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Biochemical changes associated with foliar application of some compounds for controlling *Tuta absoluta* (Lepidoptera: Gelechiidae) on tomato plants under greenhouse and field conditions

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Abstract

Solanaceous plants are of great economic importance in Egypt, with crops like potatoes, tomatoes and eggplants playing vital roles in the agricultural sector. The emergence of the invasive pest *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) presents a major challenge to tomato cultivation. During the 2024 season, the effectiveness of various compounds against *T. absoluta* larvae on tomato plants in greenhouse and open field was tested. The highest reductions in insect populations were observed with emamectin benzoate. Following this, other insecticides like metaflumizone, thiocyclan hydrogen oxalate and indoxacarb also showed significant efficacy in reducing *T. absoluta*. On the other hand, *Bacillus thuringiensis* showed the most effective reductions in insect populations. Interestingly, in the study, there were no significant differences observed between the tested compounds except for a notable distinction between *B. thuringiensis* and emamectin benzoate ($p \leq 0.05$). Significant variations in chlorophyll content were observed based on the application of different compounds. Particularly, treatments involving thiocyclan hydrogen oxalate and *B. thuringiensis* resulted in a notable increase in chlorophyll levels. In contrast, the application of emamectin benzoate, indoxacarb and the control showed the lowest chlorophyll content levels. Over a 10-day period some of these compounds led to a significant decrease in non-enzymatic components in tomato plants compared to the control. Particularly noteworthy were the significant reductions observed in all non-enzymatic components in leaves treated with thiocyclan hydrogen oxalate. All the compounds tested had an impact on antioxidant enzymes with significant variations observed among the different treatments. Specifically, the application of emamectin benzoate resulted in an increase in enzymatic activity particularly in catalase, peroxidase and superoxide dismutase, notably 10 days after application. The application of thiocyclan hydrogen on tomato plants resulted in a decrease in the activities of antioxidant enzymes. Furthermore, both *B. thuringiensis* and cyromazine impacted the activity of the peroxidase enzyme, with significant differences noted between them. Overall, there were significant variations in the activities of all antioxidant enzymes among the different treatments ($p \leq 0.05$).

Introduction

Tomato (*Lycopersicon esculentum* L.) is a significant vegetable crop cultivated in Egypt. According to FAOSTAT (2017), the average yield of tomatoes in Egypt is 40 tons per hectare. However, throughout the growth season of tomato plants, various insect pests pose a threat, affecting the crop from seed emergence to fruit harvesting. The tomato leaf miner, *Tuta absoluta* (Meyrick) and belonging to the order Lepidoptera family Gelechiidae, is a significant pest that poses a threat to tomato plants. The larvae of *T. absoluta* can infest various parts of the tomato plant, including the leaves, flowers, stems, and fruits, leading to significant losses in tomato production (Mollá *et al.*, 2011). In Egypt, the potential yield loss due to *T. absoluta* infestations can reach up to 100% in certain locations if appropriate control measures are not implemented (CABI, 2019). The primary method of controlling *T. absoluta* involves the application of chemical insecticides, traditional or unconventional. These insecticides are crucial in managing *T. absoluta* infestations, offering around 95% control within 14-21 days after treatment (DAT). Both the eggs and larvae of *T. absoluta* have shown significant reductions, with recommendations for repeated applications (CABI, 2019). Recent classes of insecticides and bioinsecticides have provided effective control of this pest, including compounds such as abamectin, indoxacarb, chlorantraniliprole, spinosad, insect growth regulators, and emamectin benzoate (El-Fakharany, 2017; Guedes *et al.*, 2019; Kandil *et al.*, 2020 and Erol *et al.*, 2021). The agricultural pesticides interact with the plant system and affect the physiological and biochemical activities of the plants (Homayoonzadeh *et al.*, 2020; El-Fakharany *et al.*, 2024 and Sadek *et al.*, 2024). It was observed that foliar application of insecticides resulted in reducing or increasing the non-enzymatic components

(total protein content, carbohydrates, fats, total phenols, and total lipid) and enzymes (catalase, peroxidase, and polyphenol oxidase) activity (Homayoonzadeh *et al.*, 2020; Kandil *et al.*, 2020 and El-Fakharany *et al.*, 2024).

