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RESEARCH ARTICLE

Salicylic acid-mediated defence in tomato: A sustainable strategy against *Helicoverpa armigera*

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Abstract

Salicylic acid (SA) is a key signalling molecule in plants, known to regulate defence responses against a wide range of biotic and abiotic stresses. The present study assessed the role of exogenous SA application in inducing resistance in tomato (*Solanum lycopersicum*) against the fruit borer, *Helicoverpa armigera* under two experimental setups (Set A: 40 days after transplanting (DAT) and Set B: 40 and 80 DAT) with five treatments (T_1-T_4: SA at 25, 50, 75 and 100 ppm and T_5: control) and spray schedules were evaluated under controlled conditions to determine their influence on physiological traits, yield performance and pest infestation. The results demonstrated that SA application significantly enhanced chlorophyll content, relative leaf water status and fruit yield, while concurrently reducing the extent of fruit damage caused by *H. armigera*. Higher concentrations combined with double spray consistently produced superior outcomes compared to single sprays or untreated controls. Larval rearing studies further indicated that insects feeding on SA-treated plants exhibited reduced growth and survival, suggesting a negative impact on pest fitness. Correlation and principal component analyses supported a strong association between improved physiological parameters and reduced infestation levels. Overall, the study provides clear evidence that SA acts as an effective resistance inducer in tomato, strengthening both plant defence and productivity. The findings highlight the potential of SA as an eco-friendly and sustainable component in integrated pest management (IPM) programs, offering a promising alternative to conventional chemical insecticides for managing *H. armigera* in tomato cultivation.

Keywords: eco-friendly; exogenous; morphological; principal component analysis; tomato fruit borer

Introduction

Tomato (*S. lycopersicum* L.) is one of the world's most significant and climacteric vegetable crops, valued both for fresh consumption and processing and is also referred to as the "poor man's apple" (1) is a major source of vitamins, minerals and bioactive compounds contributing to human health (2, 3). It experiences an increase in respiration and ethylene production when it begins to ripen (4). Despite its economic and nutritional importance, tomato production is severely constrained by a wide range of insect pests. The incidence of some important insect pests of tomato viz. fruit borer, *H. armigera* (Hübner); whitefly, *Bemisia tabaci* (Gen); jassids, *Amrasca devastans* (Ishida); leaf miner, *Liriomyza trifolii* (Blanchard); potato aphid, *Myzus persicae* (Thomas) and Hadda beetle, *Epilachana dodecastigma* (Widemann) is commonly seen during cultivation, amidst which, the tomato fruit borer, *H. armigera* (Hübner) (Lepidoptera: Noctuidae), is considered the most destructive 41.44 % damage, capable of inflicting 24 %-73 % yield losses under Indian conditions (5, 6). The larvae bore into fruits, causing both quantitative and qualitative losses and resulting in significant economic damage (7). Conventional management relies heavily on synthetic insecticides, but their indiscriminate use has escalated production costs, promoted insecticide resistance and raised serious ecological and food safety concerns (8). These challenges necessitate alternative, eco-friendly strategies such as host plant resistance and hormone-mediated defence induction. SA, along with jasmonic acid (JA) and ethylene, plays a central role in regulating plant responses to stress (9). While earlier studies have documented SA-mediated resistance against various pathogens and insect pests in crops like cotton, rice and wheat, information on its role in enhancing tomato resistance against *H. armigera* remains limited(10). Moreover, little is known about how varying concentrations and application schedules of SA influence both plant defence and yield attributes in this crop. The present study evaluates the efficacy of exogenous SA application in inducing resistance in the susceptible tomato cultivar 'Pusa Ruby' under Assam's agro-climatic conditions. By correlating physiological and yield traits with pest incidence, this work provides new insights into the potential of SA as a sustainable and eco-friendly tool for IPM.

Materials and Methods

Experimental site and materials

The current experiment was conducted in the campus of Assam Agricultural University in Jorhat, Assam, India, during 2022-23. Tomato (*S. lycopersicum*) crop (variety Pusa Ruby) was selected for the study of exogenous application of salicylic acid-induced resistance. Five treatments were applied and each replicated four times. Each experimental unit consisted of 20 pots and 2-3 seeds were placed in each pot (30×30 cm^2) containing a soil mixture (soil + FYM) in a 3:1 ratio with a spacing of 30 cm apart to allow for adequate growth and airflow.

Rearing and morphometrics of H. armigera

The first and second instar larvae of *H. armigera* were collected from fields and reared on tomato fruits as well as an artificial diet under laboratory conditions, to compare the effect of artificial diet and natural food on the biology of the insect. The diet was prepared by using standard protocol (1996),with slight modifications in the composition of ingredients (Vitamin E capsule 50 mL was used in place of 2 number, groundnut oil (5-6 drops), 1-2 drops and Formaldehyde (10 mL) was used in place of formalin) (11). The length (mm) and breadth (mm) of the immature stages of *H. armigera* were measured to compare the results between different instars. An increase in the head capsule of larvae ascertained the attainment of instars by the larvae(12, 13). The study was designed to test plant-mediated defence, where SA was applied to tomato plants to examine its role in enhancing resistance and improving growth and yield under pest pressure. Since SA itself is not directly toxic to insects but rather triggers the plant to produce defensive compounds and structural barriers, incorporating it into artificial diets would not reflect the natural plant-insect interaction we intended to study (14).

Experimental design and treatment combination

The experiment was laid out in a Completely Randomised Design (CRD) with 5 treatments, viz. T_1 (SA at 25 ppm), T_2 (SA at 50 ppm), T_3 (SA at 75 ppm), T_4(SA at 100 ppm) and T_5(control), with 4 replications each. These SA concentrations were selected based on previous studies showing effective induction of plant defence responses without phytotoxicity in tomato (14). The first foliar application was performed at 40 DAT on both sets, while Set B received a second spray at 80 DAT to assess repeated application effects. Larvae of *H. armigera* that attained the fourth instar were released at one larva per pot on all plants before the flowering stage. Fourth-instar *H. armigera* larvae were used because they feed more aggressively and have well-developed digestive systems, providing consistent pressure to assess induced resistance (15). Younger instars feed too little or die easily, while older ones can cause excessive damage that masks treatment effects. To keep conditions uniform and avoid issues like competition or cannibalism, only one larva was released per pot. This follows protocols used in earlier tomato-*H. armigera* studies on salicylic acid defences (16). Data were analysed using SPSS v. 25.0 via ANOVA and treatment means were compared using DMRT at $P < 0.05$ (17) (Fig. 1).

