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Research Article

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Monitoring and Biorational Management of *Tuta absoluta* [Lepidoptera: Gelechiidae] in Tomato in Western Nepal

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Abstract

Tuta absoluta (Meyrick), the tomato leaf miner, is a major pest of tomato in Nepal, and can cause an 80–100% reduction in yield if left untreated. Monitoring of the adult moth population and a field experiment were conducted in Surkhet District, Nepal, with eight treatments replicated three times in a RCB design. The tested treatments included (i)*Bacillus thuringiensis var. kurstaki* (Bt.k) @2 g/L of water, (ii) Nimbicidine (Azadirachtin 300 ppm) @4 ml/L of water (iii) Neem 1500 (Azadirachtin 0.15 EC) @4 ml/L of water, (iv) *Beauveria bassiana* (2.0% A.S.) @4 ml/L of water, (v) Baculovirus, SC, >2x10^{13} (TutaVir) @2ml/10L of water, (vi) Alternate spray of Bt.k and Neem 1500 and (vii) Chlorantraniliprole 18.5% SC (standard check), and (viii) Water spray (control). Observations were made in six-day intervals, in which data on leaf damage, bud damage percentage, percent fruit damage, as well as average number of larvae, bore hole, and yield attributes were recorded. The monitoring results revealed the average population of moths above Economic Threshold Level (ETL). The percentage fruit damage was lowest in the Chlorantraniliprole 18.5% SC (1.48%) followed by alternate spray of Bt.k and Neem 1500 (1.81%) while the marketable yield was at par in both treatments. The B:C ratio showed that alternate spray of Bt.k and Neem 1500 and Chlorantraniliprole 18.5% SC were the superior as compared to others. This study concludes that the alternate spray of Bt.k and Neem 1500 is the most effective biorational pesticide for the management of *T. absoluta* in field conditions.

Keywords: Biocontrol, Integrated Pest Management, Pesticide, Tomato, Tuta absoluta

Introduction:

Tomato is a major vegetable crops of Nepal with a huge demand among the consumers in the country and elsewhere. However, this crop faces significant biotic challenges including diseases, insect-pests such as *Helicoverpa armigera (Hübner)*, *Tuta absoluta* (Meyrick), and even the mollusks such as *Achatina fulica* Bowdich in the Terai region of Nepal (Jaishi et al., 2024; Khanal et al., 2025; Pandey et al., 2023). *T. absoluta* (Lepidoptera: Gelechiidae) has become one of the challenging pests in tomato production in recent years after its first record in Nepal in 2016 (iDE and Virginia Tech, 2017). If control measures are not implemented, this pest can reduce tomato productivity and quality by 80–100% in both field and greenhouse environments (Desneux et al., 2010). The affected tomato fruits are rapidly degraded in postharvest storage and transport, commercially degrading their value (Emana et al., 2017). Although the use chemical pesticides has become a major option to combat this pest, farmers are still lacking eco-friendly strategies in the country. Therefore, there is an urgent need to devise a sustainable approach to manage this pest with minimal environmental impacts to contribute to the national goal of safety food and good health of the consumer.

While trading, accidentally infected tomato lots is likely to spread internationally. All the plant parts including leaves, buds, stems, and fruits of tomatoes can harbor different life stages of *T. absoluta* pest. Through the bored fruits, pathogen invasion leads to fruit rot due to pathogen infestation. It can even survive in the weeds hosts such as *Solanum nigrum L.* and *Datura stramonium L*. It also causes damages to other plants of solanaceous family such as Eggplant (*Solanum melongena L.*), potato (*Solanum tuberosum L.*), and bell pepper (*Capsicum annum L.*) causing a substantial damage (Pereyra & Sánchez, 2006). In Nepal, farmers deliberately use harmful chemical pesticides at rates higher than recommended to manage vegetable pests, posing a serious risk to consumer health (Sapkota et al., 2025a; Sapkota et al., 2025b). The same is the case for *T. absoluta* management in tomato (Bajracharya et al., 2018*)*. The issue is more exacerbated due to the lack of awareness among the farmers, insufficient resources, poor extension service of the government, social pressure and fear of loss (Bajracharya et al., 2018; Bhandari et al., 2025a; Bhandari et at., 2025b). Therefore, overall food safety concern of the country has also weakened due to such hazardous practices (Bhandari et al., 2025b).

The population of tomato leaf miners has already become resistant to some newer generation pesticides including Spinosad, evidence emerged from South America (Reyes et al., 2011). This resistance build-up issues in combination with overuse of harmful chemicals have overall detrimental impacts on beneficial arthropods and the ecosystem as a whole heightening the need for alternative management methods (Medeiros et al., 2009). Similarly, using chemical pesticides to combat these pests might have caused serious environmental impacts including the loss of beneficial soil organisms (Bhandari et al., 2021). Likewise, the efficacy of insecticides alone may be diminished by larvae's mine-feeding behavior or insufficient spraying technology (Kinyanjui et al., 2025). Therefore, combining cultural control methods with alternative approaches of including entomopathogenic nematodes, fungi, viruses as well as predators and parasitoids is essential without harming the natural insect ecology.

