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INVESTIGATION OF THE PHYTOTOXIC EFFECTS OF THE PYRETHROID TAU-FLUVALINATE ON *LACTUCA SATIVA* (ASTERACEAE)

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ABSTRACT

The increasing use of pesticides in recent years is considered a threat to the environment and health. The current study intended to assess the potential phytotoxic impacts of tau-fluvalinate, a pyrethroid pesticide, on *Lactuca sativa* (Asteraceae) using germination and seedling development endpoints. For this purpose, germination percentage, relative seed germination, relative root growth, and germination index were determined for *L. sativa* seeds exposed to five different concentrations of tau-fluvalinate (12, 24, 48, 96, and 192 mg/L) for 48 h. Statistically significant differences were observed among the tested concentrations in terms of germination percentage, root and shoot length, relative seed germination, relative root growth, and germination index ($p < 0.0001$). Based on the calculated germination indices, the concentration of 12 mg/L was classified as non-phytotoxic but moderately inhibitory, 24 mg/L as moderately phytotoxic, and 48, 96, and 192 mg/L as highly phytotoxic. These findings indicate that tau-fluvalinate may pose environmental risks due to its acute toxic, sublethal, and phytotoxic effects, particularly at high concentrations. Furthermore, the results confirm that *L. sativa* is a sensitive and reliable bioindicator for assessing the phytotoxicity of synthetic pyrethroids.

1. INTRODUCTION

Pesticides are chemical substances utilized for combating pests, including insects, fungi, weeds, and other undesirable organisms. Although pesticides have advances in agricultural production and disease management, their usage can pose significant environmental and public health hazards [1]. Pesticide elements have continuously entered the atmosphere and then contaminated water, food, and soil, resulting in health threats [2].

The role of pesticides in agriculture has increased significantly in recent years [1,3,4]. Their uncontrolled and excessive use can cause numerous changes and disturbances in ecosystems [5]. When these substances seep into the ground, they can influence groundwater, target and non-target organisms like insects, as well as other organisms living in water or on land [5-8], and even human health [9]. Contamination of water and agricultural products by pesticides can lead to cumulative effects of these chemicals on organisms. Accumulation of these compounds can result in imbalances in cellular oxidative metabolism, which can in turn lead to changes in genetic material. They may also exhibit teratogenic, mutagenic, and carcinogenic potential [10,11]. In this regard, it is crucial to examine the toxic properties of pesticides even at low concentrations and to assess the consequences of their use, particularly in terms of environmental impact.

Today, pyrethroids constitute a main insecticide class accounting for over 30% of the global market and are utilized against members of the order Lepidoptera and other pest organisms in virtue of their broad-spectrum performance and economic efficiency [12]. Pyrethroids, synthetic analogs of pyrethrins, are commonly utilized in agriculture to manage a wide variety of pests [13] because of their significant

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insecticidal potency, low mammalian toxicity, and environmental degradability [14]. Pyrethroids, an important neurotoxic insecticide group that affects both the peripheral and central nervous systems of insects by interacting with voltage-gated sodium channels [15,16], prolong membrane depolarization, causing paralysis and death of the insect [15-17].

Biological tests are important tools for examining the toxicity of pesticides and determining their mechanisms of action. Among biological tests in which living organisms are used, plant models stand out due to their ease of performing, low cost, high sensitivity, and strong correlation with other testing systems, such as those involving mammals [18]. Lettuce (*Lactuca sativa*), a plant belonging to the family Asteraceae, has become a popular model plant for assessing environmental contamination risk [19], [20]. The current study intended to assess the potential phytotoxic impacts of tau-fluvalinate, a synthetic pyrethroid, using the model plant *L. sativa*. After 48 h of exposure to different tau-fluvalinate concentrations, the number of germinated lettuce seeds and their root and shoot lengths were determined. Germination percentage, relative seed germination, relative root growth, and germination index values were calculated. According to the obtained data, the phytotoxic effects of tau-fluvalinate on *L. sativa* were evaluated comprehensively.