Effect of SA on plant parameters

The plant growth performances were evaluated, divided into 2 groups viz. physiological parameter which includes - Chlorophyll a, Chlorophyll b, fresh weight (g), turgid weight (g), dry weight (g), relative leaf water content (%) and yield parameters including - Plant height (cm), number of branch per plant, number of fruit per plant, fruit length (cm), fruit diameter (cm), fuit individual weight (g), yield (g/plant). Both the parameters were correlated with percent fruit infestation to check the efficacy of salicylic acid. Estimation of chlorophyll content was determined through a spectrophotometer, while relative leaf water content was calculated using a standard method(19).

Statistical analysis

Application of salicylic acid was done at 40 DAT (considered as Set A), whereas twice spraying was done (considered as Set B), once at 40 DAT and 80 DAT. The analysis is carried out considering 3 subsets, viz. set A; 40 DAT, set B; 40 DAT and set B; 80 DAT. Pearson correlation was performed to compare 3 subsets with all physiological and yield parameters. Principal component analysis (PCA) was also performed to study the combined impact of exogenous application of SA to all 3 subset per treatment combinations. All the statistical analyses were done through R statistics and R Studio 4.4.2 with the help of the packages ggplot2, ggparis and correlation (20).

Fig. 1. Experimental layout (plant performances and yield) after application of SA.

Results

Duration of life stages of *H. armigera*

The results presented in Table 1 show the duration of different life stages of *H. armigera*. Incubation period of *H. armigera* ranged from 3-4 days on artificial diet, whereas on natural diet, it ranged from 3-5 days. The minimum incubation period (3 days) of *H. armigera* was recorded on artificial diet, whereas the maximum (5 days) was recorded in natural diet (Fig. 2). The larvae progressed through six instars when reared on tomato and on artificial diet, before pupation. Variations were observed on the total larval developmental duration of *H. armigera,* ranging from 16-24 and 17-27 days on artificial and natural diet, respectively (Table 1 & 2). When comparison was made between artificial and natural diets, no appreciable difference in the developmental duration of the various larval instars was found. The minimum pupal period (11-13 days) was recorded in artificial diet, while the maximum pupal period (13-16 days) was recorded in natural diets.

Biology and morphometrics of *H. armigera*

According to morphometric studies, the newly hatched eggs initially glistened and the colour shifted from yellowish-white to deep yellow after 24 hr, finally becoming dark brown before hatching (Fig. 2). The eggs of *H. armigera,* immediately after being laid, were 0.38 ± 0.02 mm in length and 0.41 ± 0.11 mm in breadth. Length and breadth of the first instar larva were 1.45 ± 0.10 and 0.25 ± 0.02 mm, respectively and the emerged larva was semi-translucent and dirty white green in colour (Table 1). The fourth instar larva showed diverse colour hues ranging from green to greenish brown and were about 13.67 ± 0.76 mm in length and 2.33 ± 0.11 mm in breadth. The growth period of larvae on artificial diet positively correlated with length (r2 = 0.319) and breadth (r2 = 0.686). Similarly, the growth period also showed positive correlation with length (r2 = 300) and breadth (r2 = 0.670) in the case of larvae reared on a natural diet.

Effect of SA on plant parameters and percent fruit infestation

Percentage fruit damage per plant after single and double dose of SA

The percentage damage of the fruits was recorded from the day of insect release and was observed till the 15th day at 1-day intervals (Table 3). The lowest damage and least preference for feeding by 4th instar larvae was recorded in T_4, where initial damage was 8.64 %, whereas the highest damage was recorded in T_5 (17.22 % damage) in the case of Set A. The percentage damage of fruit per plant by 5th and 6th instar larvae was also recorded from 7th to 11th day and the lowest (3.75 %) and highest (12.70 %) damage was observed in T_4 and T_5, respectively (Set A) (Table 3). In Set B, the percent damage by 5th and 6th instar larvae were recorded at 7th day and 9th day which revealed the highest damage (11.02 %), recorded in T_5 followed by 6.09 % damage in T_1 and the lowest damage was found in T_4 (1.25 %) (Fig. 3). Fruit damage assessment showed that T_4 treatment (both in set A and B) consistently limited larval feeding compared to other treatments, indicating enhanced plant resistance. This reduction in infestation suggests better yield protection through minimised fruit loss, highlighting the role of SA in improving host defence

Table 1. Biology and morphometrics studies of *H. armigera* on artificial and natural diets

Stages	Artificial diet (days)	Natural diet (days)	Length (mm)	Breadth (mm)
Egg/ Incubation period	3.60 ± 0.55	4.00 ± 0.71	0.38 ± 0.02	0.41 ± 0.11
Larval period				
First instar	2.40 ± 0.53	2.80 ± 0.45	1.45 ± 0.10	0.25 ± 0.02
Second instar	2.80 ± 0.84	3.00 ± 0.71	4.21 ± 0.48	0.62 ± 0.04
Third instar	4.20 ± 0.45	4.40 ± 0.52	8.15 ± 0.57	1.32 ± 0.10
Fourth instar	4.80 ± 0.42	4.60 ± 0.55	13.67 ± 0.76	2.33 ± 0.11
Fifth instar	3.20 ± 0.45	3.40 ± 0.54	20.72 ± 0.38	3.12 ± 0.04
Sixth instar	3.40 ± 0.55	3.60 ± 0.55	27.60 ± 1.24	4.07 ± 0.09
Total larval period	20.80 ± 1.30	22.00 ± 1.58	-	-
Pupa	12.80 ± 1.10	13.20 ± 1.12	18.72 ± 0.69	5.07 ± 0.28
Adult longevity	11.40 ± 0.54	11.80 ± 0.45	-	-
Total life cycle	48 ± 3.49	51 ± 3.86	-	-

