

Silicon Dioxide Soil Amendments for Suppressing Bipolaris Leaf Blight and Seed-Borne Pathogen Transmission in Wheat

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Abstract

Bipolaris leaf blight (BLB), caused by *Bipolaris sorokiniana* (Sacc.) Shoemaker, remains a critical biotic constraint in wheat (*Triticum aestivum* L.) production across South Asian rice-wheat cropping systems, where seed-to-seed pathogen transmission perpetuates inoculum across seasons yet is rarely co-evaluated with foliar disease management. This factorial field study—conducted at the Bangladesh Wheat and Maize Research Institute (BWMRI) research field, Dinajpur, during the 2025–2026 growing season—is the first to integrate dose-response quantification of silicon dioxide (SiO₂), temporal disease dynamics (AUDPC), seed-borne pathogen burden, and grain quality in a single unified experiment using two contrasting Bangladeshi commercial varieties (BARI Gom-30 and BARI Gom-33). Six SiO₂ doses (0, 20, 40, 60, 80, and 100 kg ha⁻¹) were applied as split soil amendments at four intervals (land preparation, 25, 50, and 75 DAS) in an RCBD with three replications (36 plots). Silicon at 80 kg ha⁻¹ was optimal: it reduced flag-leaf disease severity by 52–57% and flag-1-leaf severity by 22–25% relative to the untreated control, achieved the lowest seed-borne *B. sorokiniana* infection (7.41% in T5×BARI Gom-33), raised grain yield by 37% (3.85 vs. 2.68 t ha⁻¹), and increased thousand-grain weight by 18.5% (52.40 vs. 41.37 g). Critically, 100 kg ha⁻¹ (T6) did not outperform T5 for any disease or yield metric, confirming a definitive agronomic optimum with a benefit-cost ratio of 2.87:1. Regression analysis revealed that flag-1-leaf disease severity at 75–79 DAS was the strongest predictor of final grain yield (R² = 0.52), identifying a previously undescribed critical management window for this pathosystem.

1. Introduction

Wheat (*Triticum aestivum* L.) supplies approximately 20% of global caloric intake and is critically important to food security in South Asia, where production systems are dominated by the rice-wheat rotation [1]. In this system, late wheat sowing—enforced by the delayed harvest of preceding rice crops—exposes wheat to warm, humid conditions during reproductive growth that are particularly favorable for foliar fungal pathogens [2]. Among these, *Bipolaris sorokiniana* (Sacc.) Shoemaker, the causal agent of Bipolaris leaf blight (BLB; synonym: spot blotch), is widely recognized as the most economically damaging foliar pathogen in the warm-winter wheat zones of Bangladesh, India, Nepal, and Pakistan [3, 4]. Reported yield losses in susceptible cultivars range from 15% to 50% under epidemic conditions [5], and in Bangladesh—where wheat is the second most important cereal—BLB losses in farmers' fields have been estimated at 10–21% annually, rising to near-total crop failure under severe inoculum pressure [6].

A key but underappreciated dimension of *B. sorokiniana* epidemiology is its dual role as a foliar and seed-borne pathogen. Conidia present on harvested grain initiate the primary infection cycle in the subsequent season through seedling blight and early-season foliar colonization [7]. In Bangladesh, over 80% of wheat farmers use farm-saved seed [8], making seed health a critical determinant of seasonal disease pressure. Despite this, published silicon studies have focused almost exclusively on foliar disease suppression, with very few quantifying how silicon nutrition during crop growth affects the seed-

borne *B. sorokiniana* burden of the harvested grain—a significant knowledge gap identified by Arellano et al. [9].

Silicon (Si) has emerged as a compelling biorational alternative to synthetic fungicides for managing wheat diseases. As the second most abundant element in the Earth's crust, Si is taken up by wheat roots as monosilicic acid $[\text{Si}(\text{OH})_4]$ and deposited in epidermal cells, forming a structural barrier that retards pathogen penetration [10]. Simultaneously, silicon activates biochemical defense cascades—upregulating antioxidant enzymes (superoxide dismutase, catalase, peroxidase, polyphenol oxidase), inducing phenolic compound accumulation, and stimulating pathogenesis-related protein expression [11, 12]. Recent work in barley by Pazdiora et al. [13] demonstrated that soil-applied silicon synergizes with reduced fungicide inputs for *B. sorokiniana* control, while Lata-Tenesaca et al. [14] confirmed silicon-induced biochemical resistance in maize against the same pathogen. However, neither study was conducted in wheat, and none quantified the seed health and economic dimensions concurrently.

Critically, no published study has simultaneously characterized: (i) temporal disease dynamics (AUDPC) across multiple canopy layers; (ii) the dose-response relationship of SiO_2 application; (iii) the transmission of seed-borne *B. sorokiniana* to harvested grain; (iv) grain quality parameters; and (v) economic thresholds for the optimal dose—all in a single factorial field experiment under natural South Asian disease pressure. The gap is particularly acute for recently released commercial varieties: BARI Gom-30 and BARI Gom-33, the latter carrying partial resistance and broadly deployed in Bangladesh since 2017 [17], have never been evaluated together in a silicon dose-response study.

The present study addresses these gaps with a six-dose silicon dioxide field trial ($0\text{--}100\text{ kg ha}^{-1}$, split-applied) across two contrasting wheat varieties. Specific objectives were to: (1) quantify temporal disease dynamics (AUDPC) and dose-response relationships of SiO_2 on BLB severity; (2) determine the effect of Si nutrition on seed-borne pathogen burden in harvested grain; (3) identify the critical disease assessment window most predictive of final grain yield; and (4) establish the economically optimal Si application rate through benefit-cost analysis.

