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A Comparative Study on the Phytoremediation Efficiency of Sunflower and Oat in Deltamethrin-Contaminated Soil

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دراسة مقارنة لكفاءة نباتي دوار الشمس والشوفان في المعالجة النباتية للتربة الملوثة بالدلتامترين

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Abstract

This study aimed to evaluate the effects of different concentrations of deltamethrin on the growth and physiological performance of cucumber (Cucumis sativus L.) and to assess the efficiency of phytoremediation using sunflower (Helianthus annuus L.) and oat (Avena sativa L.) in mitigating the adverse effects of pesticide accumulation in soil. The experiment was conducted using a completely randomized design under pot conditions and included five deltamethrin levels (control, 0.25, 0.50, 1.00, and 2.00 of the recommended field dose). Morphological growth parameters (seedling length, fresh weight, and dry weight) and physiological traits represented by total chlorophyll content were measured. Data were statistically analyzed using one-way ANOVA followed by the Tukey's post hoc test at $p \leq 0.05$.

The results showed that deltamethrin significantly reduced all growth parameters and total chlorophyll content of cucumber plants, particularly at higher concentrations, where severe growth inhibition was observed. In contrast, phytoremediation treatments significantly improved growth and chlorophyll content compared with insecticide-treated soil alone. The cucumber + sunflower soil treatment consistently outperformed the cucumber + oat soil treatment across all concentrations. These findings indicate that sunflower is a promising phytoremediation plant for reducing deltamethrin toxicity in contaminated soils and enhancing agricultural sustainability.

Keywords: Chlorophyll content; Cucumber; Deltamethrin; Oat; Phytoremediation; Pyrethroid insecticide; Soil contamination; Sunflower.

الملخص:
هدفت هذه الدراسة إلى تقييم تأثير تراكيز مختلفة من مبيد الدلتامترين على نمو وأداء نبات الخيار (Cucumis sativus L.)، ودراسة كفاءة المعالجة النباتية باستخدام دوار الشمس (Helianthus annuus L.) والشوفان (Avena sativa L.) في التخفيف من التأثيرات السلبية لتراكم المبيد في التربة. نُفذت التجربة وفق التصميم العشوائي الكامل باستخدام أصص زراعية، وشملت خمس مستويات من المبيد (الشاهد، 0.25، 0.50، 1.00، و2.00 من الجرعة الحقلية الموصى بها). قيست صفات النمو المورفولوجي (طول النبات، الوزن الطري، الوزن الجاف) والمحتوى الفسيولوجي ممثلًا بالكلوروفيل الكلي. حُللت البيانات إحصائيًا باستخدام تحليل التباين الأحادي واختبار أقل فرق معنوي (LSD) عند مستوى دلالة. ($p \leq 0.05$)
أظهرت النتائج أن الدلتامترين سبب انخفاضًا معنويًا في جميع صفات النمو ومحتوى الكلوروفيل لنبات الخيار، خاصة عند التراكيز المرتفعة، حيث لوحظ تثبيط شبه كامل للنمو. في المقابل، حسّنت معاملات المعالجة النباتية من مؤشرات النمو والكلوروفيل مقارنة بمعاملة التربة المعاملة بالمبيد فقط. وقد تفوقت معاملة الخيار + تربة دوار الشمس على معاملة الخيار + تربة الشوفان عند جميع التراكيز. تشير النتائج إلى فاعلية دوار الشمس كخيار واعد في المعالجة النباتية للتربة الملوثة بالدلتامترين، وتحسين استدامة النظم الزراعية.

الكلمات المفتاحية: الخيار؛ الدلتامترين؛ الشوفان؛ المعالجة النباتية؛ تلوث التربة؛ دوار الشمس؛ مبيد حشري؛ محتوى الكلوروفيل .

Introduction:

The use of insecticides represents a fundamental component of modern agricultural practices aimed at improving crop productivity and controlling pest populations. Despite their undeniable benefits, the continuous and repeated application of insecticides can lead to their accumulation in agricultural soils, resulting in adverse effects on soil fertility, microbial balance, and the performance of sensitive crop plants (Pathak et al., 2022; Hashim, 2024).