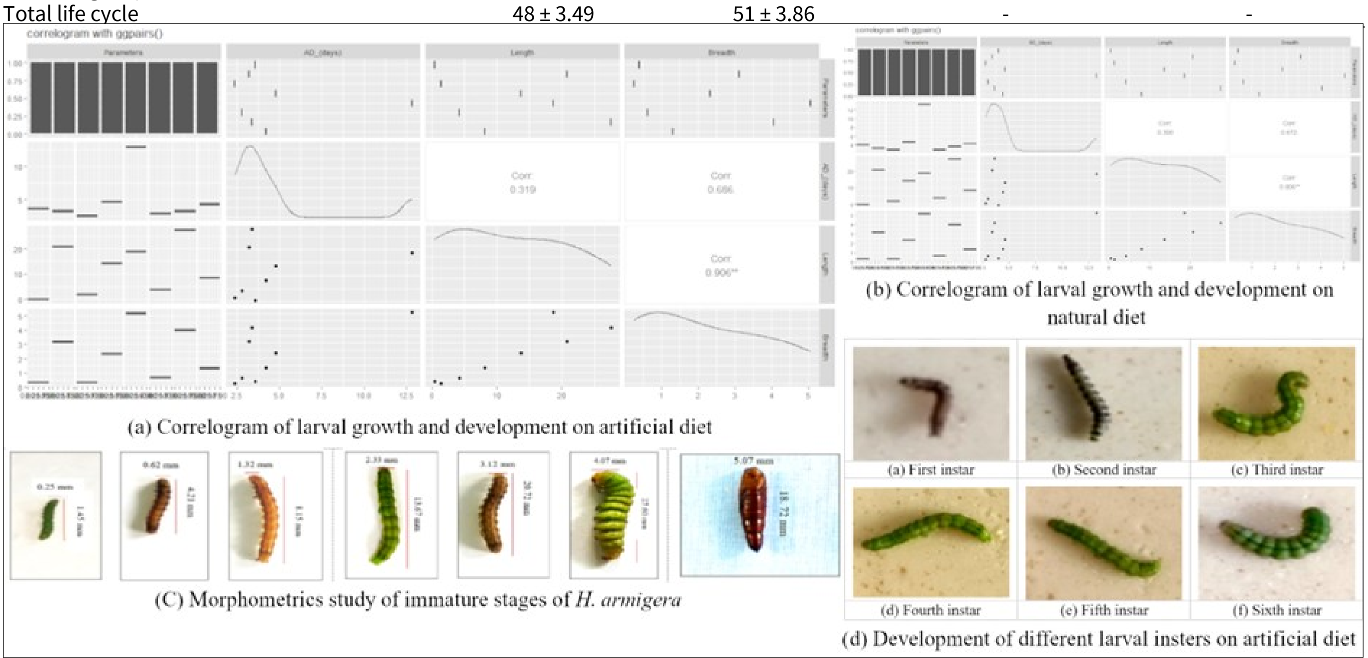


Fig. 2. Correlation of larval and pupal development of *H. armigera* on artificial and natural diet (Sig. levels = 0, 0.001, 0.01, 0.05, 0.1,1, symbols = "***", "**", "*","+", " ").

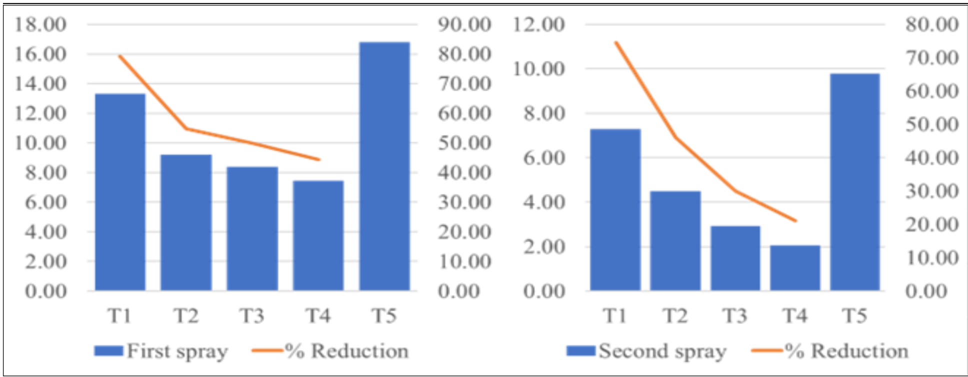
Table 2. Pearson correlation of artificial and natural diets on larval morphology and duration

Artificial diet	**AD (days)**	**Length**	**Breadth**	**Natural diet**	**ND (days)**	**Length**	**Breadth**
AD (days)	1.000	0.319	**0.686+**	ND (days)	1.000	0.300	**0.672+**
Length	0.319	1.000	**0.906****	Length	0.300	1.000	**0.906****
Breadth	**0.686+**	**0.906****	1.000	Breadth	**0.672+**	**0.906****	1.000

Sig. levels = 0.001, 0.05, symbols = "**", "+"

Table 3. Percentage fruit infestation after single application (40 DAT) and double application (40 and 80 DAT) of SA

Subset	**Treatments**	**1 day**	**3 day**	**5 day**	**7 day**	**9 day**	**11 day**	**Fruit damage/plant (%)**
	T_1	14.58	13.6	11.68	9.59	7.32	4.91	10.28
	T_2	10.43	9.22	7.88	6.9	4.9	1.67	6.83
Set A	T_3	9.45	8.75	6.94	5.12	3.35	0.33	5.66
	T_4	8.64	7.74	5.95	3.75	2.08	0.33	4.75
	T_5	17.22	16.83	16.32	12.7	10.24	6.37	13.28
	T_1	11.41	9.5	8.14	6.09	4.06	-	7.84
	T_2	8.33	6.85	4.31	4.17	0.33	-	4.80
Set B	T_3	7.42	5.93	3.06	2.7	0.33	-	3.89
	T_4	6.54	4.04	2.72	1.25	0.33	-	2.98
	T_5	14.39	14.15	12.49	11.02	7.38	-	11.89



	% Reduction (1st spray)	% Reduction (2nd spray)
T1	79.13	74.44
T2	54.65	45.95
T3	49.91	30.02
T4	44.33	21.01
T5	-	-

Fig. 3. Reduction of pest population and perentage fruit damage after first and second applications of SA.

against *H. armigera*.