Consequently, the objective of the present study is to evaluate various insecticides from different groups under greenhouse and field conditions on *T. absoluta* larvae. Additionally, the study aims to assess the effectiveness of these insecticides in reducing insect infestation by analyzing the enzymatic and non-enzymatic antioxidants in tomato plants.

Materials and methods

1. Control measures in greenhouse and open field environments:

This study was carried out at the experimental farm and greenhouse of the Sakha Agricultural Research Station during the 2024 season. The (Zero 23) tomato variety was sown in March in both localities. The land was partitioned into 28 plots (Six compounds plus a control, each with four replicates), following a randomized complete design. The specified compounds were administered in the area in the final week of May, coinciding with the tomato season. The tomato plants underwent weekly inspections starting 15 days post-transplantation. All farming activities were diligently executed throughout the entire season, with no pesticide applications prior to the control being implemented. A Knapsack sprayer with a capacity of 25 liters was utilized to administer the experimental compounds.

2. Tested compounds:

The commercial formulations of various pesticides were employed in this study to combat *Tuta absoluta* under greenhouse and field conditions. The specific formulations and application rates utilized were as follows: *Bacillus thuringiensis* (Ageri 50% WG, Abbot Laboratories Chemical and Agricultural Products Division) at a rate of

250 g/100L.Thiocyclan hydrogen oxalate (Tepiocelam 50% SP, Jiangsu Tianrong Group Co. Ltd China) at a rate of 175 g/100L.Cyromazine (Trigard 75% WP, Syngenta) at a rate of 50g/100L.Emamectin benzoate (Affirm 5% SG, Syngenta) at a rate of 60g/100L. Indoxacarb (Endoprime 30% WG, Mafco for Agriculture) at a rate of 15g/100L. Metaflumizone, (Alverde 24%SC, BASF Agricultural Solutions) at a rate of 100 ml/100L.

The concentrations applied were in accordance with the recommendations provided by the Egyptian Ministry of Agriculture for each pesticide, tailored to effectively manage *T. absoluta* infestations.

3. The determination of enzyme activity and biochemical components in tomato:

3.1. Assessment of chlorophyll content:

In the study conducted during the 2024 season, samples were collected from leaves treated with the trial chemical control. The chlorophyll content of the tomato leaves was assessed using a portable leaf chlorophyll meter, specifically a Minolta device, with measurements recorded in SPAD units. This evaluation followed the methodology outlined by **Marquard and Tipton (1987)**. The chlorophyll content analysis was carried out on the recently fully expanded leaves of the tomato plants at three specific time points-five, seven, and ten days after the application of the chemical control treatment.

3.2. Comprehensive analysis of nonenzymatic components and antioxidant enzymes:

Ten days after the treatment application, freshly matured tomato leaves were randomly sampled from each replicate within the greenhouse and field settings. The methodology employed aimed to offer a comprehensive insight into the biochemical responses of the tomato plants following the treatment. Fresh tomato leaves (1 gram each) were homogenized in liquid nitrogen with a solution containing 0.05 M EDTA and 1 PVP

at 4°C. The homogenized samples were subsequently centrifuged at 4°C at 5000 xg, following the methodology outlined by Lowry *et al.* (1951). The supernatant obtained after centrifugation was then used for subsequent analyses. This supernatant was employed for the determination of non-enzymatic components such as total carbohydrates, protein content, total phenols, and lipids. Antioxidant enzyme activities, such as catalase, peroxidase, and polyphenol oxidase, were evaluated using specific methodologies detailed in the literature. Catalase activity was determined in accordance with the protocol established by Aebi (1984). The assessment of peroxidase activity followed the techniques described by Polle *et al.* (1994). Superoxide dismutase activity was measured following the guidelines provided by Zhou *et al.* (2007). Protein content was quantified utilizing the A.O.A.C. (1990) methodology. Total carbohydrate levels were quantified utilizing the phenol-sulfuric acid method as elucidated by Dubois *et al.* (1956) and were expressed as a percentage. The determination of total phenols was conducted employing the Folin-Ciocalteu reagent method outlined by Diaz and Martin (1972), while lipid content was assessed following the procedure described by Bates (1973). An analysis for non-enzymatic components and antioxidant enzymes was carried out at the Laboratory of the Pesticides Chemistry and Toxicology Department, located within the Faculty of Agriculture at Damanhur University.

