)			
13.	Exchangeable Acidity (mEq 100 ⁻¹ g soil)	1.88	1 N KCl extractable	McLean (1965)
14.	Exchangeable Al (mEq 100 ⁻¹ g soil)	0.88	1 N KCl extractable	McLean (1965)
15.	Readily soluble Al (mg kg ⁻¹)	8.12	Pyrocatechol violet colorimetry	Hoyt and Webber (1974)

Table 2
The experimental details of the field experiment

Experiment Location	College of Agriculture, Kyrdemkulai
Test crop	Finger Millet
Spacing	25cm × 10cm
Seed rate	4 kg ha ⁻¹
Crop establishment method	Transplanting
Design	Factorial Randomized Block Design (FRBD)
Factor 1	Phosphorus
Factor 2	Silicon
No. of replication	3
No. of treatment	9
No. of plots	27
Plot size	4.5m ²
Variety	GPU-28
Date of Nursery	27 July 2023
Date of Transplanting	20 Aug 2023
Date of Harvesting	19 Nov 2023
Fertilizer application methods	Broadcasting (BC)
	Band placement (BP)
	Seedling root dip (SRD)
Plant sample collection	60DAT, 90DAT, and harvest
*DAT – Days after transplanting.	

Table 3
Treatment details used in the field experiment

Factor Combination	Treatments	Treatment Details
A1B1	T ₁	BC – P + BC – Si
A1B2	T ₂	BC – P + BP – Si
A1B3	T ₃	BC – P + SRD – Si
A2B1	T ₄	BP – P + BC – Si
A2B2	T ₅	BP – P + BP – Si
A2B3	T ₆	BP – P + SRD – Si
A3B1	T ₇	SRD – P + BC – Si
A3B2	T ₈	SRD – P + BP – Si
A3B3	T ₉	SRD – P + SRD – Si
P source: Single Super Phosphate (SSP) and Si source: Calcium silicate		
SSP @ 250 kg ha ⁻¹ for BC and BP, RD with SSP @ 112.5 mg P ₂ O ₅ kg ⁻¹ soil		
Calcium silicate @ 250 kg ha ⁻¹ for BC and BP, SRD with Calcium silicate @ 275 mg Si kg ⁻¹ soil		
BC – Broadcasting, BP – Band placement, and SRD – Seedling root dip		

2.4 Description of variety used in the experiment

The GPU-28 (Germ Plasm Unit) is a medium-duration variety of finger millet that matures in approximately 110 to 115 days. The seeds of this variety were collected from ICAR-Indian Institute of Millet Research, Rajendranagar, Hyderabad, Telangana, India. It is a blast-resistant variety suitable for both rain-fed and irrigated ecosystems. In a rain-fed ecosystem, it serves as a contingent variety for delayed sowing up to August. The ear head shape is semi-compact, and the plant produces 4 to 6 productive tillers. The finger length ranges from 5 to 7 cm, and the plant grows to a medium height, with a yield potential of 25 to 40 quintals per hectare (q ha⁻¹).

2.5 Methods of application of phosphorus and silicon

2.5.1 Broadcasting

A little amount of soil from the area where the fertilizer was applied was combined with the fertilizer in this manner due to the plot's modest size and restricted fertilizer availability. The broadcasting approach was used to provide fertilizer prior to the finger millet plants being transplanted. Single superphosphate

(SSP) and calcium silicate (CaSiO_3) were used as sources of P and Si, respectively. The application of calcium silicate and SSP to finger millet was done at the same rate of 250 kg ha^{-1} .

2.5.2 Band placement

This method involved taking a tiny amount of soil from the plot where the fertilizer was applied and mixed it with the fertilizer because the plot was small and there was a restricted amount of fertilizer. The band-placement approach involved placing the fertilizer a little distance from the roots, to the side of each row, prior to transplanting the finger millet plants. The P and Si were supplied by SSP and CaSiO_3 , respectively. The application of calcium silicate and SSP to finger millet was done at the same rate of 250 kg ha^{-1} .

2.5.3 Seedling root dip

In the SRD method, seedling roots were dipped in soil: slurry amended with Si at 275 mg kg^{-1} soil overnight (10 hours) just before transplanting. Similarly, in the SRD method, seedling roots were dipped in soil: slurry amended with P_2O_5 at 112.5 mg kg^{-1} soil overnight (10 hours) just before transplanting. In the SRD method, SSP is used at a rate of 7.7 kg ha^{-1} (0.703 g kg^{-1} soil) and calcium silicate at a rate of 57.23 kg ha^{-1} (1.145 g kg^{-1} soil).

2.6 Analysis of Soil Samples

2.6.1 Adsorbed silicon

Adsorbed silicon (Ad-Si) in soil was extracted using 0.5 M acetic acid with the soil-to-extractant ratio of 1:2.5 as outlined by Korndorfer *et al.* (2001). After shaking continuously for a period of one hour, a solution was centrifuged at 3000 rpm for 3 minutes and then the supernatant was filtered. The filtrate was then used for silicon determination. Silicon in the extracting solution was determined by adopting the procedure of Narayanaswamy and Prakash (2009).

An aliquot of 0.25 ml filtrate was taken into a plastic centrifuge tube and then added with 10.5 ml of distilled water. 0.25 ml of 1:1 hydrochloric acid and 0.5 ml of 10 per cent ammonium molybdate solution. After allowing for 5 minutes. 0.5 ml of 20 per cent tartaric acid solution was added. After allowing for an additional two minutes. 0.5 ml reducing agent (1-amino-2-naphthol-4-sulfonic acid - ANSA) was added. After 5 minutes, but not later than 30 minutes following the addition of the reducing agent. Absorbance was measured at 630 nm using a UV-visible spectrophotometer (SHIMADZU Pharma spec. UV-1700 series) with an auto sample changer (ASC-5). Simultaneously Si standards (0, 0.2, 0.4, 0.8, 1.2 and 1.6 mg L^{-1}) prepared in the same matrix were also measured using a UV-visible spectrophotometer.

2.6.2 Dissolved silicon

Dissolved silicon (DSi) in was determined by the method of continuous shaking for 16 hrs and centrifuged with 0.01M CaCl_2 (Haysom and Chapman, 1975). Two grams soil was taken in a 50ml

centrifuge tube and 20 ml of 0.01 M CaCl_2 was added. After continuous end to end shaking in a mechanical shaker for 16 h, the solution was centrifuged at 2000 rpm for 10 min and then filtered through Whatman No. 42. Silicon in the extracting solution was determined by transferring 1 ml of filtrate into plastic centrifuge tube and then added 2.5 ml 0.05M H_2SO_4 and 2.5 ml ammonium molybdate solution (pH 7). After vortex stirring for 5 min, 1.25 ml of tartaric acid solution was added. After allowing for additional 2 min, 0.25 ml reducing agent (ANSA) was added. After 5 min, but not later than 30 min following addition of the reducing agent, absorbance was measured at 820 nm using UV visible spectrophotometer. Si was expressed as mg kg^{-1} soil.

2.7 Plant analysis

2.7.1 Determination of Phosphorus in plant samples

Phosphorous content in plant sample was determined by vanadomolybdophosphoric yellow colour method (Piper, 1942). Ground plant sample (0.5g) was digested by using di-acid mixture (3:1 HNO_3 to HClO_4) at 250°C for two and half hour in digestion block (Kjel plus, Pelican Equipment, Chennai) until the mixture turned ash white colour. The digested mixture was diluted with double distilled water and filtered through Whatman No. 42 and volume was made up to 100 ml. Then, 5 ml aliquot was taken in 50 ml volumetric flask and added 10 ml vanadomolybdate reagent and diluted to 50 ml with double distilled water. After 10 min, the yellow colour intensity was determined using a spectrophotometer (Spectrascan UV-2600, Thermo Scientific, USA) at 420 nm and concentration of P was read from the standard curve. Tissue P was expressed in percentage (%).