Deltamethrin belongs to the pyrethroid class of insecticides, which are widely used due to their high efficacy against insect pests. However, numerous studies have demonstrated that residues of pyrethroid insecticides can induce unintended phytotoxic effects, negatively affecting vegetative growth, chlorophyll content, and photosynthetic efficiency in susceptible plants, even at relatively low levels of accumulation in soil (Siddiqui et al., 2024; Hashim, 2024). In addition, pesticide accumulation may disrupt soil microbial communities and impair root water and nutrient uptake, ultimately leading to progressive growth inhibition and increased oxidative stress within plant tissues (Qu, 2024).

In response to these challenges, phytoremediation has emerged as a sustainable and environmentally friendly strategy for mitigating pesticide contamination in soils. Phytoremediation is defined as the use of plants and their associated biological processes to remove, stabilize, or detoxify organic contaminants from soil or water through uptake, sequestration, transformation, or stimulation of rhizospheric microbial degradation (Pilon-Smits, 2005; Ali et al., 2013; Siddiqui et al., 2024). Recent evidence highlights that the selection of plant species with extensive root systems and high biomass production, such as sunflower and oat, can significantly contribute to reducing pesticide persistence and bioavailability in contaminated soils.

Several studies have reported that plants possessing deep and well-developed root systems can effectively reduce pesticide bioavailability either through direct uptake or by enhancing microbial activity in the rhizosphere, thereby accelerating the degradation of organic contaminants and alleviating chemical stress on cultivated crops (Siddiqui et al., 2024; dos Santos Junior et al., 2025). Moreover, recent reviews indicate that phytoremediation-based approaches may reduce the risk of pesticide accumulation in edible plant tissues, thereby improving food safety and minimizing the transfer of pesticide residues into the food chain (Fedeli et al., 2024; Qu, 2024).

Among potential phytoremediation species, sunflower (*Helianthus annuus* L.) has been widely recognized for its high capacity to absorb organic contaminants and stimulate rhizospheric biological activity, which promotes contaminant degradation. In contrast, oat (*Avena sativa* L.), while beneficial as a cover crop that improves soil structure and organic matter content, may exhibit comparatively lower phytoremediation efficiency under certain conditions (Siddiqui et al., 2024; dos Santos Junior et al., 2025). Consequently, comparative evaluation of these plant species is essential for identifying effective phytoremediation strategies to mitigate pesticide-induced stress in sensitive crops such as cucumber (*Cucumis sativus* L.).

Therefore, the present study aimed to evaluate the effects of different concentrations of deltamethrin on cucumber growth and physiological performance, as well as to assess the potential of phytoremediation using sunflower and oat in alleviating the adverse effects of this insecticide. The experimental approach focused on measuring key morphological and physiological parameters, including seedling length, fresh weight, dry weight, and chlorophyll content, to provide an integrated understanding of plant-pesticide-soil interactions. The findings of this study are expected to contribute to the development of sustainable agricultural practices for managing pesticide-contaminated soils through the use of tolerant and effective phytoremediation plants.

Research Problem

Despite the important role of insecticides in reducing crop losses and increasing agricultural productivity, the continuous and repeated use of these compounds particularly pyrethroid insecticides such as deltamethrin leads to the accumulation of their residues in agricultural soils. This accumulation constitutes a source of increasing environmental and agronomic problems, as it negatively affects the physical, chemical, and biological properties of soil, limits the growth of subsequently cultivated sensitive plants, and weakens the efficiency of essential physiological processes such as photosynthesis and nutrient uptake.

Vegetable crops, including cucumber (*Cucumis sativus* L.), are relatively sensitive to pesticide residues in soil, where symptoms of growth inhibition, reduced biomass accumulation, and deterioration of chlorophyll content appear upon exposure to such contaminants, even at relatively low concentrations. Despite the growing interest in studying the phytotoxic effects of pesticides on plants, conventional approaches for remediating contaminated soils such as physical removal or chemical treatment are often costly, limited in efficiency, or may cause additional adverse environmental impacts.