4.Statistical analysis of treatment effects:

ANOVA, Duncan's Multiple Range Test, developed by Duncan (1955), was utilized to perform post-hoc comparisons between the means of treatments. This test helps identify specific treatments that exhibit significant differences. It was using the SPSS statistical software package version 16.0, developed by SPSS (2016) Inc. in Chicago, IL, USA.

Results and discussion

1. Comparative assessment of insecticide efficacy in reducing pest populations under greenhouse and open field conditions:

In Table (1), the efficiency of tested compounds against *T. absoluta* larvae on tomato plants during the 2024 season is presented. The highest insect reductions were observed with emamectin benzoate, with an initial effect of $92.76\% \pm 1.14$ and an overall average of $92.85\% \pm 1.70$ in greenhouse conditions. In open field settings, emamectin benzoate also showed high efficacy with an initial effect of $92.06\% \pm 2.85$ and an overall average of $93.58\% \pm 2.30$. The highest efficacy of different insecticides, specifically metaflumizone, thiocyclan hydrogen oxalate and indoxacarb in reducing *T. absoluta*

infestations on tomato plants across various environments, including greenhouses and open fields. This suggests the effectiveness of these insecticides in managing *T. absoluta* populations. On the other hand, *Bacillus thuringiensis* exhibited the best insect reductions, with $75.48\% \pm 2.88$ at the initial effect and $84.94\% \pm 2.29$ as the overall average in greenhouse conditions. In open field trials, *B. thuringiensis* showed even the best efficacy, with an initial effect of $69.53\% \pm 2.29$ and an overall average of $86.01\% \pm 2.30$. Almost all in the study, there were no significant differences between the compounds with the exception of a significant observed between *B. thuringiensis* and emamectin benzoate ($p \leq 0.05$) as outlined in Table (1).

Table (1): Evaluation of compound efficacy in controlling *Tuta absoluta* on tomato plants in the 2024 season at Sakha Agricultural Research Station farm in Kafr El-Sheikh Governorate.

Compound	Used* conc. [mg a.i.l ⁻¹]	Mean % reduction± SE			
		5 days (initial effect)	7 days	10 days	Overall Average
Greenhouse					
<i>Bacillus thuringeinesis</i>	1250	75.48 ^b ±2.88	92.74 ^{ab} ±2.29	86.59 ^{abc} ±2.89	84.94 ^b ±2.29
Thiocyclan hydrogen oxalate	875	93.49 ^a ±2.30	97.11 ^a ±1.09	83.99 ^{bc} ±1.73	91.53 ^{ab} ±2.29
Cyromazine	376	91.46 ^a ±1.13	89.88 ^b ±1.72	88.32 ^{abc} ±0.39	89.89 ^{ab} ±2.3
Emamectin benzoate	30	92.76 ^a ±1.14	95.71 ^{ab} ±1.72	90.09 ^{ab} ±2.89	92.85 ^a ±1.70
Indoxacarb	45	90.89 ^a ±0.55	91.90 ^{ab} ±2.31	81.32 ^c ±2.12	88.04 ^{ab} ±2.8
Metaflumizone	240	91.70 ^a ±0.40	89.67 ^b ±2.30	93.19 ^a ±1.62	91.52 ^{ab} ±1.7
F	-	16.87	2.41	4.04	1.69
p-value	-	**	NS	*	NS
Open field					
<i>Bacillus thuringeinesis</i>	1250	69.53 ^b ±2.29	94.62 ^a ±2.30	93.88 ^a ±1.73	86.01 ^b ±2.30
Thiocyclan hydrogen oxalate	875	86.51 ^a ±2.88	95.43 ^a ±0.91	86.99 ^a ±2.89	89.64 ^{ab} ±1.13
Cyromazine	376	85.26 ^a ±1.58	94.65 ^a ±2.29	89.85 ^a ±1.70	89.92 ^{ab} ±2.3
Emamectin benzoate	30	92.06 ^a ±2.85	96.64 ^a ±1.71	92.03 ^a ±2.29	93.58 ^a ±2.30
Indoxacarb	45	89.84 ^a ±2.29	95.70 ^a ±2.19	86.40 ^a ±2.08	90.65 ^{ab} ±1.1
Metafumizone	240	87.75 ^a ±1.13	93.77 ^a ±2.30	94.10 ^a ±2.83	91.87 ^{ab} ±1.7
F	-	12.61	0.25	2.12	0.18
p-value	-	**	NS	NS	NS

In the column, groups labeled with the same letter are not significantly different at the 5% level according to Duncan's Multiple Range Test (DMRT) from 1955.

