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Effectiveness of different chemical pesticides in controlling Tomato Leaf Miner (*Tuta absoluta* Meyrick, 1917) in Kathmandu, Nepal

Asim Bastola[1,a], Bikash Kandel[1,b,*], Dipesh Bist[1,c], Suraksha Neupane[2,d], Aayush Pokhrel[1,e], Sagar Pandey[3,f]

[1]*Agriculture and Forestry University, Faculty of Agriculture, Rampur, Chitwan, Nepal*
[2]*Jibika college of agricultural sciences, Ramdhuni, Sunsari*
[3]*Muktinath Krishi Company Limited, Basundhara, Kathmandu*
[*]*Corresponding author*

A R T I C L E I N F O

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A B S T R A C T

Tomato farming in Kathmandu faces many pest problems, including leaf miners, fruit borers, and whiteflies. The most problematic is the tomato leaf miner (*Tuta absoluta*), which damage vegetative and reproductive stages, leading to up to 100% crop loss. The experiment was conducted on the tomato variety Kabita during March-June 2024 in a farmer's field in Chandragiri Municipality-1, Kathmandu, under open-field conditions. This research studied the effects of different chemical pesticides on infestation percentage in leaves and fruits, tunnels per infested leaf and fruit, and larvae per infested leaf. Seven treatments were evaluated: chlorantraniliprole 18.5% SC @3 ml/l, azadirachtin 3000 ppm @4 ml/l, control, emamectin benzoate 1.5% + indoxacarb 7.5% SC @0.625 ml/l, chlorfenapyr 10.5% + spinosad 2.5% SC @0.1 ml/l, spinetoram 11.7% SC @0.8 ml/l, and chlorfenapyr 10% + tolfenpyrad 10% SC @1 ml/l, with three replications laid out in a Randomized Complete Block Design (RCBD) with 4.32 m² per plot. The experiment showed significant pesticide effects on larval mortality and damage reduction. The lowest infestation in leaves (11.26%) and fruits (0.94%), with the fewest tunnels per infested leaf (0.41) and fruit (0.22), was in chlorfenapyr + tolfenpyrad, followed by spinetoram. The lowest larval population per infested leaf was in spinetoram (0.31), followed by chlorfenapyr + tolfenpyrad. The lowest yield loss (2.70%) was in chlorfenapyr + tolfenpyrad, followed by spinetoram. Thus, chlorfenapyr + tolfenpyrad, followed by spinetoram, were the most effective pesticides for managing *Tuta absoluta* under Chandragiri field conditions.

[a] asimbastola17@gmail.com https://orcid.org/0009-0002-8515-5636
[b] kandelbikash974@gmail.com https://orcid.org/0009-0002-7779-4796
[c] dipeshbist23@gmail.com https://orcid.org/0009-0007-3950-5638
[d] Suraksha.neupane2022@gmail.com https://orcid.org/0009-0004-0371-6706
[e] ayush20570721@gmail.com https://orcid.org/0009-0002-8233-4647
[f] nepalsagar12@gmail.com https://orcid.org/0009-0008-6096-3876

Introduction

Tomato (*Solanum lycopersicum L.*) is an annual herbaceous plant belonging to the Solanaceae family and is one of the most widely cultivated vegetable crops worldwide. Originating in the Andean region of South America, tomatoes have become a staple crop due to their nutritional value, economic importance, and versatility in food systems. Rich in essential nutrients such as vitamins A, C, and potassium, tomatoes are vital in enhancing food security and generating income for farmers. However, tomato production is often constrained by several biotic and abiotic factors, with pest infestation being one of the most significant challenges.

Global production of tomatoes was estimated to be over 186 million in 2023(Tomato Production, 2023). The total production of tomatoes in Nepal was recorded at 422,703 metric tons during the fiscal year 2021/22, with an average productivity of 18.45 tons per hectare, which is significantly lower than the global average(MoALD, 2022). This productivity gap can be attributed to multiple factors, including poor agronomic practices, pest infestations, and limited access to high-quality inputs. Additionally, overusing pesticides and using chemicals that are not advised for the pest can cause the pest to become resistant(Never et al., 2017). Among the pests, the tomato leaf miner (*Tuta absoluta* Meyrick, 1917) has emerged as one of the most destructive pests, capable of causing up to 100% crop loss if left unmanaged(Pandey et al., 2023).

Tuta absoluta, a member of the family Gelechiidae, is native to South America but has rapidly spread across Europe, Africa, and Asia, including Nepal. The pest was first reported in Nepal in 2016, in a commercial tomato farm in Kathmandu(Bajrachraya et al., 2016). Its larvae feed on the mesophyll tissue of tomato leaves, stems, and fruits, creating tunnels that reduce photosynthetic efficiency and fruit quality. This feeding behavior often leads to secondary infections, resulting in substantial yield losses(IRAC, 2011). The infestation of *T. absoluta* poses a significant threat to tomato production in Kathmandu, where climatic conditions are favorable for its rapid proliferation.

Farmers in Nepal predominantly rely on chemical pesticides for managing *T. absoluta* due to their immediate effectiveness and ease of application. However, the indiscriminate and excessive use of pesticides has led to several adverse effects, including environmental contamination, soil degradation, and the development of pesticide resistance in pests(Biondi et al., 2018). Furthermore, many farmers lack awareness about appropriate pesticide selection, dosage, and application timing. This knowledge gap often leads to the use of non-recommended pesticides such as dimethoate and dichlorvos, which are ineffective against *T. absoluta* and exacerbate the problem of resistance development(Ghimire & Chhetri, 2023).

Integrated pest management (IPM) strategies, which combine cultural, biological, and chemical control methods, are recommended for sustainable pest management. However, the adoption of IPM practices remains low among Nepalese farmers due to limited access to resources and technical knowledge(Lamsal et al., 2022). As a result, chemical pesticides remain the primary method for controlling *T. absoluta* in Nepal. The notorious tomato pest, *Tuta absoluta*, is difficult to control in a single try(Bajracharya et al., 2018). Identifying effective chemical pesticides that minimize environmental and health risks while ensuring pest control is therefore crucial.