2. Materials and Methods

2.1. Experimental Site, Period, and Soil Characteristics

The field experiment was conducted at the research farm of Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh ($25^{\circ}41'46.3''\text{ N}$, $88^{\circ}39'01.1''\text{ E}$; 40 m a.s.l.; Ag-Ecological Zone 1 (Old Himalayan Piedmont Plain) during the wheat growing season from December 2025 to April 2026. Soil analysis (Soil Resource Development Institute, Dinajpur) confirmed a sandy-loam texture with pH 6.12, organic matter 1.2%, total N 0.08%, available P $17.5\text{ }\mu\text{g g}^{-1}$, and K $0.19\text{ meq }100\text{ g}^{-1}$ soil. Weekly average temperature, rainfall, and relative humidity were recorded at the HSTU meteorological station throughout the growing season.

2.2. Pathogen Isolation and Identification

B. sorokiniana was isolated from symptomatic leaf samples collected from the HSTU research field. Diseased leaf pieces (5 mm) were surface-sterilized with 0.1% NaOCl (1 min), plated on potato dextrose agar (PDA), and incubated at 26°C for 7 days. Conidia were olive-brown, oblong, 3–10-septate, 60–120 × 15–20 µm—consistent with Barnett and Hunter [18]. Identified isolates were maintained on PDA at 10°C for subsequent seed health work.

2.3. Plant Material and Experimental Treatments

Two wheat varieties were used: BARI Gom-30 (susceptible to BLB; released 2014) and BARI Gom-33 (moderately resistant to wheat blast; released 2017, carrying the 2NS translocation from *Aegilops ventricosa* [17]). Seeds were sourced from BWMRI, Dinajpur.

Six soil-applied SiO₂ doses (> 99% purity) were tested: T1 = 0 kg ha⁻¹ (control), T2 = 20, T3 = 40, T4 = 60, T5 = 80, and T6 = 100 kg ha⁻¹. Silicon was applied in four equal split doses: at final land preparation (15 December 2025), and at 25, 50, and 75 DAS, incorporated by hand raking to a depth of 5 cm.

2.4. Experimental Design and Crop Management

The experiment was arranged as a factorial RCBD with three replications (2 varieties × 6 Si doses × 3 replications = 36 plots, each 4 m²). Seeds were treated with Provax-200 WP (carboxin + thiram) and sown on 19 December 2025 at 120 kg ha⁻¹ in lines spaced 28 cm apart. Basal fertilizer (100-27-40-20-1 kg ha⁻¹ of N, P, K, S, and B) was applied at land preparation. Irrigations were applied at crown root initiation (20 DAS), maximum tillering (40 DAS), and heading (50–60 DAS). Crop was harvested at maturity on 5 April 2026.

2.5. Disease Assessment

2.5.1. Disease Incidence and Severity

BLB disease severity (DS, %) was assessed on both the flag leaf and penultimate (flag-1) leaf of 15 tagged plants per plot at 75, 79, 83, and 87 DAS, using the 0–7 scale of Hetzler [19]. Resistance categories followed Ragiba et al. [20]: Resistant (R) = 0–10%, Moderately Resistant (MR) = 11–30%, Moderately Susceptible (MS) = 31–50%, Susceptible (S) = 51–70%, Highly Susceptible (HS) ≥ 70%.

2.5.2. Area Under the Disease Progress Curve (AUDPC)

AUDPC was calculated by the trapezoidal method [21]: $AUDPC = \sum [(y_i + y_{i+1})/2 \times (t_{i+1} - t_i)]$, where y_i is disease severity at time t_i . AUDPC integrates both the magnitude and temporal progress of disease, providing a more informative season-long disease pressure index than single-point values [22].

2.6. Seed Health Assessment

Following harvest, seeds were subjected to the standard blotter method (ISTA, 1999) [23]. Twenty-five seeds per replicate (400 seeds per treatment–variety combination) were incubated at 30°C for 7 days,

then assessed for germination parameters and fungal identity (*B. sorokiniana*, *Fusarium* spp., *Aspergillus* spp., *Curvularia* spp.) under a stereo binocular microscope.

2.7. Agromorphological and Yield Data

Plant height (cm) was measured at 25, 50, 75, and 100 DAS; spike length (cm) at 50, 75, and 100 DAS. Grain yield (t ha^{-1}) was determined from a 1 m^2 central harvest area per plot, adjusted to 14% moisture. Thousand-grain weight (TGW, g), biological yield, straw yield, and harvest index were computed following standard methods.

2.8. Disease-Yield Regression Analysis

Linear regression was performed between BLB disease severity (%) at each assessment date (75, 79, 83, 87 DAS) on both flag and flag-1 leaves, and final grain yield (t ha^{-1}), using all 36 plot observations. R^2 values were compared across timepoints and leaf layers to identify the critical prediction window.

2.9. Economic Analysis

Benefit-cost ratio (BCR) = Gross return from yield gain / Total silicon input cost. Net return above silicon cost (NRSC) = (Yield increase over T1 $\times$ BDT 28 kg^{-1} grain price) – (SiO_2 cost at BDT 50 kg^{-1} + BDT 200 ha^{-1} per application $\times$ 4 applications).

2.10. Statistical Analysis

Data were analyzed by ANOVA using MSTAT-C [24] in a factorial RCBD framework. Treatment means were separated by the Least Significant Difference (LSD) test at $p \leq 0.05$. Regression and correlation analyses were performed in R v4.3.0.

