

Effects of pesticide seed treatments on seed yield and oil quality of sunflower (*Helianthus annuus* L.)

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Abstract

Sunflower (*Helianthus annuus* L.) is a major oilseed crop, and systemic seed-applied pesticides are widely used to protect seedlings from early-season pests and diseases. However, their combined effects on agronomic performance and oil quality remain insufficiently understood. This study evaluated the effects of metalaxyl-M, thiamethoxam, and clothianidin on sunflower morphological traits, yield components, and seed fatty acid composition under field conditions during two consecutive growing seasons (2021–2022) in western Türkiye. The Sanbro MR hybrid was used, with untreated seeds serving as the control. Morphological and yield traits were analysed using analysis of variance, and principal component analysis (PCA) was conducted to explore relationships among treatments and traits. Fatty acid composition was determined to assess potential impacts on oil quality. Significant effects of year, treatment, and their interaction were detected for several traits, indicating that environmental conditions strongly influenced plant responses. In 2021, neonicotinoids, particularly thiamethoxam and clothianidin, were associated with increased plant height, head weight, and single-plant yield. In contrast, in 2022, metalaxyl-M was more strongly linked to increases in plant height and thousand-seed weight, suggesting improved seed filling. PCA results indicated that different active ingredients were associated with distinct trait groups. Seed treatments also caused significant, treatment-specific changes in fatty acid composition. Thiamethoxam promoted a shift toward a higher oleic acid profile, while metalaxyl-M was associated with increased saturated fatty acids, particularly stearic acid. Overall, these findings demonstrate that systemic seed treatments influence both agronomic performance and oil quality, emphasizing the importance of considering biochemical responses alongside yield in sunflower production.

Keywords: Clothianidin, Fatty acids, Metalaxyl-m, Morphological traits, Sunflower, Thiamethoxam

INTRODUCTION

Sunflower (*Helianthus annuus* L.) is one of the most important oilseed crops globally, ranking among the top four most widely cultivated and consumed sources of vegetable oil (FAO, 2021; Day et al., 2011). It is grown extensively worldwide, including in Türkiye, with production showing a continuous upward trend. According to USDA reports, global sunflower output exceeded 47 million tons in 2023 and reached approximately 51 million tons by 2025 (USDA, 2023, 2025), while the global cultivation area has reached nearly 28 million hectares (USDA, 2023). In Türkiye, annual production is approximately 2.4–2.5 million tons, although domestic consumption remains higher at nearly 3.0 million tons (USDA, 2023). Sunflower seeds consist of several structural components, including the rind (shell), seed coat, cotyledon, and embryo (Alberio et al., 2016). They are broadly categorized into two main groups: edible (confectionery) sunflower seeds (Hladni and Miladinovic, 2019) and oilseed sunflower varieties (Rauf et al., 2017). Edible sunflower seeds are generally larger, with striped hulls and kernels selected for flavor and texture, making them suitable for direct human consumption as snacks or bakery ingredients (Kane et al., 2013; Kaya et al., 2025). In contrast, oilseed sunflower varieties are smaller, black-seeded types with thin hulls and a higher kernel ratio, characteristics that enhance oil yield and extraction efficiency (Weiss, 2000; Adeleke and Babalola, 2020). Oilseed cultivars typically contain 40–50% oil and are bred to produce linoleic or high-oleic oil profiles for culinary, industrial, and biofuel applications (Flagella et al., 2002; Jocić et al., 2015). This distinction supports targeted breeding and maintains the crop's importance across food, feed, and industrial sectors.

Recent increases in global sunflower production have been accompanied by a parallel rise in plant protection challenges, highlighting the importance of effective crop management strategies. In conventionally managed large-scale production systems, the order of cultural practices implemented from sowing to harvest plays a decisive role in determining final yield

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outcomes. Among these practices, the preparation of an appropriate seedbed before planting and the establishment of optimal plant density are considered critical prerequisites for maximizing grain and oil productivity in sunflower (Kayın et al., 2024). Equally important is the successful emergence of seedlings and the maintenance of a healthy early growth period, during which plants must be protected from biotic stress factors. Uncontrolled pest and disease pressure during emergence and early seedling development can significantly compromise plant vigour and ultimately reduce yield potential (Kane et al., 2013). These considerations highlight the need for integrated management approaches that ensure strong early-season establishment and sustained crop health in sunflower production systems.

