Silicon
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ORIGINAL PAPER

Silicon Accumulation in Maize and its Effects on Demographical Traits of Fall armyworm, [*Spodoptera frugiperda* (J. E. Smith)]

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Abstract

Fall armyworm (*Spodoptera frugiperda*) is a serious pest of various agricultural crops, causing heavy economic losses. Mostly, chemical pesticides are used for its management, but it has developed resistance against pesticides and other commonly used control methods. Studies have shown that the exogenous application of silicon has the potential to make plants more resistant to insect herbivores without causing any negative effects on the efficiency of natural enemies. Therefore, a laboratory experiment was conducted to test the impact of silicon dioxide (SiO_2) and potassium silicate (K_2SiO_3) applied by foliar spray and soil drenching on its accumulation in maize and its impact on demographical traits of *S. frugiperda* to check its most susceptible age stage. Results of the current study revealed a significant effect of all silicon applications compared to control on survival rate, developmental duration, the reproduction rate of *S. frugiperda*, and silicon accumulation in maize. Furthermore, results indicated that *S. frugiperda* fed on the maize plants treated with foliar spray or SiO_2 showed a lower intrinsic rate of growth (r), finite rate of growth (λ), and net reproduction rate (R_0) compared to all other treatments. All the treatments showed a significant effect on the adult pre-oviposition period (APOP), total oviposition period (TPOP), pre-adult survival rate, and oviposition days compared to the control. Age stage-specific life expectancy (e_{xj}) and Age stage-specific reproductive values (v_{xj}) of *S. frugiperda* were significantly affected in all silicon treatments. From current results, it is concluded that silicon can be used as an alternate method for the management of this destructive pest.

Keywords Fall armyworm · Silicon application · Population management · Silicon accumulation

1 Introduction

The fall armyworm, *Spodoptera frugiperda*[J. E. Smith (Lepidoptera: Noctuidae)], is a migratory, extremely polyphagous pest that is endemic to the Americas [1] and reported in Africa [2] and in Asia [3]. In South and Central America, it is the most commercially significant pest of maize [4–6]. Due to the lack of a diapause characteristic, it migrates towards the north in the autumn season in the United States to infest temperate maize farming regions [7]. *S. frugiperda* consists of two biologically and behaviorally distinct strains that coexist in North and South America [8, 9]. According to reports, the "corn" type (C) mostly damages maize and cotton, while the "rice" type (R) primarily infests rice, pasture, and fodder grasses [5, 10]. These "host strains" of *S. frugiperda* are physically identical; nevertheless, mutations in the mitochondrial cytochrome oxidase subunit I gene reliably distinguished and identified the C and R types on the basis of their haplotypes [11].

The fast growth and development of *S. frugiperda* populations in Africa and Asia illustrate two key facts: (1) comparable to the Americas; the pest may rapidly spread over wide geographic regions in a short period of time [12], (2) *S. frugiperda* populations can survive year-round in tropical or sub-tropical reigons. Thus, *S. frugiperda* has become a worldwide concern, presenting a significant danger to the nutrition, food security, and livelihood of hundreds of millions of agricultural families in Africa and Asia, particularly those reliant on maize [13].

In China, it was first time reported in December 2018 and spread across 26 provinces, causing a significant damage to maize fields in Yunnan and Guangxi provinces in early 2019 [14–16]. In Ghana and Zambia, yield losses

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Extended author information available on the last page of the article in maize fields caused by *S. frugiperda* are reported to be 22 and 67%, respectively, while it caused 47% yield loss in Kenya and 32% in Ethiopia. In addition, it was reported that the larvae of *S. frugiperda* also damage peanut field, causing 78 and 65% damage during the seedling and blooming phases, respectively. In wheat fields, *S. frugiperda* causes substantial damage, with estimates ranging from 30–90%, whereas in barley fields, damage estimates range from 10–80%.

Various technologies and methods for managing *S. frugiperda* have been developed throughout the years. In Asia, novel synthetic pesticides continue to be regarded as one of the most efficient treatments against *S. frugiperda* [17–21]. Due of the minimal toxicity risks and negligible residual effects of biopesticides, scientists are developing biopesticides containing entomopathogenic fungus [22, 23], plant based insecticides [24–26] which are safer for humans, the environment, and natural predators. No one approach can offer long-term management of *S. frugiperda*. Over the years, many different technologies and ways to manage *S. frugiperda* have been developed.

Studies have shown that silicon has the potential to make plants more resistant to insect herbivores from the orders Homoptera [27], Lepidoptera [28, 29], Diptera [30], Hemiptera [31, 32], Coleoptera [33], and Thysanoptera [34] without causing any negative effects on the efficiency of natural enemies [34]. Silicon could also make it more difficult for insects to suppress a plant's defenses, making it possible for a full-fledged defense response to be set off when an abiotic threat is detected [35, 36]. In addition, the ability of a plant species to absorb and translocate silicon within its tissues differs greatly. Exogenous treatments of silicon at regular time intervals are thus advised to protect plants against herbivorous consumption [37, 38].

The demographic traits or life table has been recognized as an effective tool for evaluating the impact of various factors (such as temperatures, pesticides, and plant secondary metabolites) on the survival, reproduction, development, life expectancy, and fecundity of pest populations [39, 40]. The conventional life table is based only on the female population and so lacks information on the male population, as well as missing data on individual variances and developmental phases [41]. Incorporating data from both sexes in a population, the research based on age-stage, two-sex life tables eliminated the inherent shortcomings of female-based life tables [42, 43]. The age-stage two-sex life table can help to understand the population dynamics in particular, which can be helpful in explaining the impacts of different control methods on target insects [44, 45]. Keeping in view the above knowledge, the current experiment was carried out to check the effects of silicon application on silicon accumulation in maize and its effects on the demographical traits of *S. frugiperda*.

2 Materials and Methods

2.1 Experimental Site and Treatments

The current laboratory trial was carried out at the Biological Control Laboratory, the College of Plant Protection, Gansu Agricultural University Lanzhou, China. The experiment was conducted in a completely randomized design (CRD) with three biological replicates. Treatments consisted of two Silicon sources, Silicon dioxide (SiO_2), and Potassium silicate (K_2SiO_3) applied with two different methods of application (Foliar spray and soil drenching). In the untreated control, silicon was not applied.

