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ORIGINAL PAPER

Exogenous Application of Different Silicon Sources and Potassium Reduces Pink Stem Borer Damage and Improves Photosynthesis, Yield and Related Parameters in Wheat

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Abstract
Silicon (Si) and potassium are known to impart tolerance against numerous biotic stresses in crop plants. A study was conducted to determine the effect of diatomaceous earth (DE), a soil-applied Si source and soluble silicic acid, a foliar applied Si source at two levels of potassium for their efficacy against pink stem borer (PSB) incidence and damage in wheat under field conditions for two seasons. The effect of these Si sources and potassium levels on photosynthesis, yield, and related parameters were also studied. Soil application of DE @ 300 kg ha^{-1} significantly decreased the PSB incidence with the lowest percent white ear damage and recorded the highest grain yield of 3.31 t ha^{-1}. Both soil and foliar applied Si sources along with potassium @ 36 kg ha^{-1} significantly enhanced the net photosynthesis rate, stomatal conductance, water use efficiency, intercellular CO_2 concentration, spike length, spike weight, number of grains per spike, 1000 grains weight and significantly decreased the transpiration rate in contrast to untreated control (no Si application) and insecticidal check. Soil applied Si sources significantly enhanced plant-available Si content in soil solution and thereby Si content in stem tissues of wheat plants in contrast to foliar-applied Si sources. Maximum Benefit: Cost ratio (2.03) was recorded with soil application of DE @ 150 kg ha^{-1} which was more than recommended insecticidal check (1.74). Both Si sources proved significantly superior to insecticidal check in managing PSB in wheat under field conditions and improved photosynthesis, yield and related parameters, which can be integrated with other practices for sustainable, eco-friendly management of PSB in wheat.

Keywords Silicon · Potassium · *Sesamia inferens* · Diatomaceous earth · Silicic acid · Wheat

1 Introduction

Asiatic pink stem borer (PSB), *Sesamia inferens* (Walker) (Lepidoptera: Noctuidae) is an important and emerging pest of wheat in the northwestern plains and central parts of India, where rice-wheat cropping system has been following for many years. The PSB was originally a pest of rice in most Asian countries like India, Bangladesh, Pakistan, and Nepal [60] and has become a major pest of wheat in India, causing severe damage, due to changes in the tillage system [13]. Early larval instars of PSB bore into the central shoot of the wheat plant causing "dead hearts (yellowing and dying of central shoot)" in the vegetative stage and "white ear" (ear head turning chaffy and white) in the reproductive phase, which results in heavy yield losses [12]. Control of PSB at the early stage of the crop is very important as once it establishes inside the stem, it becomes highly difficult to control due to its hidden nature of feeding. For effective control of PSB in wheat, repeated applications of insecticide are required, which might cause an environmental hazard, pest outbreak and also makes cultivation costlier. Very few sources of plant resistance are available for this pest because of its feeding nature [1]. If the crop plants were managed carefully to minimize the vulnerability to herbivores, insecticide application and insect damage can be

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reduced to a greater extent [44]. Hence, there is a need to search for sustainable and environment-friendly alternatives for effective control of PSB.

Silicon (Si) amendment might be an alternate source for the control of PSB in wheat as Si nutrition has been shown to improve tolerance to many biotic and abiotic stresses [34, 57]. The application of Si reduced the performance of a range of herbivores, including stem borers [4, 24, 28], phloem feeders like aphids on wheat [19] brown planthopper (*Nilaparvata lugens*) on rice [65] and folivores like leaf folder (*Cnaphalocrocis medinalis*) on rice [21]. Silicon deposited in leaves and stem tissues of grass species increased the abrasiveness and deter the herbivores feeding on them and also damaged the mandibles [24, 25, 40]. Abrasive nature of Si caused damage to the midgut epithelial tissues which affected gut physiology and larvae starved to death [5]. It was also observed in a separate field experiment that Si treated plots had a lower larval number and higher larval mortality [24]. Further, Si could be able to induce resistance against leaf folder in rice by priming the jasmonate-mediated defense responses [66]. The application of Si increased the tolerance in wheat plants to aphids and promoted the synthesis of defense compounds [45]. To date, most of the literature available on the effects of Si on herbivore performance has been from either laboratory experiments or pot culture experiments. Very few researchers studied the effects of Si on herbivores under field conditions and more specifically in wheat, wherein no literature available on Si mediated tolerance against PSB.