Sunflower plants are susceptible to a range of diseases and pests caused by various factors. Among these, diseases represent one of the most significant constraints on seed quality and yield. Economically important diseases that negatively impact sunflower productivity include Downy mildew (*Plasmophora halstedii*) (Tosun ve Akatlar, 2020), Sunflower rust (*Puccinia helianthi*), Head rot (*Sclerotinia sclerotiorum*), and Verticillium wilt (*Verticillium* spp.) (Yemen & Bergüzer, 2024). Regarding pests, species such as the sunflower moth (*Homoeosoma nebulellum*), green caterpillar (*Helicoverpa armigera*), grass looper (*Lethrus brachicollis*), and cutworms (*Agrotis segetum*, *Agrotis ipsilon*) cause considerable economic losses. Although diseases, pests, and weeds are generally managed in agricultural fields, yield losses of around 30–35% still occur. These losses can reach 70–75%, and in some crops, even 100% without control measures (Birişik, 2018).

Seed coating treatments applied before sowing protect against major diseases and pests that may affect sunflowers during emergence and early growth. Typical effects of fungal pathogens such as *Pythium* spp., *Fusarium* spp., and *Rhizoctonia* spp. on sunflower include seed rot, pre- or post-emergence seedling death, stem deformation, and, in severe cases, plant lodging (Markell et al., 2015). These diseases can cause yield losses of 20–30%. Among pests, cutworm species (e.g., *Agrotis ipsilon*, *Agrotis segetum*) damage young sunflower seedlings by cutting them at the base, leading to seedling mortality. Wireworms (*Agriotes* spp.) attack underground organs of sunflower plants, injuring thin roots or severing them, and in thicker roots or the lower stem, they create galleries while feeding (Rudska and Renskyi, 2025).

In sunflower cultivation, several systemic seed treatments are widely used to protect seedlings from major diseases and pests during early growth stages. Previous studies have shown that these treatments can improve seedling emergence and vigour by reducing the effects of pathogens and early-stage pests, thereby supporting stand establishment and yield potential (Sharma et al., 2015). However, some reports also indicate that these pesticide treatments may adversely affect germination and early seedling growth (Baldini et al., 2018). Therefore, while seed treatments provide important protection, their effects on plant growth and yield performance highlight the need for careful management in sunflower production systems. Although pesticide seed treatments are commonly applied to enhance crop performance and pest control, their effects on oil quality, particularly fatty acid composition, remain poorly understood. Most previous studies have primarily focused on agronomic traits such as emergence, growth, and yield (Labrie et al., 2020; Lamichhane, 2022; Krenchinski et al., 2024), while limited attention has been given to the biochemical and compositional changes in seed oil resulting from these treatments. However, alterations in fatty acid composition may have significant implications for the nutritional quality, industrial applications, and market value of sunflower oil.

Therefore, this study was conducted to address this knowledge gap by examining the effects of systemic seed-applied pesticides, namely metalaxyl-M (Aprin), thiamethoxam (Cruiser), and clothianidin (Poncho), on sunflower growth parameters, seed yield, and fatty acid composition, thereby providing a more comprehensive understanding of the broader impacts of seed treatments beyond their protective role during early plant development.

MATERIALS AND METHODS

In the experiment, Sanbro MR sunflower hybrid developed by Syngenta was used as a plant material. It is classified as an early-maturing variety and is well adapted to the region's environmental conditions due to its lack of soil selectivity and high adaptability. The hybrid exhibits strong emergence and early vigour, together with notable tolerance to drought. Sanbro MR is characterised by a convex capitulum that is inclined downward and has a high capacity for self-pollination, enabling effective kernel filling to the centre of the head. The hybrid is distinguished by its heavy seeds and high hectolitre weight, which contribute to its quality traits. Its relative tolerance to diseases and stable yield performance were the primary reasons for selecting this variety for the study. The field experiment was arranged in a randomised complete block design (RCBD) with three replications, comprising 12 plots, each measuring 250 m². Before sowing, a standard seedbed preparation was carried out. Seeds were sown using a four-row pneumatic precision seed drill, with an inter-row spacing of 70 cm and an intra-row spacing of 25 cm. Weed control was performed by hand weeding when necessary throughout the growing period, and furrow irrigation was applied three times during the growing season to ensure optimal plant development, with all agronomic practices conducted in accordance with standard local cultivation procedures.