2.2 Insect Culture

Spodoptera frugiperda larvae were obtained from a laboratory colony and were kept in cages to maintain a colony. These larvae were provided with fresh maize leaves until pupation. The colony was maintained at 25 ± 5 ^{0}C temperature, 65 ± 5 relative humidity, and 16:8 (L:D) hours photoperiod in a growth chamber. Adults were provided with cotton balls soaked in honey: water (15:85) solution as a food source. Pots with maize plants were kept inside cages as an ovipositional site for adult females. Eggs were collected on daily bases and were kept in Petri dishes for hatching. Newly emerging larvae were used for bioassays.

2.3 Plant Material

Certified seeds of the variety Long-Fei 211 (隆非211) were received from the laboratory and were planted in pots containing standard pro mix potting soil. Those pots were kept in a controlled environment (T 25 ± 5 ^{0}C; R.H 65 ± 5 and 16:8 (L: D) h) and watered at regular intervals.

2.4 Silicon Applications

SiO_2 and K_2SiO_3 were dissolved in water to make an 800 ppm concentration solution before application. A foliar spray of both silicon sources was performed using a hand sprayer, and drenches were applied to the base of the plant in soil drenching treatments. The first silicon application was applied to the plants fifteen days after emergence. Blooming leaves of the treated and untreated plants were cut using a scissor and were provided as a food source for *S. frugiperda* larvae.

2.5 Silicon Accumulation

Forty days after germination, we collected leaves from silicon-treated and untreated plants to determine the quantity of silicon accumulated in maize leaves. The collected leaves were taken to the laboratory and frozen using liquid nitrogen. The leaves were dried to constant weight for silicon quantification following the method outlined by Acevedo et al. [46].

2.6 Life Table Bioassays

All the bioassays were conducted in a growth chamber at $25 \pm 5\ ^{0}C$ temperature, 65 ± 5 relative humidity, and 16:8 (L:D) hours photoperiod. Newly emerging larvae from the colony were kept in the Petri dishes containing filter papers and were provided with leaf discs cut from treated plants. Leaf discs were replaced daily till pupation. 1st and 2nd instar larvae were kept in groups because of their small size. From the 3rd instar, larvae were separated individually. When larvae reached 5th instar, they were transferred to plastic boxes containing filter paper and cotton balls soaked in water and clean peat soil for pupation. All the plastic boxes containing pupa were kept in boxes containing potted maize plants as an ovipositional site for adults. After adult emergence, boxes were supplied with cotton balls soaked in honey: water (15:85) solution as a food source for adults. Eggs were harvested on daily bases and transferred to Petri dishes for hatching. Fifty newly hatched neonates per treatment were transferred to Petri dishes and were provided with leaf discs from treated plants. The same procedure during larval development was followed as described above. At the pupal stage, individuals were sexed by checking their gender characteristics. Pairings of newly emerged adults were formed for the purposes of mating and oviposition. All the eggs laid by each female were harvested and counted on a daily basis as the age stage-specific fecundity. Each individual's growth period, survival rate, and fecundity were monitored on a daily basis till all of the individuals had died.

2.7 Data Analysis

The data of *S. frugiperda* reared on maize leaves treated with SiO_2 and K_2SiO_3 with two application methods and control treatment was collected and analyzed According to the age-stage table theory [47] and the methodology given by Chi and Liu [44] using the TWO SEX-MSChart software [48]. S_{xj} (is the survival rate of *S. frugiperda* from egg to *x* days and stage *j*), l_x (specific survival rate of *S. frugiperda* with respect to age), f_{xj} (fecundity of *S. frugiperda* with respect to specific age and stage), m_x (fecundity of *S. frugiperda* with respect to a specific age), $l_x m_x$ (net maternity of *S. frugiperda* with respect to a specific age), and the population parameters of *S. frugiperda* were determined, including mean generation time (T), net reproduction rate (R_0), intrinsic rate of growth (r), and finite rate of increase (λ). These were calculated using the following equations:

i) The specific survival rate of *S. frugiperda* with respect to age $(l_x) = \sum_{j=1}^{m} s_{xj}$
   Where, m represents the number of stages of *S. frugiperda* in the experiment.
ii) Fecundity of *S. frugiperda* with respect to specific age $(m_x) = \frac{\sum_{j=1}^{m} s_{xj} f_{xj}}{\sum_{j=1}^{m} s_{sj}}$
iii) The intrinsic rate of growth $(r) = \sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1$
iv) The finite rate of increase $(\lambda) = e^{r}$
v) The net reproduction rate $(R_0) = \sum_{x=0}^{\infty} l_x m_x$
vi) The mean generation time $(T) = \frac{ln R_0}{r}$
vii) The life expectancy with respect to specific age $(e_{xj}) = \sum_{i=x}^{\infty} \sum_{y=j}^{m} s'_{iy}$
   Where, the s'_{iy} is the probability of *S. frugiperda* of age x and stage j will survive to age (i) and stage (y).
viii) The reproductive value $(v_{xj}) = \frac{e^{r(x+1)}}{s_{xj}} \sum_{i=x}^{\infty} e^{-r(i+1)} \sum_{y=1}^{m} s'_{iy} f_{iy}$

The contribution of individuals of age x and stage j to the future population [49]

In this experiment, bootstrap tests were performed to check differences across all the treatments at a 5% significance level based on the confidence interval of difference [43, 50, 51]. Data for silicon accumulation was analyzed by using Statistix 8.1 software. Means were compared at a 5% level of significance using the LSD test. All the figures for life table analysis were made using Sigma Plot 14 software. The figure for Si accumulation was made by using Graphpad Prism 9.

3 Results

3.1 Si Accumulation

Figure 1 shows that all the silicon applications significantly affected the silicon accumulation in maize leaves compared to the control treatment. Results indicated that a significantly higher silicon concentration was observed in the maize plants treated with foliar spray of SiO_2 (4826.33 ± 159.55 mg Kg^{-1}) followed by foliar spray of K_2SiO_3 (4447.66 ± 108.48 mg Kg^{-1}), soil drenching of K_2SiO_3 (3198.33 ± 167.49 mg Kg^{-1}) and soil drenching of SiO_2 (3183.66 ± 101.65 mg Kg^{-1}). Silicon concentration in SiO_2 soil drenching and K_2SiO_3 soil drenching was significantly similar. Minimum silicon concentration was recorded in those maize plants which did not receive any silicon application (2621.33 ± 298.11 mg Kg^{-1}).