2.7.2 P Uptake

The uptake of P in biomass, straw and grain was determined by multiplying P content (%) with their corresponding yield data.

For Field experiment: $\text{P uptake (kg ha}^{-1}\text{)} = (\text{grain yield} \times \%P)/100$ or $(\text{straw yield} \times \%P)/100$

2.7.3 Determination of silicon in plant samples

2.7.3.1 Preparation of plant samples for digestion

After harvesting, the collected plant samples of rice from the pot culture experiment were separated into shoot and roots. Later, shoots (straw) were initially washed in tap water followed by distilled water to remove any surface contaminants and were dried in the hot air oven at 65°C for 72 hours. The dried plant samples were cut into smaller pieces and powdered in a ball mill.

2.7.3.2 Plant sample digestion

The powdered plant samples (straw and grain) were dried in an oven at 70°C for 2–3 hours prior to analysis. The sample (0.1g) was digested in a mixture of 7 ml of HNO_3 (70 per cent), 2 ml of H_2O_2 (30

per cent) and 1 ml of HF (40 per cent) using microwave digestion system (Milestone-start D) at 150⁰C with following steps: 1200 watt for 15 minutes with a ramping rate of 7⁰C per minute and 1200 watt for 10 minutes at holding temperature of 150⁰C and venting for 10 minutes. The digested samples were diluted to 50 ml with 4 per cent boric acid (Ma and Takahashi, 2002).

2.7.3.3 Estimation of silicon in plant samples

The Si concentration in the digested solution was determined as described below: 0.25 ml (straw) and 0.5 ml (grain) of digested aliquot was transferred to a plastic centrifuge tube, to which 3.75 ml of 0.2 N HCl, 0.5 ml of 10 per cent ammonium molybdate ((NH₄)₆Mo₇O₂) and 0.5 ml of 20 per cent tartaric acid and 0.5 ml of reducing agent (Amino naphthol sulphonic acid - ANSA) was added and the volume was made up to 12.5 with distilled water. After one hour, the absorbance was measured at 600 nm with a UV-visible spectrophotometer (Ma and Takahashi, 2002). Similarly, standards (0, 0.2, 0.4, 0.8, 1.2, and 1.6 ppm) were prepared by following the same procedure.

Calculation:

Straw Si (%): $(50 \times 12.5) / (0.1 \times 0.25 \times 10000)$

Grain Si (%): $(50 \times 12.5) / (0.1 \times 0.5 \times 10000)$

Where,

50 = Quantity of digested sample (mL)

12.5 = Volume made (mL)

0.1 = Weight of sample (g)

0.25 = Aliquot taken for straw (mL)

0.5 = Aliquot taken for grain (mL)

10000 = Conversion from ppm to percentage

2.7.4 Si Uptake

The uptake of Si in biomass, straw and grain was determined by multiplying Si content (%) with their corresponding yield data.

For Field experiment: Si uptake (kg ha⁻¹) = (grain yield × %Si)/100 or (straw yield × %Si)/100

2.8 Data Analysis

The data obtained from various observations recorded from the field, analytical studies from the laboratories, and computed over the computers were statistically analyzed by using the technique of analysis of variance for FRBD. The difference between the treatment means was tested for their

statistical significance with an appropriate critical difference (C.D) value at a 5% level of significance Gomez and Gomez (1984).

3 Results

3.1 Available nutrients (N, P & K) in Soil

3.1.1 Soil available nitrogen

For factor-A (phosphorus), at 60 DAS, BC resulted in the highest available nitrogen content at 341.354 kg/ha, which is statistically comparable to SRD at 307.305 kg/ha, but significantly higher than BP at 274.696 kg/ha (Table 4). However, by 90 DAS, SRD recorded the highest available nitrogen content at 361.267 kg/ha, significantly outperforming both BC at 266.769 kg/ha and BP at 224.538 kg/ha. At harvest, no significant differences among the treatments were observed. For factor-B (silicon), at 60 DAS, BC recorded the highest available nitrogen content at 358.466 kg/ha, statistically superior to both BD at 292.441 kg/ha and SRD at 272.449 kg/ha. However, by 90 DAS, there were no significant differences among the treatments. At harvest, BC again recorded the highest available nitrogen content at 318.199 kg/ha, significantly higher than both SRD at 292.693 kg/ha and BD at 261.333 kg/ha. The interaction between factor-1 (phosphorus) and factor-2 (silicon) at 60 DAS resulted in the highest available nitrogen content of 439.304 kg/ha in the A1B1 combination, which was statistically superior to all other interactions. At 90 DAS, the A3B3 combination recorded the highest nitrogen content at 413.952 kg/ha, also statistically superior to all other interactions. At harvest, A3B3 again recorded the highest nitrogen content at 344.960 kg/ha, which was statistically comparable to A2B1 at 326.144 kg/ha and A1B1, while outperforming A3B, A1B2, A1B3, A2B3, A2B2, and A3B2 (Table 4).

Table 4 Interaction of application methods of phosphorus and silicon on soil available nitrogen

Treatments	Available nitrogen (kg ha ⁻¹)		
	60 DAS	90 DAS	At harvest
Factor 1 (Phosphorus)			
A ₁ -BC	341.354	286.769	290.185
A ₂ -BP	274.698	224.538	285.167
A ₃ -SRD	307.305	361.267	298.875
S.E.(m)	12.156	6.901	5.995
C.D.(p≤0.05)	36.438	20.685	NS
Factor 2 (Silicon)			
B ₁ -BC	358.468	292.693	318.199
B ₂ -BP	292.441	278.477	261.333
B ₃ -SRD	272.449	281.404	292.693
S.E.(m)	12.156	6.901	5.995
C.D.(p≤0.05)	36.438	NS	17.970
Phosphorus × Silicon	60 DAS	90 DAS	At Harvest
A1B1	439.304	314.854	321.126
A1B2	311.460	259.661	279.731
A1B3	273.297	225.792	269.698
A2B1	298.054	213.248	326.144
A2B2	238.327	255.898	265.933
A2B3	289.708	204.467	263.424
A3B1	340.039	349.978	307.328
A3B2	327.536	319.872	238.336
A3B3	254.341	413.952	344.960
SEm ±	21.055	11.952	10.383
CD (P≤0.05)	63.113	35.827	31.125

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

BC-Broadcasting, BP – Band placement, SRD – Seedling Root Dip

3.1.2 Soil available phosphorus

For factor-1 (phosphorus), at 60 DAS, SRD recorded the highest available phosphorus content at 8.580 kg/ha, significantly outperforming both BP at 7.294 kg/ha and BC at 7.073 kg/ha (Table 5). By 90 DAS, BP recorded the highest phosphorus content at 11.056 kg/ha, statistically superior to both BC at 8.736 kg/ha and SRD at 8.080 kg/ha. At harvest, SRD again recorded the highest phosphorus content at 17.022 kg/ha, surpassing both BP at 13.639 kg/ha and BC at 13.514 kg/ha. Regarding factor-2 (silicon), at 60 DAS, BP achieved the highest available phosphorus content at 9.393 kg/ha, statistically superior to both BC at 7.104 kg/ha and SRD at 6.450 kg/ha. At 90 DAS, SRD recorded the highest phosphorus content at 10.550 kg/ha, statistically comparable to BD at 9.580 kg/ha, and significantly better than BC at 7.742 kg/ha. At harvest, BC recorded the highest phosphorus content at 15.703 kg/ha, which was statistically similar to BP at 15.115 kg/ha, but superior to SRD at 13.357 kg/ha. The interaction between factor-1 (phosphorus) and factor-2 (silicon) at 60 DAS resulted in the highest available phosphorus content of 12.344 kg/ha in the A3B2 combination, statistically superior to all other interactions. At 90 DAS, the A2B3 combination recorded the highest phosphorus content at 14.483 kg/ha, again statistically superior to all other interactions. At harvest, the A3B3 combination recorded the highest phosphorus content at

25.796 kg/ha, significantly outperforming all other interaction effects (Table 5).