The seed treatments applied were metalaxyl-M (Aprin), thiamethoxam (Cruiser), and clothianidin (Poncho). These products were chosen to represent the systemic seed treatment agents commonly used in sunflower cultivation. In Türkiye, almost all commercially available sunflower seeds are marketed as treated seeds. Details of the active ingredients and application rates of the seed treatments used in the study are provided.

Aprin XL 350 ES, a product developed by Syngenta, contains 350 g/L of metalaxyl-m, a systemic phenylamide fungicide belonging to the acylalanine group (FRAC, 2024). In sunflower cultivation, it is used as a seed treatment at a rate of 250 mL per 100 kg of seed to control sunflower downy mildew (*Plasmopara halstedii*). Beyond sunflowers, metalaxyl-m is also registered for use in various horticultural crops, such as carrots, cucumbers, and cauliflower, for the management of seedling

root rot. The compound exerts its fungicidal activity by inhibiting ribosomal RNA synthesis through interference with RNA polymerase I, thereby disrupting nucleic acid metabolism and leading to inhibition of protein synthesis. As a phenylamide fungicide, metalaxyl-m demonstrates high systemic mobility and curative as well as protective action against susceptible oomycete pathogens (FRAC, 2024; Sierotzki & Quaranta, 2019; Gisi & Ziegler, 2003).

Cruiser 350 FS (Syngenta) was used as a seed treatment to protect sunflower seeds from early-season insect pests. The formulation contains 47.6% thiamethoxam, a systemic neonicotinoid insecticide belonging to IRAC Group 4, which functions as a nicotinic acetylcholine receptor (nAChR) competitive modulator, disrupting neural transmission in target insects and providing broad-spectrum protection against sucking, chewing, and soil-dwelling pests (IRAC, 2025). The recommended application rate for sunflowers is 1000 mL per 100 kg of seed. In addition to its insecticidal activity, Cruiser 350 FS enhances seedling emergence, stand establishment, and plant uniformity, while also reducing early growth stress and promoting optimised plant spacing and improved yield potential under variable environmental conditions.

Poncho is a seed treatment product developed by BASF and contains 600 g/L clothianidin, a neonicotinoid insecticide classified within IRAC Group 4A. Clothianidin acts as a competitive modulator of nicotinic acetylcholine receptors (nAChRs), thereby disrupting synaptic transmission in target insects (IRAC, 2025). The product provides broad-spectrum protection against both above- and below-ground pests. Owing to its systemic activity, it safeguards newly sown crops by ensuring effective and continuous protection throughout the early stages of seedling development. The recommended application rate for sunflowers is 1000 ml per 100 kg of seed.

The study was conducted at the Experimental Field of the Faculty of Agriculture, Aydın Adnan Menderes University, for two years between 2021 and 2022. Before sowing, untreated (non-coated) Sanbro MR oilseed sunflower seeds were obtained from Syngenta, supplied without any pesticide treatment and subsequently divided into four approximately equal portions by weight, including the control. Thereafter, three different systemically active seed treatment products were applied to the respective seed portions using the film-coating method, in accordance with the recommended application rates of the products mentioned above. Seeds that received no pesticide treatment were used in the control plots.

Soil Properties

The soil analysis results indicate that the experimental area has a moderately textured structure, characterised by a balanced distribution of sand, silt, and clay fractions. Overall, the soils are calcareous, with relatively high CaCO_3 content and a strongly alkaline reaction (pH 8.37). The soil also exhibits low organic matter content. Phosphorus and potassium levels fall within moderate ranges, whereas calcium concentrations are comparatively high. Such calcareous and alkaline soil conditions may influence nutrient availability and early seedling development, thereby increasing the relevance of seed treatment applications for supporting optimal emergence and early growth in sunflower cultivation (Table 1).