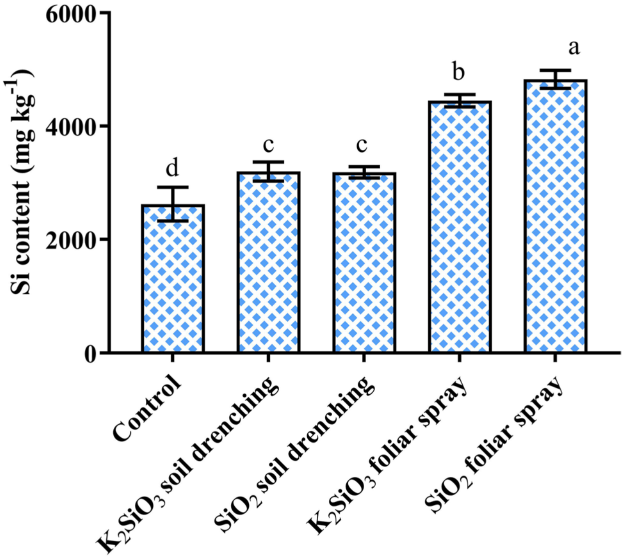

Fig. 1 Effect of silicon applications on silicon accumulation in maize. LSD test was used to compare means at p ≤ 0.05. Vertical bars indicate SE

3.2 Population Parameters

Results of the current study indicated that *S. frugiperda* fed on the maize plants treated with foliar spray or SiO_2 showed a lower intrinsic rate of growth (*r*) 0.085 ± 0.007, finite rate of growth (λ) 1.08 ± 0.007, and net reproduction rate (R_0) 29.34 ± 7.85 compared to all other treatments (Table 1). Maximum values of the intrinsic rate of growth (*r*) 0.125 ± 0.005, finite rate of growth (λ) 1.13 ± 0.005, and net reproduction rate (R_0) 83.56 ± 14.56 were recorded in the control treatment. Significantly extended mean generation time (*T*) was recorded in all silicon applications compared to control (35.34 ± 0.27). Among silicon treatments, a maximum mean generation time (40. 92 ± 0.39) was recorded in the foliar application of K_2SiO_3, followed by the foliar spray of SiO_2 (39.59 ± 0.23), soil drenching of SiO_2 (39.46 ± 0.31), and soil drenching of K_2SiO_3 (36.99 ± 0.18). Gross reproduction rate (*GRR*) and fecundity per female (*F*) were significantly lower in the foliar spray of SiO_2 (56.54 ± 13.71 and 133.36 ± 3.33) compared to other silicon treatments and the control. Maximum gross reproduction rate (*GRR*) and fecundity per female (*F*) were recorded in the control treatment (91.3 ± 15.37 and 208.9 ± 4.08). No significant difference was observed among all the treatments in the case of Female percentage (*Nf/F*) (Table 1).

3.3 Age-Stage-Specific Survival Rate

Our results showed that the growth and development rates of the different individuals were different. As shown in Fig. 2, the survival rate of a specific stage with respect to age (s_{xj}) tells us how probable it is that a newborn egg will survive to age *x* and develop to stage *j*. The survival curves of different demographic stages clearly overlap. Compared to control treatment, the survival rate of *S. frugiperda* females in all the silicon treatments (foliar spray of SiO_2, foliar spray of K_2SiO_3, soil drenching of SiO_2, and soil drenching of K_2SiO_3 is significantly low. The lowest lines in the plotted graphs showed that each developmental stage was different for the silicon treatments compared to the control. Furthermore, results showed the lowest S_{xj} values on the foliar spray of SiO_2 (i.e., 0.21 for females and 0.30 for males), whereas these values gradually increased on SiO_2 soil drenching (i.e., 0.30 for males and females), foliar spray of K_2SiO_3 (i.e., 0.36 for males and 0.30 for females), soil drenching of K_2SiO_3 (i.e., 0.40 for males and 0.31 for females) and control (i.e., 0.56 for male and 0.39 for female). A similar trend of S_{xj} was observed in all other life stages of *S. frugiperda* (Fig. 2 and Fig. S1).

3.4 Age-Specific Survival Rate and Fecundity

Results of the current study revealed that *S. frugiperda* survival rate significantly decreased in the foliar spray of

Table 1 Table of bootstrapping results of population parameters of *S. frugiperda* fed on maize leaves treated with SiO_2 and K_2SiO_3 applied by two application methods (Foliar spray and soil drenching)

	SiO_2 foliar spray	K_2SiO_3 foliar spray	SiO_2 soil drenching	K_2SiO_3 soil drenching	Control
Intrinsic rate of increase (r)	0.085 ± 0.007^d	0.09 ± 0.005^c	0.09 ± 0.005^c	0.105 ± 0.006^b	0.125 ± 0.005^a
Finite rate of increase (λ)	1.08 ± 0.007^e	1.09 ± 0.006^d	1.10 ± 0.006^c	1.11 ± 0.006^b	1.13 ± 0.005 ^{a}
Net reproduction rate (R_0)	29.34 ± 7.85^d	41.1 ± 8.89^c	46.04 ± 10.07^b	49.64 ± 10.74^b	83.56 ± 14.56^a
Mean generation time (T)	39.59 ± 0.23^b	40. 92 ± 0.39^a	39.46 ± 0.31^b	36.99 ± 0.18^c	35.34 ± 0.27^d
Gross reproduction rate (GRR)	56.54 ± 13.71^e	65.56 ± 12.49^d	75.15 ± 14.43^b	71.43 ± 14.09^c	91.3 ± 15.37^a
Fecundity per female (F)	133.36 ± 3.33^d	137 ± 1.19^d	153.47 ± 4.45^c	165.47 ± 2.64^b	208.9 ± 4.08^a
Female percentage (Nf/F)	0.22 ± 0.06^c	0.3 ± 0.06^b	0.3 ± 0.07^b	0.3 ± 0.06^b	0.4 ± 0.07^a

Means followed by the same letters in the same rows are not significantly different based on the paired bootstrap test at the 5% significance level. 50 insects were used for each treatment

Superscripts shows the statistical difference among different treatments in a row