The present study was conducted to evaluate the effectiveness of different chemical pesticides in managing *T. absoluta* under field conditions in Chandragiri Municipality, Kathmandu. The research focused on assessing the impact of these pesticides on the percentage of infestation in leaves and fruits, the number of tunnels per infested leaf and fruit, and the larval population per infested leaf. The study also aimed to identify the most effective pesticide treatments for reducing yield losses caused by *T. absoluta*.

Seven treatments were evaluated, including chlorantraniliprole 18.5% SC(Allcora, @ 0.3 ml/L), azadirachtin 3000 ppm(M-Neem Ultra, @ 4 ml/L), emamectin benzoate 1.5% + indoxacarb 7.5% SC(M-Titan @ 0.625 ml/L), chlorfenapyr 10.5% + spinosad 2.5% SC(M-Larva Off @ 0.1 ml/L), spinetoram 11.7% SC(Largo @ 0.8 ml/L), and chlorfenapyr 10% + tolfenpyrad 10% SC(M-Boronil @ 1 ml/L), along with a control. These treatments were applied twice at a 14-day interval, and the experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. The findings of this study are expected to provide valuable insights into the efficacy of these pesticides and their potential for integration into IPM programs.

This research contributes to addressing the knowledge gap regarding the local efficacy of chemical pesticides for *T. absoluta* management in Nepal. By identifying the most effective pesticide treatments, the study aims to support evidence-based decision-making for pest management and promote sustainable tomato production practices. Additionally, the results underscore the importance of adopting scientifically validated pest control strategies to enhance tomato productivity and profitability while minimizing environmental and health risks. Through the effective management of *T. absoluta*, farmers in Kathmandu can achieve higher yields and better economic returns, contributing to the overall development of the agricultural sector in Nepal.

Materials and methods

Research Site and Time of Research

The research was conducted in Dahachowk Khahare, Chandragiri Municipality-1, Kathmandu district, Bagmati province. This site is supervised by the Prime Minister Agriculture Modernization Project (PMAMP), Vegetable Zone, Kathmandu. Chandragiri is located in the Bagmati zone of central Nepal, in a sub-tropical zone at an elevation of 1381 meters above sea level (masl). It is situated between 27°70” North and 85°23” East, covering a total area of 43.9 km². The research was carried out from 22nd March 2024 to 15th July 2024 (Figure 1).

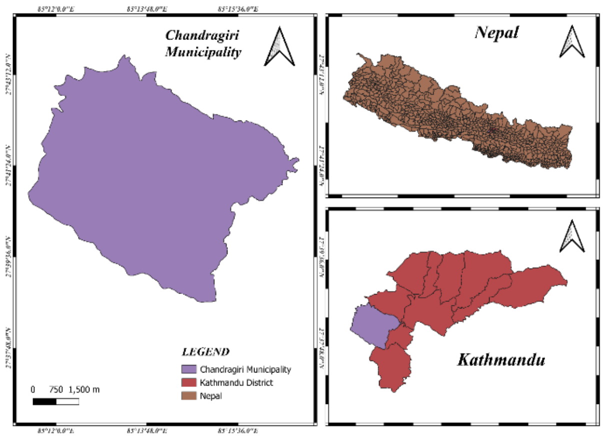

Figure 1. Study area map

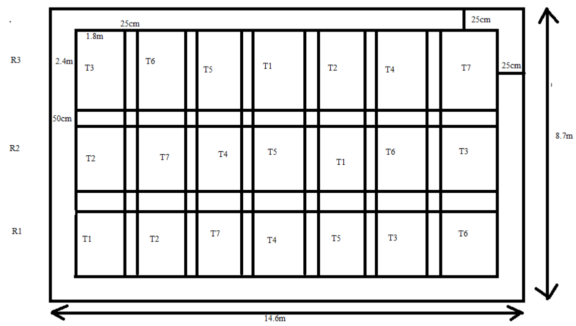

Figure 2. Layout of research field

Weather Condition

Kathmandu, located at an elevation of approximately 1400 meters (4600 feet) above sea level, experiences a subarctic climate with dry winters and cool summers (Dwc classification). The average annual temperature in Kathmandu is 18.88°C (65.98°F), which is 3.12% lower than Nepal’s average. The district receives about 345.46 millimeters (13.6 inches) of precipitation annually, spread over 205.15 rainy days (56.21% of the year) (Weather and Climate, 2024).

Experimental Details

The determinate tomato variety 'Kabita' was used in the study. Fruiting began 60-70 days after transplanting. Twenty-two day old seedlings were transplanted on 29th March 2024. Each plot measured 4.32 m² (2.4 m × 1.8 m), with 16 plants per plot arranged in four rows of four plants each. Each experimental plot measured 2.4 m in length and 1.8 m in width, with a spacing of 60 cm RR and 45 cm PP. The net plot area was 4.32 m², and a spacing of 25 cm was maintained between plots and as a border around the field. Three blocks were arranged for replication, with a replication-to-replication spacing of 50 cm. The total area of the research field was 127.02 m².

Design of Experiment

The experiment was conducted in a Randomized Complete Block Design (RCBD) with seven treatments and three replications. A total of 21 plots were used, each containing 16 plants. Border plants were excluded, and the central four plants in each plot were tagged as sample plants for data collection.