Table 1. Summary of soil analysis results for the experimental fields (2021–2022)

Parameter	pH	CaCO_3 (%)	Organic matter (%)	Sand (%)	Silt (%)	Clay (%)	K (ppm)	Ca (ppm)	Na (ppm)	P (ppm)
2021	8.37	11.64	1.53	34.80	40.82	24.38	238.61	3263.81	54.38	55.69
2022	8.37	5.82	1.53	35.75	40.23	24.02	238.61	3263.81	54.38	55.69

Experimental Conditions

Meteorological data for the experimental years indicate that the 2021–2022 sunflower growing period (April–September) generally exhibited typical Mediterranean environmental conditions with warm temperatures and limited rainfall during summer months. In both 2021 and 2022, average temperatures increased from April through July, exceeding 25 °C by June and reaching peak values above 28 °C during July–August, conditions that are known to promote rapid vegetative growth and flowering in sunflowers. Rainfall amounts declined substantially after May, showing minimal precipitation between June and August, which is typical for the region and reflects the seasonal summer drought. Nevertheless, the presence of moderate spring rainfall, particularly in April and May, likely supported early establishment and root development (Table 2). These environmental conditions suggest that the sunflower crops were exposed to a warm and predominantly dry growth period, with moisture availability concentrated in the early developmental stages.

Table 2. Monthly rainfall (mm) and mean temperature (°C) for sunflower growth period (April–September)

Month	2021		2022	
	Rainfall (mm)	Temperature(°C)	Rainfall (mm)	Temperature(°C)
April	9.3	15.7	20.3	16.1
May	3.3	22.4	3.9	21.0
June	1.9	25.2	10.2	25.9
July	0.1	29.6	0.0	28.5
August	0.0	29.0	33.6	27.5
September	0.0	23.9	0.0	23.4

Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) to determine the significance of treatment, year, and year - treatment interaction effects on the measured traits using the JMP® 14 statistical software (SAS Institute Inc. 2018). The ANOVA model included sources of variation for replication, treatment, year, and their interactions, followed by partitioning of error terms according to experimental design. Where the overall F-test indicated significance, mean separations were performed using the Least Significant Difference (LSD) test to distinguish differences among treatment means at defined probability thresholds ($P < 0.05$). Principal component analysis (PCA) was performed to observe the relation between seed treatment with morphological traits and fatty acid composition. Only the principal components with eigenvalues greater than 1 and explained variances greater than 10% were selected to describe variation in the studied traits as recommended by Çakmak et al. (2023).

RESULTS AND DISCUSSION

Effects of Pesticides on Morphological Traits

The yield trait data reveal notable year-to-year variation in sunflower morphological traits under different seed treatment conditions. In 2021, thiamethoxam and clothianidin treatments resulted in significantly greater plant height (PH) compared to the control, indicating a positive physiological growth response to neonicotinoid-based seed treatments, consistent with reports that pesticide treated sunflower seeds exhibit enhanced early growth performance (Szemruch et al., 2019). Similar growth-promoting effects of seed treatments on plant stature have been reported by Koca et al. (2021), who evaluated the influence of seed-applied pesticides on maize morphology and found that the greatest mean plant height was recorded in maize treated with Maxim XL 035 FS (fludioxonil + metalaxyl-M), followed by Poncho FS 600 (clothianidin), highlighting the role of seed treatments in enhancing plant height. Head weight (HW) in the same year was also significantly higher in all treated groups compared to the control, demonstrating that seed treatments enhanced reproductive development and head biomass formation. Single plant yield (SPY) was particularly improved in thiamethoxam and clothianidin treatments, suggesting enhanced assimilate allocation efficiency towards seed production under the prevailing environmental conditions in 2021.