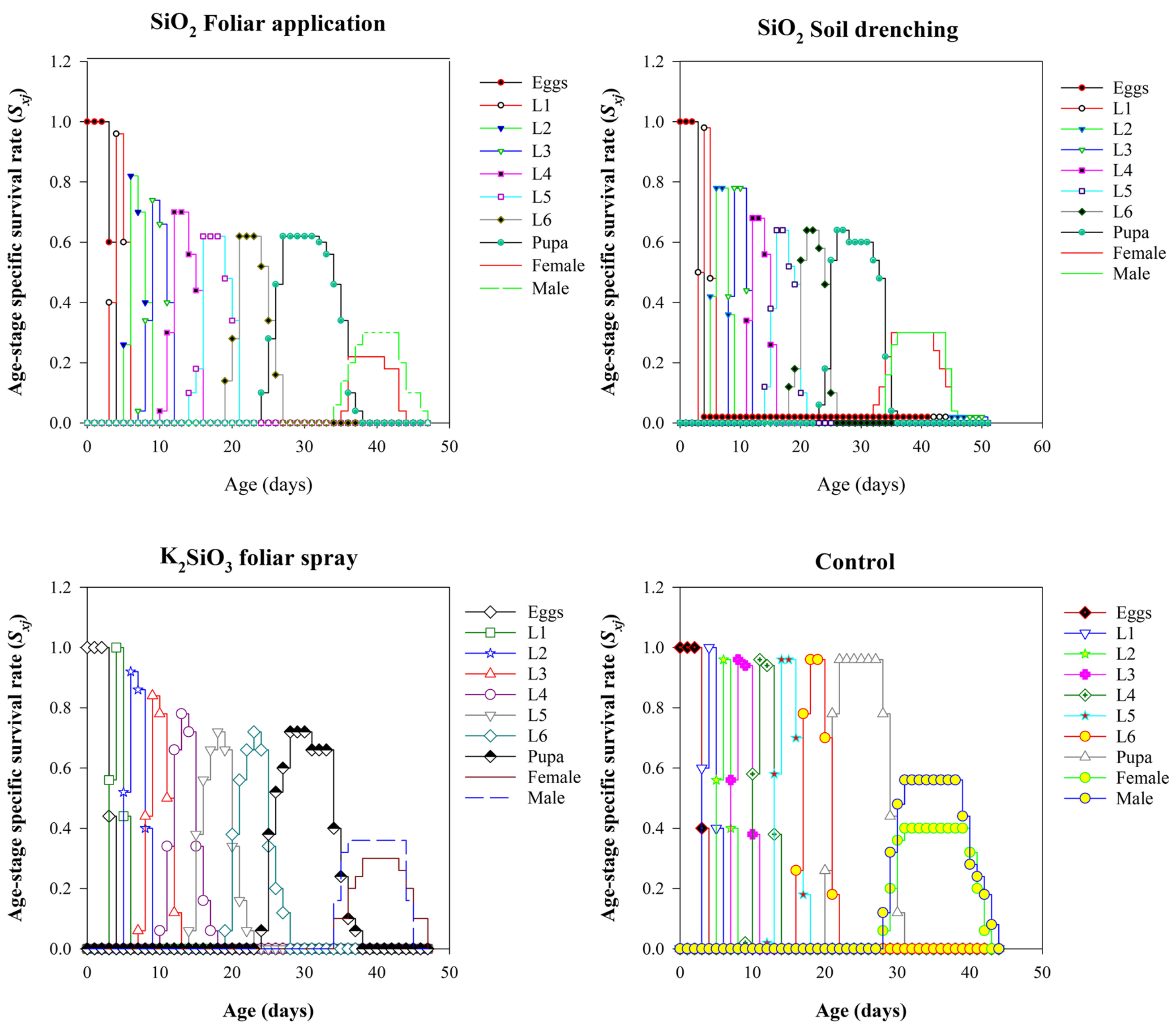

Fig. 2 Effect of silicon applications on Age-stage specific survival rate of *S. frugiperda*

SiO_2 compared to all other Si treatments and control; the graphs for *S. frugiperda* survival rate with respect to a specific age (l_x) are shown in Fig. 3 and Fig. S2. l_x value decreased to 0.68 at 0–10 days of age in females reared on the maize treated with a foliar spray of SiO_2. At the age of 30–40 days, the survival rate with respect to specific age was 0.5, which is lower than all other treatments. In the control treatment, the lowest lx value was 0.96 (Fig. 3). The results showed that per day fecundity of females was higher in the foliar spray of SiO_2 compared to all other treatments; the graphs for f_x, m_x, and $l_x m_x$, as compared to the control, are shown in Fig. 3 and Fig. S2; however, the maximum f_x value recorded in SiO_2 foliar spray was 47 eggs female^{-1} day^{-1} at 38 days, K_2SiO_3 foliar spray 24 eggs female^{-1} day^{-1} at 41 days, soil drenching of SiO_2 27 eggs female^{-1} day^{-1} at 38 days and in the control treatment, it was 29 eggs female^{-1} day^{-1} at 34 days.

3.5 Pre-adult Developmental Duration

A significant effect of all silicon applications was observed on 2nd instar larvae of *S. frugiperda* compared to the control (Table 2). A significantly extended developmental period was recorded when 2nd instar larvae were fed with the maize leaves treated with foliar spray of SiO_2 (2.73 ± 0.07 days), soil drenching of SiO_2 (3.00 ± 0.00 days), foliar spray (2.93 ± 0.04 days) and soil drenching of K_2SiO_3 (3.00 ± 0.00 days) compared to control (2.00 ± 0.00 days). There was no significant difference observed in the developmental duration of 1st