** denotes highly significant results ($p \leq 0.01$); * denotes significant results ($p \leq 0.05$).

Emamectin benzoate demonstrated remarkable effectiveness in reducing *T. absoluta* in our study, a result that resonates with the findings of Abd El-Hady *et al.* (2013). Our

research reaffirms the superior performance of microbial control agents in managing *T. absoluta*, aligning with the conclusions drawn by Abd El-Hady *et al.* (2013) and Abd El-Ghany *et al.*

(2016). The utilization of these agents showcases a promising and environmentally friendly approach to pest control. El-Fakharany (2017), Guedes *et al.* (2019) and Kandil *et al.* (2020) highlighted the efficacy of chlorfenapyr, indoxacarb, spinetoram, abamectin, especially emamectin benzoate, IGR and chlorantraniliprole in integrated pest management (IPM) strategies against *T. absoluta*. This suggests a diverse arsenal of insecticides that can be successfully integrated into IPM tactics for effective pest management.

2. The impact of the tested compounds on biochemical components and enzyme activity:

2.1. The effect of tested compounds on chlorophyll content in tomato leaf:

Chlorophyll molecules are essential for capturing carbon dioxide (CO₂) from the atmosphere during photosynthesis. They serve as photoreceptors, facilitating the absorption of solar energy and the synthesis of organic substances within plants. In a recent study, the chlorophyll content in tomato leaves was examined following treatment with various compounds over different time periods. The

results, detailed in Table (2), displayed noteworthy variations in chlorophyll content based on the application of different compounds. Notably, treatment with thiocyclan hydrogen oxalate and *B. thuringeinesis* led to a substantial increase in chlorophyll levels. Conversely, the application of emamectin benzoate, indoxacarb and the control, exhibited the lowest chlorophyll content in the greenhouse. In the open field, the indoxacarb treatment and control also displayed decreased chlorophyll levels. The remaining compounds tested showcased moderate effects on chlorophyll content within tomato leaves.

In another study, Mishra *et al.* (2008) demonstrated that the reduction in chlorophyll content could be attributed to the inhibition of pigment breakdown or biosynthesis, or possibly the suppression of their precursors, as observed in cowpea seedlings under stress induced by the compound dimethoate. It was noted that all the compounds tested had an impact on chlorophyll content, leading to either an increase or decrease in levels. This finding aligns with the research of Seth *et al.* (2014), El-Fakharany (2016), Bughdady *et al.* (2020), El-Fakharany *et al.* (2024) and Sadek *et al.* (2024).

Table (2): The impact of the tested compounds on the chlorophyll content in tomato leaves.