In contrast, the 2022 season exhibited different patterns: overall plant height increased, with the highest values observed in the metalaxyl-m treatment. The control group showed the highest head weight (HW), indicating that natural environmental conditions in 2022 were more favourable for untreated seeds relative to treated ones. Thousand-seed weight (TSW) showed considerable treatment-dependent variation, with metalaxyl-m showing greater seed mass accumulation, suggesting that the fungicidal seed coating had a positive impact on seed filling in 2022. In support of these findings, previous studies have reported that sunflower yield was improved following pyraclostrobin application without adversely affecting seed quality, indicating that certain fungicidal treatments can enhance yield-related parameters while maintaining seed quality (Tsialtas et al., 2017). In contrast to the findings of Koutroubas et al. (2014), who reported reductions in thousand seed weight following the application of plant growth regulators, the current study showed that seed treatments, particularly metalaxyl-m didn't reduce yield components and, in some cases, enhanced thousand-seed weight, suggesting a fundamentally different physiological response to seed-applied pesticides compared with foliar growth regulators.

Notably, stem diameter (SD) was consistently greater in 2022 than in 2021 across all treatments, reflecting improved vegetative structural robustness under the second-year growing conditions. Additionally, reductions in SPY among certain treatments (e.g., clothianidin) in 2022 suggest a possible seasonal sensitivity or alteration in pest pressure, soil conditions, or moisture dynamics that influenced yield expression differently compared to 2021 (Table 3). These results are consistent with those of Georgescu et al. (2020), who observed differences in pesticide effects over two years. The effects of imidacloprid, clothianidin, and thiamethoxam on the plant height of Performer sunflower hybrid were observed in the experiment. After 50 days, the plant emergence and plant height in 2018 were higher than in 2019 for all active ingredients. It was attributed to higher rainfall amounts during the summer of 2018 and a high incidence of *Agrotis* on sunflower plants in the spring of 2018. In contrast to studies where plant growth regulators such as paclobutrazol, mepiquat chloride, and chlormequat chloride reduced sunflower plant height by 11–15% through physiological growth suppression (Koutroubas et al., 2014), the seed-applied pesticides used in the current experiment either maintained or increased plant height, indicating a growth-stimulating rather than growth-restricting effect.

The ANOVA results in Table 4 demonstrate that, in sunflowers, the factor “Year” had a statistically significant influence on stem diameter (SD), single plant yield (SPY), and thousand-seed weight (TSW), indicating that environmental variation between growing seasons strongly affected plant productivity and seed development. The main effect of “Treatment” was significant for plant height (PH), stem diameter (SD), and thousand-seed weight (TSW), suggesting that different seed treatments caused measurable morphological and physiological differences relevant to yield performance. Furthermore, the significant Year $\times$ Treatment interaction observed for PH, HW, SD, SPY, and TSW indicates that seed treatment performance was inconsistent across years, suggesting that sunflowers responded differently to the applied pesticides depending on annual environmental conditions such as soil moisture, temperature, and nutrient availability. These interaction effects highlight the importance of evaluating seed treatment efficacy across multiple seasons rather than basing agronomic recommendations on a single-year response (Table 4). Similar variability in seed treatment responses has been reported by Kuca & Yağdı, (2020) at the germination and early growth stages of sunflower, where the effects of seed-applied pesticides differed depending on environmental conditions and treatment type.

Table 3. Means for yield traits

Year	Treatments	PH	HW	HD	SD	SPY	TSW
2021	Control	183.46 c	341.73 b	22.69	2.01 cd	51.43 a	39.23 b
	Metalaxyl-m	170.63 d	687.00 a	22.72	2.07 cd	32.92 cd	42.45 b
	Thiamethoxam	199.53 ab	712.73 a	20.47	1.79 d	52.24 a	39.63 b
	Clothianidin	196.37 ab	685.87 a	21.77	1.83 d	54.08 a	42.32 b
	Year Average	187.50	598.45	21.91	1.93	47.67	40.91
2022	Control	193.30 b	809.91 a	21.80	2.78 a	33.80 cd	42.25 b
	Metalaxyl-m	204.50 a	687.00 a	21.10	2.48 ab	44.79 ab	55.98 a
	Thiamethoxam	195.07 ab	750.80 a	21.77	2.24 bc	35.87 bc	44.3 b
	Clothianidin	195.70 ab	725.73 a	22.07	2.43 b	23.87 d	29.83 c
	Year Average	197.14	743.36	21.68	2.48	34.58	43.23