2. MATERIALS AND METHODS

2.1. Tested Chemical and Test Solutions

In this study, a commercial pesticide (Mavrik® 2F) containing 240 g/L tau-fluvalinate (Table 1) was used. A stock solution of this commercial pesticide was prepared with distilled water at a concentration of 1 g/L. The prepared stock solution was diluted with the required amount of distilled water to obtain tau-fluvalinate test solutions at different concentrations. The selected treatment concentrations were 12, 24, 48, 96, and 192 mg/L. This concentration range was based on the manufacturer-recommended application doses of the commercial formulation and was deliberately extended to higher levels to represent worst-case exposure scenarios, including accidental spills, excessive application, or localized accumulation of the pesticide in agricultural soils and surface waters.

Table 1. Some properties of tau-fluvalinate

CAS No	Formula	Molecular Weight	Water Solubility	Half-life
102851-06-9	$C_{26}H_{22}ClF_3N_2O_3$	502.91 g/mol	0.001 mg/L at 20°C	48 days at pH 5

2.2. Plant Material

In this study, *L. sativa* was selected as the model plant for the tests. For pre-germination, lettuce seeds were incubated in Petri dishes lined with filter paper and supplied with 3 mL of distilled water. Following germination and root emergence, seeds with roots approximately 1–2 mm long were used in the germination tests.

2.3. Seed Germination Tests

Seed germination tests were repeated five times, each with three replicates. These tests were conducted in 9 cm diameter Petri dishes with filter paper at the bottom. Ten seeds with incipient root formation were evenly distributed in each dish, and 3 mL of test solution or distilled water (negative control group) was added. Petri dishes containing seeds were closed with parafilm and stored in the dark at 25 ± 1°C for 48 h.

After a 48-h exposure, germinated seeds were counted, and root and shoot lengths were measured with a digital caliper. Based the obtained data, seed germination, relative seed germination, relative root growth, and germination index were calculated using the following formulas:

$$\text{Seed Germination (\%)} = \frac{\text{Number of Germinated Seeds}}{\text{Total Number of Seeds}} \times 100 \quad (1)$$

$$\text{Relative Seed Germination (\%)} = \frac{\text{Number of Germinated Seeds in Test Solution}}{\text{Number of Germinated Seeds in Control}} \quad (2)$$

$$\text{Relative Root Growth (\%)} = \frac{\text{Root Length in Test Solution}}{\text{Root Length in Control}} \quad (3)$$

$$\text{Germination Index (\%)} = \text{Relative Seed Germination} \times \text{Relative Root Growth} \quad (4)$$

2.4. Statistical Analysis

All data are presented as mean ± standard deviation (SD). Prior to statistical analyses, the average of three replications was taken to obtain a value for each repetition per parameter. All the parameters examined in the study were analyzed using one-way analysis of variance (ANOVA). The Dunnett test, which compares every mean to a control mean, (for seed germination, root and shoot length) or the Tukey test, which compares every mean with every other mean, (for relative seed germination, relative root growth, and germination index) was employed in the post hoc analysis. The relationship between tau-fluvalinate concentration and each of the parameters was analyzed using the Pearson correlation method, and r coefficient values were determined. These statistical analyses were performed using GraphPad Prism (version 9.5.1), and p values of < 0.05 were considered statistically significant.

3. RESULTS AND DISCUSSION

Tau-fluvalinate is a synthetic pyrethroid whose toxic effects have been demonstrated in several non-target organisms, including *Gammarus roeseli* [8], *Allium cepa* [9], *Danio rerio* [21], and *Cryptolaemus montrouzieri* [22]. Despite these findings, information regarding its phytotoxic effects on non-target plant species remains scarce. A comprehensive evaluation of tau-fluvalinate toxicity in non-target organisms is therefore essential for reliable ecosystem risk assessment. In this context, the present study represents the first investigation of tau-fluvalinate phytotoxicity using *L. sativa* as a non-target plant model.