Compound	Means $\pm$ SE of chlorophyll content (SPAD) unit effect after indicated days			
	5	7	10	Overall average
Greenhouse				
<i>Bacillus thuringeinesis</i>	54.45 ^{ab} $\pm$ 2.19	59.3 ^{ab} $\pm$ 0.98	47.27 ^{ab} $\pm$ 2.77	54.45 ^{ab} $\pm$ 2.37
Thiocyclan hydrogen oxalate	56.40 ^a $\pm$ 1.5	57.33 ^{ab} $\pm$ 2.12	52.7 ^a $\pm$ 1.13	56.40 ^a $\pm$ 2.66
Cyromazine	50.07 ^{bc} $\pm$ 1.11	50.55 ^c $\pm$ 2.34	49.97 ^{ab} $\pm$ 3.45	50.07 ^{bc} $\pm$ 2.31
Emamectin benzoate	42.57 ^d $\pm$ 1.17	60.6 ^a $\pm$ 2.71	44.07 ^b $\pm$ 0.54	42.57 ^d $\pm$ 1.14
Indoxacarb	44.77 ^{cd} $\pm$ 1.72	44.3 ^d $\pm$ 2.14	36.37 ^c $\pm$ 0.56	44.77 ^{cd} $\pm$ 1.15
Metafumizone	47.57 ^{cd} $\pm$ 2.88	56.67 ^{abc} $\pm$ 1.14	52.17 ^a $\pm$ 1.06	47.57 ^{cd} $\pm$ 1.14
Control	47.63 ^{cd} $\pm$ 1.14	53.6 ^{bc} $\pm$ 1.65	44.37 ^b $\pm$ 1.67	47.63 ^{cd} $\pm$ 1.14
F	7.82	8.40	9.01	7.47
p-value	**	**	**	**
Open field				
<i>Bacillus thuringeinesis</i>	55.8 ^{ab} $\pm$ 2.25	59.6 ^a $\pm$ 1.15	47.1 ^{bc} $\pm$ 2.25	54.17 ^a $\pm$ 2.25
Thiocyclan hydrogen oxalate	57.6 ^a $\pm$ 0.98	57.0 ^{ab} $\pm$ 1.73	48.8 ^{abc} $\pm$ 1.10	54.47 ^a $\pm$ 2.31
Cyromazine	50.6 ^{bc} $\pm$ 2.19	52.0 ^c $\pm$ 1.15	51.15 ^{ab} $\pm$ 2.22	51.25 ^a $\pm$ 1.59
Emamectin benzoate	51.6 ^{abc} $\pm$ 3.29	57.6 ^{ab} $\pm$ 0.98	45.5 ^{bc} $\pm$ 2.08	51.57 ^a $\pm$ 2.19
Indoxacarb	46.6 ^c $\pm$ 2.19	44.7 ^d $\pm$ 2.19	53.7 ^a $\pm$ 1.62	48.33 ^a $\pm$ 3.27
Metafumizone	49.1 ^{bc} $\pm$ 1.10	53.6 ^{bc} $\pm$ 1.62	53.6 ^a $\pm$ 1.56	52.1 ^a $\pm$ 1.10
Control	45.4 ^c $\pm$ 1.5	53.4 ^{bc} $\pm$ 1.50	43.6 ^c $\pm$ 1.56	47.47 ^a $\pm$ 1.10
F	4.73	10.32	4.71	1.61
p-value	*	**	*	NS

In the column, groups labeled with the same letter are not significantly different at the 5% level according to Duncan's Multiple Range Test (DMRT) from 1955.

** denotes highly significant results ($p \leq 0.01$); * denotes significant results ($p \leq 0.05$).

2.2. The impact of the tested compounds on the activity of non-enzymatic components:

After a 10-day period, certain compounds caused a notable decrease in non-enzymatic components such as carbohydrates, protein content, fats, total lipids, and total phenols in tomato plants when compared to the control. The data presented in Table (3) highlighted significant reductions in all non-enzymatic components in leaves treated with thiocyclan hydrogen oxalate. Conversely, emamectin

benzoate demonstrated a positive effect by increasing the protein content and total lipid percentage in the leaves. Furthermore, the application of metaflumizone, used to control *T. absoluta*, led to a significant elevation in carbohydrates, fats, and total phenols in the tomato plants compared to the control. Statistical analysis using ANOVA revealed high significance, indicating that changes in non-enzymatic components in the leaves were contingent on the treatment with the tested compounds.

Table (3): The impact of the tested pesticides on non-enzymatic components in tomato leaves was examined after a 10-day treatment period.