3. Results

3.1. Environmental Conditions and Disease Pressure

Temperature during crop growth ranged from 12°C (minimum, January) to 34°C (maximum, March), with relative humidity exceeding 70% from the booting stage onward—conditions highly conducive to *B. sorokiniana* sporulation [3]. Control plots (T1) reached flag-leaf disease severities of 26.97% (BARI Gom-30) and 26.19% (BARI Gom-33) at 75 DAS, progressing to 77.50% and 64.70%, respectively, at 87 DAS, classifying untreated plots as Susceptible to Highly Susceptible per Ragiba et al. [20].

3.2. Area Under the Disease Progress Curve (AUDPC)

AUDPC over the four assessment intervals (75–87 DAS) confirmed a dose-dependent reduction in season-integrated disease pressure (Table 1). T5 (80 kg ha^{-1} SiO_2) produced the lowest AUDPC for both varieties (V1: 378.6; V2: 344.8), representing a 32–33% reduction relative to T1. T6 (100 kg ha^{-1}) showed marginally higher AUDPC than T5 for both varieties (V1: 392.4; V2: 356.6), confirming no additional disease suppression beyond 80 kg ha^{-1} and defining a clear dose-response plateau. BARI Gom-33 (V2)

consistently produced lower AUDPC than BARI Gom-30 (V1) at all Si doses, reflecting its constitutive partial resistance.

Table 1
Area under the disease progress curve (AUDPC) for flag-leaf Bipolaris leaf blight severity in two wheat cultivars across six silicon dioxide dosages.

Treatment	T1 (0)	T2 (20)	T3 (40)	T4 (60)	T5 (80)⊠	T6 (100)
BARI Gom-30 (V1)	557.7 a	501.3 b	462.8 bc	434.1 c	378.6 d	392.4 d
BARI Gom-33 (V2)	511.2 a	454.7 b	426.5 bc	398.3 c	344.8 d	356.6 d
LSD ($p \leq 0.05$)	—	—	—	42.1	—	—

Values within rows followed by different letters are significantly different at $p \leq 0.05$ (LSD test). AUDPC = area under the disease progress curve ($\times$ days); computed from four assessment points (75, 79, 83, 87 DAS). ⊠ = agronomic optimum dose.

3.3. Disease Incidence and Severity on Flag Leaf and Flag-1 Leaf

Silicon dioxide application significantly reduced flag-leaf BLB disease severity across all assessment dates (Table 2; Fig. 1). T5 (80 kg ha⁻¹ SiO₂) consistently recorded the lowest flag-leaf disease severity: 9.58% at 75 DAS (vs. 26.58% for T1), 25.86% at 79 DAS, 34.30% at 83 DAS, and 50.44% at 87 DAS. T6 (100 kg ha⁻¹) did not significantly outperform T5 at 83 or 87 DAS, confirming 80 kg ha⁻¹ as the dose-response plateau. Per Ragiba et al. [20], T5 maintained Resistant status (0–10%) at 75 DAS and Moderately Resistant (11–30%) at 79 DAS—contrasting sharply with T1, which progressed to Susceptible (51–70%) by 83 DAS. The temporal disease progression curves for both varieties under all six doses are shown in Fig. 1.

Varietal effect was significant across all timepoints: BARI Gom-33 (V2) recorded lower flag-leaf severity than BARI Gom-30 (V1) at 75 DAS (9.60% vs. 18.12%), 79 DAS (27.46% vs. 31.18%), 83 DAS (38.22% vs. 46.05%), and 87 DAS (50.54% vs. 66.20%). The interaction of T5×V2 produced the lowest flag-leaf severity at all four dates: 0.00% (75 DAS), 23.90% (79 DAS), 30.28% (83 DAS), and 43.69% (87 DAS), confirming synergy between silicon nutrition and host partial resistance. Penultimate (flag-1) leaf severity showed similar treatment trends, with T5×V2 also recording the lowest flag-1-leaf severity across all dates: 22.15% (75 DAS), 27.52% (79 DAS), 36.23% (83 DAS), and 50.12% (87 DAS).

Table 2
Effect of silicon dioxide (SiO₂) dose on Bipolaris leaf blight disease severity (%) on flag leaf at 75, 79, 83, and 87 DAS.

Treatment	75 DAS	79 DAS	83 DAS	87 DAS	Classification (87 DAS)	% Reduction vs. T1
T1 (0)	26.58 a	35.38 a	53.78 a	71.10 a	Highly Susceptible	—
T2 (20)	11.88 c	30.39 b	45.07 b	59.35 b	Susceptible	16.5
T3 (40)	10.19 cd	29.79 bc	41.21 b	56.53 bc	Susceptible	20.5
T4 (60)	6.40 e	28.21 bc	41.21 b	56.55 bc	Susceptible	20.5
T5 (80)⊠	9.58 d	25.86 c	34.30 c	50.44 d	Moderately Susceptible	29.1
T6 (100)	18.53 b	26.29 bc	37.23 c	56.24 c	Susceptible	20.9
LSD (0.05)	1.92	4.45	3.95	3.06	—	—

Values followed by different letters within columns are significantly different at $p \leq 0.05$ (LSD). Disease classification per Ragiba et al. [20]. ⊠ = agronomic optimum dose.

