Optimizing Wheat Growth and Yield: The Synergistic Effects of Nitrogen and Silicon Levels

Abstract

Enhancing wheat production is essential to meet global food security needs, especially in sustainable agriculture. Among nutrient management practices, Nitrogen (N) and Silicon (Si) are known to improve growth and stress resilience in crops. However, while the individual effects of N and Si on crop performance are well-documented, limited research has explored their combined influence on wheat growth and yield. This study aimed to address this gap by evaluating the synergistic effects of N and Si fertilizer levels on wheat agronomic performance. A field experiment was conducted at the Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh, from November 2022 to March 2023. The experiment utilized wheat variety BWMRI 3 in a two-factor Randomized Complete Block Design (RCBD) with three replications. Treatments consisted of four N levels (0, 80, 120, and 160 kg N ha^{-1}) and four Si levels (0, 100, 150, and 200 kg Si ha^{-1}). Statistical analyses using R programming revealed that the combination of 120 kg N ha^{-1} and 150 kg Si ha^{-1} (N_2:S_2) resulted in the highest growth and yield performance, including a 48.32% increase in tiller number, 33.63% improvement in effective spikelets, 12.97% increase in 1000-grain weight, 34.54% rise in grain yield, and a 15.88% increase in biological yield compared to the control (without N and Si). The findings indicate that the combined application of 120 kg N ha^{-1} and 150 kg Si ha^{-1} significantly enhanced wheat growth and yield, suggesting that integrating these nutrient management practices is an effective strategy for optimizing wheat production, ultimately contributing to both higher yields and sustainable agriculture.

Keywords: wheat production, food security, biological yield, nutrient management

1.Introduction

Wheat plays a crucial role in global food security, serving as a staple food crop that sustains billions of people worldwide [1]. With global wheat demand projected to reach 840 million tons by 2050, compared to the current production of 750 million tons, there is a pressing need for a 77% increase in output, particularly in developing countries, which will primarily be achieved by enhancing yield per unit area [2].

Effective nutrient management is fundamental to sustainable wheat production, ensuring optimal soil fertility and enhancing nutrient use efficiency—both crucial for maintaining soil health and improving crop productivity. Agronomic practices that focus on balancing nutrient inputs, especially Nitrogen (N) and Silicon (Si), are essential as they significantly influence key physiological and biochemical processes that drive plant growth and yield. N, as a primary macronutrient, plays a pivotal role in protein synthesis, chlorophyll formation, and overall plant vigor, directly affecting wheat's growth, development, and grain yield [3, 4]. However, efficient N use must be managed carefully to prevent losses through leaching and volatilization, which not only reduce nutrient availability but also contribute to environmental issues such as water pollution and greenhouse gas emissions [5, 6].

AlthoughSi is often regarded as non-essential, research shows it can substantially enhance wheat's resilience to abiotic stresses like drought and salinity by fortifying plant cell walls and boosting photosynthetic efficiency.[7, 8].Si also facilitates nutrient uptake and helps reduce the toxicity of heavy metals in soil [9].Moreover, it plays a crucial role in enhancing plant growth by improving parameters such as plant height, leaf area, and root development, which contribute to overall plant health and higher yields [7]. It also strengthens disease resistance by fortifying cell walls, acting as a physical barrier against pathogens [8]. Additionally, Si boosts photosynthetic efficiency by enhancing leaf structure and minimizing water loss, thereby promoting better growth and productivity [9]. Furthermore, it optimizes nutrient uptake, ensuring plants have access to essential elements for optimal development [10]. Integrating these nutrients through precise management practices has the potential to enhance wheat's resilience and yield, contributing to both agricultural sustainability and environmental protection.

While extensive research has documented the individual roles of nitrogen and silicon in enhancing wheat growth and yield, few studies explore their combined influence. Limited research examines how N and Si interact to affect wheat's physiological attributes, growth- and yield-related traits, and overall productivity, leaving a gap in understanding the potential of integrated nutrient strategies to maximize wheat agronomic performance and yield. Therefore, this study aims to explore the interaction between N and Si, specifically focusing on their integrated effect on the growth attributes and yield of wheat. To achieve this, a two-factor randomized complete block design (RCBD) was implemented to test different levels of N and Si application in wheat crops.