Table 5
Interaction of application methods of phosphorus and silicon on soil available P

Factor 1 (Phosphorus)			
Treatments	Available P (kg ha⁻¹)		
	60 DAS	90 DAS	At harvest
A₁-BC	7.073	8.736	13.514
A₂-BP	7.294	11.056	13.639
A₃-SRD	8.580	8.080	17.022
S.E.(m)	0.186	0.186	0.354
C.D.(p ≤ 0.05)	0.556	0.556	1.061
Factor 2 (Silicon)			
B₁-BC	7.104	7.742	15.703
B₂-BP	9.393	9.580	15.115
B₃-SRD	6.450	10.550	13.357
S.E.(m)	0.186	0.186	0.354
C.D.(p ≤ 0.05)	0.556	0.556	1.061
Phosphorus × Silicon	60 DAS	90 DAS	Harvest
A1B1	6.885	9.699	15.158
A1B2	7.692	8.386	18.967
A1B3	6.641	8.123	6.416
A2B1	7.335	6.866	19.305
A2B2	8.142	11.819	13.751
A2B3	6.405	14.483	7.861
A3B1	7.091	6.660	12.645
A3B2	12.344	8.536	12.626
A1, A2 and A3 – Methods of application of phosphorus fertilizer			
B1, B2 and B3 – Methods of application of silicon fertilizer			
BC-Broadcasting, BP – Band placement, SRD – Seedling Root Dip			

Factor 1 (Phosphorus)			
Treatments	Available P (kg ha ⁻¹)		
	60 DAS	90 DAS	At harvest
A3B3	6.304	9.043	25.796
SEm ±	0.321	0.322	0.613
CD (P ≤ 0.05)	0.964	0.964	1.837
A1, A2 and A3 – Methods of application of phosphorus fertilizer			
B1, B2 and B3 – Methods of application of silicon fertilizer			
BC-Broadcasting, BP – Band placement, SRD – Seedling Root Dip			

3.1.3 Soil available potassium

For factor-1 (phosphorus), at 60 DAS, the SRD method resulted in the highest available potassium content at 113.867 kg/ha, which is statistically similar to BP at 112.085 kg/ha, and significantly higher than SRD at 106.113 kg/ha (Table 6). By 90 DAS, SRD again showed the highest available potassium content at 116.592 kg/ha, statistically comparable to BC at 112.261 kg/ha, and significantly better than BP at 99.643 kg/ha. At harvest, BC recorded the highest potassium content at 125.851 kg/ha, surpassing both SRD at 115.397 kg/ha and BP at 106.064 kg/ha. Regarding factor-2 (silicon), at 60 DAS, the BP method achieved the highest available potassium content at 114.240 kg/ha, which is statistically on par with SRD at 112.161 kg/ha, but significantly superior to SRD at 105.664 kg/ha. At 90 DAS, BC recorded the highest available potassium content at 120.811 kg/ha, outperforming both SRD at 105.243 kg/ha and BP at 102.443 kg/ha. At harvest, BC again recorded the highest available potassium content at 121.035 kg/ha, statistically superior to both BP at 114.091 kg/ha and SRD at 112.187 kg/ha. At 60 days after sowing (DAS), the combination of phosphorus and silicon (A3B3) resulted in the highest available potassium content (118.944 kg/ha). This was similar to several other combinations (A2B2, A2B3, A3B2, A1B2, and A3B1) but higher than A1B1, A2B1, and A1B3. However, at 90 DAS, the combination of phosphorus and silicon (A1B1) resulted in the highest available potassium content (125.440 kg/ha). This was similar to A3B3 and A3B1 but higher than the other combinations. By the harvest time, A1B1 had the highest available potassium content (136.640 kg/ha), which was similar to A1B2 but higher than all the other combinations (Table 6).

Table 6 Interaction of application methods of phosphorus and silicon on soil available K

Treatments	Available K (kg ha ⁻¹)		
	60 DAS	90 DAS	At harvest
Factor 1 (Phosphorus)			
A ₁ -BC	106.113	112.261	125.851
A ₂ -BP	112.085	99.643	106.064
A ₃ -SRD	113.867	116.592	115.397
S.E.(m)	2.248	2.225	2.340
C.D.(p≤0.05)	6.738	6.668	7.015
Factor 2 (Silicon)			
B ₁ -BC	105.664	120.811	121.035
B ₂ -BP	114.240	102.443	112.187
B ₃ -SRD	112.161	105.243	114.091
S.E.(m)	2.248	2.225	2.340
C.D.(p≤0.05)	6.738	6.668	7.015
Phosphorus × Silicon	60 DAS	90 DAS	At Harvest
A1B1	106.176	125.440	136.640
A1B2	110.320	110.880	128.800
A1B3	101.843	100.464	112.112
A2B1	101.616	113.568	110.656
A2B2	118.944	89.376	100.688
A2B3	115.696	95.984	106.848
A3B1	109.200	123.424	115.808
A3B2	113.456	107.072	107.072
A3B3	118.944	119.280	123.312
SEm ±	3.893	3.853	4.053
CD (P≤0.05)	11.670	11.550	12.150

A1, A2 and A3 – Methods of application of phosphorus fertilizer

3.2 Status of adsorbed Si and dissolved Si

3.2.1 Adsorbed silicon

In terms of factor-1 (phosphorus) at 60 DAS, BC recorded the highest Adsorbed silicon (Ad-Si) content ($29.571 \text{ mg kg}^{-1}$) which is statistically superior to both BP ($24.600 \text{ mg kg}^{-1}$) and SRD ($21.997 \text{ mg kg}^{-1}$) (Table 7). At 90 DAS, BC recorded the highest Adsorbed silicon (Ad-Si) content (27.122 PPM) which is statistically superior to both BP ($20.880 \text{ mg kg}^{-1}$) and SRD ($20.621 \text{ mg kg}^{-1}$). At harvest BC recorded the highest Adsorbed silicon (Ad-Si) content ($23.054 \text{ mg kg}^{-1}$) which is statistically superior to both SRD ($20.569 \text{ mg kg}^{-1}$) and BP ($19.441 \text{ mg kg}^{-1}$). In terms of factor-2 (silicon) at 60 DAS, BD recorded the highest Adsorbed silicon (Ad-Si) content ($27.265 \text{ mg kg}^{-1}$) which is statistically at par with SRD ($25.028 \text{ mg kg}^{-1}$) but it was statistically superior to BC ($23.875 \text{ mg kg}^{-1}$). At 90 DAS, BP recorded the highest Adsorbed silicon (Ad-Si) content ($25.404 \text{ mg kg}^{-1}$) which is statistically superior to SRD ($21.746 \text{ mg kg}^{-1}$) and BC ($21.474 \text{ mg kg}^{-1}$). At harvest BD recorded the highest Adsorbed silicon (Ad-Si) content ($22.544 \text{ mg kg}^{-1}$) which is statistically superior to BC ($20.342 \text{ mg kg}^{-1}$) and SRD ($20.178 \text{ mg kg}^{-1}$). The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted at 60 DAS, in highest Adsorbed silicon (Ad-Si) content A1B2 ($31.338 \text{ mg kg}^{-1}$) which is statistically at par A2B3, and A1B3 and while being statistically superior to A1B1, A3B2, A2B1, A2B2, A3B1, and A3B3. At 90 DAS, in highest Adsorbed silicon (Ad-Si) content of A1B2 ($34.365 \text{ mg kg}^{-1}$) while being statistically superior over all other interaction effects. At harvest highest Adsorbed silicon (Ad-Si) content of A1B2 ($25.626 \text{ mg kg}^{-1}$) which is statistically at par A3B2, and A1B1 and while being statistically superior to A2B3, A1B3, A3B1, A3B3, A2B1, and A2B2 (Table 7). According to Narayanswamy and Prakash (2009, 2010), the critical levels and categorization of available Si (mg kg^{-1}) using 0.5 M AcOH extractant are as follows: critical limit = 43 mg kg^{-1} , categorization: Low ($< 44 \text{ mg kg}^{-1}$), Medium ($44\text{--}116 \text{ mg kg}^{-1}$), and High ($> 116 \text{ mg kg}^{-1}$).