3.1. Seed Germination

Seed germination was highest in the control group (99.33 ± 1.49%) and decreased progressively with increasing tau-fluvalinate concentration, reaching the lowest value at 192 mg/L (1.33 ± 1.83%) (Figure 1). Statistical analysis revealed significant differences among concentrations ($F_{5, 24} = 1008$, $p < 0.0001$). Seed germination percentage showed a significant decrease compared to the control group at all tested concentrations, except at 12 mg/L (Figure 1). Germination inhibition ranged from 2.02% at 12 mg/L to 87.50% at 192 mg/L, and a strong negative correlation was observed between germination percentage and tau-fluvalinate concentration ($r = –0.9050$, $p < 0.0001$). Seed germination percentage is commonly used as an indicator of acute phytotoxicity, with substances yielding germination rates ≥83% considered non-phytotoxic [23]. Based on this criterion, 12 mg/L did not induce acute phytotoxicity, whereas concentrations of 24 mg/L and above were classified as acutely phytotoxic. These findings indicate a clear concentration-dependent increase in the acute phytotoxic effects of tau-fluvalinate.

3.2. Root and Shoot Elongation

Root length was greatest in the control group (20.11 ± 0.82 mm) and declined significantly with increasing tau-fluvalinate concentration, reaching a minimum of 3.05 ± 0.11 mm at 192 mg/L (Figure 2). Significant differences were detected among treatments ($F_{5, 168} = 865.2$, $p < 0.0001$), with root growth inhibition ranging from 3.25% to 84.85%. Root length exhibited a strong negative correlation with tau-fluvalinate concentration ($r = –0.9215$, $p < 0.0001$). A similar trend was observed for shoot length, which decreased significantly as concentration increased ($F_{5, 168} = 395.8$, $p < 0.0001$). Shoot length declined from 7.53 ± 0.57 mm in the control group to 1.02 ± 0.15 mm at 192 mg/L (Figure 3), corresponding to inhibition rates of 2.42–86.52%. Shoot length was also strongly negatively correlated with tau-fluvalinate concentration ($r = –0.8677$, $p < 0.0001$). Seedling growth parameters are considered more sensitive indicators of chronic and sublethal phytotoxicity than germination alone, as they are less influenced by cotyledonary energy reserves [24]. Root length, in particular, represents a reliable

biomonitoring endpoint due to the direct exposure of roots to contaminants in soil and water [25]. In the present study, root growth was significantly inhibited at all tested concentrations, whereas shoot growth was significantly reduced at concentrations of 24 mg/L and higher. Based on inhibition thresholds, concentrations of 12–48 mg/L exerted sublethal phytotoxic effects, while higher concentrations produced pronounced cytotoxic effects on both root and shoot development. These results suggest that elevated tau-fluvalinate concentrations may pose a substantial risk to early plant growth.