Treatment Details

Seven treatments were evaluated, including a absolute control. Chlorantraniliprole 18.5% SC @ 3 ml/L (T1), recommended by PQPMC Nepal (Progressfiles, 2078), is effective against *Tuta absoluta* larvae. It has shown good control of leaf and fruit damage in previous studies (Simkhada et al., 2018; Bastola et al., 2021). Azadirachtin 3000 ppm @ 4 ml/L (T2), a neem-based botanical insecticide, works as a repellent and growth inhibitor. Though slower-acting, it significantly reduced larval infestation compared to control in field studies (Bastola et al., 2021; Singh & Mourya, 2024; Khan et al., 2022). Emamectin benzoate 1.5% + indoxacarb 7.5% SC @ 0.625 ml/L (T4) is a neurotoxic combination with strong larvicidal effects. It has shown high efficacy in lab and field trials, with added benefits when combined (Taleh et al., 2021; Singh et al., 2024; Moustafa et al., 2023). Chlorfenapyr 10.5% + spinosad 2.5% SC @ 0.1 ml/L (T5) combines two insecticides with different modes of action. This mixture provided over 90% larval mortality in various studies and is endorsed for use against *T. absoluta* in Nepal (Taha et al., 2017; dos Santos et al., 2011; Bratu et al., 2015; Progressfiles, 2078). Spinetoram 11.7% SC @ 0.8 ml/L (T6), a spinosyn derivative, showed the best field efficacy in reducing larvae and tunnel formation (Hanafy & El-Sayed, 2013; Erol et al., 2021; Hadji et al., 2019). Chlorfenapyr 10% + tolfenpyrad 10% SC @ 1 ml/L (T7) was one of the most effective treatments. Tolfenpyrad inhibits feeding and respiration in larvae, and its combination with chlorfenapyr led to strong pest suppression (Taha et al., 2017).

Spraying of Chemicals

The first spraying of chemicals was conducted 46 days after transplanting (DAT) using motor operated Knapsack sprayer(16 litre capacity). The second spray was applied 14 days after the first spray. Data were collected a day before spraying, three days after spraying, seven days after spraying, and 14 days after spraying.

Agronomical Practices

Soil and Land Preparation

The soil was prepared through 3-4 deep ploughings followed by harrowing to break large clods and remove weeds before transplantation.

Manuring and Fertilization

Before transplanting, the field was fertilized with both organic and inorganic sources. Farmyard manure (FYM) was applied at the rate of 20 tons per hectare, 10 days before transplanting. As a basal dose, a full amount of Diammonium Phosphate (DAP) and Muriate of Potash (MOP) were applied at the rates of 130 kg/ha and 97.5 kg/ha, respectively, along with one-third of the Urea (46% Nitrogen) at 130 kg/ha total. The remaining two-thirds of urea was applied in two equal splits at 25–30 and 50–55 days after transplanting. All fertilizers were procured from the Muktinath Krishi Company Limited, Kathmandu, a licensed agro-input distributor in Nepal.

Irrigation

Irrigation was performed immediately after transplantation using a watering can. Frequent irrigation was provided until plant establishment, followed by irrigation at 3-4 day intervals. Furrows were made to divert rainwater and prevent waterlogging.

Training and Pruning

Plants were supported by tying ropes to bamboo poles to prevent lodging due to fruit weight. Side sucker branches were removed manually.

Weeding

Weeding was done thrice: first at 15 DAT, second during the application of the second urea split, and third at 45-50 DAT before applying the third urea split. Earthing up was done during the second weeding.

Disease Management

To control early blight, SAAF fungicide (Carbendazim 12% WP + Mancozeb 63% WP) was applied @ 2 g/l of water immediately after transplantation and then at weekly intervals.

Harvesting

Fruits were harvested at the pink stage (30-60% ripeness), starting 60-70 days after transplantation.

Data Collection

Average Percentage of Leaves Infested: The total number of leaves and infested leaves of sample plants (4 plants excluding border effect) were counted before spraying and on the 3rd, 7th, and 14th day after each spray. Data were collected using a non-destructive method.

Average Mining Per Infested Leaf: Five infested leaves from each sample plant were randomly selected, and the number of mines per leaf was counted.

Average Live Larvae Per Infested Leaf: The number of live larvae on five randomly selected infested leaves from each sample plant was recorded.

Average Percentage of Fruit Infestation: The total number of fruits and infested fruits per sample plant (4 plants excluding Border effect) were counted to calculate the percentage of fruit infestation.

Average Mining Per Infested Fruit: Five infested fruits per sample plant were randomly selected, and the number of mines was counted.

Average Yield Loss Per Plant: The total weight of undamaged and infested fruits per sample plant was recorded to calculate yield loss.

Data Analysis

The recorded data were systematically arranged treatment-wise under three replications. Statistical analysis, including analysis of variance (ANOVA), was performed using R programming, R Studio, and MS Excel. Duncan's Multiple Range Test (DMRT) was used for mean comparison using R Studio.

Result and Discussion

Effect of Different Chemical Pesticides on Number of Larvae per Infested Leaf

The statistical analysis showed that different chemical pesticides significantly affected the number of larvae per infested leaf (Table 1).

At 3 days after the first chemical spraying, the maximum number of larvae per infested leaf was observed in chlorantraniliprole (0.94), which was statistically at par with azadirachtin (0.92), the mixture of chlorfenapyr and tolfenpyrad (0.89), and spinetoram (0.83). The minimum number of larvae per infested leaf was observed in the mixture of emamectin benzoate and indoxacarb (0.56), which was statistically at par with the control (0.67). Interestingly, a relatively low larval population was also observed in the control group (0.67 larvae per infested leaf at 3 DAS), which might appear contradictory given the absence of chemical treatment. However, this may be attributed to natural predator activity, unfavorable microclimatic fluctuations, or reduced oviposition by adult moths in untreated plots due to the absence of pesticide-induced stress responses. Similar findings were reported by Hadji et al. (2017), where non-treated plots occasionally showed intermediate pest levels due to ecological checks. This observation underscores the complexity of pest dynamics under open-field conditions and highlights the potential role of non-chemical factors influencing pest populations.

At 7 days after the first chemical spraying, the maximum number of larvae per infested leaf was observed in the control (0.77). The minimum number of larvae per infested leaf was recorded in the mixture of chlorfenapyr and spinosad (0.53), which was statistically at par with spinetoram (0.57).

At 14 days after the first chemical spraying, the maximum number of larvae per infested leaf was observed in the control (0.83), which was statistically at par with azadirachtin (0.81). The minimum number of larvae per infested leaf was recorded in spinetoram (0.52), which was statistically at par with the mixture of chlorfenapyr and tolfenpyrad (0.55) and the mixture of emamectin benzoate and indoxacarb (0.56).