2 Materials and methods

2.1 Experimental Location and Soil

The experiment was conducted at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh, from November 2022 to March 2023. The experimental site is located at 24.75°N latitude and 90.50°E longitude, at an elevation of 18 meters above sea level. The region experienced a subtropical climate, with high temperatures and heavy rainfall from May to October, followed by scant rainfall and cooler temperatures from October to March. The soil of the experimental site belongs to the Sonatala series, under the Old Brahmaputra Floodplain (AEZ-9). The initial soil's physicochemical properties are shown in Table 1 and Table 2.

Table 1 Chemical analysis of initial soil

Soil properties	Analytical contents	Methods
Soil pH	6.49	Glass electrode pH meter [11]
Organic carbon (%)	1.13	Wet oxidation [12]
Total N (%)	0.16	Semi-micro Kjeldahl [13]
Available potassium (K) (me/100g soil)	0.060	Ammonium acetate extraction [14]

Available phosphorus (P)(ppm)	4.17	Olsen [15]
Available sulfur (S)(ppm)	13.5	$CaCl_2$ extraction [16]
Available zinc (Zn)(ppm)	0.90	[17]
CEC (meq 100 g^{-1} soil)	15	Ammonium acetate method [18]

Table 2 Physical analysis of initial soil

Constituents	Results
Sand (%)	35.24
Silt (%)	58.72
Clay (%)	6.11
Textural class**[Hydrometer method, 19]**	Silty loam
Particle Density (Mg m^{-3})	2.6
Bulk Density (Mg m^{-3})	1.35
Porosity (%)	46.67

2.2 Experimental Design and Treatments

The experiment was conducted using wheat variety BWMRI3, following a two-factor Randomized Complete Block Design (RCBD) with three replications. A total of 48 plots, each measuring 2.5 m x 2.5m (5 m^2), were established. The treatments were randomly assigned to 16 unique plots, each replicated three times. The spacing between rows and columns was maintained at 100 cm and 50 cm, respectively.

The treatments consisted of two factors:

- **Factor A: N levels**

  1. N□: 0 kg N ha^{-1}(No N)
  2. N□: 80 kg N ha^{-1}
  3. N□: 120 kg N ha^{-1}

4. N□: 160 kg N ha^{-1}

- **Factor B: Si levels**

1. S□: 0 kg Si ha^{-1} (No Si)
2. S□: 100 kg Si ha^{-1}
3. S□: 150 kg Si ha^{-1}
4. S□: 200 kg Si ha^{-1}

2.3 Crop Management

The calculated amounts of phosphorus (P), potassium (K), zinc (Zn), sulfur (S), and one-third of the N fertilizer (urea) were evenly distributed across the plots according to the treatment combinations. The remaining two-thirds of urea were applied in two splits, at 20 and 40 DAS. Si in the form of Super Silica was applied uniformly across the plots based on the treatment specifications. The fertilizer sources were Urea (N), Triple Super Phosphate (TSP) for P, Muriate of Potash (MoP) for K, Zinc Sulfate ($ZnSO_4$) for Zn, Gypsum for S, and Super Silica(72% SiO_2) for Si.

Wheat seeds were sown at a rate of 120 kg ha^{-1}, with 10 rows per plot and a row-to-row distance of 20 cm. Essential intercultural practices such as weeding, thinning, and irrigation were performed as needed to ensure optimal crop growth. The crop was infested by cereal aphids and grasshoppers during the growing period, and to manage this, the experimental plots were sprayed with Diazinon 35 DAS to control the aphids.

2.4 Recording of yield and yield components

Key growth and yield-contributing characteristics, including plant height, tiller number, dry matter content, spikelets per spike, and 1000-grain weight, were recorded from five randomly selected plants in each plot and averaged. Grain yield was determined from a 1 m^2 area in the center of each plot and expressed in tons per hectare (t ha^{-1}) at 14% moisture content. Straw yield was measured based on sun-dried weight.

2.5 Statistical analysis

Analysis of variance (ANOVA) was performed for all measured parameters using F-statistics to determine the significance of the treatment effects. Mean values were calculated, and pairwise comparisons were assessed using the Tukey HSD test at a 5% significance level (Gomez, 1984). Data analysis was conducted using R programming software(R Studio, 2024.04.0+735).

3. Results

3.1 Yield-Contributing Traits of Wheat

The growth and yield-contributing traits of wheat varied significantly across different levels of N andSi application, as demonstrated in Tables 3 and 4.