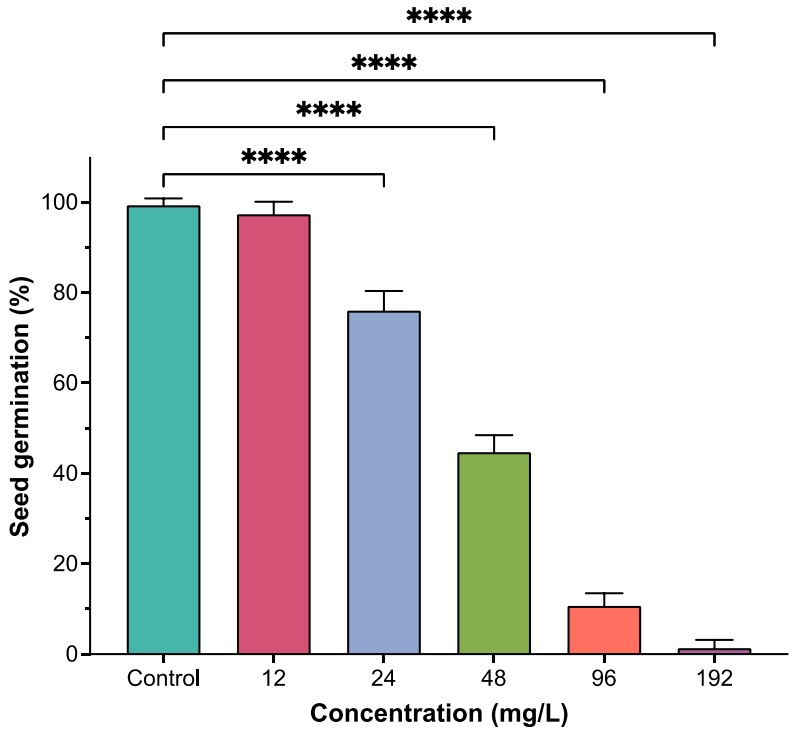


*Figure 1. Effect of tau-fluvalinate concentration on lettuce seed germination. ****: $p < 0.0001$*

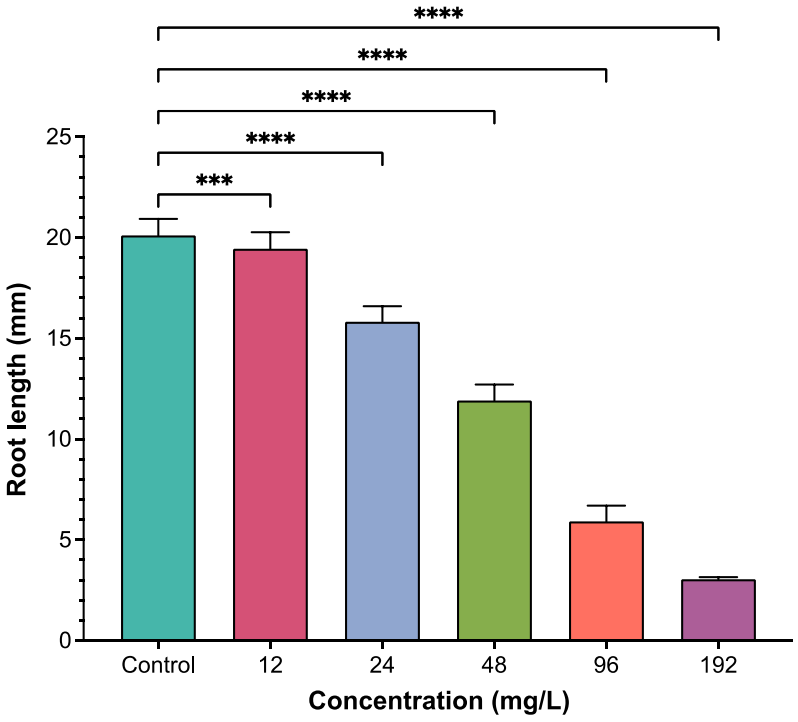


*Figure 2. Effect of tau-fluvalinate concentration on lettuce seedling root length. ***: $p < 0.001$; ****: $p < 0.0001$*