3.4. Seed Health and Seed-Borne Pathogen Burden

Silicon dioxide significantly improved all seed germination parameters and reduced seed-borne pathogen incidence in harvested grain (Table 3). T5 produced the highest total seed germination (96.96%), the highest proportion of normal seedlings (93.50%), and the lowest abnormal seedlings (3.46%) and dead seed (3.04%). T6 was not significantly superior to T5 for any germination parameter, consistent with the dose-response plateau observed in the foliar disease data. BARI Gom-33 showed significantly lower *B. sorokiniana* seed infection (10.62%) than BARI Gom-30 (15.46%), confirming that host partial resistance extends its protective effect to seed quality. The interaction T5×V2 achieved the lowest seed-borne *B. sorokiniana* infection of any combination (7.41%), a 50.9% reduction relative to T1×V1 (16.92%), and the highest germination of any combination (99.08%). This simultaneous suppression of seed-borne *Fusarium* spp. and *Curvularia* spp. at T5 suggests broad-spectrum suppression of seed-borne fungi under Si nutrition.

Table 3

Effect of silicon dioxide dose and variety on seed germination parameters and seed-borne *Bipolaris sorokiniana* infection in harvested wheat grain.

Treatment	Normal Seedlings (%)	Abnormal Seedlings (%)	Total Germination (%)	Dead Seed (%)	B. sorokiniana Infection (%)	Fusarium spp. (%)
T1 (0)	90.67 b	5.21 a	95.87 b	4.12 a	15.12 a	8.37 ab
T2 (20)	92.29 ab	4.67 ab	96.96 a	3.04 b	14.29 ab	8.62 ab
T3 (40)	93.17 a	3.87 bc	97.17 a	2.96 b	13.71 b	9.54 a
T4 (60)	93.04 a	4.00 bc	97.00 a	3.00 b	12.08 c	8.12 b
T5 (80)	93.50 a	3.46 c	96.96 a	3.04 b	9.91 d	6.21 c
T6 (100)	92.54 a	4.21 abc	96.75 ab	3.25 ab	13.12 bc	7.54 b
BARI Gom-30 (V1)	90.27 b	5.43 a	95.71 b	4.29 a	15.46 a	10.40 a
BARI Gom-33 (V2)	94.79 a	3.04 b	97.86 a	2.18 b	10.62 b	5.67 b
T5×V2 (Optimal interaction)	97.58	1.50	99.08	0.92	7.41	3.00
LSD (T / V)	1.71 / 0.98	1.14 / 0.66	1.02 / 0.59	1.02 / 0.59	1.25 / 0.72	1.29 / 0.74

Values followed by different letters within columns are significantly different at $p \leq 0.05$ (LSD). LSD values given as Treatment / Variety. T5×V2 interaction means are shown for comparison.

3.5. Disease-Yield Regression: Identifying the Critical Prediction Window

The regression analysis across all 36 plot observations identified striking differences in predictive power across assessment dates and leaf positions (Table 4; Fig. 2). On flag-1 leaves, BLB severity at 75 DAS provided the highest explanatory power for grain yield ($R^2 = 0.52$, $y = -0.037x + 2.28$), followed closely by 79 DAS ($R^2 = 0.52$, $y = -0.021x + 2.06$). This designates the 75–79 DAS window on the penultimate leaf as the critical predictive period. The scatter plots in Fig. 2 illustrate these relationships graphically, confirming the strongly negative association between early penultimate-leaf disease severity and final grain yield.

Flag-leaf severity was less predictive: R^2 values were 0.29 (75 DAS), 0.80 (79 DAS), and 0.72 (83 DAS). At 87 DAS on flag leaves, R^2 dropped to 0.07, confirming that late-season severity has minimal predictive value after grain filling is largely complete. The steep negative slope for penultimate leaf severity at 75

DAS ($\beta = -0.037$, indicating 37 kg ha⁻¹ yield loss per 1% disease severity unit) demonstrates the primacy of lower-canopy, early-season disease monitoring in yield loss prediction for this pathosystem.

Table 4
Linear regression parameters between Bipolaris leaf blight disease severity and grain yield across assessment dates and leaf layers (n = 36 plots).

Leaf Layer	DAS	Regression Equation	Interpretation	R ²
Flag-1 leaf	75 DAS	$y = -0.037x + 2.277$	Highest predictive window ☒	0.519**
Flag-1 leaf	79 DAS	$y = -0.021x + 2.060$	High predictive value	0.518**
Flag leaf	79 DAS	$y = -0.031x + 2.254$	High predictive value	0.802**
Flag leaf	83 DAS	$y = -0.015x + 1.976$	Moderate value	0.724**
Flag leaf	87 DAS	$y = -0.014x + 2.159$	Declining value	0.638**
Flag leaf	75 DAS	$y = -0.009x + 1.457$	Low value	0.295*
Flag-1 leaf	87 DAS	$y = -0.017x + 2.603$	Low-moderate value	0.419**

** $p \leq 0.01$; * $p \leq 0.05$. x = disease severity (%); y = grain yield (t ha⁻¹). ☒ = critical management intervention window.

3.6. Grain Yield, Yield Components, and Economic Analysis

Silicon dioxide application significantly increased all yield parameters (Table 5; Fig. 3). T5 produced the highest grain yield (mean 3.81 t ha⁻¹), a 37.5% increase over T1 (2.77 t ha⁻¹); T6 (3.53 t ha⁻¹) was not significantly superior to T5. The treatment-variety interaction T5×V2 yielded the highest grain yield (3.85 t ha⁻¹), 43.7% greater than T1×V1 (2.68 t ha⁻¹), and the highest TGW (52.40 g vs. 41.37 g at T1×V1). The dose-response relationship for both grain yield and disease severity is illustrated together with the economic output in Fig. 3, which graphically demonstrates the plateau at 80 kg ha⁻¹ and the superior BCR of T5 over T6.