In this context, phytoremediation has emerged as a sustainable environmental option based on the use of plants capable of reducing the bioavailability of contaminants in soil or accelerating their degradation. However, the effectiveness of this strategy largely depends on the plant species used and its physiological and root-system capacity to cope with contaminants. Although several studies indicate the potential efficiency of plants such as sunflower and oat in remediating pesticide-contaminated soils, direct comparisons of their relative efficiency in

alleviating deltamethrin toxicity on the growth and performance of cucumber remain limited and unclear, particularly under different insecticide concentration levels.
Accordingly, the research problem centers on the lack of clarity regarding the ability of different phytoremediation plants especially sunflower and oat to reduce the adverse effects of deltamethrin accumulation in soil on cucumber growth and physiological efficiency, and the need for a comparative scientific evaluation to determine which plant is more effective in phytoremediation based on precise morphological and physiological growth indicators.

Objectives of the Study

This study aims to:

- Evaluate the effects of different concentrations of deltamethrin on cucumber growth based on seedling length, fresh weight, and dry weight.
- Investigate the effect of deltamethrin accumulation in soil on the physiological performance of cucumber plants as represented by total chlorophyll content.
- Compare the efficiency of sunflower and oat in alleviating the negative effects of deltamethrin on cucumber growth and physiological efficiency through phytoremediation.
- Statistically analyze the results to determine the significance of differences among treatments and concentration levels using appropriate analysis (ANOVA) through the SPSS software.

Materials and Methods

Experimental Design and Treatment Preparation

The experiment was conducted under pot conditions using a completely randomized design (CRD) with a factorial arrangement of treatments. Two experimental factors were investigated. The first factor was deltamethrin concentration, applied at five levels: 0.00 (control), 0.25, 0.50 (the recommended field dose), 1.00-fold, and 2.00-fold of the recommended field dose.
The second factor was soil treatment type, which included three levels: insecticide-treated soil, oat-remediated soil, and sunflower-remediated soil. The definitions and descriptions of these soil treatments are provided in Table 1.

Table 1: Explanation of soil and treatment terminology used in the study

Term used in the table	Description
Insecticide soil	Soil treated directly with deltamethrin without any phytoremediation treatment, representing insecticide-contaminated soil.
Oat soil	Soil treated with deltamethrin and subsequently cultivated with oat (*Avena sativa L.*); after oat harvest, the soil was used for cucumber cultivation to assess phytoremediation efficiency.
Sunflower soil	Soil treated with deltamethrin and cultivated with sunflower (*Helianthus annuus L.*); after completion of sunflower growth, the soil was reused for cucumber cultivation to evaluate phytoremediation efficiency.
Cucumber + insecticide soil	Cucumber plants grown in deltamethrin-contaminated soil without prior phytoremediation.
Cucumber + oat soil	Cucumber plants grown in soil previously phytoremediated using oat.
Cucumber + sunflower soil	Cucumber plants grown in soil previously phytoremediated using sunflower.

Deltamethrin concentrations were prepared based on the recommended field dose for cucumber (0.50 mL/L), using fractional and multiple proportions of this dose. Equal volumes of each prepared solution were thoroughly mixed with the soil in each pot to ensure homogeneous distribution of the insecticide. Each treatment combination was replicated three times, and each pot was considered an independent experimental unit.

For phytoremediation treatments, oat (*Avena sativa L.*) or sunflower (*Helianthus annuus L.*) plants were initially cultivated in the insecticide-treated soil. After 60 days of growth, the same soil was reused for cucumber cultivation to assess the effectiveness of phytoremediation in reducing deltamethrin toxicity.

Plant Materials

Seeds of oat (*Avena sativa L.*), sunflower (*Helianthus annuus L.*), and cucumber (*Cucumis sativus L.*) were used in this study. All seeds were obtained from agricultural supply stores in Sebha, Libya.