After the second spraying, the minimum number of larvae per infested leaf continued to be observed in spinetoram and the mixture of chlorfenapyr and tolfenpyrad across all intervals. spinetoram, a spinosyn-based pesticide, acts on the nervous system of the larvae, effectively reducing their population when they feed on treated leaves and fruits. Similar results were reported by Hadji, who found spinetoram to be the most effective pesticide for reducing *Tuta absoluta* larvae under open field conditions (Hadji et al., 2017). Furthermore, spinetoram's superiority in reducing the larval population is also noted in Erol's work (Erol et al., 2021).

All pesticide treatments reduced larval numbers compared to the control. The lowest larval count (0.31) was observed in spinetoram, followed closely by chlorfenapyr + tolfenpyrad (0.31). A gradual decline in the efficacy of chlorantraniliprole was observed from 3 to 14 days after 1st spraying (DAS), which was inadequate for sustained suppression of the pest population.These pesticides act on the insect nervous system, quickly paralyzing larvae. Emamectin benzoate + indoxacarb (0.53) and chlorfenapyr + spinosad (0.54) also significantly reduced larvae due to their dual-action neurotoxic effects. Chlorantraniliprole (0.72) and azadirachtin (0.85) were less effective. Azadirachtin's slower, antifeedant mode and chlorantraniliprole's reduced contact action in open-field conditions may explain the limited effectiveness. The control group showed moderate larval presence (0.67), possibly due to natural mortality, microclimate variation, or predation.

Effect of Different Chemical Pesticides on Percentage of Infested Leaves

The statistical analysis revealed significant differences in the percentage of infested leaves among treatments (Table 2). At 3 days after the first chemical spraying, the maximum percentage of infested leaves was recorded in the control (16.16%). The minimum percentage of infested leaves was observed in spinetoram (11.00%), which was statistically at par with the mixture of chlorfenapyr and tolfenpyrad (11.38%).

Table 1. Effect of different chemical pesticides on number of larva per infested leaf

Treatment	No. of larva per infested leaf					
	1st spray			2nd spray		
	3DAS	7DAS	14DAS	3DAS	7DAS	14DAS
Chlorantraniliprole	0.94^{a}	0.67^{b}(0.22)	0.76^{b}(0.25)	0.63^{c}(0.21)	0.55^{c}(0.19)	0.72^{c}(0.24)
Azadirachtin	0.92^{a}	0.64^{bc}(0.22)	0.81^{a}(0.26)	0.74^{b}(0.24)	0.68^{b}(0.23)	0.85^{b}(0.27)
Control	0.67^{cd}	0.77^{a}(0.25)	0.83^{a}(0.26)	0.86^{a}(0.27)	0.95^{a}(0.29)	0.97^{a}(0.29)
EBI	0.56^{d}	0.41^{f}(0.15)	0.56^{d}(0.19)	0.50^{d}(0.18)	0.42^{d}(0.15)	0.53^{d}(0.18)
CS	0.74^{bc}	0.53^{e}(0.18)	0.63^{c}(0.21)	0.51^{d}(0.18)	0.43^{d}(0.16)	0.54^{d}(0.19)
Spinetoram	0.83^{abc}	0.57^{de}(0.20)	0.52^{d}(0.18)	0.41^{e}(0.15)	0.27^{e}(0.10)	0.31^{e}(0.12)
CT	0.89^{ab}	0.61^{cd}(0.21)	0.55^{d}(0.19)	0.43^{e}(0.15)	0.27^{e}(0.10)	0.31^{e}(0.12)
LSD	0.16	0.02	0.01	5.09e-03	0.01	0.01
SE$_{m}$(±)	0.05	4.79e-03	3.40e-03	1.6e-03	4.23e-03	3.63e-03
F-probability	1.34e-03**	2.09e-07***	8.16e-09***	1.14e-14***	6.66e-12***	7.39e-13***
CV%	11.15	4.09	3.13	1.45	4.20	3.14
Grand Mean	0.79	0.60(0.20)	0.67(0.22)	0.58(0.20)	0.51(0.17)	0.60(0.20)

Note: EBI: Emamectin Benzoate + Indoxacarb; CS: Chlorfenapyr + Spinosad ; CT: Chlorfenapyr +Tolfenpyrad ; Means in the column with same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance based on DMRT; "***" = significant at p-value <0.001; "**" = significant at p-value<0.01; "*" = significant at p-value<0.05; LSD= Least significant difference; SE$_{m}$= Standard error of mean; CV= coefficient of variation; DAS= Days after spraying; figures inside bracket() are obtained after transforming via log transformation

Table 2. Effect of different chemical pesticides on percentage of infested leaves

Treatment	Percentage of infested leaves					
	1st spray			2nd spray		
	3DAS	7DAS	14DAS	3DAS	7DAS	14DAS
Chlorantraniliprole	13.07^{b}(1.12)	13.77^{b}	15.73^{b}	15.47^{b}	16.18^{b}	16.22^{b}
Azadirachtin	12.38^{b}(1.09)	13.79^{b}	15.71^{b}	15.83^{b}	16.11^{b}	16.76^{b}
Control	16.16^{a}(1.20)	16.28^{a}	18.39^{a}	18.84^{a}	18.60^{a}	19.40^{a}
EBI	12.95^{b}(1.11)	13.90^{b}	15.85^{b}	15.10^{b}	15.08^{bc}	15.81^{bc}
CS	12.41^{b}(1.09)	13.13^{b}	14.44^{c}	13.98^{c}	14.28^{c}	14.80^{c}
Spinetoram	11.00^{c}(1.04)	10.73^{c}	11.99^{d}	10.71^{d}	10.63^{d}	11.36^{d}
CT	11.38^{c}(1.06)	10.87^{c}	11.55^{d}	10.56^{d}	10.64^{d}	11.26^{d}
LSD	0.03	1.06	0.84	0.99	1.45	1.14
SE$_{m}$(±)	0.01	0.34	0.27	0.32	0.47	0.37
F-probability	4.53e-06 ***	1.17e-06 ***	6.90e-09 ***	4.20e-09***	3.22e-07 ***	2.16e-08***
CV%	1.72	4.50	3.18	3.87	5.62	4.23
Grand Mean	12.76(1.10)	13.21	14.81	14.36	14.50	15.09