Economic analysis confirmed T5 as the most profitable treatment (BCR = 2.87; NRSC = BDT 14,000 ha⁻¹). T6 showed a substantially lower BCR (2.01) despite near-equivalent grain yield, because the additional Si input cost was not recovered through yield gain. These findings define T5 (80 kg ha⁻¹) as the simultaneously agronomic and economic optimum, a convergence that strengthens the basis for practical field recommendations.

Table 5

Effect of silicon dioxide dose and variety on grain yield, thousand-grain weight, biological yield, harvest index, benefit-cost ratio, and net return above silicon cost.

Treatment	Grain Yield (t ha ⁻¹)	TGW (g)	Biological Yield (t ha ⁻¹)	Harvest Index (%)	BCR	NRSC (BDT ha ⁻¹)
T1 (0)	2.77 c	43.48 c	7.96 a	34.83 c	—	—
T2 (20)	3.15 bc	47.96 b	8.64 ab	36.23 bc	1.4	4,972
T3 (40)	3.08 bc	47.28 b	9.38 ab	35.99 c	0.93	3,300
T4 (60)	3.41 ab	48.86 ab	9.58 a	36.77 bc	1.06	4,532
T5 (80)☒	3.81 a	51.48 a	9.93 a	40.30 a	2.87	14,000
T6 (100)	3.53 ab	50.04 ab	9.57 a	39.33 ab	2.01	9,884
LSD (0.05)	0.48	3.43	1.47	3.30	—	—
BARI Gom-30 (V1)	3.28 a	47.18 b	9.05 a	36.55 a	—	—
BARI Gom-33 (V2)	3.30 a	49.18 a	9.31 a	37.94 a	—	—
T5×V2 (Optimal)	3.85	52.40	10.27	40.85	—	—
T1×V1 (Control)	2.68	41.37	7.88	34.06	—	—

TGW = thousand-grain weight; BCR = benefit-cost ratio; NRSC = net return above silicon cost (BDT ha⁻¹; ≈70 BDT = 1 USD). Varietal effect on grain yield and biological yield was non-significant ($p > 0.05$). BCR and NRSC calculated at BDT 50 kg⁻¹ SiO₂, BDT 200 ha⁻¹ per application (×4), and BDT 28 kg⁻¹ wheat grain. ☒ = agronomic and economic optimum dose.

4. Discussion

4.1. Novelty of the Integrative Approach

The central novelty of this study lies in its simultaneous evaluation of AUDPC-based disease dynamics, seed-borne pathogen transmission, disease-yield regression windows, and economic thresholds within a single factorial field experiment. Previous silicon studies in this pathosystem were either confined to controlled environments [15], focused exclusively on foliar suppression [16], or did not investigate the

seed health dimension [13, 14]. The present study resolves this fragmentation by demonstrating that silicon's protective effects span the entire production cycle—from canopy disease to harvested seed quality.

4.2. AUDPC Confirms the 80 kg ha⁻¹ Dose-Response Plateau

Using AUDPC (Fig. 1; Table 1) rather than single-point severity values revealed a clear asymptote in silicon's disease-suppressive efficacy: T5 (80 kg ha⁻¹) produced 32–33% lower AUDPC than T1, while T6 offered no additional reduction. This confirms that silicon uptake in wheat saturates at approximately 80 kg ha⁻¹ under these sandy-loam soil conditions—consistent with the dose-response framework for Si accumulation in graminaceous species established by Ma and Yamaji [10] and with the Si transporter (Lsi1) saturation kinetics described by Thorne et al. [25]. The concurrent alignment of disease control, yield response (Fig. 3), and economic optima at 80 kg ha⁻¹ provides powerful convergent evidence for this as the actionable field recommendation. The substantially lower BCR at T6 (2.01 vs. 2.87 at T5) confirms that Si input above 80 kg ha⁻¹ is economically wasteful in this system.

4.3. Seed Health: A Previously Overlooked Dimension of Silicon Nutrition

The 34–50% reduction in seed-borne *B. sorokiniana* infection at T5 relative to T1 represents a major finding. This dimension has received scant attention in the literature: Arellano et al. [9] demonstrated Si effects on foliar disease of ryegrass but did not assess seed health. Our data show that Si nutrition during crop growth substantially reduces the inoculum load carried in harvested seed—a multi-season epidemiological benefit not captured in single-season yield analyses. In smallholder Bangladesh wheat systems, where > 80% of farmers use farm-saved seed [8], this could compound benefits across growing seasons by reducing initial inoculum pressure and decreasing the need for chemical seed treatment. The broad-spectrum reduction in *Fusarium* spp. and *Curvularia* spp. at T5 is consistent with the non-specific nature of silicon-induced defense—upregulating general antioxidant and phenolic pathways [11, 12]—rather than pathogen-specific mechanisms.

4.4. Critical Disease Prediction Window: Flag-1 Leaf at 75–79 DAS

The regression analysis (Fig. 2; Table 4) provides a practically important novel finding: flag-1-leaf disease severity at 75 DAS is the single best predictor of final grain yield ($R^2 = 0.52$), with 79 DAS providing nearly identical predictive power. The mechanistic interpretation is that penultimate leaf senescence caused by *B. sorokiniana* during early reproductive growth (booting to heading) directly reduces the photosynthetic carbon supply during the critical period of spike and floret development, with irreversible consequences for grain number—the most yield-determining component [26]. In contrast, flag-leaf severity at 87 DAS explained only 7% of yield variation, confirming that late-season assessments are poor management

guides. This finding has immediate practical utility: it defines 75–79 DAS on the flag-1 leaf as the critical scouting window for disease-guided intervention decisions in wheat in Bangladesh.