Silicon can be supplied to the plants from different source's viz., calcium silicate (Ca_2SiO_4) and calcium meta-silicate ($CaSiO_3$) (wollastonite) [4, 30, 31], bagasse furnace ash or fly ash and blast-furnace slag (Slagment) [29], sodium silicate (Na_2SiO_3) [7, 45], potassium silicate (K_2SiO_3) [47], rice husk ash (RHA) [24] and imidazole [24, 64]. Most of these studies were carried out in the laboratory or greenhouse conditions. The performances of these sources also varied differently with their application in different climatic conditions. However, studies on diatomaceous earth (DE) and foliar silicic acid are gaining greater momentum in different crops [54, 59]. Hence, a study was conducted with the DE and foliar silicic acid to know its effect on the wheat crop.

Diatomaceous earth (DE) refers to the sedimentary rock which is made up of fossilized unicellular diatoms and a rich source of SiO_2 [49]. It has low mammalian toxicity, high persistence, insects are unlikely to develop resistance, and is easily separable from food grains and seeds, and has been registered as grain protectant in many countries [6, 30, 37].

Apart from Si, potassium (K) is also known for imparting resistance to many of the biotic and abiotic stresses. The lowest white ear damage by stem borer, *Tryporyza incertulas* in rice treated with the highest level of potassium (180 kg ha^{-1}) [27]. Also increasing rates of potassium application from 0 to 250 kg ha^{-1} decreased the damaged leaves of leaf folder, *Cnaphalocrocis medinalis* in two rice varieties [63]. Potassium is known for imparting resistance against pathogens and its fertilization reduces the severity of leaf rust in wheat and increased yield and related parameters [61]. The inverse relationship between various diseases and K fertilization was reported in rice [22].

Silicon being a non-essential nutrient for crop plants, can affect plant growth and development in stressed [36, 51] or normal conditions [20]. Many researchers reported that Si application had a significant positive effect on leaf area, net photosynthesis rate, antioxidant enzymes, total phenol, total soluble sugars and stomatal conductance in non-stressed plants [5, 39]. Further, Si application to monocotyledon plants not only improves growth and development but also increases tolerance against many abiotic stresses [32]. Potassium being a macronutrient has a significant effect on enzyme activation, protein synthesis, photosynthesis, stomatal conductance, and water use efficiency in crop plants [9]. Increased application of K has been shown to increase photosynthetic rate, yield and related parameters in different crops [14]. Potassium amendment had a significant effect on salinity stress in wheat [3] and pepper [26]. Hence, it is important to study the combined effect of Si and K amendment on photosynthesis in stressed and or normal crop plants under field conditions.

With this background, given the importance of Si and K in rendering resistance against biotic stresses and improving growth and development of crop plants, investigations were carried out to study the effect of the application of different Si sources (diatomaceous earth and soluble silicic acid) and K on PSB incidence and damage in the wheat crop and also to study their effect on photosynthesis, yield and related parameters under field conditions.

2 Material and Methods

2.1 Experimental Location

Field experiments were carried out at ICAR-National Institute of Biotic Stress Management, Raipur, Chhattisgarh state, India for two consecutive dry seasons (winter) during 2016–18. The experimental site is located at an altitude of 281.8 m, latitude of 21° 22′ 59.79" N and longitude of 81° 49′ 37.28″ E and receives an annual average rainfall of 1150 mm. Weather parameters during experimentation are given in supplementary Table 1. The soil of the experimental site had a loamy texture (sand-35%; silt-45% and clay-20%) with 0.34% organic carbon and pH of 6.8. Available nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) content in the soil were 209.3, 14.1 and 328.5 kg ha^{-1}, respectively.

2.2 Experimental Details

Field experiments were laid out to study the effect of exogenous application of Si and K on the incidence and damage by PSB in wheat and photosynthesis related parameters under field conditions for two consecutive dry seasons during 2016–18. The experiment was laid out in a factorial design with two factors i.e. Si and K, respectively tested at six and two levels with three replications. Muriate of potash (MOP) was used as a K source with two levels (P1–18 and P2–36 kg ha^{-1}). Si sources tested were T1-No Si application (Control); T2-Foliar application of soluble silicic acid (SSA) @ 2 ml L^{-1}; T3-Foliar application of SSA @ 4 ml L^{-1}; T4-Soil application of diatomaceous earth (DE) @ 150 kg ha^{-1}; T5- Soil application of diatomaceous earth (DE) @ 300 kg ha^{-1}. Apart from these Si sources, T6-Insecticidal check (Quinalphos 25 EC @ 2 ml L^{-1}) was also included as positive control. Diatomaceous earth (DE) was the main source for soil-applied Si with 30% Si concentration and soluble silicic acid was the main source for foliar Si with 2% Si concentration. The dosage for soil-applied Si was fixed based on the dissolution rates of DE at field capacity moisture regime and plant-available Si in soil solution [49, 54]. To understand the behavior of PSB and the effect on photosynthesis and related parameters at different levels of Si and potassium, the different doses of Si and potassium were used in the study. Both DE and soluble silicic acid were procured from the Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, Bengaluru, Karnataka state, India. Wheat variety, GW 273, very much popular among farmers of this region, was selected for this experiment. The wheat crop was grown in an individual plot of the size of 20 m^2 by following the recommended package of practices except for plant protection measures.