Influence of SA on larval survivability

Survivability was recorded from fourth instar larvae till adult emergence. In T_4, complete larval mortality was observed with initial survivability of 50 % by fourth and fifth instar larvae and 25 % by sixth instar larvae, whereas T_5 displayed complete pupation with 75 % successful adult emergence in case of Set A, whereas, survivability when recorded from fourth instar larvae till the emergence of the adult displayed 100 % larval and pupal survivability in T_5, whereas T_4 showed 100 % larval mortality with initial survivability of 50 % by fourth and fifth instar larvae and no survivability was recorded by sixth instar stage in Set B.

Effect on physiological and economic parameters of the tomato plant

The result revealed that T_4 (114.25 ± 4.42 cm) excelled in plant height after double application of SA and lowest in T_5 (75.50 ± 3.31cm) in Set B, as compared to Set A (T_4; 84.50 ± 2.06 cm). In the present investigation, results revealed that the second spray showed better results as compared to the first spray. The maximum number of branches (23.75 ± 2.50) was observed in T_4 (second spray) as compared to first spray (Set A) in T_4 (19.50 ± 2.08). Other physiological parameters like total chlorophyll content (3.09 ± 0.64 mg g^1 fresh weight) and highest relative leaf water content (RLWC) (88.60 ± 1.64 %) was recorded in second spray (Set B) as compared to first spray (Set A) and the lowest value was observed in T_5 in both the

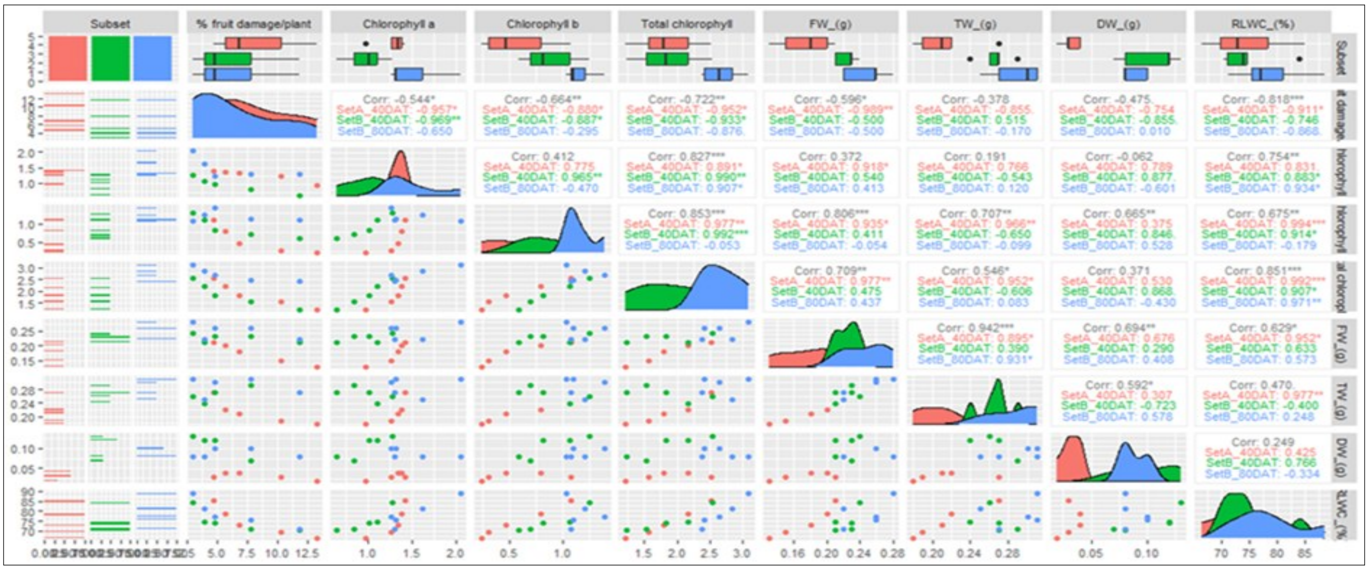


Fig. 4. Correlogram showing correlations between SA treatments, physiological traits and over % fruit damage.

Table 4. Physiological parameters of tomato crops after exogenous application of SA