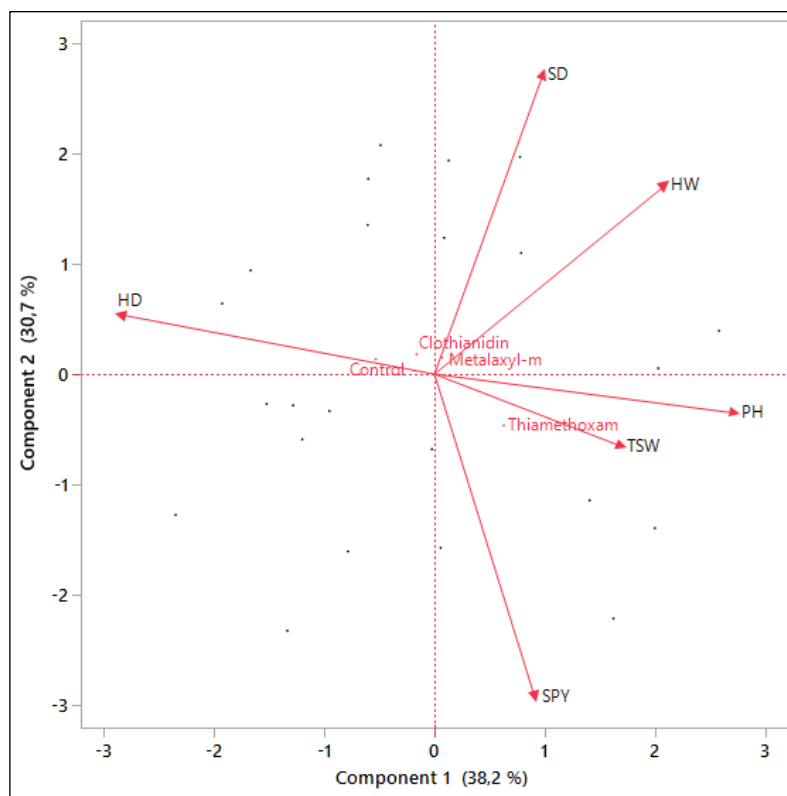
PH: Plant height (cm); HW: Head weight (g); HD: Head diameter (cm); SD: Stem diameter (cm); SPY: Single plant yield (g); TSW: Thousand seed weight (g). When the interaction was significant, means not followed by the same letter(s) are significantly different by the LSD test.

Table 4. ANOVA for yield traits

SOV	df	PH	HW	HD	SD	SPY	TSW
Year	1	557.96	125993.00	0.31	1.87**	1027.57**	32.33*
Error-1-	4	188.17	45962.20	0.93	0.04	11.65	3.07
Treatment	3	153.41*	27926.80	1.38	0.16*	41.16	177.62**
Year x Treatment	3	446.10**	69676.80*	2.49	0.04*	473.70**	176.83**
Error-2-	12	29.57	18006.50	1.63	0.03	37.33	13.08
General	23						

*: $p < 0.05$, **: $p < 0.01$. PH: Plant height (cm); HW: Head weight (g); HD: Head diameter (cm); SD: Stem diameter (cm); SPY: Single plant yield (g); TSW: Thousand seed weight (g).

The principal component biplot (in Figure 1) showed the relationships between seed treatments and sunflower morphological traits across both growing seasons. The first two principal components explained a substantial proportion of the total variation, indicating that the biplot adequately captured the main structure of the dataset. Stem diameter, single plant yield, thousand-seed weight, plant height, head weight, and head diameter were the main contributors to variability, as reflected by the length and orientation of their vectors.

**Figure 1.** Bi-plot graph based on PCA for seed treatments × morphological traits

Stem diameter and seed weight were closely aligned with the metalaxyl-m treatment, suggesting an association with enhanced vegetative robustness and biomass-related traits. In contrast, plant height, thousand-seed weight, and single-plant yield were more strongly associated with the thiamethoxam treatment, indicating a closer relationship with yield-forming traits. The head diameter was positioned closer to the control group, indicating a comparatively lower sensitivity to seed treatments.