3.1.1 Plant height

Plant height was significantly influenced by the application of both N and Si. The tallest plants (82.08 cm) were observed with the application of 120 kg N ha^{-1}, which was statistically similar to the plant height under 160 kg N ha^{-1}. In contrast, the shortest plants (75.77 cm) were recorded in the control (N_0). A similar trend was seen with Si levels, where the tallest plants (81.44 cm) were recorded at 150 kg Si ha^{-1} (S_2), statistically equivalent to 200 kg Si ha^{-1}(S_3), while the shortest plants (77.72 cm) were observed in the absence of Si fertilization (S_0).

3.1.2 Effective tillers plant^{-1}

This feature also followed a significant pattern. The maximum number of effective tillers (4.23) was obtained with 120 kg N ha^{-1}, a value comparable to that of 160 kg N ha^{-1}(N_3). On the other hand, the minimum number of tillers (3.04) was recorded in the control (N_0). Similarly, the application of 150 kg Si ha^{-1} resulted in the highest number of tillers (4.38), while the control (S_0) produced the fewest tillers (3.31).

3.1.3 Spike length

It was influenced by both N and Si levels. Spike length ranged from 10.14 cm under the control (N□) to 12.01 cm with 120 kg N ha^{-1} (N_2). In terms of Si, the longest spike length (12.02 cm) was recorded at 150 kg Si ha^{-1} (S_2), while the shortest (10.31 cm) occurred in the control (S_0).

3.1.4 Effective spikelets

When looking at effective spikelets per spike, the highest number (15.13) was observed in plants fertilized with 120 kg N ha^{-1}, a value statistically similar to that under 160 kg N ha^{-1}. Si also played a significant role, with the maximum number of effective spikelets (15.54) obtained at 150 kg Si ha^{-1}, while the control (S_0) produced the fewest spikelets (14.25).

3.1.5 1000-grain weight

Finally, the 1000-grain weight ranged from 42.64 g under the control (N_0) to 44.79 g in plants fertilized with 120 kg N ha^{-1}. A similar pattern was observed with Si application, where the highest 1000-grain weight (44.96 g) was recorded at 150 kg Si ha^{-1}, while the control (S_0) had the lowest value (42.13 g).

Table 3. Effect of N level on yield attributes of wheat

N level	Plant height (cm)	Effective tillers plant^{-1} (No.)	Spike length (cm)	Effective spikelets spike^{-1} (No.)	Sterile spikelets spike^{-1} (No.)	1000-grain weight (g)
N_0	75.77b	3.04b	10.14b	13.26b	0.98	42.64b
N_1	78.64ab	3.68ab	10.97ab	14.76a	0.85	44.08ab
N_2	82.08a	4.23a	12.01a	15.13a	0.76	44.79a
N_3	80.32a	3.95a	11.2ab	15.10a	0.82	43.43ab
Level of significance	*	**	*	*	NS	*
CV (%)	**6.71**	**11.44**	**14.17**	**11.82**	**14.42**	**7.01**

Means with the same letters or without letters within the same column do not differ significantly.
** = Significant at 1 % level of probability, * = Significant at 5 % level of probability, NS = Not significant
Here, N_0 = 0 kg N ha^{-1}, N_1 = 80 kg N ha^{-1}, N_2 = 120 kg N ha^{-1}, N_3 = 160 kg N ha^{-1}

Table 4.Effect of Si level on yield attributes of wheat

Si level	Plant height (cm)	Effective tillers plant^{-1}(No.)	Spike length (cm)	Effective spikelets spike^{-1} (No.)	Sterile spiketet spike^{-1}(No.)	1000-grain weight (g)
S_0	77.72b	3.31b	10.31b	14.25ab	0.97	42.13b
S_1	77.95ab	3.58b	10.74ab	13.57b	0.69	43.77ab
S_2	81.44a	4.38a	12.02a	15.54a	0.79	44.96a
S_3	79.71a	3.63b	11.25ab	14.87ab	0.96	44.07ab
Level of significance	*	*	*	*	**NS**	*
CV (%)	**6.71**	**11.44**	**14.17**	**11.82**	**14.42**	**7.01**

Means with the same letters or without letters within the same column do not differ significantly
*= Significant at 5 % level of probability,
NS = Not significant
S_0 = 0 kg Siha^{-1}, S_1 = 100 kg Siha^{-1}, S_2 = 150 kg Siha^{-1}, S_3= 200 kg Siha^{-1}.