Studies on alternative practices have already begun in Nepal for the management of tomato pests such as *Helicoverpa armigera* demonstrating a potent efficacy of alternative measures (Khanal et al., 2025). Also, Pandey et al. (2023) noted that farmers can be encouraged to adopt sustainable pest management techniques, such as Integrated Pest Management (IPM) techniques in managing *T. absoluta*, which prioritize biological control measures and limits the use of chemical pesticides encouraging less hazardous active ingredients. Other global studies suggest that, when neem oil (Azadirachtin) is applied as a foliar spray, it controls modest infestations of *Tuta absoluta* larvae in tomato (Chhetri, 2018). Similarly, an entomopathogenic bacterium, *Bacillus thuringiensis* (*Bt.)* has been employed as a highly successful bio-insecticide to manage tomato plant pests (Youssef et al., 2013). *Bt.* could be used in combination with Azadirachtin at low to medium infestation levels. Moreover, entomopathogenic fungi such as *Metarhizium anisopliae* and *Beauveria bassian* have also been known to target a wide array of agricultural pests, including all life stages *T. absoluta* (Khanal, 2016; Pires et al., 2009). Koller et al. (2024) provided evidence that the baculovirus PhopGV, used alone or in combination with the parasitoid *Necremnus tutae*, can be an effective approach in lowering larval densities and minimizing plant damage due to *T. absoluta* larva.

In light of the above-mentioned evidences, we hypothesized that the use of sustainable biorational pesticides and their combinations can effectively manage *T. absoluta* larva in tomato. Thus, the major objective of this study was to devise a sustainable and economically acceptable, integrated biorational management strategy for *T. absoluta*. The findings of this study could be crucial evidence to employ a sustainable approach to the farmers in managing this invasive pest, lower the dependency of harmful chemical pesticides, as well as improve the food safety concern of the country. In parallel, the findings will provide the global researchers the evidence of alternative measures encourage them to work on improving the efficacy of these approaches.

Materials and Methods:

Experiment Site

The field experiment was carried out in a farmers' field inside the plastic tunnel at Birendranagar Municipality, Ward No. 4, Surkhet, Karnali Province, Nepal (28°36′29″ N, 81°36′34″ E; 725 meters above average sea level). The site lies in the inner Terai region with a subtropical climate. The plastic tunnel was equipped with drip irrigation facility and plastic mulching. The experimental site is shown in **Fig. 1.**

Monitoring of T. absoluta moth through pheromone trap

The presence and population dynamics of *T. absoluta* moths were monitored using pheromone-based WOTA-T traps installed 60 cm above the ground, as described by Sah (2017). A single trap was used per greenhouse. Each trap contained a synthetic sex pheromone lure impregnated with 2.0 mg of pheromone in a rubber septum (Tomato Leaf Miner Lure, Pest Control India Pvt. Ltd.). The lure was positioned between the upper plastic plate and the WOTA-T trap, attracting male moths, which were then trapped. The traps were installed one week prior to the transplantation for early detection and