Chemical Materials

Deltamethrin (2.5% EC) was used due to its widespread application in local agricultural practices. The insecticide concentrations (0.00, 0.25, 0.50, 1.00, and 2.00 mL/L) were prepared based on the recommended field dose for cucumber (0.50 mL/L). Additional chemicals used in the study included hydrochloric acid (HCl, 1%), commercial sodium hypochlorite (3%), ethanol (70%), acetone (80%), and distilled water.

Experimental Setup

The experiment was carried out in pots filled with prepared and sterilized sandy soil. Treatments were randomly assigned according to the CRD. After application of the insecticide treatments, oat and sunflower seeds were sown in the designated pots and irrigated daily with distilled water. Following the phytoremediation period (60 days), cucumber seeds were planted in the same soil under identical experimental conditions.

Seedling Growth Test and Morphological Measurements

seedling length was measured using a graduated ruler. Fresh weight was recorded immediately after harvest, and dry weight was determined after drying plant samples in an oven at 85 °C until constant weight was achieved.

Determination of Chlorophyll Content and Physiological Measurements

Total chlorophyll content in cucumber leaves was determined using the acetone (80%) extraction method. Absorbance was measured at wavelengths of 645 and 663 nm using a spectrophotometer. Total chlorophyll contents were calculated according to the equations described by Arnon (1949).

Statistical Analysis

All data were statistically analyzed using SPSS software. One-way analysis of variance (ANOVA) was performed to determine the significance of differences among treatments at each insecticide concentration. When significant differences were detected, Tukey's post hoc test was applied to compare treatment means. Statistical significance was accepted at $p \leq 0.05$, and results were expressed as mean values ± standard deviation (SD).

Results

First: Seedling Growth Test Results

The results of morphological growth parameters (Table 2) indicated significant effects of deltamethrin concentration and phytoremediation treatment type, with statistically significant differences among all treatments ($p \leq 0.05$). The growth of cucumber plants in insecticide-treated soil exhibited a gradual and severe decline in growth parameters with increasing deltamethrin concentration, reaching complete growth inhibition at the 1.00 and 2.00 concentration levels.

In contrast, cucumber plants grown in soil previously cultivated with phytoremediation plants showed marked improvements in all growth parameters compared with the insecticide-treated soil alone. The cucumber + sunflower soil treatment achieved the highest mean values for seedling length, fresh weight, and dry weight.

Table 2. Effects of deltamethrin concentration and phytoremediation treatments on morphological growth parameters of cucumber plants

Concentration	Treatment	Seedling length mean (cm) ± SD	Fresh weight mean (g) ± SD	Dry weight mean (g) ± SD
		***	***	***
0.00	Cucumber + soil	17.93 ± 0.51[c]	3.31 ± 0.49[c]	0.74 ± 0.01[c]
	Cucumber + oat soil	23.27 ± 2.04[b]	6.10 ± 1.72[b]	1.77 ± 1.24[b]
	Cucumber + sunflower soil	26.13 ± 2.06[a]	6.85 ± 4.61[a]	4.02 ± 1.99[a]
0.25	Cucumber + insecticide soil	17.10 ± 1.20[c]	2.35 ± 0.49[c]	0.06 ± 0.02[c]
	Cucumber + oat soil	24.10 ± 3.00[b]	7.05 ± 1.85[b]	2.47 ± 1.34[b]
	Cucumber + sunflower soil	27.20 ± 1.70[a]	10.04 ± 1.76[a]	5.15 ± 1.80[a]
0.50	Cucumber + insecticide soil	13.00 ± 0.80[c]	1.08 ± 0.05[c]	0.06 ± 0.03[c]
	Cucumber + oat soil	23.93 ± 2.28[b]	6.14 ± 1.73[b]	1.77 ± 1.25[b]
	Cucumber + sunflower soil	27.57 ± 1.37[a]	10.49 ± 1.31[a]	5.43 ± 1.92[a]
1.00	Cucumber + insecticide soil	0.00 ± 0.00[c]	0.00 ± 0.00[c]	0.00 ± 0.00[c]
	Cucumber + oat soil	22.90 ± 2.65[b]	6.00 ± 1.81[b]	1.83 ± 1.62[b]
	Cucumber + sunflower soil	28.17 ± 0.49[a]	11.11 ± 0.26[a]	5.90 ± 0.73[a]
2.00	Cucumber + insecticide soil	0.00 ± 0.00[c]	0.00 ± 0.00[c]	0.00 ± 0.00[c]
	Cucumber + oat soil	21.65 ± 1.30[b]	5.98 ± 1.82[b]	1.89 ± 1.71[b]
	Cucumber + sunflower soil	27.33 ± 0.91[a]	10.34 ± 1.08[a]	5.10 ± 0.99[a]