Subset	Treatments	Chlorophyll a	Chlorophyll b	Total Chlorophyll	FW (g)	TW (g)	DW (g)	RLWC (%)
Set A	T_1	1.26 ± 0.17^a	0.30 ± 0.17^a	1.56 ± 0.32^a	0.15 ± 0.28	0.19 ± 0.26	0.03 ± 0.37	69.75 ± 2.06^{ab}
Set A	T_2	1.34 ± 0.27^a	0.46 ± 0.16^a	1.80 ± 0.43^{ab}	0.18 ± 0.13	0.21 ± 0.10	0.04 ± 0.32	72.92 ± 2.59^b
Set A	T_3	1.38 ± 0.43^a	0.79 ± 0.15^a	2.17 ± 0.51^{bc}	0.20 ± 0.18	0.22 ± 0.17	0.04 ± 0.22	78.35 ± 1.22^c
Set A	T_4	1.42 ± 0.27^b	1.08 ± 1.01^b	2.52 ± 0.74^{bc}	0.21 ± 0.09	0.27 ± 0.10	0.03 ± 0.18	84.92 ± 2.14^d
Set A	T_5	0.98 ± 0.24^a	0.23 ± 0.05^a	1.21 ± 0.27^a	0.13 ± 0.22	0.18 ± 0.21	0.02 ± 0.31	66.40 ± 3.33^a
F value		**7.341**	**8.009**	**5.012**	**-**	**-**	**-**	**7.954**
p-value (≤0.05)		**0.002**	**0.001**	**0.009**	**-**	**-**	**-**	**0.001**
Set B_40 DAS	T_1	0.84 ± 0.14^{ab}	0.70 ± 0.10^a	1.54 ± 1.15^a	0.23 ± 0.04	0.29 ± 0.05	0.07 ± 0.02	71.15 ± 0.02^a
Set B_40 DAS	T_2	1.01 ± 0.09^{bc}	0.82 ± 0.55^a	1.83 ± 0.63^a	0.23 ± 0.01	0.27 ± 0.01	0.12 ± 0.01	73.86 ± 4.70^{ab}
Set B_40 DAS	T_3	1.10 ± 0.04^{bc}	1.07 ± 1.05^a	2.17 ± 1.02^b	0.21 ± 0.01	0.24 ± 0.01	0.12 ± 0.02	74.58 ± 2.96^{ab}
Set B_40 DAS	T_4	1.27 ± 0.28^c	1.26 ± 0.94^a	2.53 ± 0.92^b	0.24 ± 0.02	0.26 ± 0.03	0.13 ± 0.02	84.04 ± 3.47^b
Set B_40 DAS	T_5	0.65 ± 0.08^a	0.59 ± 0.08^a	1.24 ± 0.09^a	0.21 ± 0.01	0.27 ± 0.03	0.08 ± 0.01	70.36 ± 3.32^a
F value		**10.126**	**1.657 (NS)**	**4.258**	**-**	**-**	**-**	**3.76**
p-value (≤0.05)		**0.001**	**0.631**	**0.02**	**-**	**-**	**-**	**0.02**
Set B_80 DAS	*H. armigera*	1.32 ± 0.68^b	1.10 ± 0.71^a	2.42 ± 1.38^{ab}	0.26 ± 0.04	0.31 ± 0.04	0.10 ± 0.01	75.51 ± 3.70^{ab}
Set B_80 DAS	*H. armigera*	1.26 ± 0.11a^b	1.40 ± 0.28^a	2.65 ± 0.23^{ab}	0.26 ± 0.02	0.30 ± 0.02	0.10 ± 0.02	77.04 ± 2.56^{ab}
Set B_80 DAS	*H. armigera*	1.62 ± 0.27^b	1.21 ± 0.13^a	2.83 ± 0.37^b	0.22 ± 0.03	0.25 ± 0.02	0.08 ± 0.03	81.00 ± 3.52^b
Set B_80 DAS	*H. armigera*	2.05 ± 0.46^b	1.04 ± 0.27^a	3.09 ± 0.64^b	0.28 ± 0.02	0.31 ± 0.03	0.08 ± 0.02	88.60 ± 1.64^c
Set B_80 DAS	*H. armigera*	1.30 ± 0.15^a	1.08 ± 0.24^a	2.38 ± 0.07^a	0.22 ± 0.01	0.27 ± 0.02	0.08 ± 0.02	71.22 ± 2.96^a
F value		**9.022**	**1.337 (NS)**	**4.358**	**-**	**-**	**-**	**10.784**
p-value (≤0.05)		**0.001**	**0.302**	**0.015**	**-**	**-**	**-**	**0.001**

FW: Fresh weight, TW: Turgid Weight, DW: Dry weight, RLWC: Relative leaf water content. Mean within column with different alphabets indicates significantly different variations (p ≤ 0.05), Tukey's HSD Test.

set of experiment (Fig. 4; Table 4). The second SA spray (T_4) enhanced plant vigour and resilience compared to the first spray, indicating greater yield potential.

Effect on yield parameters

Observations on yield parameters revealed that the highest number of fruits per plant was recorded in Set B (T_4; 20.50 ± 0.06) as compared to Set A (T_4; 14.50 ± 1.29) and the lowest was recorded in T_5 in both experimental sets. Yield parameters of the test crop varied significantly in Set B due to different concentrations of salicylic acid after the second spray. Different parameters were also found to excel superior in Set B in treatment (T_4) when compared to Set A- Length of fruit (Set B; 2.84 ± 0.02 & Set A; 2.72 ± 0.56 cm), diameter of fruit (Set B; 2.74 ± 0.02 & Set A; 2.68 ± 0.09), mean weight (Set B; 10.35 ± 0.13 & Set A; 10.27 ± 0.16 g) of individual fruit and fruit yield (Set B; 212.17 ± 13.85 & Set A; 148.18 ± 10.92 g) per plant (Fig. 5). The second SA spray (T_4) significantly enhanced fruit yield and quality, indicating clear superiority over the first spray Table 5.

Principal component analysis (PCA)

PCA was performed for 2 groups (set A and set B) and the physiological and yield parameters were subdivided into 3 subsets, viz. Set A_40 DAT, Set B_40 DAT and Set B_80 DAT. Bartlett's test of sphericity suggests that there is a sufficient correlation in the data for factor analysis (Chisq (91) = 403.99, p < .001). Contribution biplot of PCA revealed that PC1 explained a total of 69.66 % and PC2 explained a total of 14.02 % with total cumulative variability of 83.685 explained (Table 6 & 7). The 3 subsets forming 3 different clusters explained that the experiment set A is totally different from set B, forming a distinctive cluster and set B (40 DAT) and set B (80 DAT) unite to form a single cluster because of the subsequent application of SA at 40 and 80 DAT (Fig. 6).