3.2Interaction Effect of N and Si on Wheat Growth Attributes

The interaction between N and Si levels significantly impacted various growth attributes of wheat (Table 5). Notably, the combination of 120 kg N ha^{-1} and 150 kg Si ha^{-1} (N_2 :S_2) produced the tallest plants, reaching 86.87 cm, while the shortest plants (72.47 cm) were observed in the control interaction (N_0 :S_0) (16.57% increase over control).Moreover, the N_2 :S_2 interaction also resulted in the highest number of effective tillers per plant (5.43) (63.72% over control), the longest spike length (14.52 cm) (34.57% over control), the greatest number of effective spikelets per spike (16.83) (29.9% over control), and the heaviest 1000-grain weight (44.87 g) (9.09% over control).

Table 5. Interaction effect of N and Si levels on yield attributes of wheat

N: Si	Plant height (cm)	Total tillers plant^{-1} (No.)	Effective tillers plant^{-1} (No.)	Non-effective tillers plant^{-1} (No.)	Spike length (cm)	Effective spikelets spike^{-1} (No.)	1000-grain weight (g)
N_0 :S_0	72.47c	2.93d	1.97c	0.97	9.50b	11.77d	40.79c
N_0 :S_1	75.33bc	3.8cd	3.40b	0.40	9.84b	12.79cd	42.85c

N□:S□	76.35bc	4.00cd	3.47b	0.53	10.18b	14.39a-d	43.09bc
N□:S□	78.93a-c	3.8cd	3.32b	0.48	11.03b	14.07a-d	43.81a-c
N□:S□	79.2abc	4.00cd	3.60b	0.40	9.92b	14.38a-d	42.49c
N□:S□	79.47a-c	4.20c	3.80b	0.40	11.46b	14.83a-c	43.51a-c
N□:S□	79.53a-c	4.60a-c	4.07b	0.53	11.78b	15.00a-c	46.28ab
N□:S□	76.37bc	3.73cd	3.27bc	0.47	10.70b	14.80a-c	44.04a-c
N□:S□	79.07a-c	4.40bc	3.87b	0.53	10.81b	15.30a-c	42.63c
N□:S□	79.6a-c	4.13c	3.47b	0.67	10.93b	12.89cd	44.69a-c
N□:S□	86.87a	5.67a	5.43a	0.23	14.52a	16.83a	46.87a
N□:S□	82.8ab	4.40bc	4.13ab	0.27	11.78b	15.49a-c	44.96a-c
N□:S□	80.13a-c	4.60a-c	3.80b	0.80	10.99b	15.56a-c	42.61c
N□:S□	77.40bc	4.27bc	3.67b	0.60	10.71b	13.75b-d	44.04a-c
N□:S□	83.00ab	5.40ab	4.53ab	0.87	11.60b	15.95ab	43.59a-c
N□:S□	80.73a-c	4.53a-c	3.80b	0.73	11.49b	15.12a-c	43.48bc
Level of significance	*	*	*	**NS**	*	*	*
CV (%)	**6.71**	**16.23**	**11.44**	**13.49**	**14.17**	**11.82**	**7.01**

Means with the same letters or without letters within the same column do not differ significantly
* = Significant at 5 % level of probability, NS = Not significant
N□ = 0 kg N ha^{-1}, N_1 = 80 kg N ha^{-1}, N_2 = 120 kg N ha^{-1}, N_3 = 160 kg N ha^{-1};
S_0 = 0 kg $Siha^{-1}$, S_1 = 100 kg $Siha^{-1}$, S_2 = 150 kg $Siha^{-1}$, S_3 = 200 kg $Siha^{-1}$.

3.3Effect of N, Si, and Their Interaction on Dry Weight of Wheat

Dry weight per plant did not vary significantly at 20 and 40 days after sowing (DAS), but by 60 DAS, N application showed a significant effect at the 5% probability level (Figure 1). At this stage, plants treated with N produced a maximum dry weight of 9.69 g, while the absence of N (N_0) resulted in the lowest weight of 8.73 g.

Similarly, Si had no significant impact on dry weight at 20 and 40 DAS but became significant at 60 DAS. The highest dry weight of 10.62 g was observed under 150 kg Si ha^{-1} (S_2), whereas plants without Si (S_0) displayed the lowest dry weight at 8.17 g.

The interaction between N and Si levels showed a significant effect across all growth stages (Table 6). At 20, 40, and 60 DAS, the combination of 120 kg N ha^{-1} and 150 kg Si ha^{-1} (N_2S_2) produced the highest dry weights of 0.81 g (35.8% over control), 1.99 g (44.72% over control), and 11.58 g (45.85% over control), respectively. Conversely, the control treatment (N_0S_0) yielded the lowest values at each stage, with dry weights of 0.52 g, 1.10 g, and 6.27 g at 20, 40, and 60 DAS, respectively.