*** Significant at $p \leq 0.001$ Similar letters = Not significa Different letters = Significant
± = standard deviation around the mean SD = Standard Deviation Mean = Arithmetic mean

Second: Total Chlorophyll Content Results

As shown in Table 3, the results of total chlorophyll content revealed statistically significant differences among treatments at all tested concentrations ($p \leq 0.05$). Cucumber plants grown in insecticide-treated soil showed complete depletion of chlorophyll content at all concentrations, whereas phytoremediation treatments resulted in a significant increase in chlorophyll content.

Across all concentrations, the cucumber + sunflower soil treatment recorded the highest total chlorophyll values, followed by the cucumber + oat soil treatment, indicating the superior efficiency of sunflower in maintaining the physiological performance of cucumber plants compared with oat under deltamethrin stress.

Table 3. Effects of deltamethrin concentration and phytoremediation treatments on total chlorophyll content of cucumber plants

Concentration	Treatment	Total chlorophyll Mean ± SD
	***	***
0.00	Cucumber + insecticide soil	0.00 ± 0.00^{c}
	Cucumber + oat soil	85.88 ± 0.00^{b}
	Cucumber + sunflower soil	162.60 ± 1.73^{a}
0.25	Cucumber + insecticide soil	0.00 ± 0.00^{c}
	Cucumber + oat soil	74.30 ± 0.00^{b}
	Cucumber + sunflower soil	135.40 ± 0.00^{a}
0.50	Cucumber + insecticide soil	0.00 ± 0.00^{c}
	Cucumber + oat soil	63.56 ± 0.00^{b}
	Cucumber + sunflower soil	128.30 ± 0.00^{a}
1.00	Cucumber + insecticide soil	0.00 ± 0.00^{c}
	Cucumber + oat soil	53.55 ± 0.00^{b}
	Cucumber + sunflower soil	123.80 ± 0.00^{a}
2.00	Cucumber + insecticide soil	0.00 ± 0.00^{c}
	Cucumber + oat soil	51.15 ± 0.00^{b}
	Cucumber + sunflower soil	122.80 ± 0.00^{a}

*** = Significant at $p \leq 0.001$ Similar letters = Not significant Different letters = Significant
± = standard deviation around the mean SD = Standard Deviation Mean = Arithmetic mean

Discussion:

First: Discussion of Seedling Growth Test Results

The results demonstrated that exposure to deltamethrin caused a pronounced decline in the morphological growth parameters of cucumber plants (seedling length, fresh weight, and dry weight), in a concentration-dependent manner, reaching complete growth inhibition at the two highest concentrations. This growth suppression is consistent with recent reports describing the phytotoxic mechanisms of pyrethroid insecticides, which include the induction of oxidative stress, disruption of cell division and elongation processes, and imbalance in water and nutrient homeostasis within plant tissues (Pathak et al., 2022; Hashim, 2024).

The presence of phytoremediation plants (oat and sunflower) in the soil significantly reduced these negative effects. The cucumber + sunflower soil treatment exhibited the best growth performance, followed by the cucumber + oat soil treatment. This pattern supports two complementary mechanisms described in the literature: first, the ability of certain plants to reduce the bioavailability of organic compounds through uptake or sequestration within root biomass; and second, the role of root exudates in stimulating rhizospheric microbial communities that accelerate contaminant degradation (Pathak et al., 2022; Qu, 2024). Experimental studies and recent reviews have shown that sunflower possesses a larger root biomass and more active rhizospheric microbial stimulation compared with cover crops such as oat, which explains its superior effectiveness in reducing phytotoxicity and improving growth indicators (Siddiqui et al., 2024; dos Santos Junior et al., 2025).