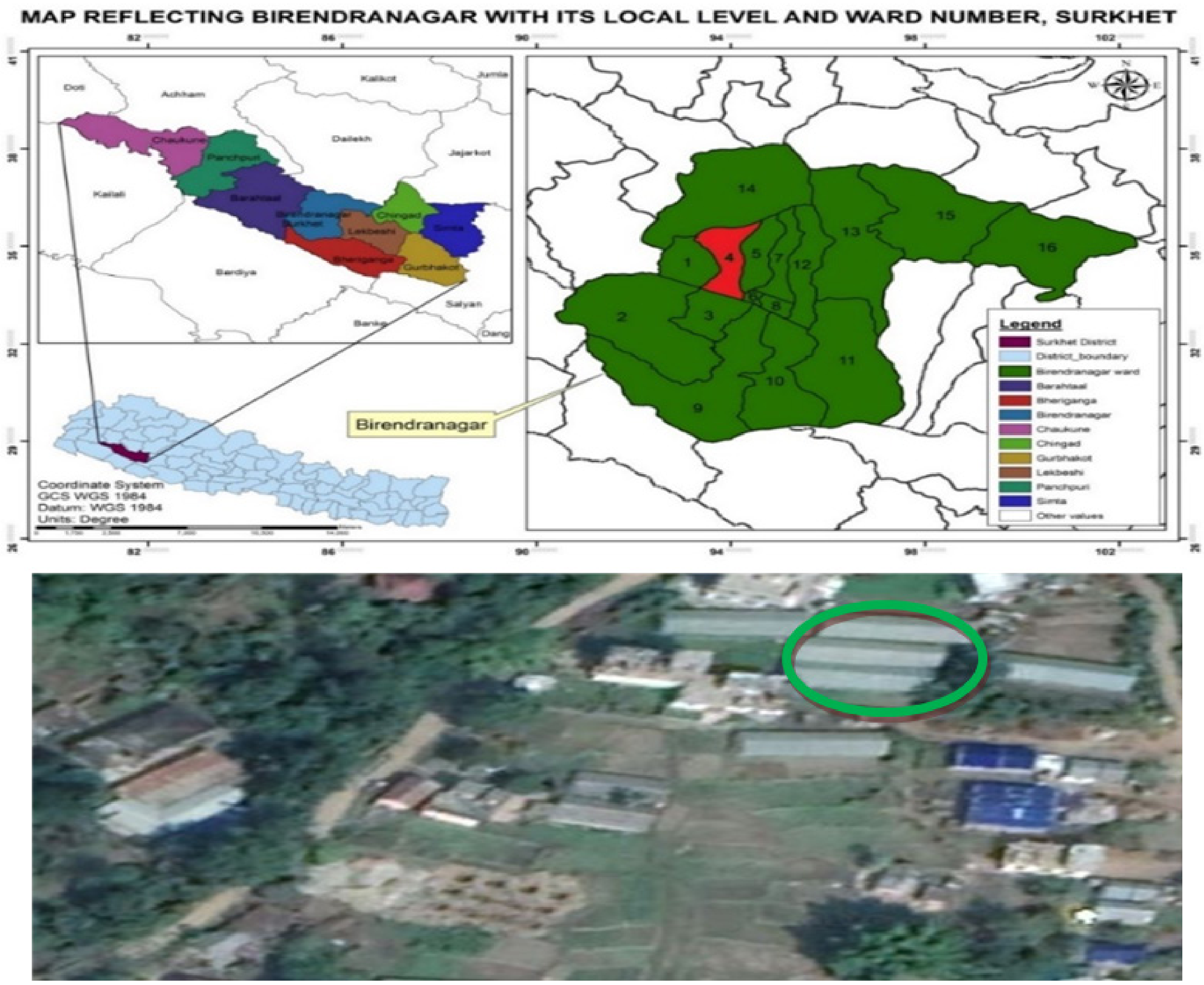

Figure 1. Map of experimental site constructed through Arc. GIS version 10.5 and Google Earth

monitoring. Captured moths were counted and removed daily, and the pheromone septum was replaced every 30 days as per the manufacturer's instructions.

Experimental Setup and treatments

The experimental setup including the agronomic practices is presented in **Table 1**, while the details of the treatments used is shown in **Table 2**.In the case of liquid and powder commercial biological pesticides, like Mahastra, Neem 1500, Nimbicidine, Daman, TutaVir, and Chlorantraniliprole, the required quantity of the insecticides was diluted to a small quantity of water and stirred thoroughly, and then the remaining quantity of water was poured to get the required concentration of the final spray. The amounts of insecticides required per liter of water was calculated by the formula provided by ADB (1987) which is:

$$\text{Insecticides per liter water} = 1 + \frac{\text{desired a.i Conconcentraion of insecticide}}{\text{a.i in formulated insecticides}} \times 1000$$

Treatment materials were sprayed on the tomato with the help of 16-litre capacity Knapsack Sprayer. The plant was thoroughly sprayed, and this was repeated every 15 days. Treatment material was applied in the late afternoon, directed at the canopy of the tomato plant.

Observation and damage assessment

Ten tomato plants were randomly selected from the inner rows of each plot for data observation. Data on the damaged numbers of leaves, buds, and fruits, as well as the number of live larvae per plant and the number of boreholes per fruit were recorded. Observations were conducted before treatment application and at 6 and 12 days after spraying for each of the five spray treatments. Before the first application, terminal buds were carefully examined to assess *T. absoluta* infestation, and larvae were counted before and after spraying. During the fruiting stage, data on the total and damaged fruits, along with the number of boreholes per fruit, were collected and compared. All observations were based on 10 randomly selected plants per treatment per replication. The incidence of *T. absoluta* was assessed through observations of larval presence on various plant parts (leaves, buds, and fruits) and by counting moths captured in WOTA-T traps. To evaluate treatment effectiveness, two main parameters: damage percentage and yield were measured. The damage percentage of leaves, buds, and fruits was

Table 1. Experimental setup for the field experiment

Parameter	Details
Crop	Tomato
Variety	GAURABH-555 (F1)
Spacing	75 cm (RR) × 50 cm (PP)
Chemical fertilizers	100:70:60 kg NPK/ha (MoALD, 2077)
Compost	20 t/ha (MoALD, 2077)
Design	RCBD
Treatments	8
Replications	3
Plot size	4 m × 2.5 m =10 m^2
Total plots	24
Spacing between treatment	1 m
Sample plants/plot	10
Size of plastic house	6 m × 20 m = 120 m^2 each
Irrigation type	Drip + Plastic Mulching
Date of seedling raising	1^{st} April, 2019
Date of transplanting	1^{st} May, 2019