2.2.1 Treatment Imposition

The foliar silicic acid treatments (T2 and T3) were applied by mixing 2 ml and 4 ml respectively in 1 L of water per plot and insecticidal treatment (T6) was applied by mixing 2 ml per liter of water per plot using a knapsack sprayer. The treatments T2, T3 and T6 were imposed three times in the whole experiment preferably in the morning hours at an interval of two weeks and the first spray was given at 21 days after sowing. The treatments P1 and P2 (potassium) and T4 and T5 (diatomaceous earth) were applied in rows at the time of sowing along with fertilizers. Immediately after treatment imposition, the plots were irrigated to field capacity level and plots were irrigated as and when necessary.

2.3 Efficacy Studies

The incidence and damage of PSB was recorded by observing the number of white ears and healthy panicle bearing tillers in ten randomly selected plants per replication at harvest of the crop. Then the percent white ear damage was calculated using the following equation:

Percent white ear

$$= \frac{\text{Total number of white ears}}{\text{Total number of panicle bearing tillers}} \times 100$$

Yield parameters like spike length (cm), spike weight (g), number of grains per spike and 1000 grains weight (g) were recorded during the harvest of the crop. Grain yield was recorded on a net plot basis leaving border rows to avoid border effect.

2.4 Measurement of Photosynthesis and Related Parameters

Photosynthesis related parameters viz., photosynthetic rate (P), transpiration rate (E) stomatal conductance (gs), water use efficiency (WUE) and sub-stomatal CO_2 concentration (Ci) were measured from the flag leaf of five randomly selected plants at flag leaf stage of the wheat crop per plot using infrared gas analyzer (CIRAS-3, PP Systems International, Inc., Amesbury, Massachusetts, USA). All the observations were recorded between 10 AM to 12 noon.

2.5 Estimation of Si Content in Soil and Plant Samples

Soil samples were collected from all treatment plots before the application of treatments and one day after the harvest of the crop. Plant samples (only stem tissues) were collected by cutting near ground leaving stubble fifteen days before harvest and were dried in an oven at 70 °C for 2–3 h and then powdered by grinding for Si content analysis. Extraction and estimation of plant-available Si in soil were carried out using 0.01 M $CaCl_2$ extractant by adopting standard procedure [49].

2.5.1 Estimation of Si Content in Plant Samples

The sample (0.1 g) was digested in a mixture of 7 ml of HNO_3 (70%), 2 ml of 30% H_2O_2 and 1 ml of 40% HF using microwave digestion system (Milestone-start D) with following steps: 1000 watt for 17 min, 1000 watt for 10 min and venting for 10 min [46]. The digested samples were diluted to 50 ml with 4% boric acid. The Si concentration in the digested solution was determined as described below: 0.5 ml of digested aliquot was transferred to a plastic centrifuge tube, to this 3.75 ml of 0.2 N HCl, 0.5 ml of 10% ammonium molybdate ($(NH_4)6Mo_7O_2$) and 0.5 ml of 20% tartaric acid and

0.5 ml of reducing agent (Amino naphtholsulphonic acid - ANSA) was added and the volume was made up to 12.5 ml with distilled water. After one hour, the absorbance was measured at 600 nm with a UV-visible spectrophotometer. Standards (0, 0.2, 0.4, 0.8 and 1.2 ppm) were prepared using Merck Certipur® Si standard solution (1000 mg L^{-1}) and then assessed by following the same procedure [36].