Moreover, the results reveal a threshold behavior, whereby phytoremediation and rhizospheric microbial mechanisms can mitigate damage at moderate contaminant concentrations, whereas their protective efficiency declines at excessive concentrations, leading sensitive plants to reach a collapse stage. This observation aligns with recent reviews emphasizing the limitations of phytoremediation efficiency at high pollutant levels and the necessity of complementary measurements such as pesticide residue analysis, antioxidant enzyme activity, and microbial community profiling before extrapolating practical applications (Pathak et al., 2022; Qu, 2024).

From an applied perspective, these findings support the selection of sunflower as a companion plant or cover crop in strategies for managing soils contaminated with pyrethroids. Sunflower provides a dual benefit by contributing to contaminant removal or stabilization while simultaneously enhancing soil fertility and biological activity, thereby reducing pesticide stress on sensitive crops and maintaining acceptable agricultural productivity (dos Santos Junior et al., 2025; Fedeli et al., 2024).

Second: Discussion of Total Chlorophyll Content Results

Soil treatment with deltamethrin resulted in a pronounced depletion of chlorophyll content in cucumber plants across the tested concentrations, indicating direct damage to the photosynthetic apparatus and deterioration of chloroplast integrity. Recent evidence explains this effect through two main pathways: increased oxidative stress leading to pigment degradation, and inhibition of enzymes and pathways involved in chlorophyll biosynthesis (Siddiqui et al., 2024; Hashim, 2024). Studies on pyrethroid impacts on plant pigments further indicate that chlorophyll reduction often precedes visible growth decline, serving as a sensitive indicator of chemical stress on photosynthetic efficiency (Pathak et al., 2022).

In contrast, oat- and sunflower-based phytoremediation treatments led to a significant restoration of chlorophyll content, with sunflower showing a clear advantage. This physiological recovery can be attributed to the ability of these plants to reduce deltamethrin bioavailability either through direct uptake or by enhancing microbial degradation conditions thereby alleviating oxidative pressure on chloroplasts in the subsequently grown crop. In addition, improved soil nutrient balance may further contribute to chlorophyll stability (Qu, 2024; Siddiqui et al., 2024). Recent studies also suggest that phytoremediation plants may indirectly stimulate antioxidant enzyme activity in the harvested crop through their influence on rhizospheric microbial communities, supporting chlorophyll stability and photosynthetic efficiency (Pathak et al., 2022).

The consistency between chlorophyll and growth results confirms a logical causal relationship: pigment depletion limits light capture and carbon fixation, thereby reducing biomass accumulation, whereas chlorophyll preservation enables the restoration of photosynthetic functions and supports growth (Siddiqui et al., 2024; dos Santos Junior et al., 2025). Consequently, chlorophyll measurements can be considered an early and sensitive indicator of the success or failure of phytoremediation strategies when addressing contaminants such as deltamethrin.

Overall, sunflower demonstrated a higher capacity to mitigate deltamethrin-induced stress than oat, in terms of both growth performance and protection of the photosynthetic apparatus. This finding high lights sunflower as a practical option for integrated phytoremediation systems or as a cover crop for pyrethroid-contaminated soils (dos Santos Junior et al., 2025; Qu, 2024).

Conclusion

The results of this study demonstrate that the accumulation of deltamethrin in agricultural soil induces pronounced negative effects on the growth and physiological performance of cucumber plants, manifested by significant reductions in seedling length, fresh weight, and dry weight, as well as deterioration of total chlorophyll content, particularly at higher insecticide concentrations. These findings confirm the sensitivity of cucumber plants to pyrethroid insecticide residues and their direct impact on essential physiological processes.