Table 7 Interaction of application methods of phosphorus and silicon on adsorbed silicon

Treatments	Acetic acid extractable soil available silicon (mg kg ⁻¹)		
	60 DAS	90 DAS	At harvest
Factor 1 (Phosphorus)			
A ₁ -BC	29.571	27.122	23.054
A ₂ -BP	24.600	20.880	19.441
A ₃ -SRD	21.997	20.621	20.569
S.E.(m)	0.502	0.910	0.420
C.D.(p≤0.05)	1.506	2.729	1.260
Factor 2 (Silicon)			
B ₁ -BC	23.875	21.474	20.342
B ₂ -BP	27.265	25.404	22.544
B ₃ -SRD	25.028	21.746	20.178
S.E.(m)	0.502	0.910	0.420
C.D.(p≤0.05)	1.506	2.729	1.260
Phosphorus × Silicon	60 DAS	90 DAS	At Harvest
A1B1	28.572	22.223	23.956
A1B2	31.338	34.365	25.626
A1B3	28.803	24.779	19.579
A2B1	22.791	19.026	18.071
A2B2	21.945	20.431	17.963
A2B3	29.064	23.183	22.289
A3B1	20.263	23.171	19.000
A3B2	28.511	21.414	24.042
A3B3	17.217	17.277	18.667
SEm ±	0.870	1.577	0.728
CD (P≤0.05)	2.608	4.727	2.182

A1, A2 and A3 – Methods of application of phosphorus fertilizer

3.2.3 Dissolved silicon

In terms of factor-1 (phosphorus) at 60 DAS, BC recorded the highest Dissolved silicon (D-Si) content ($22.578 \text{ mg kg}^{-1}$), which is statistically superior to both BP ($18.633 \text{ mg kg}^{-1}$) and SRD ($18.144 \text{ mg kg}^{-1}$) (Table 8). At 90 DAS, BC recorded the highest Dissolved silicon (D-Si) content ($22.561 \text{ mg kg}^{-1}$) which is statistically superior to both BP ($19.494 \text{ mg kg}^{-1}$) and SRD ($13.170 \text{ mg kg}^{-1}$). At harvest DAS BC recorded the highest Dissolved silicon (D-Si) content ($23.653 \text{ mg kg}^{-1}$) which is statistically superior to both SRD ($17.041 \text{ mg kg}^{-1}$) and BP ($16.295 \text{ mg kg}^{-1}$). In terms of factor-2 (silicon) at 60 DAS, BP recorded the highest Dissolved silicon (D-Si) content ($21.032 \text{ mg kg}^{-1}$) which is statistically at par with SRD ($19.350 \text{ mg kg}^{-1}$) and which is statistically superior to BC ($18.973 \text{ mg kg}^{-1}$). At 90 DAS, BP recorded the highest Dissolved silicon (D-Si) content ($20.538 \text{ mg kg}^{-1}$) which is statistically at par with BC ($20.302 \text{ mg kg}^{-1}$) and which is statistically superior to SRD ($14.385 \text{ mg kg}^{-1}$). At harvest no significant differences among the treatments were recorded. The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted at 60 DAS in highest Dissolved silicon (D-Si) content of A1B2 ($25.220 \text{ mg kg}^{-1}$) while being statistically superior over all other interaction effects. At 90 DAS in highest Dissolved silicon (D-Si) content of A1B1 ($23.053 \text{ mg kg}^{-1}$) which is statistically at par A1B2, A1B3, and while being statistically superior to A2B3, A2B2, A3B2, A3B1, A2B1. At harvest no significant differences among the treatments were recorded (Table 8). According to Narayanswamy and Prakash (2009, 2010), the critical levels and categorization of available Si (mg kg^{-1}) using 0.01 M CaCl_2 extractant are as follows: critical limit = 43 mg kg^{-1} , categorization: Low ($< 42 \text{ mg kg}^{-1}$), Medium ($42\text{--}65 \text{ mg kg}^{-1}$), and High ($> 65 \text{ mg kg}^{-1}$).

Table 8 Interaction of application methods of phosphorus and silicon on dissolved silicon

Treatments	Calcium Chloride extractable soil available silicon (mg kg ⁻¹)		
	60 DAS	90 DAS	At harvest
Factor 1 (Phosphorus)			
A ₁ -BC	22.578	22.561	23.653
A ₂ -BP	18.633	19.494	16.295
A ₃ -SRD	18.144	13.170	17.041
S.E.(m)	0.399	0.742	0.382
C.D.(p≤0.05)	1.196	2.223	1.144
Factor 2 (Silicon)			
B ₁ -BC	18.973	20.302	19.663
B ₂ -BP	21.032	20.538	18.526
B ₃ -SRD	19.350	14.385	18.800
S.E.(m)	0.399	0.742	0.382
C.D.(p≤0.05)	1.196	2.223	NS
Phosphorus × Silicon	60 DAS	90 DAS	At Harvest
A1B1	23.085	23.053	24.142
A1B2	25.220	22.363	24.474
A1B3	19.429	22.267	22.343
A2B1	17.217	18.900	17.287
A2B2	19.333	19.750	15.141
A2B3	19.349	19.833	16.456
A3B1	16.616	18.953	17.559
A3B2	18.542	19.500	15.963
A3B3	19.273	1.056	17.602
SEm ±	0.691	1.285	0.661
CD (P≤0.05)	2.071	3.851	NS

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

BC-Broadcasting, BP – Band placement, SRD – Seedling Root Dip

3.3 Yield parameters

3.3.1 Grain yield

Band placement recorded the highest grain yield for factor-1 (phosphorus) at 2651 kg/ha, which is statistically superior to both broadcasting at 2255 kg/ha and seedling root dip at 1987 kg/ha (Table 9). Similarly, for factor-2 (silicon), band placement also resulted in the highest grain yield at 2651 kg/ha, outperforming both broadcasting at 2255 kg/ha and seedling root dip at 1987 kg/ha. The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) produced the highest grain yield with the A2B2 combination at 2967 kg/ha, which is statistically comparable to A2B1 at 2879 kg/ha and superior to the other combinations: A1B2, A1B1, A3B2, A2B3, A1B3, A3B3, and A3B1.

Table 9. Interaction of application methods of phosphorus and silicon on grain yield, Stover yield and biological yield of finger millet

Treatments		Yield (kg ha ⁻¹)		
		Grain Yield	Stover Yield	Biological Yield
Factor 1 (Phosphorus)				
A ₁ -BC		2255	3776	6031
A ₂ -BP		2651	4222	6874
A ₃ -SRD		1987	3328	5316
S.E.(m)		45.819	75.095	120.903
C.D.(p≤0.05)		137.346	225.101	362.413
Factor 2 (Silicon)				
B ₁ -BC		2331	3800	6131
B ₂ -BP		2569	4187	6756
B ₃ -SRD		1994	3340	5334
S.E.(m)		45.819	75.095	120.903
C.D.(p≤0.05)		137.346	225.101	362.413
Phosphorus× Silicon		Grain Yield	Stover Yield	Biological Yield
A1B1		2325	3956	6281
A1B2		2465	4107	6572
A1B3		1976	3265	5241
A2B1		2879	4435	7314
A2B2		2967	4665	7632
A2B3		2108	3567	5675
A3B1		1789	3008	4797
A3B2		2276	3789	6065
A3B3		1898	3187	5085
SEm ±		79.362	130.068	209.411
CD (P≤0.05)		237.890	389.886	627.718

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

BC-Broadcasting, BP – Band placement, SRD – Seedling Root Dip

3.3.2 Stover yield

Band placement recorded the highest stover yield for factor-1 (phosphorus) at 4222 kg/ha, which is statistically superior to both broadcasting at 3776 kg/ha and seedling root dip at 3328 kg/ha (Table 9). Similarly, for factor-2 (silicon), band placement resulted in the highest stover yield at 4187 kg/ha, surpassing both broadcasting at 3800 kg/ha and seedling root dip at 3340 kg/ha. The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) produced the highest stover yield with the A2B2 combination at 4665 kg/ha, which is statistically comparable to A2B1 at 4435 kg/ha, and superior to the other combinations: A1B2, A1B1, A3B2, A2B3, A1B3, A3B3, and A3B1.