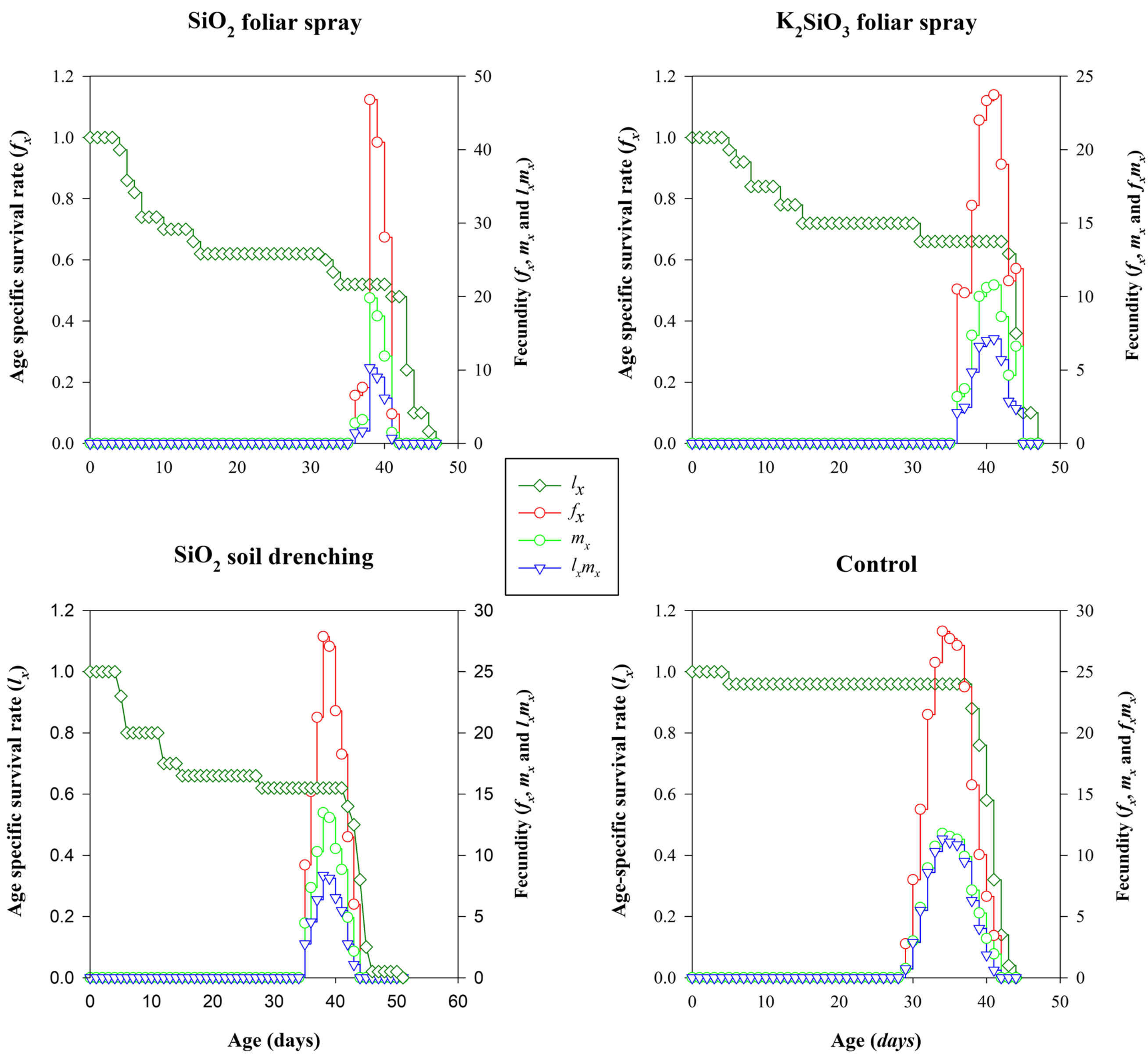

Fig. 3 Effect of silicon applications on Age specific survival rate and fecundity of *S. frugiperda*

instar larvae in all the treatments. Moreover, extended larval duration was observed in 3rd (3.28 ± 0.07 days), 4th (4.08 ± 0.07 days), and 5th (5.00 ± 0.00 days) instar larvae when fed on leaves treated with foliar application of K_2SiO_3 compared to other Si treatments and the control (2.96 ± 0.03 days, 3.00 ± 0.00 days, and 3.54 ± 0.07 days, respectively). Furthermore, an extended 6th instar larval duration (5.32 ± 0.08 days) and pupal duration (10.35 ± 0.09 days) was recorded in the foliar spray of SiO_2 compared to other silicon treatments and the control (4.00 ± 0.00 days and 8.48 ± 0.07 days, respectively). Overall, a significantly extended total pre-adult developmental period of larvae was observed in the foliar spray of SiO_2 (35.81 ± 0.21 days) compared to other silicon treatments and the control (29.4 ± 0.13 days).

3.6 APOP, TPOP, Pre-adult Survivorship, Oviposition Days, and Adult Sex Ratio

The results of the current experiment showed a significant effect on the adult pre-oviposition period (APOP), total oviposition period (TPOP), pre-adult survival rate, and oviposition days compared to control (Table 3). A significantly shorter APOP (1.82 ± 0.12 days) and Ovi-days (3.18 ± 0.12 days) were recorded in the foliar spray of SiO_2 compared to the control (2.00 ± 0.00 days and

Table 2 Table of number of females, APOP, TPOP, preadult survivorship, and oviposition days estimated by using the bootstrap method

	SiO_2 foliar spray	K_2SiO_3 foliar spray	SiO_2 soil drenching	K_2SiO_3 soil drenching	Control
nF	11.00 ± 2.93^{c}	15.00 ± 3.24^{b}	15.00 ± 3.25^{b}	15.00 ± 3.23^{b}	20.00 ± 3.45^{a}
RepF	11.00 ± 2.93^{c}	15.00 ± 3.24^{b}	15.00 ± 3.25^{b}	15.00 ± 3.23^{b}	20.00 ± 3.45^{a}
Male	15.00 ± 3.23^{d}	18.00 ± 3.39^{c}	15.00 ± 3.24^{d}	20.00 ± 3.45^{b}	28.00 ± 3.51^{a}
N-type	24.00 ± 3.54^{a}	17.00 ± 3.34^{c}	20.00 ± 3.47^{b}	15.00 ± 3.23^{d}	2.00 ± 1.39^{e}
APOP	1.82 ± 0.12^{c}	2.00 ± 0.00^{b}	2.47 ± 0.13^{a}	2.00 ± 0.00^{b}	2.00 ± 0.00^{b}
TPOP	37.64 ± 0.24^{a}	37.87 ± 0.39^{a}	36.13 ± 0.29^{b}	34.06 ± 0.11^{c}	31.45 ± 0.19^{d}
Sa	0.52 ± 0.07^{d}	0.66 ± 0.07^{b}	0.60 ± 0.06^{c}	0.70 ± 0.06^{b}	0.96 ± 0.03^{a}
Ovi-days	3.18 ± 0.12^{d}	5.33 ± 0.12^{b}	5.80 ± 0.11^{b}	4.6 ± 0.19^{c}	8.00 ± 0.14^{a}

Fn = No. of females; RepF = No.of reproductive females; N-type = No. of unknown individuals; APOP = Adult pre-oviposition period; TPOP = Total pre-oviposition period; Sa = Preadult survival rate; Ovi-days = Oviposition days

Means followed by the same letters in the same rows are not significantly different based on the paired bootstrap test at the 5% significance level. 50 insects were used for each treatment

Superscripts shows the statistical difference among different treatments in a row

Table 3 Age stage-specific developmental time (days) of *S. frugiperda* fed on maize leaves treated with SiO_2 and K_2SiO_3 applied by two application methods (Foliar spray and soil drenching)