Note: EBI: Emamectin Benzoate + Indoxacarb; CS: Chlorfenapyr + Spinosad ; CT: Chlorfenapyr +Tolfenpyrad; Means in the column with same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance based on DMRT; "***" = significant at p-value <0.001; "**" = significant at p-value<0.01; "*" = significant at p-value<0.05; LSD= Least significant difference; SE$_{m}$= Standard error of mean; CV= coefficient of variation; DAS= Days after spraying; figures inside bracket() are obtained after transforming via log transformation

Table 3. Effect of different chemical pesticides on number of tunnels per infested leaf

Treatment	No. of tunnels per infested leaf					
	1st spray			2nd spray		
	3DAS	7DAS	14DAS	3DAS	7DAS	14DAS
Chlorantraniliprole	1.53	1.34^{ab}	1.37^{ab}	1.05^{bc}(0.31)	0.90^{b}(0.28)	1.01^{c}(0.30)
Azadirachtin	1.34	1.31^{ab}	1.34^{ab}	1.11^{b}(0.32)	1.05^{b}(0.31)	1.12^{b}(0.33)
Control	1.26	1.50^{a}	1.45^{a}	1.55^{a}(0.41)	1.58^{a}(0.41)	1.63^{a}(0.42)
EBI	1.17	1.05^{bc}	1.13^{abc}	0.85^{bcd}(0.27)	0.58^{c}(0.20)	0.94^{d}(0.29)
CS	1.50	0.91^{c}	1.01^{bc}	0.72^{cde}(0.23)	0.36^{d}(0.13)	0.90^{e}(0.28)
Spinetoram	1.52	1.05^{bc}	1.10^{abc}	0.65^{de}(0.21)	0.28^{d}(0.11)	0.63^{f}(0.21)
CT	1.37	1.06^{bc}	0.91^{c}	0.42^{e}(0.15)	0.20^{d}(0.08)	0.41^{g}(0.15)
LSD	0.56	0.27	0.34	0.08	0.06	0.01
SE$_{m}$(±)	0.18	0.09	0.11	0.03	0.02	3.27e-3
F-probability	NS	4.88e-03**	0.03*	1.77e-04***	4.91e-08***	1.76e-14***
CV%	22.80	12.95	15.97	16.24	14.35	2.00
Grand Mean	1.38	1.17	1.18	0.91(0.27)	0.71(0.22)	0.95(0.28)

Note: EBI: Emamectin Benzoate + Indoxacarb; CS: Chlorfenapyr + Spinosad ; CT: Chlorfenapyr +Tolfenpyrad; Means in the column with same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance based on DMRT; "***" = significant at p-value <0.001; "**" = significant at p-value<0.01; "*" = significant at p-value<0.05; LSD= Least significant difference; SE$_{m}$= Standard error of mean; CV= coefficient of variation; DAS= Days after spraying; figures inside bracket() are obtained after transforming via log transformation; NS= Non Significant

Similar trends were observed at subsequent intervals. At 14 days after the second chemical spraying, the maximum percentage of infested leaves was recorded in the control (19.40%). The minimum percentage of infested leaves was observed in the mixture of chlorfenapyr and tolfenpyrad (11.26%), which was statistically at par with spinetoram (11.36%).

The mixture of chlorfenapyr and tolfenpyrad was effective in reducing the percentage of infested leaves by targeting larval activity. This combination affects the pest's nervous system, thereby reducing feeding and tunneling. Taha et al. (2017) reported chlorfenapyr's effectiveness in reducing leaf damage, while Priyanka et al. (2024) highlighted tolfenpyrad's outstanding performance against *Tuta absoluta.* The analysis showed that all chemical treatments significantly reduced leaf infestation compared to the control. The most effective were chlorfenapyr + tolfenpyrad (11.26%) and spinetoram (11.36%), with similarly low infestation levels at 14 DAS. Moderate reductions were observed with chlorfenapyr + spinosad (14.80%) and emamectin benzoate + indoxacarb (15.81%), likely due to their neurotoxic effects, though less systemic than tolfenpyrad based treatments. The combination of chlorfenapyr and tolfenpyrad effectively reduced the percentage of infested leaves at 3 days after the first spray (3 DAS); however, this effect was not sustained up to 14 DAS. Chlorantraniliprole (16.22%) and azadirachtin (16.76%) were less effective, possibly due to their reduced field persistence and slower modes of action. These results align with Chouikhi et al. (2022) and Biondi et al. (2018), who noted similar limitations in open-field conditions.

Effect of Different Chemical Pesticides on Number of Tunnels per Infested Leaf

The statistical analysis demonstrated significant differences in the number of tunnels per infested leaf among treatments (Table 3). At 7 days after the first chemical spraying, the maximum number of tunnels per infested leaf was observed in the control (1.50), which was statistically at par with chlorantraniliprole (1.34) and azadirachtin (1.31). The minimum number of tunnels per infested leaf was observed in the mixture of chlorfenapyr and spinosad (0.91), which was statistically similar to spinetoram (1.05), the mixture of emamectin benzoate and indoxacarb (1.05), and the mixture of chlorfenapyr and tolfenpyrad (1.06).

At 14 days after the second chemical spraying, the maximum number of tunnels per infested leaf was recorded in the control (1.63). The minimum number of tunnels per infested leaf was observed in the mixture of chlorfenapyr and tolfenpyrad (0.41).