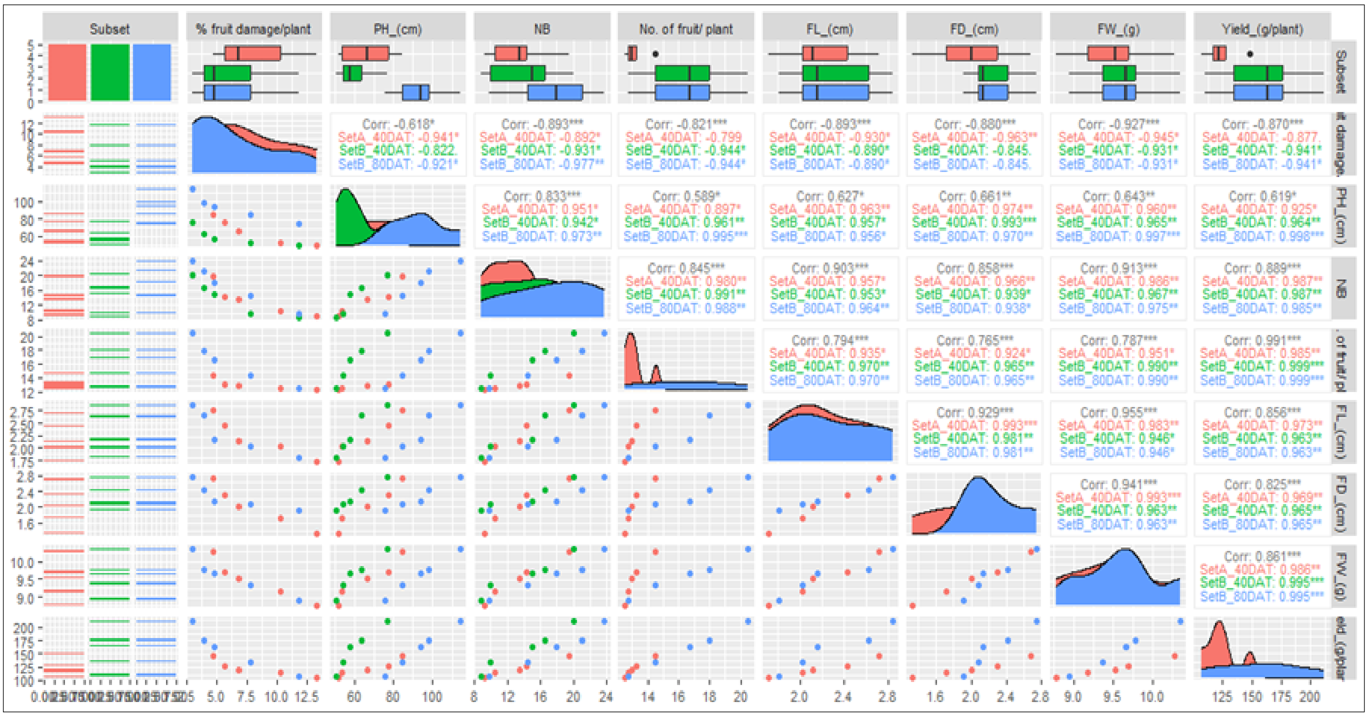


Fig. 5. Correlogram depicting associations of SA on the yield parameters of tomato plants over percentage fruit damage.

Table 5. Yield parameters of tomato crops after exogenous application of SA

Subset	Treatments	PH (cm)	NB/P	No. of fruit/plant	FL (cm)	FD (cm)	Few (g)	Yield (g/plant)
Set A	T_1	53.75 ± 3.30^{a}	10.50 ± 1.73^{ab}	12.75 ± 0.96^{a}	2.02 ± 0.11^{ab}	1.72 ± 0.18^{b}	9.17 ± 2.54^{a}	117.00 ± 15.54^{a}
Set A	T_2	66.50 ± 2.65^{b}	13.50 ± 1.92^{b}	13.00 ± 2.16^{a}	2.12 ± 0.10^{ab}	2.01 ± 0.15^{bc}	9.52 ± 1.14^{ab}	122.02 ± 8.50^{a}
Set A	T_3	77.25 ± 2.63^{c}	14.25 ± 1.71^{b}	13.25 ± 2.21^{a}	2.43 ± 0.03^{b}	2.30 ± 0.20^{c}	9.69 ± 3.02^{a}	127.21 ± 16.57^{a}
Set A	T_4	84.50 ± 2.06^{d}	19.50 ± 2.08^{c}	14.50 ± 1.29^{a}	2.72 ± 0.56^{c}	2.68 ± 0.09^{d}	10.27 ± 1.06^{b}	148.18 ± 10.92^{b}
Set A	T_5	51.50 ± 3.92^{a}	9.25 ± 2.06^{a}	12.50 ± 2.52^{a}	1.72 ± 0.07^{a}	1.34 ± 0.10^{a}	8.78 ± 1.81^{a}	106.49 ± 6.37^{a}
F value		**8.643**	**6.498**	**0.655 (NS)**	**6.762**	**5.995**	**6.324**	**3.407**
p-value (≤ 0.05)		**0.001**	**0.003**	**0.632**	**0.001**	**0.001**	**0.003**	**0.024**
Set B_40 DAS	T_1	54.25 ± 3.77^{ab}	10.00 ± 1.41^{a}	-	-	-	-	-
Set B_40 DAS	T_2	57.75 ± 2.21^{b}	15.00 ± 1.39^{b}	-	-	-	-	-
Set B_40 DAS	T_3	63.50 ± 3.41^{b}	16.50 ± 1.29^{bc}	-	-	-	-	-
Set B_40 DAS	T_4	76.50 ± 3.87^{c}	20.00 ± 0.82^{c}	-	-	-	-	-
Set B_40 DAS	T_5	50.75 ± 1.95^{a}	8.75 ± 2.75^{a}	-	-	-	-	-
F value		**12.34**	**6.18**	**-**	**-**	**-**	**-**	**-**
p-value (≤ 0.05)		**0.001**	**0.001**	**-**	**-**	**-**	**-**	**-**
Set B_80 DAS	T_1	84.50 ± 4.20^{b}	14.50 ± 3.00^{b}	14.50 ± 0.17^{ab}	2.02 ± 0.03^{ab}	2.08 ± 0.03^{a}	9.36 ± 0.97^{ab}	134.77 ± 12.04^{ab}
Set B_80 DAS	T_2	94.25 ± 4.64^{c}	18.00 ± 1.15^{bc}	16.75 ± 0.16^{ab}	2.16 ± 0.04^{b}	2.14 ± 0.03^{a}	9.65 ± 0.82^{ab}	162.80 ± 17.12^{abc}
Set B_80 DAS	T_3	98.25 ± 3.86^{c}	21.00 ± 1.41^{cd}	18.00 ± 0.10^{ab}	2.62 ± 0.03^{c}	2.41 ± 0.04^{b}	9.77 ± 0.95^{ab}	175.86 ± 12.26^{bc}
Set B_80 DAS	T_4	114.25 ± 4.42^{d}	23.75 ± 2.50^{d}	20.50 ± 0.06^{b}	2.84 ± 0.02^{c}	2.74 ± 0.02^{b}	10.35 ± 0.13^{b}	212.17 ± 13.85^{d}
Set B_80 DAS	T_5	75.50 ± 3.31^{a}	9.75 ± 1.26^{a}	12.75 ± 0.23^{a}	1.81 ± 0.04^{a}	1.92 ± 0.03^{a}	8.93 ± 1.80^{a}	110.04 ± 3.75^{a}
F value		**8.65**	**9.89**	**3.69**	**4.83**	**5.51**	**3.48**	**6.36**
p-value (≤ 0.05)		**0.001**	**0.022**	**0.028**	**0.001**	**0.001**	**0.033**	**0.003**