	SiO_2 foliar spray	K_2SiO_3 foliar spray	SiO_2 soil drenching	K_2SiO_3 soil drenching	Control
Egg (n)	3.6 ± 0.07^{b}	3.44 ± 0.07^{c}	4.26 ± 0.77^{a}	3.44 ± 0.07^{c}	3.40 ± 0.07^{d}
1st instar (days)	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}	2.02 ± 0.02^{a}	2.00 ± 0.00^{a}	2.00 ± 0.00^{a}
2nd instar (days)	2.73 ± 0.07^{c}	2.93 ± 0.04^{b}	3.00 ± 0.00^{a}	3.00 ± 0.00^{a}	2.00 ± 0.00^{d}
3rd instar (days)	3.00 ± 0.00^{c}	3.28 ± 0.07^{a}	3.06 ± 0.04^{b}	3.00 ± 0.00^{c}	2.96 ± 0.03^{d}
4th instar (days)	3.97 ± 0.07^{b}	4.08 ± 0.07^{a}	3.75 ± 0.08^{c}	3.51 ± 0.08^{d}	3.00 ± 0.00^{e}
5th instar (days)	4.77 ± 0.08^{b}	5.00 ± 0.00^{a}	4.47 ± 0.09^{c}	4.00 ± 0.00^{d}	3.54 ± 0.07^{e}
6th instar (days)	5.32 ± 0.08^{a}	5.14 ± 0.06^{b}	5.09 ± 0.05^{c}	5.00 ± 0.00^{d}	4.00 ± 0.00^{e}
Pupa (days)	10.35 ± 0.09^{a}	9.58 ± 0.09^{b}	9.37 ± 0.09^{c}	8.43 ± 0.08^{d}	8.48 ± 0.07^{d}
Adult (days)	7.96 ± 0.19^{d}	9.58 ± 0.09^{c}	10.2 ± 0.11^{b}	9.51 ± 0.23^{c}	11.9 ± 0.12^{a}
Preadult (days)	35.81 ± 0.21^{a}	35.21 ± 0.22^{a}	34.13 ± 0.19^{b}	32.31 ± 0.13^{c}	29.4 ± 0.13^{d}

Means followed by the same letters in the same rows are not significantly different based on the paired bootstrap test at the 5% significance level. 50 insects were used for each treatment

Superscripts shows the statistical difference among different treatments in a row

8.00 ± 0.14 days). An extended TPOP (37.87 ± 0.39 days) was recorded in the foliar spray of K_2SiO_3 compared to all other treatments. A significantly lower pre-adult survival rate was recorded in the foliar spray of SiO_2 (0.52 ± 0.07) followed by soil drenching of SiO_2 (0.60 ± 0.06), foliar spray (0.66 ± 0.07), and soil drenching of K_2SiO_3 (0.70 ± 0.06) compared to the control (0.96 ± 0.03). No significant difference was observed among all the treatments in the adult sex ratio and reproductive females (Table 3).

3.7 Longevity and Reproductive Values for Specific Age stage

The life expectancy with respect to specific age and stage (e_{xj}) shows how long an individual of age x and stage j is likely to live after age x. overall, the males of *S. frugiperda* reared on silicon-treated maize leaves survived longer than female adults, but in the control treatment, e_{xj} values are the same for both male and female adults. The e_{xj} values of *S. frugiperda* individuals reared on maize leaves without silicon application were longer than those reared on leaves treated with Si applications, regardless of the age and stage (Fig. 4 and Fig. S3). The reproductive values of specific age-stage (v_{xj}) of *S. frugiperda* represented the contribution of an individual at age x and stage j to the population. The v_{xj} increased significantly with an initial of viable eggs produced: the *S. frugiperda* showed an increasing v_{xj} from age 35 d and reached the highest value of 111.9 at 38 days in the foliar spray of SiO_2 in soil drenching of K_2SiO_3, v_{xj} increased from age 30 days and reached the highest value of 133.45 at 34 days. In the control treatment, v_{xj} value increased