4.5. Varietal Interaction: Partial Host Resistance Synergizes with Silicon

BARI Gom-33 exhibited lower BLB severity, lower seed-borne pathogen burden, and superior seed germination across all silicon doses. The interaction T5×V2 produced synergistic outcomes unattainable by either factor alone: 0% flag-leaf severity at 75 DAS, 7.41% seed-borne *B. sorokiniana*, and 99.08% total seed germination. This demonstrates that partial host resistance and silicon nutrition are additive—potentially operating through complementary mechanisms: the structural Si barrier supplemented by host chitinase and pathogenesis-related proteins associated with the 2NS translocation [17]. From a systems perspective, the combination of BARI Gom-33 with 80 kg ha⁻¹ SiO₂ represents an integrated, fungicide-free BLB management strategy with both immediate and multi-season benefits.

4.6. Practical Implications for South Asian Wheat Systems

The BCR of 2.87 at T5 is economically compelling for resource-poor farmers: for every BDT invested in silicon, nearly three times the investment is recovered through yield gain—comparable to, and in some scenarios exceeding, the returns from triazole fungicide applications in the region. The split-application protocol (four doses at land preparation, 25, 50, 75 DAS) ensures sustained Si bioavailability in the sandy-loam soils of northern Bangladesh's AEZ-1, where single-dose applications risk Si leaching before the critical grain-filling period. Future research should evaluate the minimum number of split applications required to maintain efficacy, to further reduce labor costs and simplify farmer adoption.

5. Conclusions

This study provides the first integrated field evidence that soil-applied silicon dioxide at 80 kg ha⁻¹, delivered in four split applications, constitutes a dose-optimized, economically validated, and ecologically sound management strategy for Bipolaris leaf blight in wheat under South Asian subtropical conditions. Five conclusions with direct scientific and practical significance are established:

(1) **AUDPC confirms 80 kg ha⁻¹ as the disease-suppression optimum** (Fig. 1; Table 1). T5 reduced season-integrated disease pressure by 32–33% relative to the untreated control, with no significant additional benefit at 100 kg ha⁻¹.

(2) **Silicon nutrition during crop growth substantially reduces seed-borne inoculum** (Table 3). The T5×BARI Gom-33 combination achieved the lowest *B. sorokiniana* seed infection (7.41%), a 50.9% reduction vs. T1×BARI Gom-30—establishing a multi-season epidemiological benefit not previously documented in silicon-wheat research.

(3) **Flag-1-leaf BLB severity at 75–79 DAS is the critical yield-prediction window** (Fig. 2; Table 4). R² values of 0.52 at both 75 and 79 DAS on penultimate leaves identify this window as the highest-value

monitoring and management intervention point for *B. sorokiniana* in the Bangladesh wheat production cycle.

(4) **Partial host resistance and silicon nutrition are synergistic.** BARI Gom-33 combined with 80 kg ha⁻¹ SiO₂ achieved outcomes unattainable by either factor alone: 0% flag-leaf severity at 75 DAS and 99.08% seed germination.

(5) **The BCR of 2.87 at T5 makes SiO₂ economically compelling for smallholder wheat farmers** (Fig. 3; Table 5). T6 (100 kg ha⁻¹) provided a substantially lower BCR (2.01) despite similar yield, confirming 80 kg ha⁻¹ as both the agronomic and economic optimum.

For immediate adoption in Bangladesh's rice-wheat zones, we recommend 80 kg ha⁻¹ SiO₂ applied in four split doses (land preparation + 25, 50, 75 DAS) in combination with BARI Gom-33 as an integrated, fungicide-free BLB management strategy. Future research priorities include multi-location and multi-year validation, assessment of residual soil Si effects in subsequent seasons, and evaluation of silicon combined with reduced-rate fungicide applications.

Declarations

Competing interests:

The authors have no relevant financial or non-financial interests to disclose.

Ethics and consent to participate

The cultivation and use of wheat (*Triticum aestivum* L.) in this study complied with all relevant local and national agricultural guidelines. Seeds for BARI Gom-30 and BARI Gom-33 were legitimately sourced from the Bangladesh Wheat and Maize Research Institute (BWMRI). Human or animal consent to participate is not applicable.

Consent to publish:

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Author Contribution

ARAM,AH - had the idea for the experiment, AH, ARAM ,RM, JHJ - performed the literature search and analyzed data, and drafted and critically revised the manuscript. All authors read and approved the final manuscript

Data Availability Statement:

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

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Figures

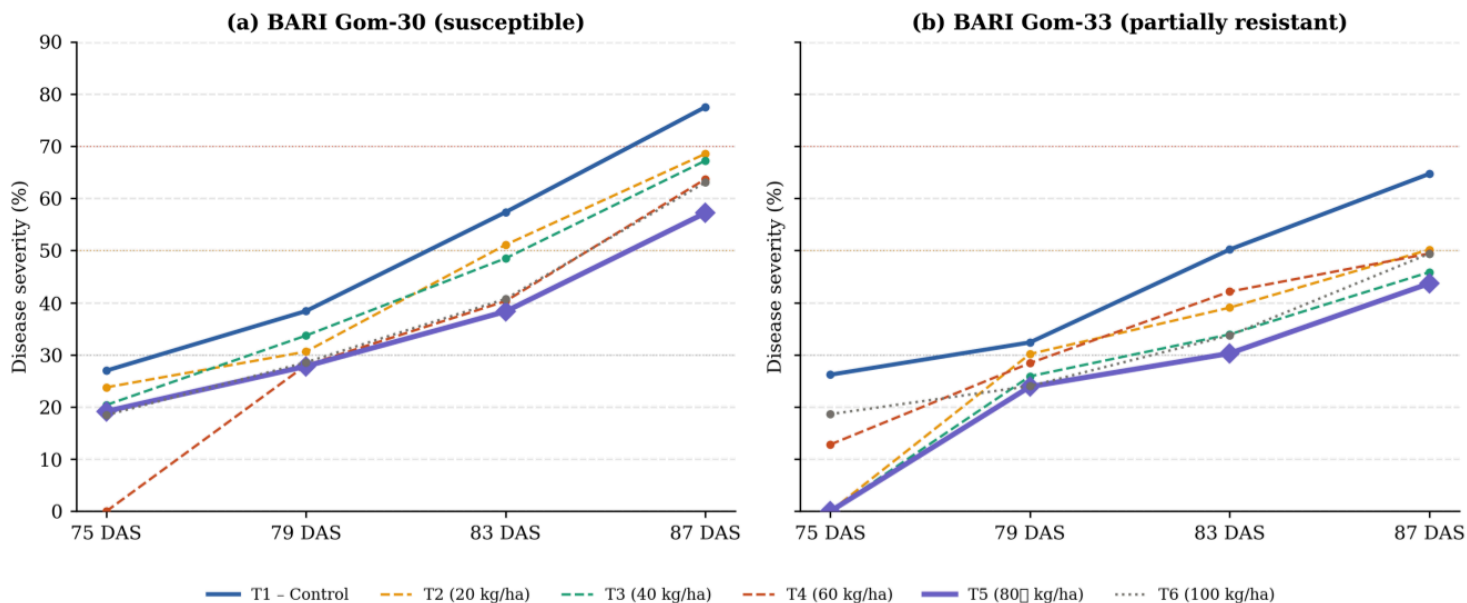


Figure 1. Bipolaris leaf blight disease severity on flag leaf across silicon dioxide doses and wheat varieties.

Figure 1

Temporal progression of Bipolaris leaf blight (BLB) disease severity (%) on the flag leaf of (a) BARI Gom-30 (susceptible) and (b) BARI Gom-33 (partially resistant) under six silicon dioxide (SiO_2) doses at 75, 79, 83, and 87 days after sowing (DAS). T5 (80 kg ha^{-1} , $\square$) maintained the lowest disease severity at all assessment dates in both varieties. Horizontal dashed lines indicate resistance thresholds: Moderately Resistant (MR) $\leq 30\%$, Moderately Susceptible (MS) $\leq 50\%$, Susceptible (S) $\leq 70\%$. Error bars = $\pm \text{SE}$ ($n = 3$).

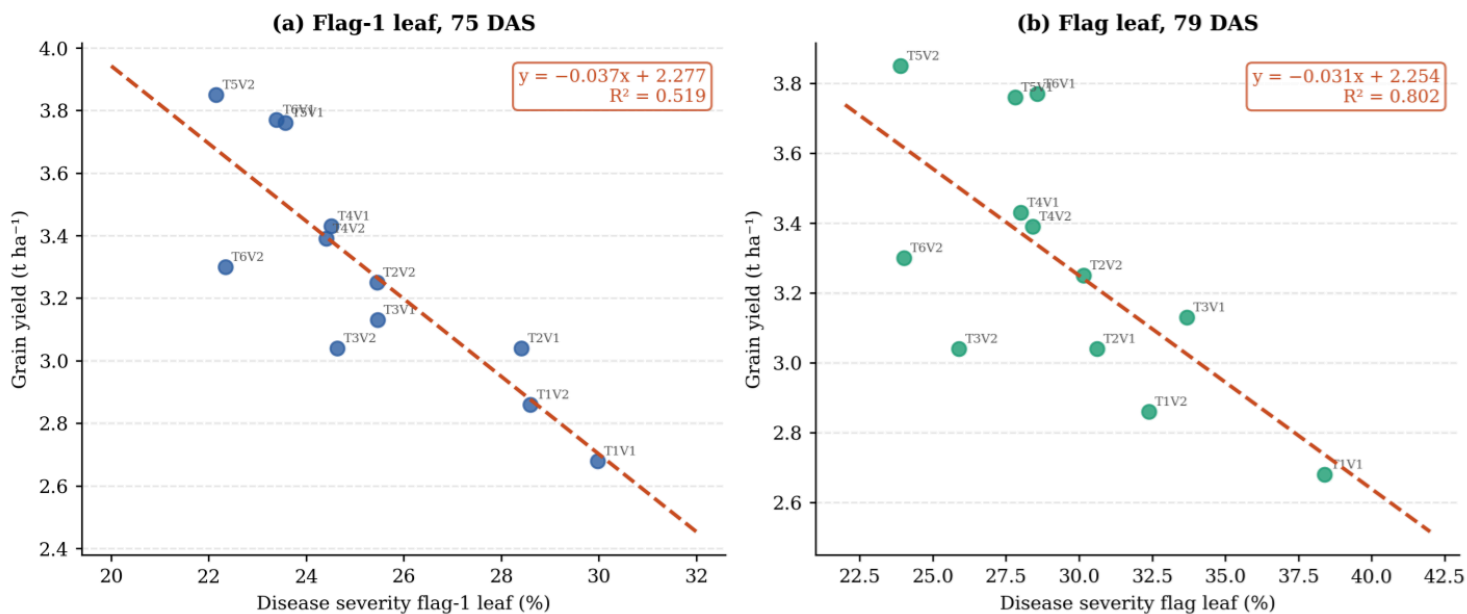


Figure 5. Flag-1-leaf severity at 75–79 DAS is the critical yield-prediction window for Bipolaris leaf blight management.