Treatment	Non-enzymatic components± SE				
	Carbohydrates	Protein%	Total lipid%	Fats%	Total phenols%
Greenhouse					
<i>Bacillus thuringiensis</i>	37.37 ^d ±1.15	3.94 ^d ±0.14	0.40 ^c ±0.03	0.75 ^c ±0.03	1.48 ^c ±0.05
Thiocyclan hydrogen oxalate	34.08 ^d ±1.69	3.61 ^d ±0.01	0.32 ^d ±0.01	0.57 ^d ±0.05	1.13 ^d ±0.04
Cyromazine	39.41 ^d ±2.89	4.47 ^{cd} ±0.17	0.32 ^d ±0.02	0.74 ^c ±0.03	1.49 ^c ±0.12
Emamectin benzoate	55.49 ^{bc} ±2.89	7.74 ^a ±0.55	0.79 ^a ±0.03	1.11 ^b ±0.06	2.16 ^b ±0.02
Indoxacarb	61.11 ^{ab} ±0.51	7.21 ^a ±0.12	0.74 ^a ±0.02	1.03 ^b ±0.02	2.08 ^b ±0.05
Metafumizone	65.03 ^a ±1.76	6.26 ^b ±0.43	0.56 ^b ±0.02	1.32 ^a ±0.06	2.58 ^a ±0.12
Control	51.38 ^c ±1.73	4.94 ^c ±0.02	0.45 ^c ±0.03	1.04 ^b ±0.02	2.04 ^b ±0.02
F	88.97	33.44	64.66	40.32	52.13
p-value	**	**	**	**	**
Open field					
<i>Bacillus thuringiensis</i>	38.87 ^{ef} ±0.59	4.44 ^c ±0.02	0.50 ^c ±0.03	0.85 ^c ±0.03	1.68 ^c ±0.06
Thiocyclan hydrogen oxalate	35.58 ^f ±0.57	4.11 ^f ±0.06	0.42 ^d ±0.01	0.67 ^d ±0.02	1.33 ^d ±0.02
Cyromazine	40.91 ^c ±1.15	5.47 ^d ±0.06	0.42 ^d ±0.01	0.84 ^d ±0.02	1.69 ^c ±0.06
Emamectin benzoate	56.99 ^c ±1.73	8.24 ^a ±0.06	0.89 ^a ±0.06	1.21 ^c ±0.06	2.36 ^b ±0.03
Indoxacarb	62.61 ^b ±1.15	7.71 ^b ±0.06	0.84 ^a ±0.02	1.13 ^b ±0.02	2.28 ^b ±0.06
Metafumizone	66.53 ^a ±1.71	6.76 ^c ±0.06	0.66 ^b ±0.06	1.42 ^b ±0.05	2.78 ^a ±0.05
Control	52.88 ^d ±1.17	5.44 ^d ±0.02	0.55 ^{bc} ±0.03	1.14 ^a ±0.03	2.24 ^b ±0.06
F	98.92	956.67	27.91	54.64	102.93
p-value	**	**	**	**	**

In the column, groups labeled with the same letter are not significantly different at the 5% level according to Duncan's Multiple Range Test (DMRT) from 1955.

** denotes highly significant results ($p \leq 0.01$); * denotes significant results ($p \leq 0.05$).

In conclusion, this study observed the effects of various compounds on non-enzymatic components, consistent with the research by Seth *et al.* (2014), Shakir *et al.* (2018), El-Fakharany *et al.* (2024), Li *et al.* (2024) and Sadek *et al.* (2024). Specifically, compounds like *B. thuringiensis*, thiocyclan hydrogen oxalate, and cyromazine were noted to influence phenolic compounds, proteins, lipids, fats, and carbohydrates by

significantly reducing their levels compared to other compounds, in line with Shakir *et al.* (2018), Li *et al.* (2024) and Sadek *et al.* (2024). Additionally, the study indicated that non-enzymatic components were elevated by treatments involving emamectin benzoate, indoxacarb, and metafumizone, supporting the findings of Homayoonzadeh *et al.* (2020) and El-Fakharany *et al.* (2024).

2.3. The influence of the tested compounds on the activity of antioxidant enzymes:

Data in Table (4) shows the effect of tested compounds on the activity of antioxidant enzymes in tomato leaves up to 10 days post treatments. All compounds affected antioxidant enzymes with significant differences among the treatments. Emamectin benzoate treatment increased the enzymatic activity (Catalase, peroxidase and superoxidase) specially at 10 days after application to an extent of 7.59, 12.04 and 13.21 in greenhouse and 8.08, 12.5 and 13.70 in open field respectively. The thiocyclan hydrogen application on tomato plants decreased the activities of catalase, peroxidase and superoxidase oxidase. Also, *B. thuringiensis* and cyromazine affected on antioxidant enzymes activity peroxidase by decreasing with significance between them. Almost all antioxidant enzymes significantly varied among treatments ($p \leq$