2.6 Economic Analysis

Benefit-cost analysis for all the treatments was carried out using the following relations according to [42] with some modifications. Cost (T1) = costs of (land preparation + fertilizer application (including potassium application) + sowing + irrigation + weeding + harvesting + threshing; Cost (T2) = Cost (T1) + cost of (SSA) + cost of labor for SSA application; Cost (T3) = Cost (T1) + cost of (SSA) + cost of labor for SSA application; Cost (T4) = Cost (T1) + cost of (DE) + cost of labor for DE application; Cost (T5) = Cost (T1) + cost of (DE) + cost of labor for DE application; Cost (T6) = Cost (T1) + cost of insecticide (quinalphos) + cost of labor for quinalphos application. Net income (INR ha^{-1}) = (Grain yield × Price of grain) - Costs. Benefit: cost ratio was calculated using the following equation:

$$B : C = \frac{\text{Gross returns from treatment}}{\text{Treatment cost}}$$

2.7 Statistical Analysis

All the experimental data were transformed with suitable transformations before statistical analysis. All values were presented as mean ± SE. The general linear model (GLM) procedure was followed for all the experimental analyses using SAS 9.3 [56] software. Three-way analysis of variance (ANOVA) technique was used for statistical analysis of all the parameters tested during experimentation.

3 Results

3.1 Efficacy Studies

With respect to percentage white ear damage, seasons, potassium and all interaction effects showed no significant influence. However, there was a statistically significant difference between Si sources (supplementary Table 2).

Soil applied Si sources had a significant influence in reducing PSB damage than foliar-applied Si sources and insecticidal check (Table 1). T5-Soil application of DE @ 300 kg ha^{-1} was the best treatment with 45% and 37% reduction in white ear damage in comparison to T1-No Si application (Control) and T6-Insecticidal check, respectively. T4-Soil application of DE @ 150 kg ha^{-1} was the next best treatment with 33% and 24% reduction in white ear damage compared to T1 (No Si application) and T6 (Insecticidal check) (Table 1).

3.2 Photosynthesis and Related Parameters

Seasons and interactions between factors had no significant influence on all parameters tested concerning photosynthesis (supplementary Table 1).

Potassium and Si application had statistically significant effects on photosynthetic rate and transpiration rate. The treatment P2 with 36 kg ha^{-1} had recorded an increased photosynthetic rate to the tune of 18% and a lowered transpiration rate to the tune of 10% when compared to P1–18 kg ha^{-1}. Among Si sources, T5-Soil application of DE @ 300 kg ha^{-1} recorded maximum photosynthetic rate (23.20 mol CO_2 m^{-2} s^{-1}) with 49% increase and lowest transpiration rate with 135 lower over T1-No Si application (Control) (Table 2).

Both soil and foliar applied Si treatments significantly enhanced the stomatal conductance (*gs*) in contrast to untreated control. Further, potassium had no significant effect on stomatal conductance (Table 2). Maximum water use efficiency (WUE) was noticed in soil-applied Si treatments followed by foliar-applied Si sources, which were significantly different from each other. WUE was enhanced by 60% due to soil-applied Si sources and 31% in foliar-applied Si sources in comparison to untreated control. Among potassium levels, P2–36 kg ha^{-1} recorded maximum WUE of 1.74 mmol CO_2 mol^{-1} H_2O which was 25% more than P1 (Table 2). Potassium and Si interacted significantly positive with respect to WUE (Supplementary Table 1).

Intercellular CO_2 concentration (*Ci*) significantly decreased in T5-Soil application of DE @ 300 kg ha^{-1} (324.16 mmol CO_2 m^{-2} s^{-1}) in contrast to T1-Untreated control (339.68 mmol CO_2 m^{-2} s^{-1}). However, potassium had no significant effect (Table 2).

3.3 Yield and Related Parameters

Seasons and interactions between factors had no significant effect on yield and related parameters (supplementary Table 1). Both soil and foliar applied Si sources significantly enhanced yield and related parameters. Spike length was improved by 8–10% due to both soil and foliar applied Si sources in comparison to untreated control (No Si application). T5-Soil application of DE @ 300 kg ha^{-1} was the best treatment that enhanced the number of grains per spike by 14%, 1000 gains weight by 11% in comparison to untreated control. Grain yield was improved by 29–37% in comparison to untreated control and 8–18% in comparison to insecticidal check, upon application of both soil and foliar Si sources (Table 2).