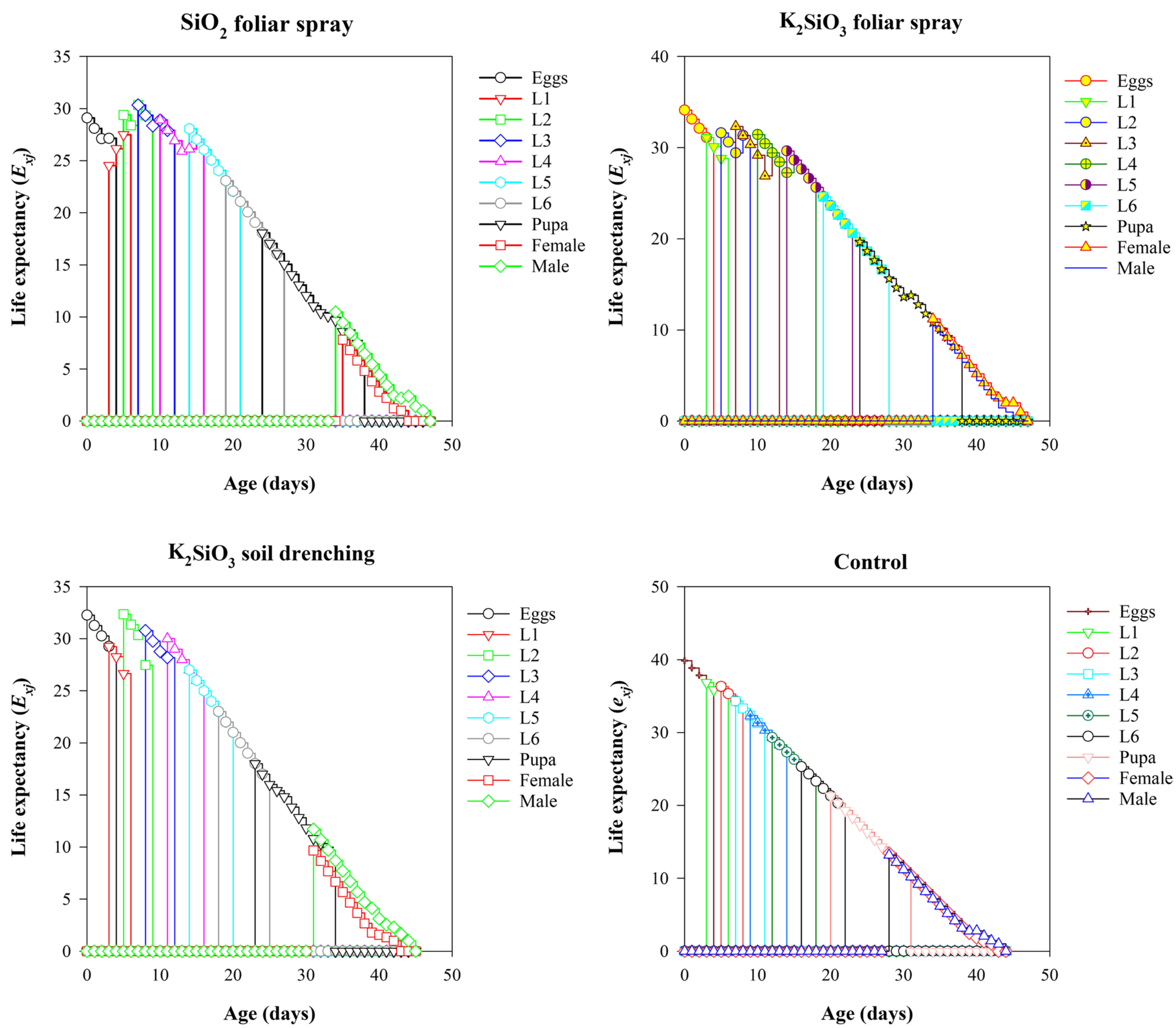

Fig. 4 Effect of silicon applications on life expectancy of *S. frugiperda*

from age 27 days and reached a maximum value of 136.9 at 32 days (Fig. 5 and Fig. S4).

4 Discussion

Silicon absorption in plants is a complicated process that varies based on the ability of a plant to absorb silicon and the selectivity of transportation routes within and across species. Ma et al. [52] refined the species categorization by identifying three pathways: active pathway, passive pathway, and rejective, based on the mechanistic technique of silicon absorption. According to the researchers, active accumulator plants, such as *Sorghum bicolor*, *Oryza sativa*, and *Triticum*, demonstrate a 1.5 percent to 10 percent buildup of silicon levels in the shoot. Many researchers have observed an increase in silicon concentration in various crops as a result of the use of this beneficial element in maize [53, 54]. According to the findings of this research work, silicon concentration was increased in the plants receiving silicon applications compared to control, where no silicon was applied. Furthermore, results of the current study showed higher silicon accumulation in maize leaves treated with foliar spray of silicon compared to soil drenching, which is well supported by the findings of Abbasi [55], who found that plants that were sprayed with SiO_2 and K_2SiO_3 on their leaves accumulated more silicon than plants that received soil drenching of SiO_2 and K_2SiO_3. Similarly, Dogramaci [56], reported that foliar application of K_2SiO_3 increased the amount of silicon in pepper leaves by up to two times

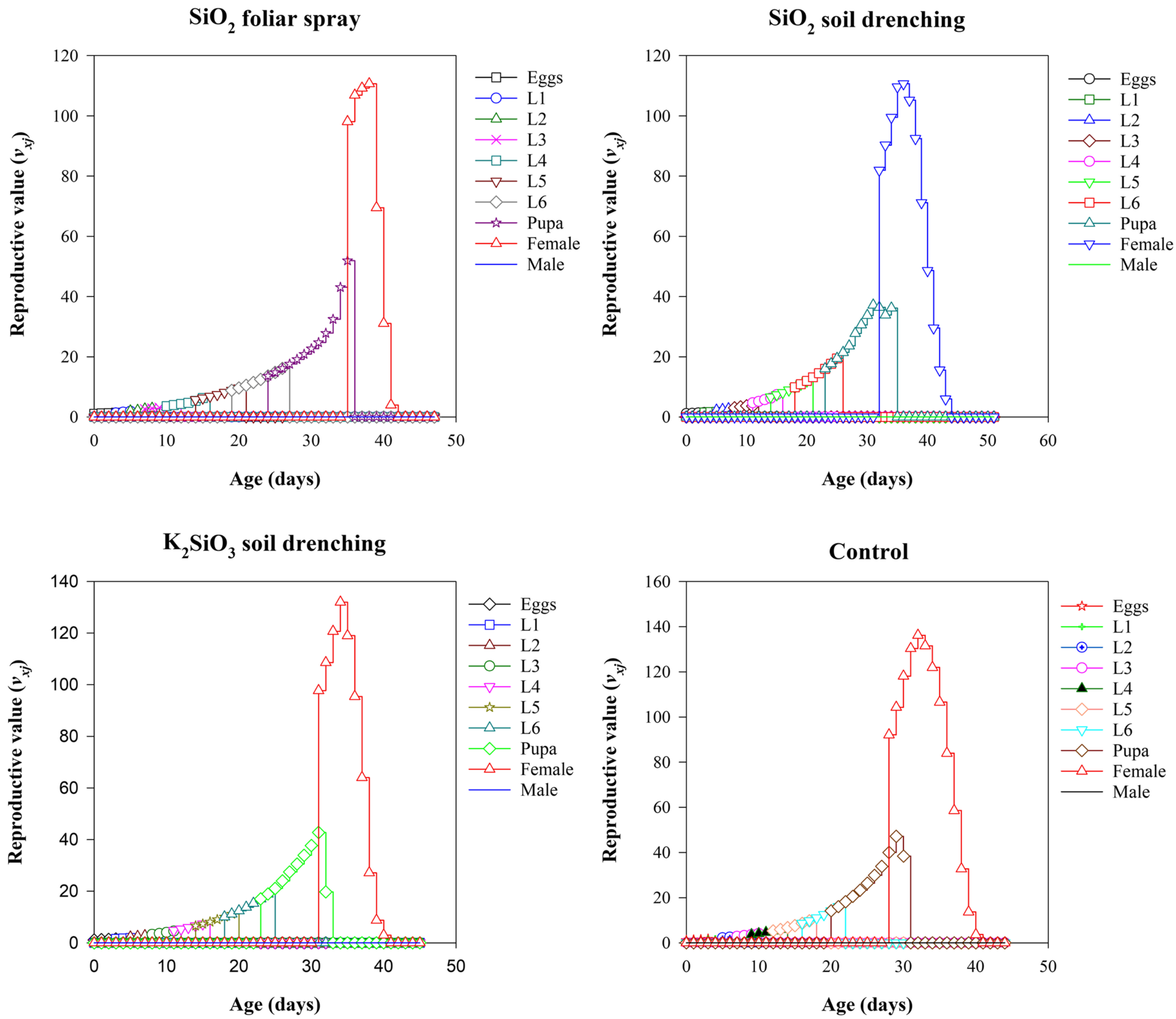

Fig. 5 Effect of silicon applications on reproductive value of *S. frugiperda*

compared to drenching applications of silicon. However, silicon supplied to the soil directly was unable to translocate the same Si concentration reported in pepper leaf roots to pepper leaf tissue [56]. The importance of foliar treatment is further highlighted by the fact that plant roots are not well developed during the early development stages to receive mineral nutrients from the soil [57]. During a plant's embryogenesis, it is essential for these mineral nutrients to be transported from the application site throughout the whole plant body. When a fresh flush of leaves grows on plants, the spray treatment needs to be regularly repeated if the supplied mineral nutrient cannot translocate from treated tissues to developing ones [58].