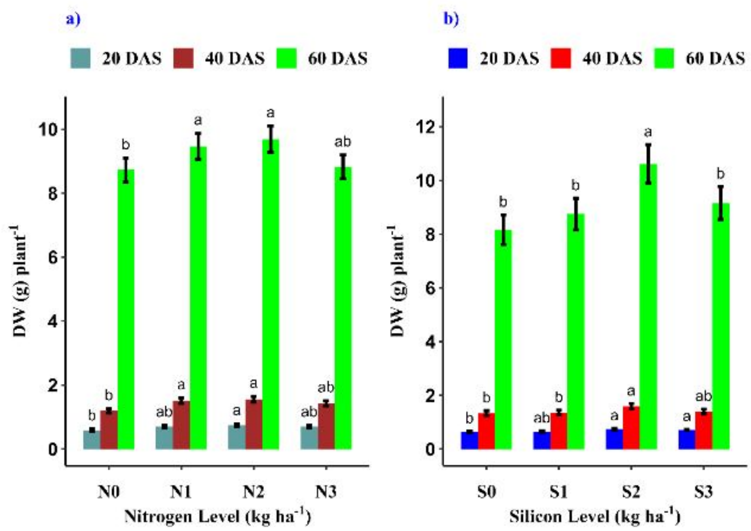

Figure 1 Dry weight (DW) of wheat as influenced by different levels of N and Si fertilizers. (a) N levels (kg ha^{-1}) and (b) Si levels (kg ha^{-1}).

(Data are presented as mean ± SE, n = 3; α=0.05)

N_0 = 0 kg N ha^{-1}, N_1 = 80 kg N ha^{-1}, N_2 = 120 kg N ha^{-1}, N_3 = 160 kg N ha^{-1};

S_0 = 0 kg Si ha^{-1}, S_1 = 100 kg Si ha^{-1}, S_2 = 150 kg Si ha^{-1}, S_3 = 200 kg Si ha^{-1}.

Table 6. Interaction effect of N and Si levels on dry weight of wheat at different days after sowing

N: Si	Dry weight (g) plant^{-1}		
	Days after sowing (DAS)		
	20	40	60
$N_0:S_0$	0.52b	1.10c	6.27c
$N_0:S_1$	0.56ab	1.21bc	7.81bc
$N_0:S_2$	0.61ab	1.35bc	10.51ab
$N_0:S_3$	0.68ab	1.11c	10.33ab

N□:S□	0.66ab	1.36bc	8.97a-c
N□:S□	0.61ab	1.56a-c	9.13ab
N□:S□	0.76ab	1.57a-c	10.22ab
N□:S□	0.75ab	1.55a-c	9.55ab
N□:S□	0.70ab	1.62ab	8.78a-c
N□:S□	0.78a	1.29bc	10.09ab
N□:S□	0.81a	1.99a	11.58a
N□:S□	0.71ab	1.33bc	8.30bc
N□:S□	0.67ab	1.29bc	8.66bc
N□:S□	0.66ab	1.39bc	7.98bc
N□:S□	0.76ab	1.45bc	10.16ab
N□:S□	0.71ab	1.6a-c	
Level of significance	*	*	*
CV (%)	**12.05**	**11.23**	**8.54**

Means having the same letters within the same column do not differ significantly.
* = Significant at 5% level of probability
N□ = 0 kg N ha^{-1}, N_1 = 80 kg N ha^{-1}, N_2 = 120 kg N ha^{-1}, N_3 = 160 kg N ha^{-1};

S_0 = 0 kg Si ha^{-1}, S_1 = 100 kg Si ha^{-1}, S_2 = 150 kg Si ha^{-1}, S_3 = 200 kg Si ha^{-1}.

3.4Yield Attributes of Wheat as influenced by different levels of N and Si

The yield components of wheat were significantly influenced by the different levels of N and Si fertilization, as well as their interactions (Figures 2 and 3). The highest grain yield (3.96 t ha^{-1}) and straw yield (5.08 t ha^{-1}) were recorded under the application of 120 kg N ha^{-1} (N_2), which was statistically similar to the yield obtained with 160 kg N ha^{-1} (N_3). In terms of Si application, plants treated with 150 kg Si ha^{-1} (S_2) produced the highest grain yield (3.72 t ha^{-1}) and straw yield (4.89 t ha^{-1}). In both N and Si treatments, the control plots (N_0 and S_0) had the lowest yields.