Table 1 Pink stem borer damage and yield related parameters of wheat treated with different silicon and potassium sources

Treatments	White ear damage (%)	Spike length (cm)	Spike weight (g)	Number of grains per spike	1000 grains weight (g)	Grain Yield (t ha^{-1})
Seasons						
Dry season 2016–17	17.55 ± 0.48a	7.77 ± 0.06a	2.65 ± 0.03a	38.85 ± 0.38a	49.25 ± 0.39a	3.03 ± 0.29a
Dry season 2017–18	17.26 ± 0.02a	7.65 ± 0.47a	2.63 ± 0.05a	39.66 ± 0.28a	50.42 ± 0.45a	2.96 ± 0.16a
Potassium levels						
P1 (18 kg ha^{-1})	17.46 ± 0.57a	7.61 ± 0.05a	2.70 ± 0.03a	38.85 ± 0.39a	48.67 ± 0.47a	2.88 ± 0.18a
P2 (36 kg ha^{-1})	17.35 ± 0.38a	7.70 ± 0.06a	2.60 ± 0.03a	40.32 ± 0.27a	51.00 ± 0.36a	3.07 ± 0.27a
Silicon sources[a]						
T1	22.75 ± 1.25e	7.45 ± 0.10c	2.58 ± 0.05b	36.95 ± 0.58c	47.18 ± 0.82c	2.06 ± 0.79c
T2	18.24 ± 1.20c	8.13 ± 0.15a	2.77 ± 0.09a	38.12 ± 1.04c	49.76 ± 0.40b	2.93 ± 0.66a
T3	17.83 ± 1.26c	8.23 ± 0.11a	2.68 ± 0.05ab	40.08 ± 0.55bc	52.63 ± 0.90a	2.98 ± 0.25a
T4	15.16 ± 0.25b	7.89 ± 0.07b	2.66 ± 0.06ab	39.89 ± 0.47bc	53.00 ± 0.92a	3.17 ± 0.22a
T5	12.47 ± 0.37a	8.31 ± 0.11a	2.80 ± 0.03a	42.96 ± 0.42a	53.13 ± 0.93a	3.31 ± 0.19a
T6	19.95 ± 0.61d	7.46 ± 0.04c	2.32 ± 0.02c	37.25 ± 0.37c	43.33 ± 0.38d	2.72 ± 0.25b
SED	2.73	0.31	0.17	1.95	2.72	1.59
LSD (5%) for Season and potassium	1.59	0.17	0.1	1.13	1.23	0.92
LSD (5%) for Silicon levels	2.75	0.31	0.17	1.96	2.13	1.6
d.f	46	46	46	46	46	46

[a] T1- Untreated control (No Si application); T2-Foliar application of soluble silicic acid (2 ml L^{-1}); T3- Foliar application of soluble silicic acid (4 ml L^{-1}); T4-Soil application of DE (150 kg ha^{-1}); T5- Soil application of DE (300 kg ha^{-1}); T6- Insecticide check (Quinalphos 25 EC @ 2 ml L^{-1})

Values in columns represent mean ± SE; SED-Standard error of the difference between two means; LSD 5%-Least significant difference between two means at $P = 0.05$; d.f.-degrees of freedom

In columns, means followed by same letter do not differ significantly from each other by LSD ($P = 0.05$)

3.4 Si Content in Soil and Plant Samples

With respect to plant-available Si (PAS) content in the soil, there was no significant difference among all sources of variations at sowing (supplementary Table 1). However, significant differences were observed among Si sources at harvest. Maximum PAS was noticed in T5-Soil application of DE @ 300 kg ha^{-1} (75.48 ppm) which was 26.4% higher than at sowing followed by T4-Soil application of DE @ 150 kg ha^{-1} (22% higher). However, a slight decrease in PAS was observed in foliar-applied Si sources (Table 3).

Silicon content in stem tissues of plants varied significantly among Si sources. However, seasons, potassium levels and interaction between factors had no significant effect on Si content in stem tissues. Maximum Si deposition in stem tissues at harvest was observed in T5-Soil application of DE @ 300 kg ha^{-1} (4.86%) which was 62% more than untreated control (Table 3).

3.5 Economic Analysis

Highest benefit: cost ratio (2.03) was recorded in T4-Soil application of DE @ 150 kg ha^{-1} followed by T2- Foliar application of SSA @ 2 ml L^{-1} (1.85) in contrast to insecticidal check and untreated control (Fig. 1).

4 Discussion

With increasing awareness and demand for pesticide-free agricultural produce on one side and insect pests attacking the crops on the other, the development of eco-friendly, sustainable insect pest management practices is the concern of the hour. Silicon is one such element that has been used for mitigating many biotic and abiotic stresses [32, 57]. Silicon application to counter biotic stresses is a viable option and can be easily integrated with other management practices and it has no side effects like pesticide residue problem and environmental pollution [33].