PH: Plant height, NB/P: Numbers of branch/plant, FL: Fruit length, FD: Fruit diameter, Few: Fruit weight. Mean within column with different alphabets indicate significantly different variations ($p \leq 0.05$), Tukey's HSD Test.

Table 6. Eigenvalues and total variability of 14 factors/principal components

Growth factors	Factors	Dimensions	Variance	% of var.	Cumulative % of var.
Physiological parameters	Chlorophyll a	Dim. 1	9.753	69.665	69.665
	Chlorophyll b	Dim. 2	1.963	14.02	83.685
	Fresh weight (g)	Dim. 3	1.166	8.332	92.017
	Turgid weight (g)	Dim. 4	0.488	3.486	95.503
	Dry weight (g)	Dim. 5	0.284	2.026	97.528
	RLWC (%)	Dim. 6	0.141	1.01	98.538
Yield attributing parameters	Plant height (cm)	Dim. 7	0.111	0.79	99.328
	No. of branches	Dim. 8	0.036	0.259	99.587
	No. of fruit/plant	Dim. 9	0.029	0.208	99.795
	Fruit length (cm)	Dim. 10	0.021	0.153	99.947
	Fruit diameter (cm)	Dim. 11	0.004	0.03	99.978
	Fruit weight (g)	Dim. 12	0.003	0.022	99.999
	Yield (g/plant)	Dim. 13	0	0.001	100
NA	% fruit damage/plant	Dim. 14	0	0	100

Table 7. Individual contributions of the first 3 PCs (dim 1/PC1, dim 2/PC2 and dim 3/PC3) subset components from experiment set A and B after PCA analysis

Treatments	Subset	Dim.1	Dim.2	Dim.3
T_1	Set A	10.32785	10.28265	0.552459667
T_2	Set A	2.603154	8.587685	0.001011819
T_3	Set A	0.056421	8.991719	0.617067272
T_4	Set A	3.471026	10.55485	2.085398163
T_5	Set A	22.85518	6.12014	0.336355948
T_1	Set B_40 DAS	1.953097	7.154016	0.569660591
T_2	Set B_40 DAS	0.044749	6.385116	10.82006216
T_3	Set B_40 DAS	1.367485	0.614925	23.34078909
T_4	Set B_40 DAS	12.80801	0.224323	21.29668764
T_5	Set B_40 DAS	8.602363	10.23734	0.137641463
T_1	Set B_80 DAS	0.065666	10.96464	11.92017687
T_2	Set B_80 DAS	2.645914	8.040191	4.169795569
T_3	Set B_80 DAS	5.705373	2.805738	0.46176618
T_4	Set B_80 DAS	24.13904	2.994284	8.487802665
T_5	Set B_80 DAS	3.354674	6.042383	15.20332491

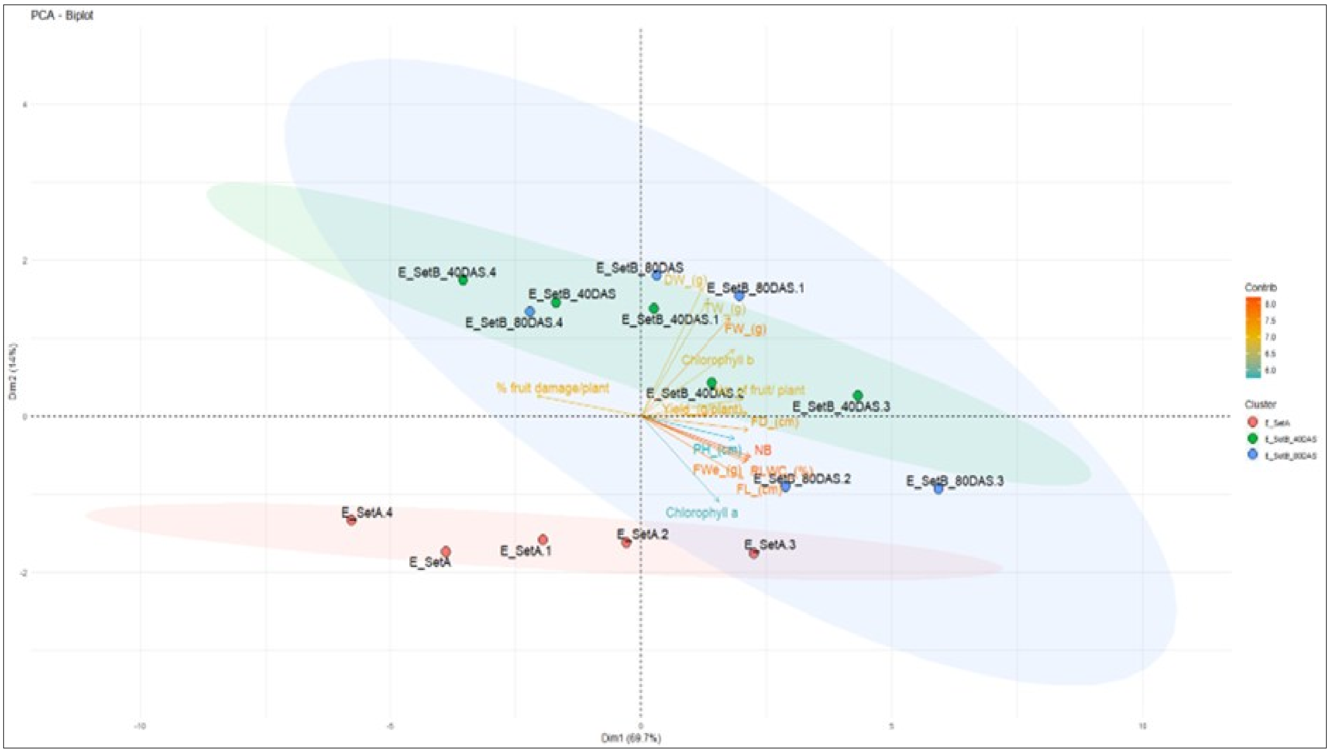


Fig. 6. PCA biplot integrating physiological, yield and infestation traits under single (Set A) and double SA applications (Set B).