The combination of chlorfenapyr and tolfenpyrad reduced tunneling by affecting the larval feeding mechanism and reducing their activity. Chouikhi et al. (2022) reported that tolfenpyrad significantly reduced tunneling by disrupting the larval feeding process. This reduction in tunneling highlights the potential of this chemical mixture to minimize leaf damage and improve tomato productivity. Tunnel formation was significantly lower in chlorfenapyr + tolfenpyrad (0.41) and spinetoram (0.63), both of which inhibit feeding and cause rapid larval mortality. Chlorfenapyr + spinosad (0.90) and emamectin benzoate + indoxacarb (0.94) also limited tunneling, albeit less effectively. Chlorantraniliprole (1.01) and azadirachtin (1.12) showed the highest tunnel counts among treated plots, indicating less suppression of larval feeding behavior. The control had the most tunnels (1.63), showing the extent of unchecked infestation.

Effect of Different Chemical Pesticides on the Number of Tunnels per Infested Leaf

The statistical analysis indicated a significant effect of different chemical pesticides on the number of tunnels per infested leaf (Table 4). However, 3 days after the first chemical spraying, treatment showed no significant difference.

7 Days After First Chemical Spraying: The maximum number of tunnels per infested leaf was observed in the control (1.50), which was statistically at par with chlorantraniliprole (1.34) and azadirachtin (1.31). The minimum number of tunnels was recorded in the mixture of chlorfenapyr and spinosad (0.91), which was statistically similar to spinetoram (1.05), the mixture of emamectin benzoate and indoxacarb (1.05), and the mixture of chlorfenapyr and tolfenpyrad (1.06).

14 Days After First Chemical Spraying: The maximum number of tunnels per leaf was recorded in the control (1.45), statistically at par with chlorantraniliprole (1.37) and azadirachtin (1.34). The minimum number of tunnels was observed in the mixture of chlorfenapyr and tolfenpyrad (0.91), which was statistically similar to the mixture of chlorfenapyr and spinosad (1.01), spinetoram (1.10), and the mixture of emamectin benzoate and indoxacarb (1.13).

3 Days After Second Chemical Spraying: The maximum number of tunnels per leaf was recorded in the control (1.55), while the minimum was observed in the mixture of chlorfenapyr and tolfenpyrad (0.42), statistically at par with spinetoram (0.65) and the mixture of chlorfenapyr and spinosad (0.72).

7 Days After Second Chemical Spraying: The control exhibited the highest number of tunnels per leaf (1.58), while the mixture of chlorfenapyr and tolfenpyrad recorded the lowest (0.20), statistically similar to spinetoram (0.28) and the mixture of chlorfenapyr and spinosad (0.36).

14 Days After Second Chemical Spraying: The control again recorded the highest number of tunnels per leaf (1.63), while the lowest was observed in the mixture of chlorfenapyr and tolfenpyrad (0.41).

The reduction in tunneling observed with the mixture of chlorfenapyr and tolfenpyrad can be attributed to its dual mode of action, which affects the larvae's nervous system, reducing their feeding activity. The absorbed chemical acts on leaf tissues, poisoning larvae upon ingestion, thereby reducing tunneling. Previous studies have shown the superior efficacy of tolfenpyrad in minimizing tunneling damage(Chouikii et al., 2022). Similar to leaf tunneling, the least number of fruit tunnels occurred in chlorfenapyr + tolfenpyrad (0.22) and spinetoram (0.23), likely due to their ingestion-based action and systemic absorption. Moderate reduction was observed in chlorfenapyr + spinosad (0.52) and emamectin benzoate + indoxacarb (0.63). Chlorantraniliprole (0.88) and azadirachtin (1.05) were again less effective, perhaps due to poor residual control on fruit surfaces.

Table 4. Effect of different chemical pesticides on percentage of infested fruits

Treatment	Percentage of infested fruits					
	1st spray			2nd spray		
	3DAS	7DAS	14DAS	3DAS	7DAS	14DAS
Chlorantraniliprole	11.88^{b}	9.36^{b}	9.88^{b}(0.99)	7.45^{b}(0.87)	4.88^{bc}(0.76)	6.53^{bc}(0.87)
Azadirachtin	11.62^{b}	9.95^{b}	10.11^{b}(0.99)	8.56^{b}(0.92)	6.33^{b}(0.84)	7.65^{b}(0.91)
Control	14.39^{a}	15.01^{a}	15.86^{a}(1.20)	16.66^{a}(1.22)	16.69^{a}(1.25)	16.75^{a}(1.25)
EBI	12.37^{b}	8.55^{b}	8.80^{b}(0.94)	7.13^{b}(0.85)	4.26^{bc}(0.72)	4.75^{cd}(0.76)
CS	11.81^{b}	7.99^{b}	8.04^{b}(0.90)	5.99^{b}(0.77)	3.31^{c}(0.62)	4.2367^{d}(0.71)
Spinetoram	11.90^{b}	7.37^{bc}	6.08^{c}(0.78)	2.40^{c}(0.37)	0.21^{d}(0.07)	1.03^{e}(0.31)
CT	9.57^{c}	5.38^{c}	4.54^{d}(0.66)	1.38^{d}(0.13)	0.02^{d}(0.01)	0.94^{e}(0.29)
LSD	1.82	2.39	0.10	0.18	0.19	0.14
SE_m(±)	0.59	0.78	0.03	0.06	0.06	0.04
F-probability	5.23e-03 **	5.99e-05***	2.39e-06***	3.59e-07***	7.39e-08***	2.858e-08***
CV%	8.56	14.78	6.19	13.93	17.36	10.44
Grand Mean	11.94	9.09	9.04(0.92)	7.08(0.73)	5.10(0.60)	5.99(0.73)

Note: EBI: Emamectin Benzoate + Indoxacarb; CS: Chlorfenapyr + Spinosad ; CT: Chlorfenapyr +Tolfenpyrad; Means in the column with same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance based on DMRT; "***" = significant at p-value <0.001; "**" = significant at p-value<0.01; "*" = significant at p-value<0.05; LSD= Least significant difference; SE_m= Standard error of mean; CV= coefficient of variation; DAS= Days after spraying; figures inside bracket() are obtained after transforming via log transformation

Table 5. Effect of different chemical pesticides on number of tunnels per infested fruit