According to previous findings, its role in lowering illnesses and insect pest assaults is attributed to the establishment of barriers via silicon deposition and chemical protection through enzyme synthesis [59, 60]. Insect herbivores may be affected by silicon in either a direct or indirect way [61]. Direct effects include a decrease in the amount of agricultural damage caused by insects, as well as a reduction in the number of insects that survive, reproduce, and develop [29]. After feeding on maize leaves treated with Si, the life cycle characteristics of *S. frugiperda* were adversely affected, reflecting the detrimental effects on development and growth. Especially, survival rate with respect to specific age and stage (S_{xj}), fecundity with respect to specific age and stage (f_{xj}), and age-specific fecundity with respect to a specific age (m_x) were considerably reduced when fed on silicon-treated maize leaves.

The elevated mortality of larvae stages may be attributable to decreased digestibility or poor nutritional properties of plants treated with silicon [62]. The reduced digestibility of Si-treated plants may result from the higher abrasiveness of the plant parts (i.e., the physical impact of Si deposition) or enhanced induced plant defenses as a consequence of the synergy with the jasmonic acid-modulated mechanism [33, 62]. Similar results are reported by Pereira et al. [63], who stated that silicon supplementation severely impacts not only 3rd *S. frugiperda* larvae but also neonates, which were much more vulnerable than 3rd larvae. Goussain et al. [64], stated that higher mortality and cannibalism were observed in groups of *S. frugiperda* at the end of the second instar, and more mortality of the larvae was observed at the end of the second and sixth instars compared to control. Our results are in line with the findings of Nascimento et al. [65], who published that silicon treatment stimulates rice growth and inhibits *S. frugiperda* development. Nagaratna et al. [66] investigated how silicon treatments and PGRs affected *S. frugiperda's* physiology and survival. Their experiments found that silicon foliar spray significantly reduced *S. frugiperda's* larval survival, larval weight, pre-pupal weight, pupal weight, adult fecundity, and fertility.

The age-stage reproductive value (v_{xj}) in the current study indicated that Si treatments could have a major impact on the length of the early growth stages and shorten the longevity of adults. The prolonged larval duration seen in the silicon treatment may have been caused by a nutritional deficiency in the feeding substrate, which prolonged the larval duration. The increased duration of the larval stage may facilitate the activity of natural enemies, making this sort of reaction beneficial in integrated pest control approaches. This will result in the larvae being exposed for a longer period of time. In addition to this, throughout the course of one corn phenological cycle, *S. frugiperda* will finish fewer generations. Similarly, Hou and Han [28] In their study, they found that calcium silicate treatment resulted in more significant silicon deposition in rice plants than in control. Reduced *Chilo suppressalis* infestation, increased growth, and protection of the stems and leaves from damage were all results of the high Si concentration in rice. This research showed that silicon-induced antibiotic efficacy might be used to control herbivorous pests. Furthermore, he discovered that the length of the larval and pupal stages was significantly longer in the potassium silicate applications than in the control treatment. According to Abbasi et al. [55], silicon treatments significantly influenced the developmental duration of all nymphs and the complete cycle of *B. tabaci* feeding on cotton plants. Cotton plants treated with foliar sprays of silicon resulted in an increase in the duration of the whole nymphal and adult life cycle of *B. tabaci*, as compared to drenching applications.

The effect of silicon applications is most evident in the fecundity of *S. frugiperda*. The decrease in fertility seen in this study indicates that the silicon treatments had a negative effect on insects. This could lead to fewer insects, which would mean less damage to plants. In this study, the adults made from larvae that fed on the plants treated with silicon had less fecundity and were not as fertile as in the control [67]. According to Nagaratna et al. [66], the foliar application of silicon resulted in a decrease in the fertility of *S. frugiperda*. A reduction in fecundity and egg viability in *S. frugiperda* was also observed when rice plants were treated with silicon [65, 68]. Adults of *S. frugiperda* developed from larvae reared on cotton leaves treated with silicon applications deposited fewer eggs [69]. In potatoes, silicon also served as a resistance inducer against aphids by reducing female fertility [70]. According to the findings of the present research, the detrimental effect of silicon on fecundity and fertility may be the result of silicon accumulation in plants, which may stimulate and increase the production of defensive metabolites [71]. The presence of a high Si concentration in leaf tissue may prevent caterpillars from consuming sufficient amounts of nutrients and water, and the fitness of *S. frugiperda* was negatively impacted as a result of the physiological changes [66]. As a result, the negative effects of silicon on *S. frugiperda* could limit its reproductive potential. On the first and second days of oviposition, fewer eggs were recorded on plants treated with silicon through the foliar spray and soil drenching. In addition, soil drenching decreased egg viability by 50% on the first and second days of oviposition compared to the control [65]. Silicon treatments decreased *Nilaparvata lugens'* intrinsic growth rate, finite growth rate, and net reproduction rate [72].

Abbasi et al. [73] discovered reduced fertility in whitefly adults developed from nymphs fed on silicon-treated cotton leaves. He demonstrated that foliar Silicon treatments produced 75.05 eggs than soil drenching of silicon (87.08 eggs). According to Alvarenga et al. [67], treatment with Si and gibberellic acid impacted the adult phase characteristics of *S. frugiperda*. When females were developed from larvae fed on plants treated with silicon, their fertility was reduced.

5 Conclusions

Our results of the study indicated that foliar spray and soil drenching of SiO_2 and K_2SiO_3 significantly affected the survival rate, developmental duration, and reproductive value of *S. frugiperda*. According to our findings, a significant decrease in the survival rate was observed in the early stages larvae of *S. frugiperda* in all silicon treatments. Hence, exogenous application of silicon can prevent crop from early damage by this destructive pest. Furthermore, all the silicon applications significantly affected reproductive value of *S. frugiperda*. It is concluded that silicon can be a promising alternative in integrated pest management to prevent crop damage and suppress pest population.

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Declarations

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