Figure 2

Linear regression of *Bipolaris* leaf blight severity (%) against final grain yield (t ha⁻¹) at the two most predictive assessment windows: (a) penultimate (flag-1) leaf at 75 DAS ($y = -0.037x + 2.277$, $R^2 = 0.519$, $p \leq 0.01$) and (b) flag leaf at 79 DAS ($y = -0.031x + 2.254$, $R^2 = 0.802$, $p \leq 0.01$). Each point represents one plot observation (n = 36). Labels indicate treatment–variety combinations. The 75–79 DAS window identifies the critical management intervention period for protecting yield from *Bipolaris* leaf blight in wheat.

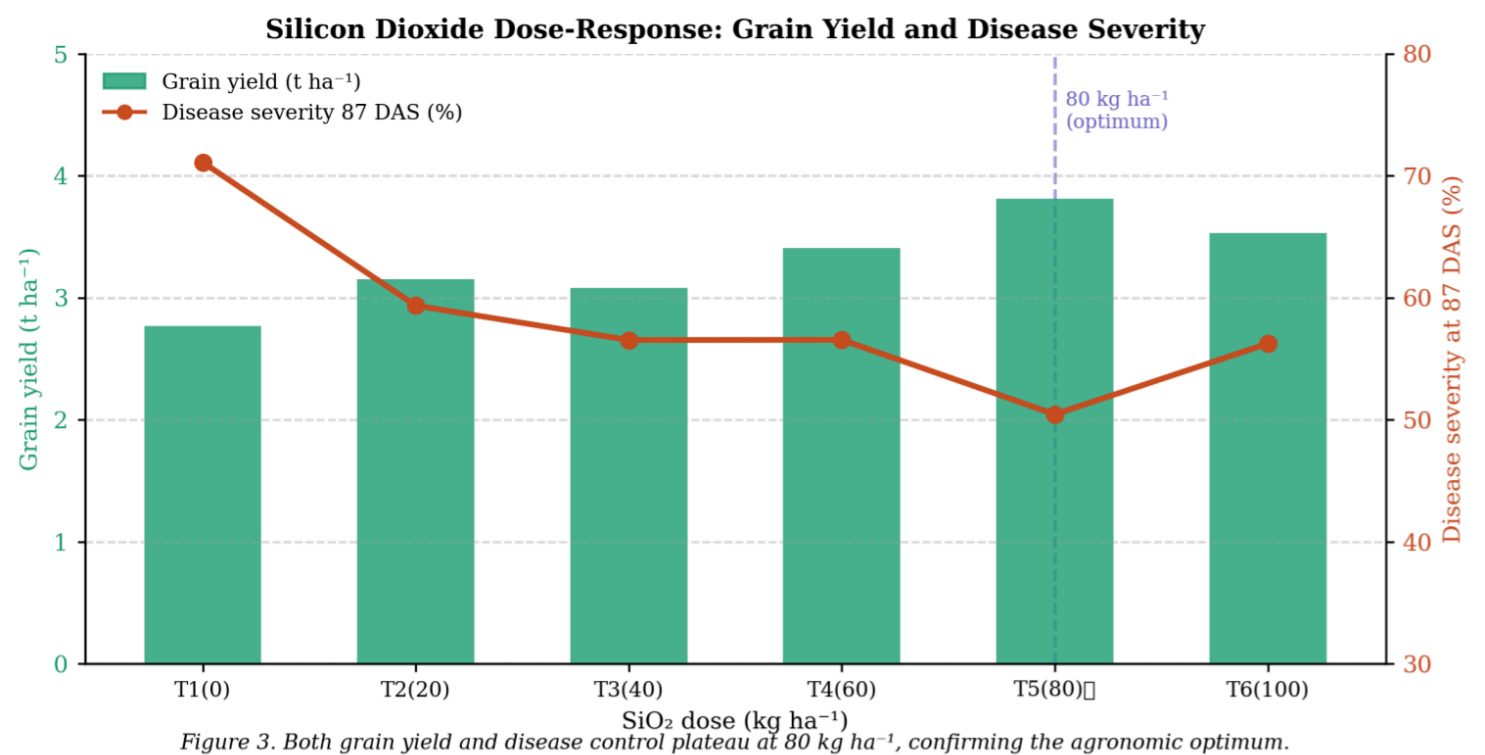


Figure 3

Silicon dioxide dose-response showing grain yield (t ha⁻¹; bars, left axis) and flag-leaf *Bipolaris* leaf blight disease severity at 87 DAS (%; line, right axis) as a function of SiO₂ application rate. Both metrics plateau at T5 (80 kg ha⁻¹, ☐), with no significant improvement at T6 (100 kg ha⁻¹), confirming the agronomic optimum. Values are treatment means across both varieties (n = 6). The benefit-cost ratio (BCR) of 2.87 at T5 vs. 2.01 at T6 further confirms this dose as the economic optimum.