Discussion

Exogenous application of SA imparts a significant boost in their natural defence in plants against insect pest attack by encouraging the plant to produce protective physical traits, harmful secondary compounds and repellent plant volatiles (21, 22). Therefore, the present investigation was undertaken to explore the effects of SA against tomato fruit borer (*H. armigera*) infestation and plant parameters under protected conditions. The incubation period of *H. armigera* ranged from 3-4 days on artificial diet and 3-5 days on natural diet (23). The incubation period of *H. armigera* eggs ranged between 3-4, 3-5 and 2-4 days respectively, which closely aligns with the findings of the current study (12, 13, 24). The average length and breadth were recorded with respect to ten eggs. The mean length and breadth of the egg were recorded to be 0.38 ± 0.02 mm and 0.41 ± 0.1 mm, respectively, which are in agreement (0.42 mm - 0.60 mm in length and 0.40 - 0.55 mm in breadth) (12). During the present investigations, the length and breadth of six larval instars were recorded. The mean length and breadth of pupae were recorded to be 5.07 ± 0.28 and 18.72 ± 0.69 mm, respectively (12, 13). Research indicates that total larval periods varied from 15 to 26 days, with an average of 22.44 ± 2.75 and 21.8 ± 0.79 days, respectively, aligning with the present study (25).

In response to a variety of stimuli, including insect herbivory or the application of elicitors, induced resistance develops in plants and makes them phenotypically less nutritious and more plastic, making them less desirable for insects to feed (26, 27). Feeding preference of larvae towards tomato fruit was recorded in both sets of experiments, which revealed that both Set A and B in T_4 (SA at 100 ppm) had the lowest recorded infestations. Similar conclusions reported that the lowest percentage of damage by *E. insulana* larvae in okra was when plants were treated with SA at 100 ppm (28). More or less similar findings were concluded that an increased anti-feeding effect on *H. armigera* was observed in plants treated with SA; conversely, the most significant damage occurred in the untreated control plants (29). Moreover, a high rate of pupal mortality was observed in *H. armigera* under laboratory conditions when correlated with a high concentration of SA (30). No feeding damage was recorded by fourth instar larvae towards tomato leaves as influenced by the effect of SA when assessed in both sets under greenhouse conditions (31). The possible reason for no recorded feeding damage on leaves likely results from plants that received foliar applications of SA, which showed the least preference for foliage feeding among the phytohormones and growth regulators (32).

In the case of test crop growth-related physiological traits, SA at 100 ppm was found to enhance the height of the plants as compared to other treatments. Supportive evidence regarding the height of the plants was reported in tomato (33, 34) and *Nigella sativa* L. (35). The highest number of branches per plant was recorded at SA at 100 ppm of SA. Foliar application of SA increased the number of branches per plant and leaf area (cm^2) of plants (36). One crucial photosynthetic pigment that affects a plant's ability to photosynthesise and, eventually, its ability to grow is chlorophyll. Gradual promotion of chlorophyll pigments was found with increasing SA concentration (100 ppm). Plants treated with SA showed improved CO_2 assimilation, chlorophyll content, photosynthetic rate and higher mineral uptake (37). Total chlorophyll content of leaves was increased by foliar spray of SA, which agrees with the present findings, in tomato, cucumber and roselle (38-41). The use of SA foliar spray had a positive impact on plant hydration status, proliferation and biomass of shoot roots and maintenance of cell turgor and enhanced RLWC (42-44).

The treatment, T_4 was found to be significantly superior in terms of number of flowers per plant, highest fruit length, number of fruits per plant, diameter of the fruit, mean weights of individual fruit and yield per plant which were influenced by exogenous application of SA and the best results were recorded at SA at 100 ppm and also foliar SA sprays raised phytochemical content and fruit yield in tomato, supporting the findings on both defense and yield under SA application (45-48).

Conclusion

The present investigation establishes that foliar application of SA, particularly at 100 ppm with two sprays at 40 and 80 DAT, markedly enhances tomato resistance to *H. armigera* while simultaneously improving physiological traits and yield performance. The observed reduction in larval feeding on foliage and fruits underscores SA's potential as an eco-friendly substitute for chemical pesticides. For large-scale adoption, it is essential to validate these findings through multi-location field trials across diverse agro-climatic zones and to integrate SA application within IPM frameworks in combination with biological control agents, microbial biopesticides and cultural practices. Furthermore, standardising application schedules and concentrations across different crop varieties, along with the development of farmer-oriented formulations, will facilitate wider adoption. Comprehending the molecular mechanisms governing signalling pathways can aid in creating new chemicals that activate the plant's innate disease resistance mechanisms. An understanding of (SA) related defence signalling and its potential applications in agriculture is essential for developing methods that enhance sustainable crop production by efficiently managing abiotic and biotic stress (49). Future work should focus on unravelling the molecular basis of SA-mediated resistance to aid in the design of advanced plant defence activators, positioning SA as a strategic tool for sustainable pest management and global food security.

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Authors' contributions

DS conducted the experiments, collected the data, performed the formal analysis of results and prepared the original draft. SB conceived the experiment, designed the methodology and supervised the work. KSB and MSK reviewed and corrected the manuscript. AD coordinated the statistical analysis. KD and BB verified the data and assisted in draft correction.

Compliance with ethical standards

Conflict of interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical issues: None

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