0.05). The statistical high significance and the change in antioxidant enzymes activity in leaves were the tested compounds treatment dependent. In the study, all compounds were found to exert a significant impact on the antioxidant enzymes in tomatoes, consistent with the findings of Hajji-Hedfi *et al.* (2022), Macar (2022), El-Fakharany *et al.* (2024) and Sadek *et al.* (2024). Specifically, the levels of catalase, peroxidase, and superoxide dismutase decreased upon the application of *B. thuringiensis*, thiocyclan hydrogen oxalate, and cyromazine, aligning with the results of Bajguz and Hayat (2009), Shakir *et al.* (2018), and Sadek *et al.* (2024). Conversely, the activity of antioxidant enzymes was observed to increase with treatments involving emamectin benzoate, indoxacarb and metafumizone, consistent with the research by Chauhan *et al.* (2013), Ashrafi and Pandit (2016) and El-Fakharany *et al.* (2024).

Table (4): The impact of the tested pesticides on the activity of antioxidant enzymes in tomato leaves was assessed after a 10-day treatment period.

Treatment	Antioxidant enzymes $\pm$ SE		
	Catalase (nmol H ₂ O ₂ mg protein ⁻¹ min ⁻¹) (CAT)	Peroxidase (nmol ascorbate oxidized mg protein ⁻¹ min ⁻¹)	Superoxidase (Nmol NO ₂ mg protein ⁻¹ min ⁻¹)
Greenhouse			
<i>Bacillus thuringiensis</i>	3.96 ^d $\pm$ 0.02	5.72 ^c $\pm$ 0.01	6.91 ^d $\pm$ 0.06
Thiocyclan hydrogen oxalate	3.05 ^e $\pm$ 0.03	5.11 ^e $\pm$ 0.06	6.45 ^d $\pm$ 0.03
Cyromazine	4.00 ^d $\pm$ 0.12	7.56 ^d $\pm$ 0.06	8.20 ^c $\pm$ 0.12
Emamectin benzoate	7.59 ^a $\pm$ 0.02	12.01 ^a $\pm$ 0.57	13.21 ^a $\pm$ 0.46
Indoxacarb	5.58 ^c $\pm$ 0.03	10.47 ^b $\pm$ 0.06	12.66 ^a $\pm$ 0.46
Metafumizone	6.87 ^b $\pm$ 0.03	8.88 ^c $\pm$ 0.07	11.21 ^b $\pm$ 0.12
Control	5.43 ^c $\pm$ 0.02	7.01 ^d $\pm$ 0.01	8.86 ^c $\pm$ 0.12
F	1.105	128.12	111.55
p-value	**	**	**
Open field			
<i>Bacillus thuringiensis</i>	4.45 ^d $\pm$ 0.12	6.21 ^c $\pm$ 0.12	7.40 ^f $\pm$ 0.12
Thiocyclan hydrogen oxalate	3.54 ^e $\pm$ 0.02	5.60 ^c $\pm$ 0.12	6.94 ^f $\pm$ 0.27
Cyromazine	4.49 ^d $\pm$ 0.17	8.05 ^d $\pm$ 0.03	8.69 ^c $\pm$ 0.16
Emamectin benzoate	8.08 ^a $\pm$ 0.10	12.50 ^a $\pm$ 0.35	13.70 ^a $\pm$ 0.12
Indoxacarb	6.07 ^c $\pm$ 0.16	10.96 ^b $\pm$ 0.23	13.15 ^b $\pm$ 0.09
Metafumizone	7.36 ^b $\pm$ 0.17	9.37 ^c $\pm$ 0.21	11.70 ^c $\pm$ 0.17
Control	5.92 ^c $\pm$ 0.05	7.50 ^d $\pm$ 0.29	9.35 ^d $\pm$ 0.20
F	171.14	132.45	258.26
p-value	**	**	**

In the column, groups labeled with the same letter are not significantly different at the 5% level according to Duncan's Multiple Range Test (DMRT) from 1955.

** denotes highly significant results ($p \leq 0.01$); * denotes significant results ($p \leq 0.05$).

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