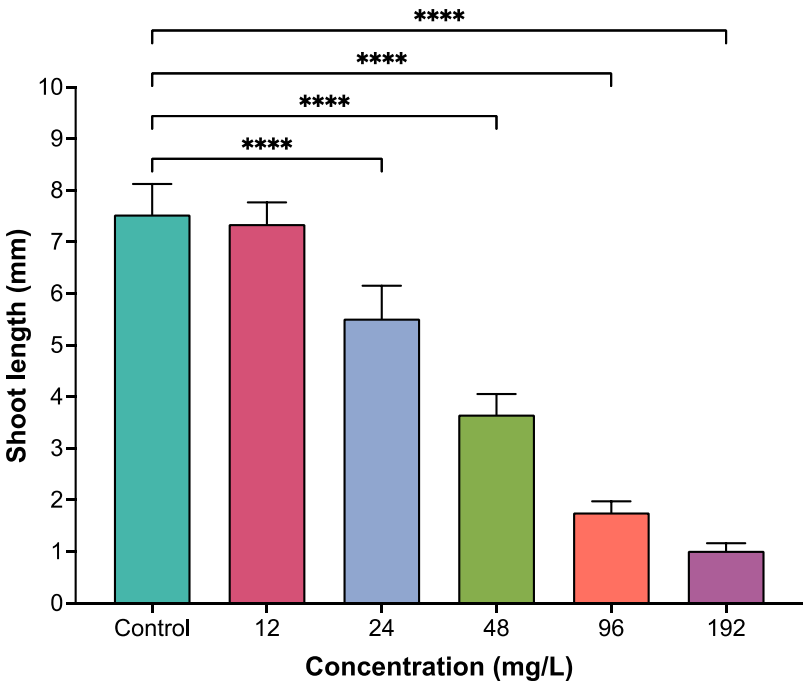


*Figure 3. Effect of tau-fluvalinate concentration on lettuce seedling shoot length. ****: $p < 0.0001$*

3.3. Relative Seed Germination

Relative seed germination values decreased consistently with increasing tau-fluvalinate concentration, ranging from 0.980 ± 0.030 at 12 mg/L to 0.034 ± 0.001 at 192 mg/L (Table 2). Significant differences were observed among concentrations ($F_{4, 17} = 573.9$, $p < 0.0001$), and relative seed germination was strongly negatively correlated with concentration ($r = –0.8721$, $p < 0.0001$). These results are consistent with absolute germination data and indicate that all concentrations except 12 mg/L inhibited seed germination.

Table 2. Relative seed germination values of lettuce seeds at different tau-fluvalinate concentrations. Values with different superscript letters are significantly different from each other ($p < 0.0001$)

Concentration (mg/L)	Relative Seed Germination
12	0.980 ± 0.030^{a}
24	0.765 ± 0.046^{b}
48	0.449 ± 0.034^{c}
96	0.108 ± 0.029^{d}
192	0.034 ± 0.001^{d}

3.4. Relative Root Growth

Relative root growth declined from 0.968 ± 0.022 at 12 mg/L to 0.152 ± 0.009 at 192 mg/L (Table 3), with significant differences among treatments ($F_{4, 17} = 543.8$, $p < 0.0001$). Relative root growth exhibited a strong negative correlation with tau-fluvalinate concentration ($r = –0.9151$, $p < 0.0001$). All values were below 1, indicating growth inhibition rather than stimulation [23]. The inhibitory effect intensified with increasing concentration, corroborating the results obtained from absolute root and shoot length measurements.

3.5. Germination Index

The germination index showed a pronounced concentration-dependent decline, decreasing from 0.949 ± 0.042 at 12 mg/L to 0.005 ± 0.000 at 192 mg/L (Table 4). Differences among concentrations were statistically significant ($F_{4, 17} = 808.2$, $p < 0.0001$), and the germination index was strongly negatively correlated with tau-fluvalinate concentration ($r = –0.8056$, $p < 0.0001$). The germination index integrates

seed germination and root growth, providing a comprehensive assessment of phytotoxicity [23,26]. According to established threshold values [23,27-29], 12 mg/L can be classified as non-phytotoxic with moderate inhibitory effects, 24 mg/L as moderately phytotoxic, and concentrations of 48 mg/L and above as highly phytotoxic.