Furthermore, the interaction between N and Si had a notable impact on yield (Figure 3). The highest grain yield (4.14 t ha^{-1}) was achieved under the N_2:S_2 combination (34.54% over the control), while the maximum straw yield (5.36 t ha^{-1}) was observed in the N_3:S_2 interaction. Both were statistically similar to the yields in the N_2:S_2 interaction for straw production.

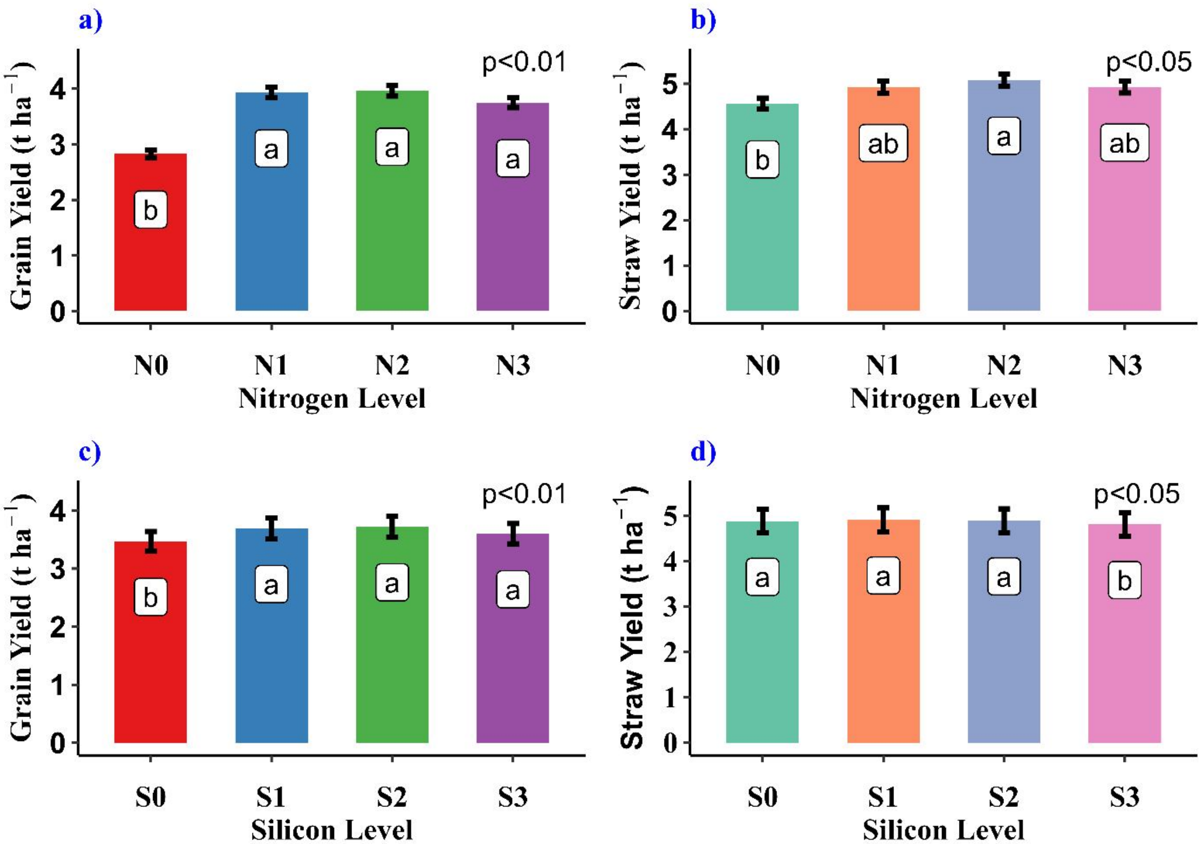

Figure 2 Yield attributes of wheat as influenced by different levels of N and Si fertilizers. a) Grain yield influenced by different N levels, b) Straw yield affected by different N levels, c) Grain yield affected by different Si levels, and, d) Straw yield affected by different levels of Si. (Data are presented as mean ± SE, n = 3; α=0.05)

N_0 = 0 kg N ha^{-1}, N_1 = 80 kg N ha^{-1}, N_2 = 120 kg N ha^{-1}, N_3 = 160 kg N ha^{-1};

S_0 = 0 kg Si ha^{-1}, S_1 = 100 kg Si ha^{-1}, S_2 = 150 kg Si ha^{-1}, S_3 = 200 kg Si ha^{-1}.