Treatment	No. of tunnels per infested fruit					
	1st spray			2nd spray		
	3DAS	7DAS	14DAS	3DAS	7DAS	14DAS
Chlorantraniliprole	1.32	1.17^{c}	1.28^{c}	0.99^{c}(0.30)	0.67^{c}(0.22)	0.88^{c}(0.27)
Azadirachtin	1.32	1.23^{b}	1.35^{b}	1.55^{b}(0.33)	0.92^{b}(0.28)	1.05^{b}(0.31)
Control	1.31	1.32^{a}	1.46^{a}	1.56^{a}(0.41)	1.53^{a}(0.40)	1.52^{a}(0.40)
Control	1.41	1.08^{d}	1.16^{d}	0.85^{d}(0.26)	0.52^{d}(0.18)	0.63^{d}(0.21)
EBI	1.48	1.09^{d}	1.17^{d}	0.83^{d}(0.27)	0.47^{d}(0.17)	0.52^{e}(0.18)
CS	1.30	1.03^{e}	1.03^{e}	0.64^{e}(0.22)	0.14^{e}(0.06)	0.23^{f}(0.09)
Spinetoram	1.18	0.93^{f}	0.98^{e}	0.60^{f}(0.20)	0.16^{e}(0.06)	0.22^{f}(0.09)
LSD	0.20	0.04	0.07	0.01	0.02	0.01
SE_{m}(±)	0.07	0.01	0.02	3.30e-03	0.01	4.58e-03
F-probability	NS	8.01e-10***	1.81e-08***	1.83e-13***	8.18e-13***	2.52e-14***
CV%	8.43	1.90	3.06	2.01	5.69	3.57
Grand Mean	1.33	1.12	1.20	0.94(0.28)	0.63(0.20)	0.72(0.22)

Note: EBI: Emamectin Benzoate + Indoxacarb; CS: Chlorfenapyr + Spinosad ; CT: Chlorfenapyr +Tolfenpyrad; Means in the column with same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance based on DMRT; "***" = significant at p-value <0.001; "**" = significant at p-value<0.01; "*" = significant at p-value<0.05; LSD= Least significant difference; SE_{m}= Standard error of mean; CV= coefficient of variation; DAS= Days after spraying; figures inside bracket() are obtained after transforming via log transformation; NS= Non Significant

Effect of Different Chemical Pesticides on Percentage of Infested Fruits

Statistical analysis revealed a significant effect of different chemical pesticides on the percentage of infested fruits (Table 5).

3 Days After First Chemical Spraying: The control showed the highest percentage of infested fruits (14.39%). The lowest percentage was recorded in the mixture of chlorfenapyr and tolfenpyrad (9.57%).

7 Days After First Chemical Spraying: The control exhibited the maximum percentage of infested fruits (15.01%). The minimum percentage was observed in the mixture of chlorfenapyr and tolfenpyrad (5.38%), which was statistically at par with spinetoram (7.37%).

14 Days After First Chemical Spraying: The control had the highest percentage of infested fruits (15.86%), while the mixture of chlorfenapyr and tolfenpyrad recorded the lowest (4.54%).

3 Days After Second Chemical Spraying: The maximum percentage of infested fruits was recorded in the control (16.66%), while the mixture of chlorfenapyr and tolfenpyrad showed the lowest percentage (1.38%).\

7 Days After Second Chemical Spraying: The control exhibited the highest percentage of infested fruits (16.69%), whereas the lowest percentage was observed in the mixture of chlorfenapyr and tolfenpyrad (0.02%), statistically similar to spinetoram (0.21%).

14 Days After Second Chemical Spraying: The control again showed the highest percentage of infested fruits (16.75%), while the mixture of chlorfenapyr and tolfenpyrad had the lowest (0.94%), statistically similar to spinetoram (1.03%).

Chlorfenapyr + tolfenpyrad (0.94%) and spinetoram (1.03%) were the most effective in reducing fruit infestation, significantly outperforming the control (16.75%). Chlorfenapyr + spinosad (4.24%) and emamectin benzoate + indoxacarb (4.75%) showed moderate effectiveness, likely due to their neurotoxic action. Chlorantraniliprole (6.53%) and azadirachtin (7.65%) were less effective, possibly because of their slower action and reduced stability under field conditions. The reduction in fruit infestation percentage with the mixture of chlorfenapyr and tolfenpyrad is attributed to its efficacy in reducing the larval population. Chlorfenapyr's role in reducing fruit damage has been well-documented (Santos et al., 2017), and tolfenpyrad has demonstrated outstanding performance against lepidopteran pests (Priyanka et al., 2024).

Effect of Different Chemical Pesticides on Number of Tunnels per Infested Fruit

The statistical analysis revealed that different chemical pesticides had a significant effect on the number of tunnels per infested fruit (Table 6). However, at 3 days after the first chemical spraying, no significant differences among treatments were observed.

7 Days After First Chemical Spraying: The maximum number of tunnels per infested fruit was observed in the control (1.32). The minimum was recorded in the mixture of chlorfenapyr and tolfenpyrad (0.93).

14 Days After First Chemical Spraying: The control exhibited the highest number of tunnels per infested fruit (1.46), while the lowest was observed in the mixture of chlorfenapyr and tolfenpyrad (0.98), statistically at par with spinetoram (1.03).

3 Days After Second Chemical Spraying: The control recorded the highest number of tunnels per infested fruit (1.56). The lowest number was observed in the mixture of chlorfenapyr and tolfenpyrad (0.60).

7 Days After Second Chemical Spraying: The maximum number of tunnels per infested fruit was observed in the control (1.53). The lowest was recorded in spinetoram (0.14), statistically at par with the mixture of chlorfenapyr and tolfenpyrad (0.16).

14 Days After Second Chemical Spraying: The control again recorded the maximum number of tunnels per infested fruit (1.52). The minimum number was observed in the mixture of chlorfenapyr and tolfenpyrad (0.22), statistically at par with spinetoram (0.23).