Table 2. The details of the treatments used in the experiment

Treatment	Active ingredient (A.I.)	Trade name	Dose	Group
T1	*Bacillus thruingeinsis*var. Kurstaki (0.5 % WP)	Mahastra	2gm/L	Microbial
T2	Neem leaf extract (Azadirachtin 300 ppm)	Nimbicidine	4 ml/L	Botanical
T3	Neem kernel extract (Azadirachtin 0.15% EC)	Neem 1500	4 ml/L	Botanical
T4	*Beuveria bassiana* (2.0% AS)	Daman	4 ml/L	Microbial
T5	Baculovirus >2x10^{13} PhopGV/liter SC	TutaVir	2 ml/ 10 L	Microbial
T6	Alternate spray of *Bt.k* And Azadirachtin 0.15 EC	Mahastra +Neem 1500	2 gm/ L + 4 ml/L	Microbial+ Botanical
T7	Chlorantraniliprole 18.5% SC	Allcora	3ml/10 L	Ryanodine
T8	Control (Pure water spray)	N/A	N/A	N/A

Note: WP = Wettable powder, EC = Emulsifiable concentrate, AS = Aqueous suspension, SC= Soluble concentrate, N/A = Not applicable

visually estimated to compare infestation levels among treatments, with data recorded in Excel and damaged parts removed after observation. Pest incidence (P.I) was calculated as the percentage of infected plant parts relative to the total number of those parts per plant. Tomato yield was recorded across four consecutive harvests to determine the overall impact of treatments on

$$\text{Damage (\%)} = \frac{\text{Number of infected leaves/buds/ fruits per plant}}{\text{Total number of leaves/ buds/ fruits per plant}} \times 100$$

Statistical Analysis

All data obtained from the field experiment were organized and processed using Microsoft Excel 2013, while statistical analyses were performed using ADEL-R version 2.0 and R-Studio version 3.5.1. Treatment means were separated using Duncan's Multiple Range Test (DMRT) at a 5% level of significance. Additionally, a benefit-cost analysis through B:C ratio was conducted to evaluate the economic viability of each treatment. This analysis incorporated factors such as insecticide prices, labor costs, land rent, sprayer expenses, and other cultivation costs.

Result:

Relationship between WOTA-T trap monitoring and temperature

The climatic data during the experimental period was obtained from DHM, Karnali Province, Nepal. In 15^{th} of May, 2019, the average population of trapped moths in the WOTA-T trap was 23.60, while the average temperature was 27.70 °C. Afterwards, with the increase in average temperature (29.390 °C), the mean number of moths captured also increased (25.49). Later, the number of moths captured per WOTA-T trap exhibited a decreasing trend (**Fig. 2**).

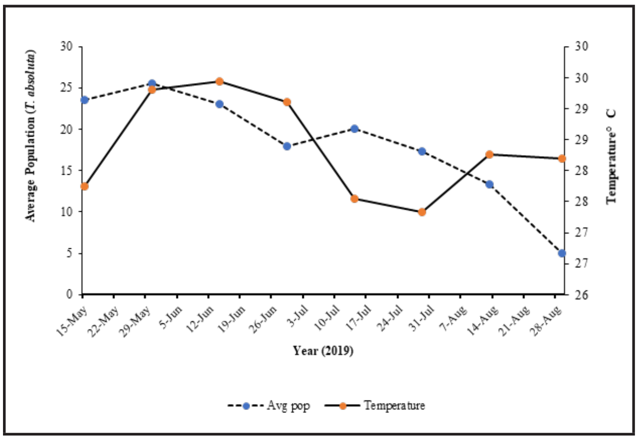

Figure 2. Relationship between temperature and the WOTA-T trap monitoring data

Percentage leaf damage

Across all five treatments, a consistent trend was observed in leaf damage percentages as recorded on 6 days after treatment application (DAT) and 12 DAT of each spray, among the treatments (Figure 3). Following the first spray at 6DAT, the highest leaf damage was recorded in the control plot (pure water spray) (32.29%), while the lowest was observed in plots treated with Chlorantraniliprole (20.26%). After 12 days, the control plot again resulted in the highest leaf damage (29.10%), whereas *B. bassiana* showed the least (13.90%). A similar pattern persisted after the second spray application on the same consecutive days, with the control plot recording the highest initial damage (26.98%) and Chlorantraniliprole (9.61%) exhibiting the least. Similarly. After 12 DAT, the control plot had the highest leaf damage (23.83%), contrasting with the lowest value in the *Bt*. k (6.36%). In the third, fourth, and fifth spray applications, the control consistently showed the highest damage levels, while the combination of *Bt.* k and Neem 1500, along with Chlorantraniliprole, demonstrated superior efficacy with minimal leaf injury.