Table 3. Relative root growth values of lettuce seeds at different tau-fluvalinate concentrations. Values with different superscript letters are significantly different from each other ($p < 0.0001$)

Concentration (mg/L)	Relative Root Growth
12	0.968 ± 0.022^{a}
24	0.787 ± 0.020^{b}
48	0.591 ± 0.025^{c}
96	0.300 ± 0.043^{d}
192	0.152 ± 0.009^{e}

Table 4. Germination index values of lettuce seeds at different tau-fluvalinate concentrations. Values with different superscript letters are significantly different from each other ($p < 0.0001$)

Concentration (mg/L)	Germination Index
12	0.949 ± 0.042^{a}
24	0.602 ± 0.033^{b}
48	0.266 ± 0.027^{c}
96	0.032 ± 0.009^{d}
192	0.005 ± 0.000^{d}

3.6. Possible Mechanisms of Tau-fluvalinate-Induced Phytotoxicity

Although pyrethroid insecticides such as tau-fluvalinate are primarily designed to disrupt the nervous system of insects via interactions with voltage-gated sodium channels, growing evidence indicates that pesticide exposure can also induce significant physiological and biochemical stress responses in non-target plant species. Numerous studies have demonstrated that pesticides may cause phytotoxic effects through indirect mechanisms, particularly by disrupting cellular redox homeostasis, rather than through their intended biochemical targets.

Oxidative stress is one of the most widely documented mechanisms underlying pesticide-induced phytotoxicity in plants [30]. Pesticide exposure can enhance the production of reactive oxygen species, leading to lipid peroxidation, protein oxidation, and DNA damage, which ultimately impair cellular metabolism and growth [31,32]. Actively dividing tissues, such as root and shoot meristems, are especially sensitive to oxidative damage, and alterations in antioxidant enzyme activities are frequently associated with reduced growth, inhibited cell elongation, and decreased biomass accumulation [33]. In addition to oxidative stress, disruption of phytohormone homeostasis is considered an important contributor to pesticide-induced growth inhibition. Plant hormones, particularly auxin, play central roles in regulating root and shoot development through the control of cell division and elongation in meristematic tissues [34,35]. Chemical stressors such as pesticides may interfere with hormone biosynthesis, transport, or signaling, resulting in abnormal growth patterns and impaired meristem activity [36,37]. Moreover, oxidative stress can further modulate hormonal signaling, amplifying growth inhibition [31]. Taken together, these findings suggest that the reduction in root and shoot length observed in *L. sativa* seedlings exposed to tau-fluvalinate is likely mediated by general stress-related physiological pathways, including oxidative stress and hormonal imbalance, rather than by the insect-specific neurotoxic mechanisms of pyrethroids. This highlights the importance of considering plant-specific toxicity mechanisms in environmental risk assessments of synthetic pyrethroids.

3.7. Environmental Relevance

The tau-fluvalinate concentrations used in this study (12–192 mg/L) exceed typical environmental levels, where pyrethroids in surface waters and soils are generally in the ng/L to low µg/L range [38,39].

Nonetheless, the use of elevated concentrations is standard practice in ecotoxicological assays to establish dose–response relationships, determine effect thresholds, and simulate worst-case exposure scenarios [5,8,9]. Acute tests often require higher levels to elicit measurable biological responses, such as effects on germination, root elongation, and seedling growth. Localized accumulation from repeated applications or spills can also create microenvironments with elevated concentrations, supporting the relevance of testing a broad concentration range for environmental risk assessment.

4. CONCLUSION

This study indicates that *L. sativa* serves as an effective biological model for assessing the toxicity of synthetic pyrethroids, with particular emphasis on tau-fluvalinate. In light of the results obtained, tau-fluvalinate, especially at higher concentrations, may pose environmental risks owing to its acute toxic, sublethal, and phytotoxic effects. Consequently, the application of lower doses in agricultural activities should be preferred whenever feasible.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

Artificial intelligence (AI) tools were used solely for the purpose of improving the grammatical accuracy and linguistic clarity of the manuscript. All scientific content, including experimental design, data analysis, figures, and the structural composition of the manuscript, was entirely generated by the authors without any AI assistance.

Contributions of the Authors

Adile Sari: Methodology, investigation, interpretation of results, literature review, writing-original draft, writing-review & editing. Fikret Sari: Methodology, investigation, statistical analysis, interpretation of results, writing-original draft, writing-review & editing.

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