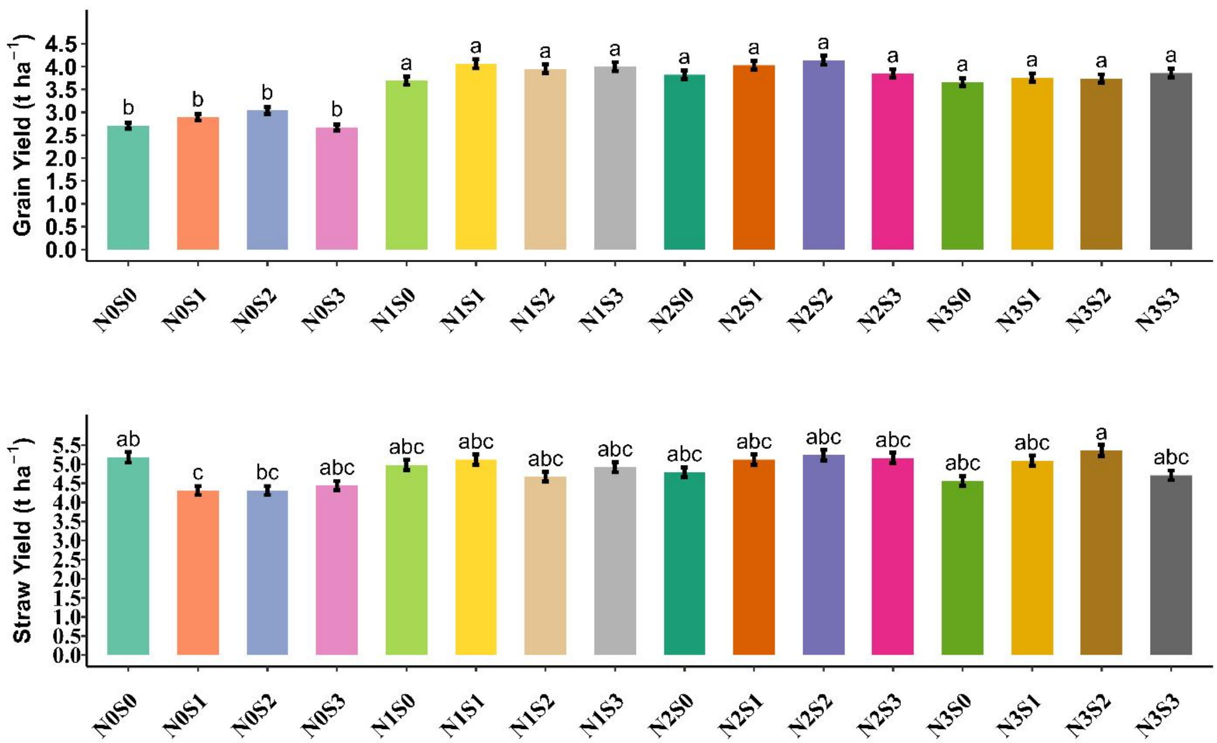

Figure 3. Yield parameters of wheat as influenced by the interaction between different levels of N and Si fertilizers: (a) Grain yield and (b) Straw yield.

(Data are presented as mean ± SE, n = 3; α=0.05)
N_0 = 0 kg N ha^{-1}, N_1 = 80 kg N ha^{-1}, N_2 = 120 kg N ha^{-1}, N_3 = 160 kg N ha^{-1};
S_0 = 0 kg Si ha^{-1}, S_1 = 100 kg Si ha^{-1}, S_2 = 150 kg Si ha^{-1}, S_3 = 200 kg Si ha^{-1}.

4.Discussion

The maximum growth factors of the crop were observed with the application of 120 kg N ha^{-1}and 150 kg Si ha^{-1}(N_2:S_2), which aligns with Popal*et al*. [21], who reported that 110 kg N ha^{-1}resulted in the highest grain yield of 2891.1 kgha^{-1} and a maximum plant height of 85.97 cm. This can be attributed to adequate N levels enhancing the uptake and utilization of essential nutrients, promoting overall plant vigor and height, while also influencing the production of hormones like auxins and gibberellins, which are essential for cell elongation and division, as noted by Luo *et al*. [22]. Additionally, Si application may have improved nutrient uptake and photosynthetic efficiency, which in turn boosted wheat yields by significantly enhancing spike length, grain weight, and overall plant height [23]. In addition to thatsuper silica fertilizer may have made the plant disease-resistant and strengthened the stem of the plant so that it didn't fall easily [24].