Percentage bud, leaf and fruit damage

The highest percentage infestation of buds was recorded in plot with control (23.89±0.08), followed by Chlorantraniliprole (18.18±0.57), and the lowest in Baculovirus (8.65±0.25), followed by *Bt.k* (9.33±0.39) ($p<0.01$). While in the case of leaf damage, the plot with treatment control revealed the maximum percentage of infestation (15.39±1.10) followed by Baculovirus (12.23±0.31), whereas the lowest leaf infestation percentage was observed in *B. bassiana* (8.84±0.11) and Chlorantraniliprole (8.90±0.06) ($p<0.01$) (**Fig. 4**). Similarly, **Fig. 4**. shows that fruit damage percentage was also highest in the control (6.24±0.11) following Azadirachtin 0.15 EC (3.06 ±0.05). On the other hand, the lowest damage percentage was recorded in Chlorantraniliprole (1.48 ±0.08) and alternate spray of *Bt. k* and Azadirachtin (1.81±0.08) ($p<0.01$).

Live larvae, bore holes, and yield

The control recorded the highest larval infestation (6.68

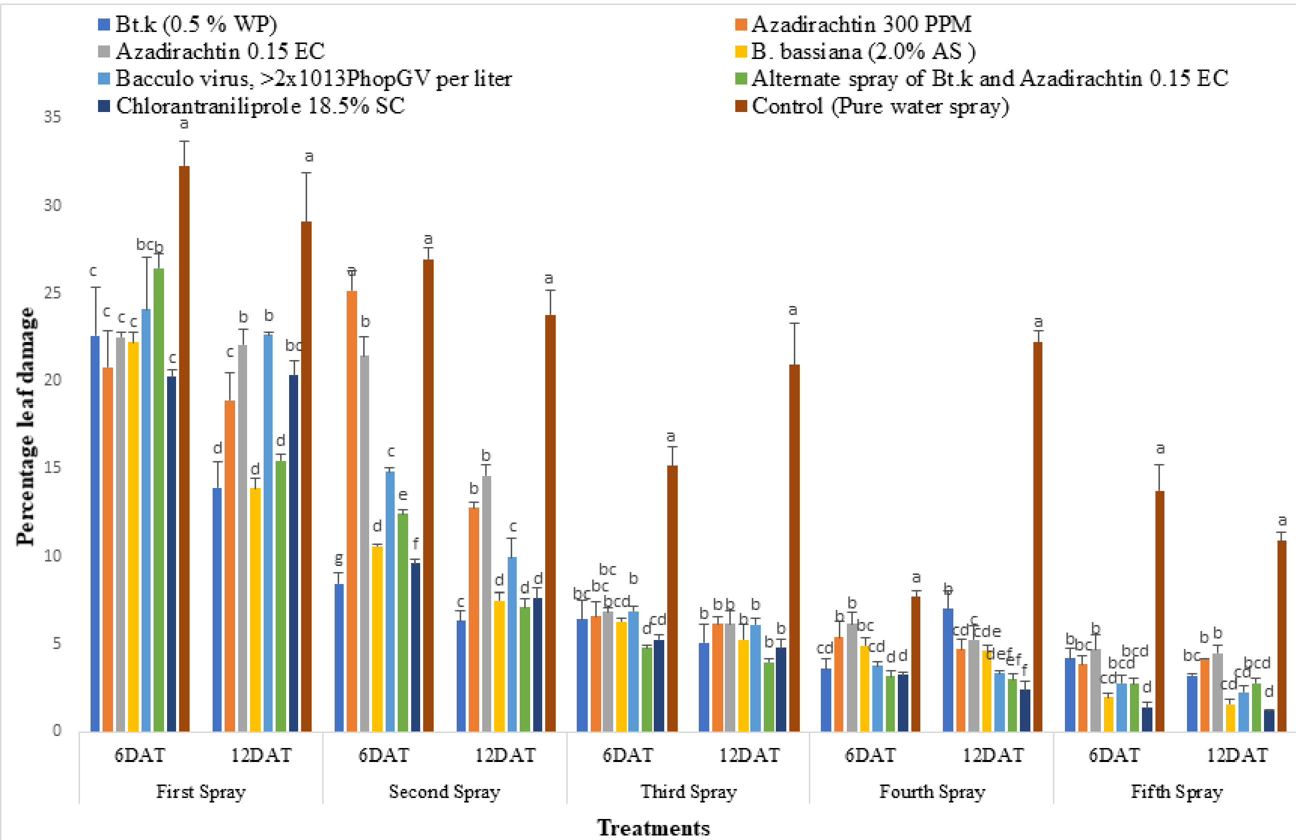

Figure 3. Percentage damage of leaves by *T. absoluta* at 6DAT and 12DAT of five different sprays. *DAT*, Days after Treatment application