4.1 Efficacy Studies

It was apparent from the field efficacy experiment that all the Si sources significantly affected the performance of PSB and among the Si sources the soil application of DE had a predominant negative impact on pink stem borer (PSB) activity with significantly reducing the percent white ear damage and was superior over the insecticidal check; which may be due to maximum Si dissolution in soil solution and deposition in stem tissues by application of DE. The Si deposited in stem tissues might be acting as a physical barrier and hindering feeding activity of PSB larvae due to wearing of the mandibles

Table 2 Effect of seasons, potassium and silicon sources on photosynthesis related parameters in wheat treated with different levels of potassium and silicon sources

Treatments	Photosynthetic rate (P) (μmol CO_2 m^{-2} s^{-1})	Transpiration rate (E) (mmol H_2O m^{-2} s^{-1})	Stomatal conductance (gs) (mmol H_2O m^{-2} s^{-1})	Water use efficiency (WUE) (mmol CO_2 mol^{-1} H_2O)	Intercellular CO_2 concentration (C_i) (mmol CO_2 m^{-2} s^{-1})
Seasons					
Dry season 2016–17	15.18 ± 0.13a	10.28 ± 0.2a	1111.90 ± 25.9a	1.53 ± 0.02a	331.83 ± 1.5a
Dry season 2017–18	15.40 ± 0.02a	10.38 ± 0.11a	1112.67 ± 21.a	1.48 ± 0.11a	328.31 ± 1.4a
Potassium levels					
P1 (18 kg ha^{-1})	13.78 ± 0.14a	10.80 ± 0.10a	1084.43 ± 21.47a	1.30 ± 0.02a	328.28 ± 1.67a
P2 (36 kg ha^{-1})	16.81 ± 0.10b	9.86 ± 0.14b	1140.14 ± 26.16a	1.74 ± 0.02b	331.86 ± 1.27a
Silicon levels[a]					
T1	11.74 ± 0.30d	10.94 ± 0.34b	947.87 ± 66.50c	0.91 ± 0.06d	339.68 ± 3.1a
T2	12.70 ± 0.27c	10.62 ± 0.19b	1169.18 ± 32.91ab	1.24 ± 0.03c	332.99 ± 4.0ab
T3	13.18 ± 0.23c	10.58 ± 0.24b	1180.61 ± 38.36ab	1.33 ± 0.03c	335.01 ± 1.98ab
T4	20.32 ± 0.15b	9.72 ± 0.16a	1134.34 ± 57.23ab	2.20 ± 0.03b	329.93 ± 2.30b
T5	23.20 ± 0.17a	10.13 ± 0.17b	1190.32 ± 43.68a	2.36 ± 0.05a	324.16 ± 2.74b
T6	10.56 ± 0.13e	10.20 ± 0.12c	1051.41 ± 9.07b	0.84 ± 0.02d	331.66 ± 1.24ab
SED	0.70	0.65	132.87	0.12	7.92
LSD (5%) for Season and potassium	0.41	0.38	77.21	0.07	4.6
LSD (5%) for Silicon levels	0.70	0.66	133.73	0.12	7.97
d.f	46	46	46	46	46

[a] T1- Untreated control (No Si application); T2-Foliar application of soluble silicic acid (2 ml L^{-1}); T3- Foliar application of soluble silicic acid (4 ml L^{-1}); T4-Soil application of DE (150 kg ha^{-1}); T5- Soil application of DE (300 kg ha^{-1}); T6- Insecticide check (Quinalphos 25 EC @ 2 ml L^{-1})

Values in columns represent mean ± SE; SED-Standard error of the difference between two means; LSD 5%-Least significant difference between two means at $P = 0.05$; d.f.-degrees of freedom

In columns, means followed by same letter do not differ significantly from each other by LSD ($P = 0.05$)

and preventing further feeding as in the case of yellow stem borer larvae in rice [24]. In the present investigation, all the Si sources were superior over insecticidal check in reducing PSB damage, which suggests that Si sources might be used as one of the alternatives for sustainable management of PSB. The present investigation is first of its kind to reveal the significant effect of Si on PSB incidence and damage in wheat and as such, there is no supporting literature to support our current studies. However, many researchers studied Si mediated resistance in wheat against green bug, *Scizaphis graminum* [16, 19] and reported significant effects of Si on the pest.

Studies on plant-available Si content as influenced by DE and its effect on crop growth and development are lacking [33]. The effect of different grades and levels of DE as Si source at varied soil pH and moisture levels by enumerating the dissolution rate and total plant-available Si content in DE was studied in rice [49, 50, 52]. Application of soluble silicic acid as a foliar source of Si is promising as evidenced in different crops [8, 48, 59]. Many researchers evaluated the efficacy of orthosilicic acid as foliar Si source against insect pests and pathogens [27, 62]. The significant effect in the management of yellow stem borer with the application of orthosilicic acid @ 4 ml L^{-1} was noticed in rice [62].