3.3.3 Biological yield

Band placement recorded the highest biological yield in the factor-1 (phosphorus) of 6874 kg ha⁻¹ which is statistically superior to both broadcasting (6031 kg ha⁻¹) and seedling root dip (5316 kg ha⁻¹) (Table 9). Band placement recorded the highest biological yield in the factor-2 (silicon) of 6756 kg ha⁻¹ which is statistically superior to both broadcasting (6131 kg ha⁻¹) and seedling root dip (5334 kg ha⁻¹). The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted in highest biological yield of A2B2 (7632 kg ha⁻¹) which is statistically at par with A2B1 (7314 kg ha⁻¹) and which is statistically superior to A1B2, A1B1, A3B2, A2B3, A1B3, A3B3, and A3B1 (Table 9).

3.4 Nutrient content in different parts of plant

3.4.1 P and Si content in grains

In terms of factor-1 (phosphorus) in grains SRD recorded the highest P content of (0.197%) which is statistically at par BP (0.196%) and which is statistically superior to BC (0.175%). In grains BP recorded the highest Si content of (0.412%) which is statistically at par BC (0.396%) and which is statistically superior to SRD (0.389%). In terms of factor-1 (silicon) in grains SRD recorded the highest P content of (0.197%) which is statistically at par BP (0.192%) and which is statistically superior to BC (0.179%). In grains BC recorded the highest Si content of (0.407%) which is statistically at par SRD (0.407%) and which is statistically superior to BP (0.384%). The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted in grains highest P content of A3B3 (0.215%) which is statistically at par A2B1, A2B2, A1B3, and A3B2 and which is statistically superior to A3B1, A1B2, A2B3 and A1B1. In grains, the highest Si content is A2B3 (0.424%), which is statistically at par with A1B3, A2B1, A3B1, A1B1, and A2B2, while being statistically superior to A3B2, A1B2, and A3B3 (Table 10).

Table 10 Interaction of application methods of phosphorus and silicon on total phosphorus and silicon content in grains of finger millet

Treatments	Grain (%)	
	P	Si
Factor 1 (Phosphorus)		
A ₁ -BC	0.175	0.396
A ₂ -BP	0.196	0.412
A ₃ -SRD	0.197	0.389
S.E.(m)	0.004	0.006
C.D.(p≤0.05)	0.013	0.018
Factor 2 (Silicon)		
B ₁ -BC	0.179	0.407
B ₂ -BP	0.192	0.384
B ₃ -SRD	0.197	0.406
S.E.(m)	0.004	0.006
C.D.(p≤0.05)	0.013	0.018
Phosphorus × Silicon	P	Si
A1B1	0.149	0.392
A1B2	0.179	0.373
A1B3	0.198	0.422
A2B1	0.205	0.420
A2B2	0.203	0.391
A2B3	0.179	0.424
A3B1	0.182	0.409
A3B2	0.195	0.387
A3B3	0.215	0.372
SEm ±	0.007	0.010
CD (P≤0.05)	0.022	0.031

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

3.4.2 P content in stover at 60DAS, 90DAS, and at harvesting stage

In terms of factor-1 (phosphorus) at 60 DAS BC recorded the highest P content in stover of (0.140%) which is statistically superior to both BP (0.085%) and SRD (0.045%). At 90 DAS BC recorded the highest P content in stover of (0.077%) which is statistically superior to both BP (0.068%) and SRD (0.048%). At harvest no significant differences among the treatments were recorded. In terms of factor-1 (silicon) at 60 DAS BP recorded the highest P content in stover of (0.105%) which is statistically superior to both BC (0.096%) and SRD (0.069%). At 90 DAS SRD recorded the highest P content in stover of (0.069%) which is statistically superior to both BP (0.062%) and BC (0.062%). at harvest BP recorded the highest P content in stover of (0.62%) which is statistically superior to both BC (0.057%) and SRD (0.052%). The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted at 60 DAS in highest P content in stover of A1B2 (0.169%) which is statistically at par A1B1 (0.164%), while being statistically superior to A2B2, A1B3, A2B1, A2B3, A3B3, A3B1, and A3B2. At 90 DAS in highest P content in stover of A1B3 (0.095%) while being statistically superior over all other interaction effect. By the at harvesting stage in highest P content in stover of A3B2 (0.090%) while being statistically superior over all other interaction effect (Table 11).

Table 11 Interaction of application methods of phosphorus and silicon on total phosphorus content in stover finger millet

Treatments	Total P content in stover (%)		
	60 DAS	90 DAS	At harvest
Factor 1 (Phosphorus)			
A ₁ -BC	0.140	0.077	0.058
A ₂ -BP	0.085	0.068	0.055
A ₃ -SRD	0.045	0.048	0.059
S.E.(m)	0.002	0.002	0.001
C.D.(p≤0.05)	0.006	0.005	NS
Factor 2 (Silicon)			
B ₁ -BC	0.096	0.062	0.057
B ₂ -BP	0.105	0.062	0.062
B ₃ -SRD	0.069	0.069	0.052
S.E.(m)	0.002	0.002	0.001
C.D.(p≤0.05)	0.006	0.005	0.004
Phosphorus × Silicon	60 DAS	90 DAS	At Harvest
A1B1	0.164	0.061	0.061
A1B2	0.169	0.075	0.050
A1B3	0.089	0.095	0.063
A2B1	0.082	0.086	0.067
A2B2	0.111	0.054	0.045
A2B3	0.062	0.063	0.051
A3B1	0.043	0.039	0.043
A3B2	0.035	0.055	0.090
A3B3	0.057	0.050	0.043
SEm ±	0.004	0.003	0.002
CD (P≤0.05)	0.011	0.008	0.007

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

BC-Broadcasting, BP – Band placement, SRD – Seedling Root Dip

3.4.2 Si content in stover at 60DAS, 90DAS, and at harvesting stage

In terms of factor-1 (phosphorus) at 60 DAS BP recorded the highest Si content in stover of (1.958%) which is statistically superior to both SRD (1.844%) and BC (1.832%). At harvest no significant differences among the treatments were recorded. At harvest BP recorded the highest Si content in stover of (2.098%) which is statistically superior to both BC (2.027%) and SRD (2.005%). In terms of factor-2 (silicon) no significant differences were seen at 60 DAS, 90 DAS and harvest. The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted whereas at 60 DAS no significant differences among the treatments were recorded. At 90 DAS, the highest Si content in the stover is A1B3 (2.151%), which is statistically at par with A1B2, A2B3, A3B1, A2B1, A3B3, and A2B2, while being statistically superior to A1B1 and A2B3. whereas at harvest, no significant differences among the treatments were recorded (Table 12).