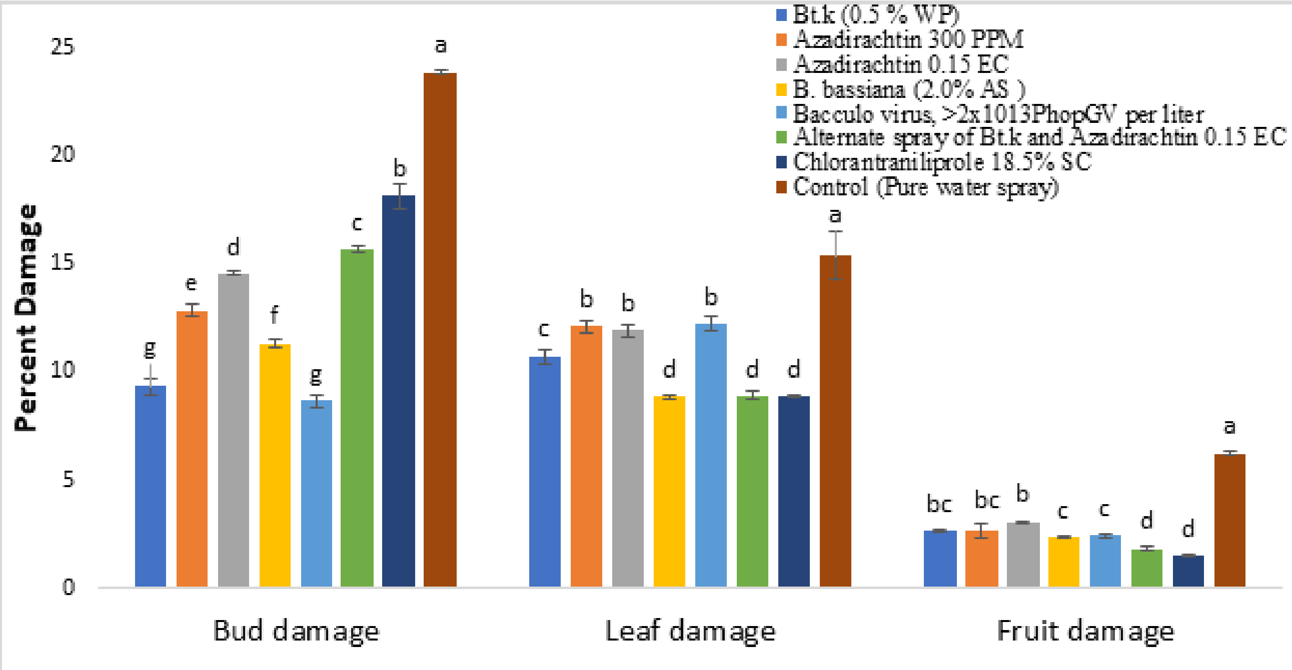

Figure 4. Percentage damage of buds, leaves and fruit by *T. absoluta*

Table 3. Average number of live larva count, bore holes per fruit and total yield

Treatments	Average no. of live larvae	Average Bore holes per fruit	Yield (t/ha)
Bt.k (0.5 % WP)	$3.64^{e} \pm 0.16$	$2.06^{b} \pm 0.20$	$30.06^{d} \pm 0.32$
Azadirachtin 300 PPM	$3.37^{f} \pm 0.07$	$1.82^{bc} \pm 0.19$	$33.64^{c} \pm 0.23$
Azadirachtin 0.15 EC	$5.25^{b} \pm 0.02$	$1.79^{bcd} \pm 0.03$	$33.53^{c} \pm 0.32$
B. bassiana (2.0% AS)	$4.17^{c} \pm 0.02$	$1.85^{bc} \pm 0.11$	$38.23^{b} \pm 1.32$
Baculovirus, >2x10^{13}PhopGV per liter	$4.18^{c} \pm 0.07$	$2.03^{b} \pm 0.13$	$35.72^{c} \pm 1.46$
Alternate spray of *Bt.k* and Azadirachtin 0.15 EC	$3.75^{de} \pm 0.04$	$1.57^{cd} \pm 0.12$	$40.99^{a} \pm 0.93$
Chlorantraniliprole 18.5% SC	$3.89^{d} \pm 0.01$	$1.39^{d} \pm 0.12$	$39.16^{ab} \pm 0.41$
Control (Pure water spray)	$6.68^{a} \pm 0.07$	$4.18^{a} \pm 0.19$	$23.78^{e} \pm 0.40$
Mean	4.37	2.09	34.39
CV (%)	2.81	11.64	4.03
F-Value	236.87	38.92	21.4
LSD (5%)	0.22	0.43^{**}	2.43^{**}

CV: Coefficient of Variation; LSD: Least Significant Difference; ± Value indicates standard error of mean; Means followed by the same letters within each column are not significantly different at 5 % level of significance. All treatment effects were significant at $p<0.01$ according DMRT.

larvae/fruit) and the highest number of bore holes (4.18 per fruit), resulting in the lowest yield (23.78 t/ha). In contrast, the alternate spray of *Bt. k* and Azadirachtin 0.15 EC recorded a lower larval count (3.75), fewer bore holes (1.57), and the highest yield (40.99 t/ha). Similarly, Chlorantraniliprole 18.5% SC also proved highly effective, producing a comparatively low larval count (3.89), the fewest bore holes (1.39), and a high yield (39.16 t/ha). Treatments with Azadirachtin 300 PPM, *B. bassiana*, and Baculovirus showed moderate effectiveness, while *Bt. k* (0.5% WP) significantly reduced larval infestation but yielded less than the top-performing treatments.