4.2 Photosynthesis and Related Parameters

Soil application of Si sources (DE @ 300 kg ha^{-1}) significantly enhanced photosynthetic rate, water use efficiency (WUE), stomatal conductance and decreased transpiration rate and intercellular CO_2 concentration in the present investigation. The increased photosynthesis upon Si application might be due to increased activity of antioxidant enzymes, RuBP carboxylase and increase in chlorophyll content [36]. Silicon application was reportedly increased the net photosynthesis rate in various crops like wheat [18], sorghum [2] and soybean [58] which supports current findings. A possible explanation for the lowest transpiration rate upon Si application might be due to decreased stomatal activity. It was also reported that Si plays an important role in decreasing the transpiration rate to protect the moisture content of the plants [35]. WUE is essential for wheat plants for transportation of essential salts and other nutrients which are essential for all physiological activities. Si application significantly decreases transpiration and increase in WUE in wheat and maize plants, respectively as reported by [9, 15]. However, the increased transpiration, WUE and decreased intercellular CO_2 concentration in wheat plants under drought stress, which might be due to increased

Table 3 Effect of seasons, potassium and silicon sources on plant available Si in soil (ppm) and Si content in stem tissue at harvest (%)

Treatments	Plant available Si in soil (ppm)		Si content in stem tissues (%)
	At sowing	At harvest	At harvest
Seasons			
Dry season 2016–17	55.64 ± 0.36a	60.15 ± 0.15a	2.36 ± 0.11a
Dry season 2017–18	56.38 ± 0.28a	60.64 ± 0.22a	2.41 ± 0.06a
Potassium levels			
P1 (18 kg ha^{-1})	55.48 ± 1.02a	64.56 ± 0.54a	3.25 ± 0.21a
P2 (36 kg ha^{-1})	54.89 ± 0.65a	63.58 ± 0.35a	3.58 ± 0.14a
Silicon sources[a]			
T1	55.64 ± 0.15a	52.36 ± 0.10e	1.56 ± 0.03c
T2	54.36 ± 0.21a	53.45 ± 0.12d	2.15 ± 0.05b
T3	56.48 ± 0.14a	55.61 ± 0.14c	2.35 ± 0.10b
T4	54.59 ± 0.06a	69.89 ± 0.50b	3.68 ± 0.06a
T5	55.54 ± 0.08a	75.48 ± 0.45a	4.12 ± 0.05a
T6	56.36 ± 0.10a	53.48 ± 0.11d	1.69 ± 0.02c
SED	0.12	0.76	1.04
LSD (5%) for Season and potassium	1.23	1.54	0.65
LSD (5%) for Silicon levels	1.36	1.11	0.75
d.f	46	46	46

[a] T1- Untreated control (No Si application); T2-Foliar application of soluble silicic acid (2 ml L^{-1}); T3- Foliar application of soluble silicic acid (4 ml L^{-1}); T4-Soil application of DE (150 kg ha^{-1}); T5- Soil application of DE (300 kg ha^{-1}); T6- Insecticide check (Quinalphos 25 EC @ 2 ml L^{-1})

Values in columns represent mean ± SE; SED-Standard error of the difference between two means; LSD 5%-Least significant difference between two means at $P = 0.05$; d.f.-degrees of freedom

In columns, means followed by same letter do not differ significantly from each other by LSD (P=0.05)

stomatal conductance, one of the mechanisms in maintaining dry matter production under drought conditions [38]. Si application significantly increased the stomatal conductance, net leaf area and activity of antioxidant enzymes under non-stressed conditions in different crops [5, 10, 58].