The reduction in tunneling observed with the mixture of chlorfenapyr and tolfenpyrad can be attributed to its ability to reduce larval feeding activity by affecting their nervous system. The chemical is absorbed by the plant, affecting all tissues, including the fruit. Larvae feeding on treated fruits are poisoned, reducing their feeding rate and subsequent tunneling. Tolfenpyrad has demonstrated superior efficacy in reducing larval damage of lepidopteran pests in various crops. Tunnel numbers followed the same trend. The lowest was found in chlorfenapyr + tolfenpyrad (0.22) and spinetoram (0.23), demonstrating strong larval suppression. Moderate results were seen with chlorfenapyr + spinosad (0.52) and emamectin benzoate + indoxacarb (0.63). Chlorantraniliprole (0.88) and azadirachtin (1.05) were the least effective. The control (1.52) again showed the most damage, consistent with earlier parameters.

Effect of Different Chemical Pesticides on Percentage of Yield Loss

The statistical analysis revealed that different chemical pesticides had a significant effect on percentage of yield loss (Table 6).

After harvesting all fruits, the control exhibited the maximum percentage of yield loss (16.81%). The minimum percentage of yield loss was observed in the mixture of chlorfenapyr and tolfenpyrad (2.70%), statistically at par with spinetoram (3.35%).

The ability of chlorfenapyr and tolfenpyrad to reduce larval population and mining damage on leaves and fruits contributed to the reduced yield loss. Effective control of *Tuta absoluta* during the vegetative phase minimized leaf area index loss, ensuring proper photosynthesis and nutrient accumulation. By preventing damage up to harvest, the number of damaged fruits was significantly reduced, thereby preserving yield. The greatest yield protection was achieved with chlorfenapyr + tolfenpyrad (2.70%) and spinetoram (3.35%). Chlorfenapyr + spinosad (5.70%) and emamectin benzoate + indoxacarb (7.26%) were moderately effective. Chlorantraniliprole (10.51%) and azadirachtin (12.93%) led to higher yield losses, reflecting limited pest control. The control showed the highest loss (16.81%), highlighting the economic impact of unmanaged *Tuta absoluta* infestations.

Table 6. Effect of different chemical pesticides on percentage of yield loss

Treatments	Percentage Loss in Yield
Chlorantraniliprole	10.51^{c}
Azadirachtin	12.93^{b}
Control	16.81^{a}
Emamectin Benzoate + Indoxacarb	7.26^{d}
Chlorfenapyr + Spinosad	5.70^{d}
Spinetoram	3.35^{e}
Chlorfenapyr +Tolfenpyrad	2.70^{e}
LSD	1.78
$SE_m(\pm)$	0.58
F-probability	5.17e-09***
CV%	11.81
Grand Mean	8.47

Note: Means in the column with same letter (s) in superscript indicate no significant difference between treatments at 0.05 level of significance based on DMRT; “***” = significant at p-value <0.001; “**” = significant at p-value<0.01; “*” = significant at p-value<0.05; LSD= Least significant difference; SE_m= Standard error of mean; CV= coefficient of variation; DAS= Days after spraying

Conclusion

The study reveals the significant impact of different chemical pesticides on the management of *Tuta absoluta* in tomato (*Solanum lycopersicum var.* Kabita) under field conditions. Among the tested pesticides, spinetoram and the combination of chlorfenapyr and tolfenpyrad consistently demonstrated superior efficacy in reducing pest infestation across various parameters, including the percentage of infested leaves and fruits, number of tunnels per infested leaf and fruit, and larval population. The control plot exhibited the highest pest infestation and yield loss, while the mixture of chlorfenapyr and tolfenpyrad and spinetoram showed the lowest yield loss percentages (2.70% and 3.10%, respectively), indicating their effectiveness in mitigating pest damage. chlorantraniliprole and azadirachtin were relatively less effective, ranking between spinetoram and the untreated control. These findings suggest that spinetoram and the chlorfenapyr-tolfenpyrad combination are promising alternatives for controlling *Tuta absoluta* in tomatoes. Their ability to minimize yield losses while effectively reducing pest populations highlights their potential for integration into pest management strategies. Further research focusing on their economic feasibility and environmental safety is recommended to optimize their use in sustainable tomato production systems.

Recommendation for Future Research

This study assessed the efficacy of various chemical pesticides in controlling *Tuta absoluta* under open field conditions in a specific location. However, it was limited to a single agroecological zone, which restricts the generalization of findings to other regions with different climatic and environmental conditions. The research emphasized chemical control methods, neglecting the integration of biological, cultural, and physical control measures. The study also did not account for the long-term effects of repeated pesticide applications, such as the potential development of resistance in *Tuta absoluta*. Furthermore, pesticide use’s environmental and health implications, including impacts on non-target organisms, were not evaluated.

Future studies should explore the efficacy of these pesticides across diverse agroecological zones and seasons to enhance the applicability of results. Integrated Pest Management (IPM) strategies combining chemical, biological, cultural, and physical control methods should be investigated to develop sustainable solutions. Monitoring the development of pesticide resistance in *Tuta absoluta* through molecular studies is crucial for effective pest management. Additionally, evaluating pesticides' environmental and health impacts, particularly on non-target organisms, is essential. Economic analysis of IPM practices could further support their adoption by demonstrating cost-effectiveness for farmers, ensuring both productivity and environmental sustainability.

Declarations

Author Contribution Statement

Performed and designed the experiments;

Asim Bastola: Experimental setup; Data collection; Analyzed and interpreted the data; Literature review; Wrote the paper, Proofreading, Revision.

Bikash Kandel: Assist on design of experiment, Data collection; Analyzed and interpreted the data;Literature review; Wrote the paper; Proofreading.

Suraksha Neupane: Data collection; Analyzed and interpreted the data; Literature review; Wrote the paper; Proofreading.

Aayush Pokhrel: Data collection; Analyzed and interpreted the data; Literature review; Wrote the paper; Proofreading.

Sagar Pandey: R&D Head of Muktinath Krishi Company Limited, Management of the research Field and necessary equipment (Fertilizers/Insecticides Used in Experiments).

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Declaration of Competing Interest

The authors declare no conflict of interest.

Ethical Approval

This study did not involve human or animal subjects. Field experiments were conducted with the permission of the landowner, and all applicable guidelines for the Ethical Approval

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