In contrast, phytoremediation played an effective role in alleviating deltamethrin toxicity, as the cultivation of oat and sunflower significantly improved growth parameters and preserved the photosynthetic efficiency of cucumber plants compared with insecticide-treated soil alone. Sunflower clearly outperformed oat across all tested concentrations, indicating its superior capacity to reduce insecticide bioavailability in soil and improve the rhizospheric environment. Overall, the study confirms that phytoremediation using tolerant, high-biomass plants such as sunflower represents a sustainable and effective environmental strategy for rehabilitating insecticide-contaminated soils and mitigating their adverse effects on sensitive crops. The integration of this approach into modern agricultural practices may contribute to enhancing production sustainability while reducing environmental and health risks associated with intensive pesticide use.

Recommendations

In light of the results obtained in this study, the following recommendations are proposed:

- The adoption of sunflower as an effective option in phytoremediation programs for rehabilitating agricultural soils contaminated with deltamethrin, given its high efficiency in mitigating the negative effects of the insecticide on cucumber growth and performance.
- Limiting the repeated and excessive use of deltamethrin and adhering strictly to the recommended field application rates in order to reduce residue accumulation in soil and its adverse effects on sensitive crops.
- Encouraging the integration of phytoremediation plants, such as sunflower and oat, into crop rotation systems or as cover crops, with the aim of improving soil properties and reducing residual pesticide toxicity.
- Conducting future studies to quantify pesticide residues in soil and plant tissues and to relate these residues to indicators of oxidative stress and antioxidant enzyme activity, in order to better understand the biological mechanisms associated with phytoremediation processes.
- Expanding the scope of research to include other types of pesticides and agricultural crops, as well as testing additional phytoremediation plant species under different field conditions, to ensure broader applicability of the findings.
- In addition, the integration of phytoremediation plants such as sunflower and oat into crop rotations or as cover crops is advised to improve soil properties and reduce residual pesticide toxicity, thereby contributing to enhanced agricultural sustainability.

- With regard to future research perspectives, there is a clear need for extended field-scale studies to evaluate the long-term efficiency of phytoremediation and to compare field results with pot experiments.
- Furthermore, it is recommended to quantify deltamethrin residues in soil and plant tissues using advanced analytical techniques and to link these measurements with physiological and biochemical indicators, such as antioxidant enzyme activity and changes in rhizospheric microbial communities.
- In addition, future studies should explore the effectiveness of other phytoremediation plant species or integrated agricultural systems combining phytoremediation with soil biological amendments, with the aim of developing more efficient and safer strategies for managing pesticide-contaminated soils.

References

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. *Saudi Journal of Biological Sciences, 20*(3), 231–238.

Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts. Polyphenol oxidase in *Beta vulgaris*. *Plant Physiology, 24*(1), 1–15.

dos Santos Junior, E. R., Silva, J. R., & Pereira, A. S. (2025). Phytoremediation potential of sunflower (*Helianthus annuus* L.) cultivars in pesticide-contaminated soils. *Environmental Science and Pollution Research*. Advance online publication.

Fedeli, R., Petruzzelli, G., & Renella, G. (2024). Biochar amendment mitigates pesticide-induced oxidative stress in *Avena sativa* L. *Journal of Environmental Management, 351*, 119765.

Hashim, S. N. (2024). Effects of deltamethrin insecticide on soil properties and physiological responses of crop plants. *Journal of Agricultural and Food Research, 15*, 100564.

Pathak, V. M., Verma, V. K., Rawat, B. S., & Kaur, B. (2022). Current status of pesticide effects on environment, human health and their sustainable management. *Environmental Science and Pollution Research, 29*, 48185–48201.

Pilon-Smits, E. A. H. (2005). Phytoremediation. *Annual Review of Plant Biology, 56*, 15–39.

Qu, K., Zhang, Y., & Li, H. (2024). Toxicological effects of deltamethrin on enzymatic and physiological responses of crop plants. *Ecotoxicology and Environmental Safety, 259*, 115029.

Siddiqui, S., Khan, M. I., Alamri, S., & Al-Amri, A. A. (2024). Physiological and biochemical responses of crop plants exposed to pyrethroid insecticides. *Frontiers in Sustainable Food Systems, 8*, 1298743.

Ibrahim, M. A. (2009). Plant growth responses to soil contamination and remediation strategies. *Journal of Plant Nutrition*, 32(9), 1537–1550.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.