Table 12 Interaction of application methods of phosphorus and silicon on total silicon content in stover finger millet

Treatments	Total Si content in Stover (%)		
	60 DAS	90 DAS	At harvest
Factor 1 (Phosphorus)			
A ₁ -BC	1.832	2.098	2.027
A ₂ -BP	1.958	2.009	2.098
A ₃ -SRD	1.844	2.074	2.005
S.E.(m)	0.035	0.025	0.021
C.D.(p≤0.05)	0.106	NS	0.064
Factor 2 (Silicon)			
B ₁ -BC	1.842	2.051	2.061
B ₂ -BP	1.897	2.090	2.044
B ₃ -SRD	1.895	2.040	2.025
S.E.(m)	0.035	0.025	0.021
C.D.(p≤0.05)	NS	NS	NS
Phosphorus × Silicon	60 DAS	90 DAS	Harvest
A1B1	1.788	1.999	2.034
A1B2	1.858	2.145	2.025
A1B3	1.849	2.151	2.022
A2B1	1.915	2.075	2.126
A2B2	1.947	2.033	2.086
A2B3	2.011	1.918	2.083
A3B1	1.822	2.079	2.023
A3B2	1.886	2.091	2.021
A3B3	1.824	2.052	1.971
SEm ±	0.061	0.043	0.037
CD (P≤0.05)	NS	0.128	NS

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

3.5 Nutrient uptakes

3.5.1 Plant P uptake at 60DAS, 90DAS, and harvesting stage

In terms of factor-1 (phosphorus) in grains BP recorded the P uptake (5.24 kg ha^{-1}) which is statistically superior to both BC (3.94 kg ha^{-1}) and SRD (3.94 kg ha^{-1}). In stover no significant differences among the treatments were recorded. In total BP recorded the highest P uptake (7.55 kg ha^{-1}) which is statistically superior to both BC (6.12 kg ha^{-1}) and SRD (5.97 kg ha^{-1}). In terms of factor-2 (silicon) in grains BP recorded the P uptake (4.96 kg ha^{-1}) which is statistically at par BC (4.22 kg ha^{-1}) which is statistically superior to SRD (3.93 kg ha^{-1}). In stover BP recorded the highest P uptake (2.54 kg ha^{-1}) which is statistically superior to both BC (2.24 kg ha^{-1}) and SRD (1.76 kg ha^{-1}). In total BP recorded the highest P uptake (7.50 kg ha^{-1}) which is statistically superior to both BC (6.46 kg ha^{-1}) and SRD (5.69 kg ha^{-1}). The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted in grains highest P uptake of A2B2 (6.02 kg ha^{-1}) which is statistically at par, A2B1, and which is statistically superior to A3B1, A1B2, A2B3, A1B3, A3B2, A3B3, and A1B1. In stover the highest P uptake is A3B2 (3.42 kg ha^{-1}), which is statistically at par with A2B1, and while being statistically superior to A1B1, A3B1, A2B2, A2B2, A1B2, A1B3, and A3B3. In total recorded the highest P uptake BP recorded the highest P uptake A2B1 ($108.92 \text{ kg ha}^{-1}$), which is statistically at par with A2B2, and A3B2 while being statistically superior to A3B1, A1B1, A2B2, A1B2, A1B3, and A3B3 (Table 13).

Table 13. Interaction of application methods of phosphorus and silicon on phosphorus uptake in finger millet

Treatments	Phosphorus uptake (kg/ha)		
	Grain	Stover	Total
Factor 1 (Phosphorus)			
A ₁ -BC	3.94	2.19	6.12
A ₂ -BP	5.24	2.31	7.55
A ₃ -SRD	3.94	2.04	5.97
S.E.(m)	0.184	0.097	0.280
C.D.(p≤0.05)	0.553	NS	0.839
Factor 2 (Silicon)			
B ₁ -BC	4.22	2.24	6.46
B ₂ -BP	4.96	2.54	7.50
B ₃ -SRD	3.93	1.76	5.69
S.E.(m)	0.184	0.097	0.280
C.D.(p≤0.05)	0.553	0.292	0.839
Phosphorus × Silicon	Grain	Stover	Total
A1B1	3.47	2.42	5.88
A1B2	4.42	2.08	6.50
A1B3	3.93	2.07	5.99
A2B1	5.92	2.99	8.91
A2B2	6.02	2.12	8.14
A2B3	3.78	1.82	5.60
A3B1	3.27	1.31	4.57
A3B2	4.45	3.42	7.86
A3B3	4.10	1.39	5.49
SEm ±	0.319	0.169	0.485
CD (P≤0.05)	0.957	0.506	1.453

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

3.5.2 Plant Si uptake at 60DAS, 90DAS, and harvesting stage

In terms of factor-1 (phosphorus) in grains BP recorded the Si uptake (10.84 kg ha^{-1}) which is statistically superior to both BC (8.91 kg ha^{-1}) and SRD (7.68 kg ha^{-1}). In stover BP recorded the highest Si uptake (88.61 kg ha^{-1}) which is statistically superior to both BC (76.42 kg ha^{-1}) and SRD (66.78 kg ha^{-1}). In total BP recorded the highest Si uptake (99.45 kg ha^{-1}) which is statistically superior to both BC (85.33 kg ha^{-1}) and SRD (74.46 kg ha^{-1}). In terms of factor-2 (silicon) in grains BP recorded the Si uptake (10.84 kg ha^{-1}) which is statistically at par BC (9.52 kg ha^{-1}) which is statistically superior to SRD (8.12 kg ha^{-1}). In stover BP recorded the highest Si uptake (85.67 kg ha^{-1}) which is statistically superior to both BC (78.47 kg ha^{-1}) and SRD (67.68 kg ha^{-1}). In total recorded the highest Si uptake BP recorded the highest Si uptake (95.47 kg ha^{-1}) which is statistically superior to both BC (87.98 kg ha^{-1}) and SRD (75.80 kg ha^{-1}).

The interaction effect of factor-1 (phosphorus) and factor-2 (silicon) resulted in grains highest Si uptake of A2B1 (12.08 kg ha^{-1}) which is statistically at par, A2B2, and which is statistically superior to A3B1, A1B2, A2B3, A1B3, A3B2, A3B3, and A1B1. In stover the highest Si Uptake is A2B2 (97.38 kg ha^{-1}), which is statistically at par with A2B1, and while being statistically superior to A3B2, A3B1, A1B1, A2B2, A1B2, A1B3, and A3B3. In total recorded the highest Si uptake BP recorded the highest Si uptake A2B2 ($108.92 \text{ kg ha}^{-1}$), which is statistically at par with A2B1, and while being statistically superior to A3B2, A3B1, A1B1, A2B2, A1B2, A1B3, and A3B3 (Table 14).

Table 14. Interaction of application methods of phosphorus and silicon on silicon uptake in finger millet

Treatments	Si Uptake (kg/ha)		
	Grain	Stover	Total
Factor 1 (Phosphorus)			
A ₁ -BC	8.91	76.42	85.33
A ₂ -BP	10.84	88.61	99.45
A ₃ -SRD	7.68	66.78	74.46
S.E.(m)	0.181	1.567	1.692
C.D.(p≤0.05)	0.543	4.698	5.073
Factor 2 (Silicon)			
B ₁ -BC	9.52	78.47	87.98
B ₂ -BP	9.80	85.67	95.47
B ₃ -SRD	8.12	67.68	75.80
S.E.(m)	0.181	1.567	1.692
C.D.(p≤0.05)	0.543	4.698	5.073
Phosphorus × Silicon	Grain	Stover	Total
A1B1	9.28	80.35	89.63
A1B2	9.21	82.97	92.18
A1B3	8.24	65.95	74.19
A2B1	12.08	94.25	106.33
A2B2	11.54	97.38	108.92
A2B3	8.91	74.20	83.11
A3B1	7.20	60.80	67.99
A3B2	8.64	76.66	85.30
A3B3	7.21	62.88	70.09
SEm ±	0.314	2.715	2.931
CD (P≤0.05)	0.941	8.137	8.787

A1, A2 and A3 – Methods of application of phosphorus fertilizer

B1, B2 and B3 – Methods of application of silicon fertilizer

4 Discussions

4.1 Effect of application methods on nutrient availability

The P-BC method was proven to be the most effective compared to BP and SRD at 60 DAS, 90 DAS, and harvesting stage in terms of Adsorbed silicon (Ad-Si) and Dissolved silicon (D-Si). It was found that, similar to the results of a comparative assessment of various silicon sources for enhancing soil quality and crop productivity, applying calcium silicate increased soil pH, available silicon content, nutrient levels, as well as rice growth and yield in acidic soils (Narayanaswamy and Prakash, 2010; Rajimol et al., 2019a,b; Sandhya and Prakash, 2016; Yogendra et al., 2015). At 60 DAS, BC was proven to be the most effective compared to SRD and BP in terms of soil available nitrogen (N). However, at 90 DAS, SRD showed the highest N compared to BC and BP. At the harvesting stage, no significant variation was found among treatments. At 60 DAS, SRD was proven to be the most effective compared to BP and BC in terms of soil available phosphorus (P), soil available potassium (K). At 90 DAS, BP was proven to be the most effective compared to BC and SRD in terms of P. By the harvesting stage, SRD was proven to be the most effective compared to BP and BC in terms of P. At 90 DAS, SRD was proven to be the most effective compared to BP and BC in terms of K. At the harvesting stage, BC was proven to be the most effective compared to BP and SRD in terms of K.