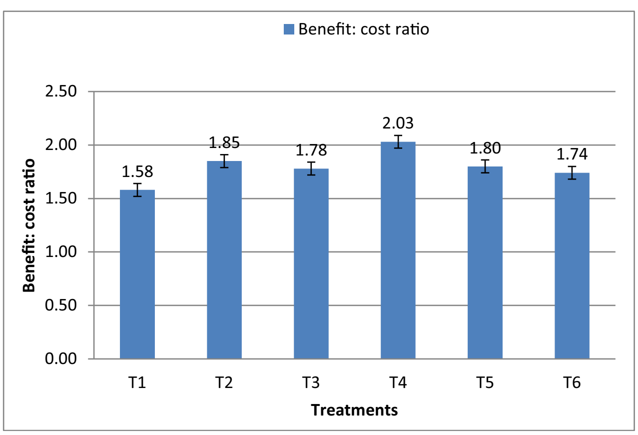

Fig. 1 Economic analysis of benefit: cost ratios of different Si sources for the management of pink stem borer in wheat under field conditions, Note: T1- Untreated control (No Si application); T2-Foliar application of silicic acid (2 mlL^{-1}); T3- Foliar application of silicic acid (4 mlL^{-1}); T4-Soil application of DE @ 150 kg ha^{-1}); T5- Soil application of DE @ 300 kg ha^{-1}; T6- Insecticide check (Quinalphos 25 EC @ 2 mlL^{-1}). Cost of human labour per day- 300 INR; cost of DE- 20 INR kg^{-1}; cost of silicic acid-1200 INR L^{-1}; cost of quinalphos - 600 INR L^{-1}; cost of wheat procurement (Minimum support price)-1300 INR q^{-1}

Potassium application (36 kg ha^{-1}) significantly increased photosynthesis rate, WUE and decreased transpiration rate in present findings. However, it had no significant effect on stomatal conductance and intercellular CO_2 concentration. Photosynthesis is majorly driven by the activity of RuBP carboxylase enzyme and potassium is known for its involvement in biosynthesis and activity of this enzyme [42]. The application of potassium significantly increased the photosynthesis rate in different crops [15]. The decreased intercellular CO_2 concentration due to potassium application was observed in cucumber [23] and wheat [38].

4.3 Yield and Related Parameters

Yield and related parameters significantly enhanced by both the Si sources and potassium in comparison to no Si application and insecticidal check in the present investigation. It might be attributed to the lowest white ear damage, the highest photosynthesis rate with reduced transpiration rate and maximum water use efficiency upon combined application of Si sources and potassium (36 kg ha^{-1}). Si and potassium application to wheat significantly increased seed weight, seed number, ear number and final seed yield [9]. Many studies revealed a significant increase in yield and related parameters with Si application in wheat [17] and rice [11, 24, 41, 48, 55]. Application of 300–600 kg ha^{-1} of DE along with recommended fertilizer dose significantly improved yield and related parameters in rice under field capacity moisture regime [53].

4.4 Content of Silicon and Potassium in Soil and Plant Samples

The target pest, pink stem borer of wheat, mainly feeds on stem tissues and it doesn't feed on either root or leaves. Hence, it was mainly emphasized on silicon content in stem tissues.

In the present experiment, soil-applied Si sources significantly enhanced the plant-available Si (PAS) in soil and Si content in stem tissues of wheat plants in contrast to foliar-applied Si sources. It might be due to the high dissolution rate of DE at favorable soil pH and the availability of PAS for wheat plants. In the present investigation, it was mainly emphasized to relate the Si content in stem and PSB damage as it mainly feeds on stem tissues The availability of PAS in different grades of DE at various soil pH and moisture levels in rice was studied and found that PAS availability was relatively higher under submergence in contrast to field capacity moisture regime and maximum dissolution of DE was at slightly higher soil pH [49]. Application DE as a silicon source for rice also increased the silicon content in soil and plant samples as evidenced by other researchers [43, 52, 54].

In all the treatments, the content of potassium was found to be non significant (data not shown) which can be attributed to higher available potassium content in the soil. Further, the interaction effect of Si and potassium was also found to be non- significant (supplementary Table 2).

5 Conclusion

It was well proven that Si is known to mitigate the influence of biotic stresses in a variety of crops [6, 50]. Soil application of diatomaceous earth as a Si source along with potassium significantly affected the performance of pink stem borer in wheat under field conditions and decreased its damage in contrast to insecticidal check. Our studies also proved that soil application of DE or foliar silicic acid along with potassium significantly enhanced the photosynthesis, yield and related parameters. With growing awareness and increasing demand for pesticide-free, organically grown agro-produce, application of Si paves the way for sustainable, eco-friendly management of insect pests under field conditions without compromising for yield levels.

In the context of the present agricultural scenario, with limited land and other resources, we have to give more emphasis on producing good quality, pesticide-free agricultural produce with less cost of cultivation. Soil application of DE or foliar application of silicic acid with a special emphasis on the proper dosage of potassium can be a viable and more economical option for managing insect pests in general and pink stem borer in particular in a sustainable and eco-friendly manner with enhanced photosynthesis, yield, and related parameters.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no potential conflict of interest.

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