Yield and economics of treatments

The net profit was the highest in *Bt. k* and Azadirachtin 0.15 EC alternately sprayed plots (NRs. 2191433 per ha.) followed by Chlorantraniliprole (NRs. 2070033 per ha.) and *B. bassiana* (NRs 1962300 per ha.). The lowest net profit was observed in control (NRs.889633) (Table 4). The highest B:C Ratio was recorded in alternate spray of *Bt. k* and Azadirachtin 0.15 EC (3.02), followed by Chlorantraniliprole (2.95) and *B. bassiana* (2.79), and the lowest in control (1.88).

Discussion:

The monitoring results revealed that the average *T.*

Table 4. Benefit-cost analysis of the tested treatments

Treatment	Yield (t/ha)	Total returns (NRs. /ha)	Cost of cultivation (NRs. /ha)	Net Profit (NRs. /ha)	B:C ratio
Bt. k (0.5 % WP)	30.06	2404533.33	1012500.11	1392033.22	2.37[d]
Azadirachtin 300 PPM	33.64	2691200.00	1079166.78	1612033.22	2.49[cd]
Azadirachtin 0.15 EC	33.53	2682400.00	1079166.78	1603233.22	2.49[cd]
B. bassiana (2.0% AS)	38.23	3058133.33	1095833.44	1962299.89	2.79[b]
Baculovirus	35.72	2857866.67	1112500.11	1745366.56	2.57[c]
Alternate spray of *Bt. k* and Azadirachtin 0.15 EC	40.99	3278933.33	1087500.11	2191433.22	3.02[a]
Chlorantraniliprole 18.5% SC	39.16	3132533.33	1062500.11	2070033.22	2.95[ab]
Control (Pure water spray)	23.78	1902133.33	1012500.11	889633.22	1.88[e]

Note: The average selling price of Tomato at the farm gate was NRs. 80 per kg in Surkhet from May to September 2019

absoluta moth population in Surkhet, Nepal, exceeded the Economic Threshold Level (ETL). This finding was corroborated by Shahini et al. (2021), who reported 1-3 male moths per trap per week, suggesting that the local climate was conducive to the growth and development of the moth. Since its first detection in Nepal in 2016, this invasive insect may not have the specific biotic factor necessary to naturally limit its spread. According to reports by Mohamed et al. (2022), once an invasive insect such as *T. absoluta* is detected in a new area, its economic threshold may always be higher due to the lack of effective natural biocontrol agents. Therefore, suitable control measures should be developed to keep its population below ETL.

Overall, the findings of the biorational pesticides test revealed that integrated or alternate applications of these pesticides, particularly *Bt. k* combined with Azadirachtin, were most effective in minimizing fruit borer infestation and achieving the highest productivity compared to individual applications or the untreated control. In line with our findings, Bajracharya et al. (2017) reported the lowest leaf infestation percentage in Chlorantraniliprole-treated plants (38.49 %). Chlorantraniliprole is also found be to a superior pesticide to manage other lepidopteran pests such as *H. armigera* in Nepal (Khanal et al., 2025). To contrl the leaf damage by *T. absoluta*, Simkhada & Thapa (2019) reported that Chlorantraniliprole@ 0.3ml/L (38.49 %), Bt.k @ 2g/L (45.03 %), and Azadirachtin 300 ppm@ 5ml/L (71.70 %) were equally effective. With regard to larval population, Chlorantraniliprole and Azadirachtin 300 ppm also highlighted significant effect to control their population level followed by *Bt. k* which was further supported by the findings of (Shiberu and Getu, 2018). Similar reports were also suggested by Simkhada & Thapa (2019) who exhibited that the plot sprayed with Chlorantraniliprole had the lowest number of live larva count (0.11/leaf), followed by Azadirachtin 300 ppm (1.04/leaf). Similarly, Bajracharya *et al.* (2017) reported that the lowest percentage of fruit infestation was observed in the chlorantraniliprole-treated plants (14.52 %). The differences in efficacy among biorational pesticides can be attributed to their modes of action. Chlorantraniliprole is an anthranilic diamide that activates ryanodine receptors in insects which has a rapid knockdown effect compared to other treatments used in our experiment (Li et al., 2019).

With respect to marketable fruit yield, treatments that reduced *T. absoluta* damage correspondingly produced higher yields. Thus, it is projected that mean marketable fruit yield production was greatly influenced by the percentage of fruit damage and a higher level of infestation. Our results showed that Chlorantraniliprole, alternate spray of *Bt. k* and Neem 1500, and *B. bassiana* reduced the number of leaves infested and fruit tunneled per plant, and the baculovirus significantly reduced the percentage of bud damage compared to other treatments, which is supported by the results of Hamdy and Walaa (2013). Shiberu and Getu (2017), also observed the highest yield obtained from plots sprayed with Chlorantraniliprole (85.34 t/ha), followed by Azadirachtin (55.23 t/ha).