The Si-BP method was proven to be the most effective compared to BC and SRD at 60 DAS, 90 DAS, and harvesting stage in terms of Adsorbed silicon (Ad-Si) and Dissolved silicon (D-Si). By the harvesting stage no significant variation was found among the treatments in terms of Dissolved silicon (D-Si). At 60 DAS, BP was proven to be the most effective compared to BC and SRD in terms of P, and K. At 90 DAS SRD was proven to be the most effective compared to BC and BP in terms of P. By at the harvesting stage, BC was proven to be the most effective compared to BP and SRD in terms of N, P, and K. Our study agrees with Subramanian and Gopalswamy (1991) that adding silicon to soil increases nitrogen availability. Moreover, higher silicon levels lead to more phosphorus in soil, as it becomes more easily available and not retained by soil, making phosphatic fertilizer more effective. At 60 DAS, BC was proven to be the most effective compared to BP and SRD in terms of N. At 90 DAS, BC was proven to be the most effective compared to BP and SRD in terms of K.

The interaction between P-BC and Si-BP was proven to be the most effective compared to all other interactions at 60 DAS, 90 DAS, and harvesting stage in terms of Acetic acid extractable soil available silicon. The interaction between P-BC and Si-BP was proven to be the most effective compared to all other interactions at 60 DAS, in terms of calcium chloride extractable soil available silicon. However, at 90 DAS, the interaction between P-BC and Si-BC was proven to be the most effective compared to all other interactions in terms of calcium chloride extractable soil available silicon. By the harvesting stage, no significant variation was found among the treatments in terms of calcium chloride extractable soil available silicon. The interaction between P-BC and Si-BC was proven to be the most effective compared

to all other interactions at 60 DAS, in terms of N. However, at 90 DAS and harvesting stage, the interaction between P-SRD and Si-SRD was proven to be the most effective compared to all other interactions in terms of N. The interaction between P-SRD and Si-BP was proven to be the most effective compared to all other interactions at 60 DAS, in terms of P. However, at 90 DAS, the interaction between P-BP and Si-SRD was proven to be the most effective compared to all other interactions in terms of P. By the harvesting stage, the interaction between P-SRD and Si-SRD was proven to be the most effective compared to all other interactions in terms of P. It was found that similar to the results of Li et al. (2019) and Schaller et al. (2021), silicon helps increase the availability of phosphorus in soil through pH changes, due to competition between P and Si. The interaction between P-BP and Si-BP was proven to be the most effective compared to all other interactions at 60 DAS, in terms of K. However, at 90 DAS and harvesting stage, the interaction between P-BC and Si-BC was proven to be the most effective compared to all other interactions in terms of K.

4.2 Effect of application methods on nutrient content and uptake by plant

The phosphorus band placement (BP) method was proven to be the most effective compared to broadcasting (BC) and seedling root dip (SRD) at 60 DAS and 90 DAS, in terms of total phosphorus (P) content in stover. Similarly, the silicon BP method was proven to be the most effective compared to BC and SRD at 60 DAS and the harvesting stage, in terms of total phosphorus (P) content in stover. However, at 90 DAS, SRD showed the highest P content in stover compared to BC and BP. The interaction between P-BC and Si-BC was proven to be the most effective compared to all other interactions at 60 DAS, in terms of P content in stover. However, at 90 DAS, the interaction between P-BC and Si-SRD showed the highest P content in stover compared to all other interactions. By the harvesting stage, the interaction between P-SRD and Si-BP was proven to be the most effective compared to all other interactions.

Additionally, the silicon BP method was proven to be the most effective compared to BC and SRD at 60 DAS and the harvesting stage, in terms of total silicon (Si) content in stover. The interaction between P-BC and Si-SRD was proven to be the most effective compared to all other interactions at 90 DAS, in terms of P content in stover.

In terms of grain content, the phosphorus SRD method was proven to be the most effective compared to BP and BC in terms of total P content. The phosphorus BP method was proven to be the most effective compared to BC and SRD in terms of total Si content. The silicon SRD method was proven to be the most effective compared to BP and BC in terms of total P content, while the silicon BC method was proven to be the most effective compared to SRD and BP in terms of total Si content. The interaction between P-SRD and Si-SRD was proven to be the most effective compared to all other interactions in P content in grains. However, the interaction between P-BP and Si-SRD showed the highest Si content in grains compared to all other interactions. This study had similar findings to Neeru *et al.* (2019), which showed that silicon (Si) nutrition increased the levels of phosphorus (P), calcium (Ca), and magnesium (Mg) in rice plants.

Phosphorus (P) and silicon (Si) uptake through phosphorus band placement (BP) and silicon band placement (BP) was proven to be the most effective compared to broadcasting (BC) and seedling root dip (SRD) in terms of grain, stover, and total. This study agrees with Zhang et al. (2019) that silicon helps plants grow when phosphorus is scarce. Silicon fertilization increases phosphorus uptake in plants, which has been widely reported. The uptake of P in the interaction between P-BP and Si-BP was proven to be the most effective compared to all other interactions in grains. However, in stover and total, the interaction between P-BP and Si-BC showed the highest P uptake compared to all other interactions. Similarly, Si uptake in the interaction between P-BP and Si-BC was proven to be the most effective compared to all other interactions in grains, while in stover and total, the interaction between P-BP and Si-BP showed the highest Si uptake compared to all other interactions. This study found similar results to Cuong's (2017) study, which showed that applying silicon (Si) with the recommended amount of fertilizer significantly improved the uptake of Si, N, P, and K nutrients in rice plants and grains. The application of silicon greatly enhanced the uptake of nitrogen, phosphorus, and potassium in rice plants, aligning with previous studies by Pati et al. (2016) and Crooks and Prentice (2017).

The phosphorus band placement (BP) method was proven to be the most effective compared to broadcasting (BC) and seedling root dip (SRD) in yield (grain, stover and biological yield). Similarly, silicon band placement (BP) method was proven to be the most effective compared to broadcasting (BC) and seedling root dip (SRD) in yield (grain, stover and biological yield). The interaction between phosphorus-BP and silicon-BP was proven to be most effective compared to BC and SRD in yield (grain, stover and biological yield). Hence, it was found that similar to the results of Patra and Neue (2010), the amount of phosphorus and silicon in rice plants during the early growth stage has a significant impact on the eventual rice yield. Our results match those of previous studies (Prakash et al., 2011; Pati et al., 2016), indicating that silicon positively affects growth and yield, leading to increased grain and straw production.

5 Conclusions

In conclusion, this study compared the effects of P and Si nutrients on plant growth, yield, and soil parameters across different application methods: BC, BP and SRD. The results showed that the combination of P and Si applied through BP (A2B2) achieved the highest plant parameters, grain yield, and straw yield, nutrient uptake (P and Si) similar to the combination of P through band placement and Si through BC (A2B1). Additionally, the study revealed that the combination of P and Si applied through seedling root dip (A3B3) resulted in the highest available soil parameters, including nitrogen, phosphorus, potassium, and available silicon, similar to the combination of P through seedling root dip and Si through band placement (A3B2).