Higher N levels also significantly enhanced wheat tiller formation. Popal*et al.* [21] observed the highest tiller number of 152.76 m² at 110 kg N ha^{-1}, while Rafiq [25] reported increases to 948,300 and 666,650 ha^{-1} at 171 and 200 kg N ha^{-1}, respectively, and Shrestha *et al.* [26] found maximum tiller formation at 150 kg N ha^{-1}in both experimental years. This could be explained by the ability of N to enhance tiller numbers in crops like barley, correlating with increased cytokinin translocation, although excessive N may lead to non-productive tillers in rice [27]. Additionally, the transcription factor OsGATA8 which is crucial for coordinating N uptake and tiller formation, may have promoted productive tillers by regulating key genes [28]. Moreover, N application can also affect endogenous hormone levels, increasing IAA and ZT, both of which are vital for tillering [29].

Si application at 150 kg ha^{-1} significantly increased effective tillers per plant to 6.12 compared to the control, as reported by Choudhary *et al.* [30]. This effect is likely due to Si enhancing nutrient utilization, promoting organic residue mineralization, and improving plant structural integrity and water status, as suggested by Ahmad *et al.* [31], and White [32]. Moreover, the combination of higher N and Si levels (N_2:S_2) improved spike length and 1000-grain weight, corroborating White [32], and can be linked to the synergistic effect of N and Si, which promotes better nutrient accumulation and stress resilience, ultimately resulting in higher grain weights in wheat crops.

The dry weight of wheat was significantly higher under the N_2:S_2treatment (120 kg N ha^{-1} and 150 kg Si ha^{-1}), consistent with findings by Yadav [33]. This increase in dry weight can be attributed to the role ofNin promoting leaf production and expansion, which boosts the Leaf Area Index (LAI). A higher LAI allows the plant to capture more Photosynthetically Active Radiation (PAR), resulting in greater dry matter accumulation [33]. Moreover, Waseem*et al.* [34] found that Si enhances root system efficiency, improving moisture and nutrient absorption, which also contributes to increased dry weight.

The interaction between N and Si further amplified dry weight at all growth stages, demonstrating the synergistic effect of these nutrients on wheat growth. This combined application improves overall plant health, leading to greater biomass production and better growth outcomes.

The combination of 120 kg N ha^{-1} and 150 kg Si ha^{-1}resulted in a 34.54% increase in grain yield, a 15.88% increase in biological yield, and significantly higher straw yield compared to the control (N_0:S_0), where no N or Si was applied. These findings are consistent with White [32]. Similarly, De Oliveira *et al*. [35] observed a linear increase in grain yield with higher Si levels (up to 200 kg ha^{-1}). Popal*et al*. [21] also reported the highest yield parameters with 110 kg N ha^{-1}.

The yield improvement can be attributed to N fertilizer enhancing photosynthesis, tiller formation, root development, and nutrient uptake, as supported by Ghafoor *et al*. [4], Azam *et al*. [36], Yu *et al*. [37], and Cheng *et al*. [38]. On the other hand, Si application might have improved stress tolerance, strengthened plant structure, boosted the activity of photosynthetic enzymes, enhanced resistance to diseases and pests, and balanced essential nutrients, as suggested by Cheraghi *et al*. [9], Harizanova[39], and Da Silva [40].

5.Conclusion

The results of this study demonstrated that the combined application of N at 120 kg $ha^{-1}$and Si at 150 kg ha^{-1}significantly enhanced the growth and yield parameters of wheat. N improved photosynthesis, root growth, and nutrient uptake, while Si enhanced stress tolerance, nutrient efficiency, and plant structural integrity. The synergistic effect of N and Si underscores the potential of integrated nutrient management to maximize wheat production. Therefore, it can be suggested that a combination of N @120 kg ha^{-1} and Si @150 kg ha^{-1} can be applied to get a higher yield of wheat. Further research across diverse regions and wheat cultivars is recommended to validate these findings and establish more comprehensive guidelines for optimal N and Si application in wheat cultivation.

Author'sContribution

Jannatul FerdouseJote: Writing – original draft, Methodology, Investigation. *Sadia Rahaman*: Formal analysis. *Md Roconuzzaman Nasim*: Writing –Visualization, Formal analysis, review & editing.*Md.Sohel Rana:* Writing – review & editing, *Kazi Rifat Shahrin*: Writing – review & editing, Validation, Supervision.*Ahmed Khairul Hasan*: Writing – review & editing, Supervision, Funding acquisition. *Mahfuza Begum:* Supervision.

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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