In our study baculovirus emerged as a promising alternative in controlling *T. absoluta* damage and helped reduce yield loss by reducing tomato bud infestation, which is a crucial finding in terms of biorational pesticides use. Rotational application of baculovirus with Chlorantraniliprole and *Bt.* has proved to be effective against lepidopteran pests in protected as well as open field vegetable cultivation (Landwehr, 2021). The same study further suggested that it is a promising alternative to include in IPM programs in vegetable cultivation. The baculovirus alters the feeding behavior of infected insects, disrupts the insect's physiology, and kills them. Unlike entomopathogenic fungi, this virus must be ingested for it to be effective against the host insect (Landgren *et al*., 2009; Martínez-Balerdi et al., 2025). Therefore, its efficacy in the field conditions largely depends upon the ingestion of the viruses by the insects. Furthermore, *B. Bassiana* showed a medium effectiveness in our study in controlling *T. absoluta.* among other treatments. It should be noted that, the entomopathogenic fungi should first penetrate the insect cuticle to initiate infection which is largely determined by the prevailing environmental conditions (Kabaale et al., 2022; Shapiro-Ilan et al., 2005; Vega et al., 2012). In addition, the strains of the fungi also determine the infection on the host. Furthermore, their efficacy is expected to be higher, when the strain is isolated from the same insect species.

The highest benefit-cost (B:C) ratio was recorded in the alternate spray of *Bt. k* And Neem 1500 (3.02) followed by Chlorantraniliprole (2.95) and *B. basiana* (2.79), and the lowest in control (1.88). The lower B:C ratio in alternate spray *Bt. k* and Neem 1500 could be due to the lower production cost of locally formulated Neem products. Thus, alternating *Bt.k* and Azadirachtin 1500 ppm sprays would be one of the checks for chemical insecticides, similar to the research conducted by Sah (2017). Recently, Khanal et al. (2025) also emphasized the significance of Neem-based products in controlling other lepidopteran pests of tomato due to their cost-effectiveness in local conditions. Therefore, Neem-based products should be locally produced and integrated in IPM programs of *T. absoluta* in tomato.

Furthermore, alternative applications of *Bt. k* and Azadirachtin effectively controlled pests and reduced the yield loss caused by *T. absoluta* damage. In this treatment, there is a combination of the stomach-contact mode of action of *Bt. k* (Nawaz et al., 2020) as well as the insecticidal and repellent properties of Azadirachtin (Jat & Pareek, 2001). *Bt.* produces Cry toxins disrupting the midgut epithelium of lepidopteran insects while azadirachtin a need-based botanical alters their feeding behavior, reproduction and molting. Therefore, we argue that mixing different biorational pesticides with differing modes of action could enhance their effectiveness through selection pressures on *T. absoluta* with delayed resistance build-up (Abedi et al., 2014; Ndereyimana et al., 2020). Therefore, this strategy could be a novel approach in the IPM of *T. absoluta*.

Conclusion:

In Surkhet, Nepal, average population of *T. absoluta* moths was at Economic Threshold Level, which underscored the potential influence of climatic variations on their seasonal dynamics. The results further demonstrate that different bio-pesticides and insecticides significantly influenced the infestation level and yield of tomato. The alternate spray of *Bt. k* and Neem 1500 (Azadirachtin 0.15 EC) and Chlorantraniliprole 18.5% SC were found to be the most effective treatments, recording the lowest larval infestation, fruit damage, and the highest yield. The lowest bud damage was observed with baculovirus and leaf damage was considerably lower in all bio-pesticide-treated plots compared to the untreated control. The highest economic return was also achieved with the alternate spray of *Bt. k* and Neem 1500 demonstrating both control efficacy and cost effectiveness. Overall, the results suggested that integrated use of bio-pesticides, particularly the alternate application of *Bt.k* and Neem 1500, can serve as a sustainable and eco-friendly alternative to synthetic chemicals for the effective management of *Tuta absoluta*, ensuring higher yield and profitability while reducing environmental risks. Therefore, the rational and judicious use of Chlorantraniliprole, alternate application of Neem 1500 and *Bt. k* is recommended for the effective control of *T. absoluta.* However, further studies using different botanicals and entomopathogenic agents under diverse climatic conditions is recommended to determine their lethal as well as sublethal effects.

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Declaration of conflict of interest and ethical approval:

The authors declare that there is no conflict of interest regarding the publication of this article.

Authors' contribution statement

Krishna Lamsal conducted the experiment, analyzed the data, and prepared the initial manuscript draft. Pooja Poudel Chhetri wrote the manuscript, reviewed and edited the initial draft. Rekha Sapkota and Dipak Khanal supervised the work, reviewed and edited the draft. All authors read and approved the final manuscript.

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