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review paper.

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Authors' contributions:

Dinesh Choudhary- Conducting field experiment, collection of soil and plant samples, Data analysis, writing-original draft; **Sabyasachi Majumdar**: Conceptualization, Implementation of field experiment, Data analysis, review and editing. **Dwipendra Thakuria**: Conceptualization, Review, editing and supervision. Pranab Dutta: Suggestions and Supervision of the work; **Pranab Dutta**: Review, editing and supervision; **Pallavi Thimappa**: Analysis of Silicon content and editing; **Nagabovanalli Basavarajappa Prakash**: Review, editing and supervision. All authors read and approved the final manuscript.

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“Data availability” statements:

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Figures

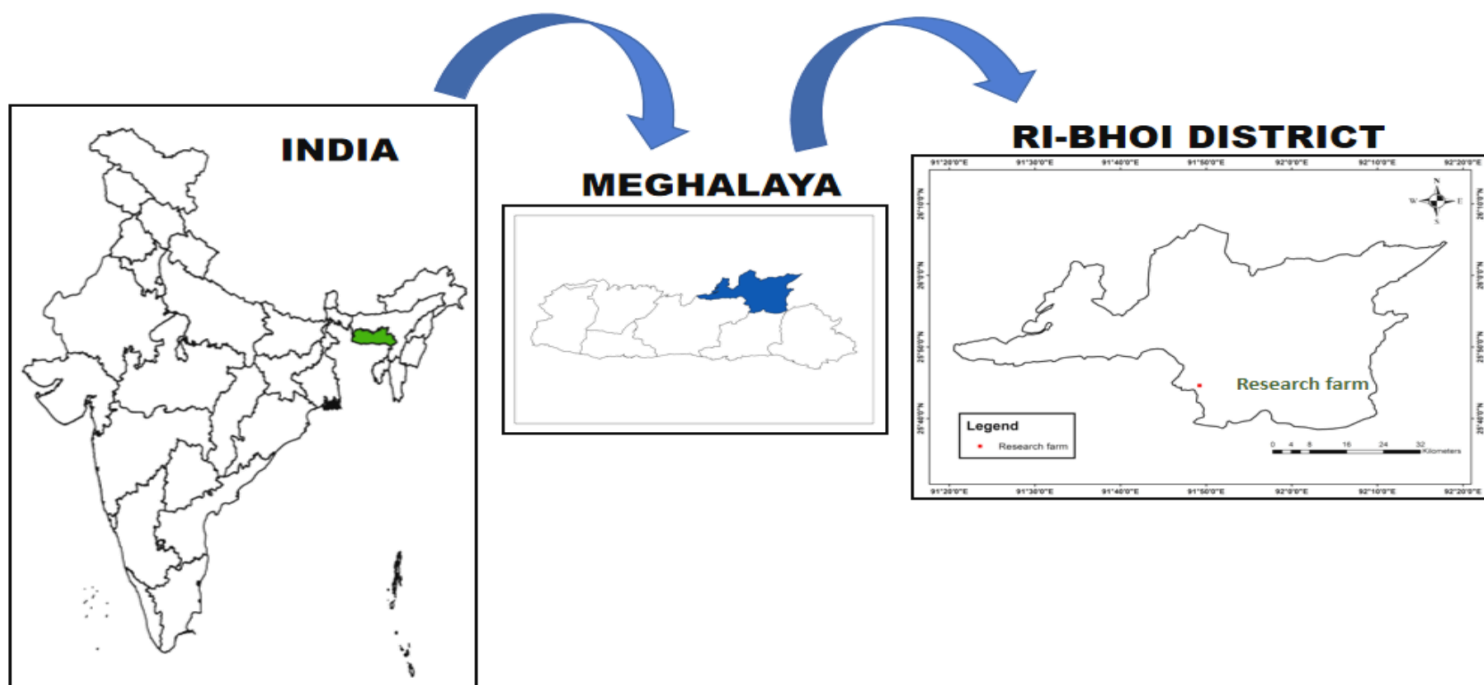


Figure 1

Location of the field experiment

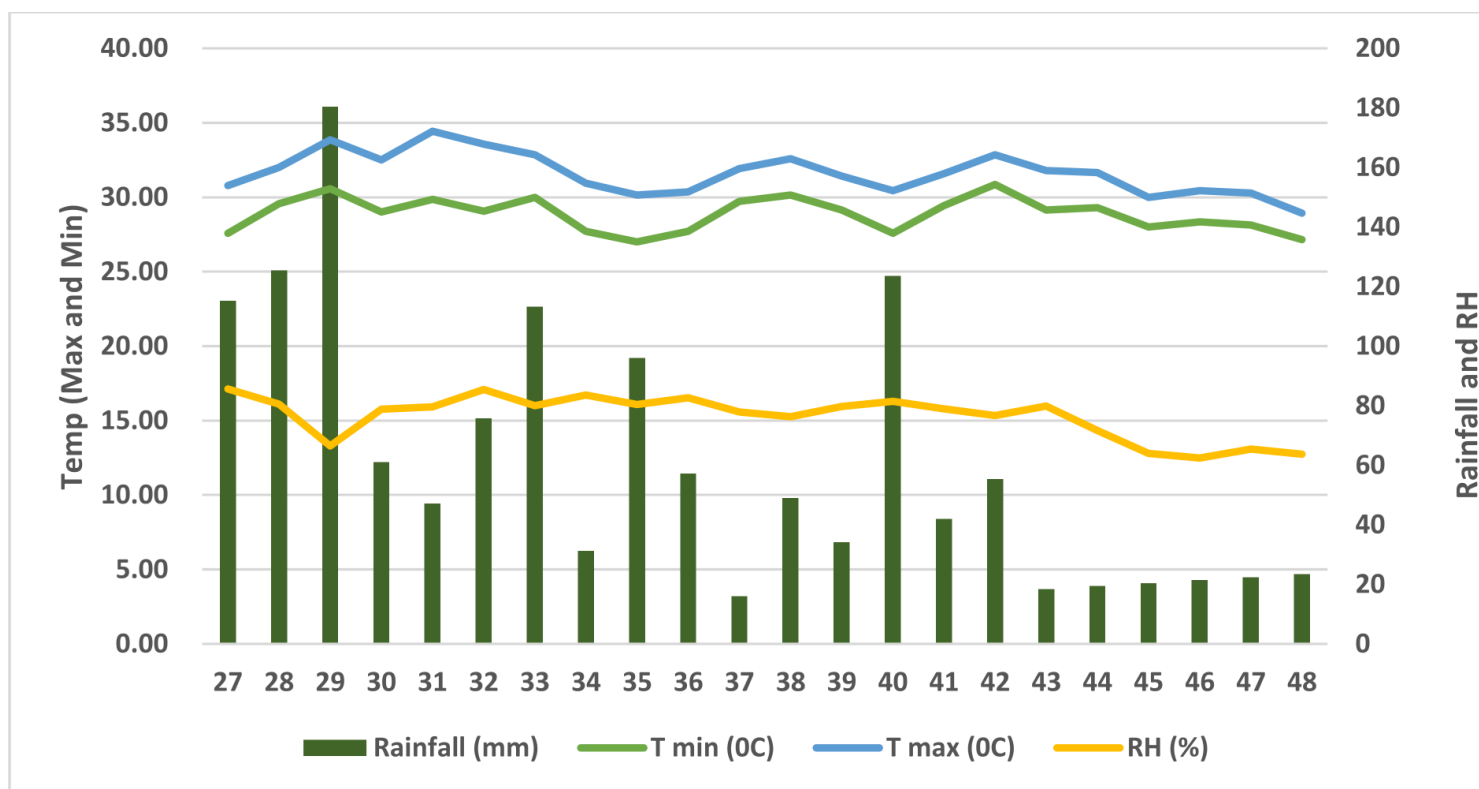


Figure 2

Weather condition during the field experiment (July, 2023 to November, 2023)