Influence of Systemic Seed Treatments on Sunflower Seed Fatty Acid Profiles

Analysis of the fatty acid composition revealed that the pesticide seed treatments induced distinct shifts in the fatty acid profiles of sunflower oil. Thiamethoxam treatment was associated with the highest oleic acid content (52.19%), indicating a tendency toward a high-oleic oil profile. In contrast, the control and clothianidin treatments maintained relatively similar linoleic acid proportions (40.82% and 41.07%, respectively). Palmitic and stearic acid levels, which typically exhibit limited environmental variability, showed minor but statistically significant differences, particularly under metalaxyl-m treatments for stearic acid (3.59%) and reduced palmitic acid concentrations under thiamethoxam treatments (5.47%) (Table 5). These results demonstrate that different seed-applied pesticide treatments can modulate the biochemical composition of developing seeds, resulting in measurable alterations in key fatty acids that contribute to the nutritional and industrial quality of oil. While the present study revealed biochemically meaningful and statistically supported changes in fatty acid composition, characterised by a pronounced increase in oleic acid and a concomitant decrease in linoleic acid following seed treatment, Hulai et al. (2022) reported no significant effects of seed-applied pesticides on fatty acid profiles, a discrepancy that may be attributed to differences in seed coating techniques and the active ingredients used. More broadly, sunflower seed biochemical composition is known to be highly responsive to agronomic inputs during seed development. Numerous studies have reported that fatty acid composition in sunflowers is influenced by genotype, environmental conditions, and agronomic practices (Baydar and Erbaş, 2005; Koutroubas et al., 2014; Skarpa and Lamak, 2019; Canavar and Gören, 2025). For example, herbicide applications may negatively influence plant development and seed oil components under stress conditions (Önemli and Tetik, 2022), while biocontrol treatments can induce biochemical changes in fatty acid profiles (Lamba et al., 2008). In contrast, the present study revealed an increase in oleic acid and a decrease in linoleic acid under certain pesticide treatments, indicating that different external inputs may influence lipid metabolism depending on their mode of action. These treatment-specific shifts in fatty acid composition further demonstrate that pesticide seed treatments can act as regulatory factors influencing oil quality in sunflowers. Furthermore, fatty acid composition has been shown to respond dynamically to environmental conditions and agronomic inputs (Ernst et al., 2022), supporting the view that both environmental and chemical factors collectively shape lipid biosynthesis in sunflower. Accordingly, the increase in oleic acid and the concomitant decrease in linoleic acid observed following thiamethoxam treatment are consistent with the growing evidence that sunflower oil composition is sensitive to pesticide treatments during seed formation.

Table 5. Means for fatty acids.

	Linoleic	Oleic	Palmitic	Stearic
Control	40.82 a	48.19 c	5.76 a	3.43 c
Metalaxyl-m	39.21 b	49.57 b	5.85 a	3.59 a
Thiamethoxam	37.21 c	52.19 a	5.47 b	3.41 c
Clothianidin	41.07 a	47.97 c	5.77 a	3.50 b

When the interaction was significant, means not followed by the same letter(s) are significantly different by the LSD test.

The ANOVA results for the fatty acid composition of sunflower seeds demonstrate that treatment effects were statistically significant for all measured fatty acids, namely linoleic, oleic, palmitic, and stearic acids ($p < 0.01$). While variation among replications was minimal and non-significant, the treatment sum of squares exhibited sufficiently high values to confirm a robust influence of seed-applied pesticides on fatty acid metabolism in the developing seeds. These results indicate that pesticide seed treatments induced measurable biochemical shifts in oil composition, leading to differential accumulation of both major (linoleic and oleic) and minor (palmitic and stearic) fatty acid fractions (Table 6).

Table 6. ANOVA for the studied fatty acids

SOV	df	Linoleic	Oleic	Palmitic	Stearic
Replications	2	0.42	0.48	0.00	0.00
Treatments	3	28.56**	33.89**	0.25**	0.06**
Error	6	0.07	0.08	0.00	0.00
General	11				

*, $p < 0.05$, **, $p < 0.01$.

The relationships between seed treatments and sunflower seed fatty acid composition were effectively demonstrated by the PCA biplot shown in Figure 2. The first two principal components explained almost all of the total variation, indicating a strong differentiation of fatty acid profiles among treatments. Oleic acid was closely associated with the thiamethoxam treatment, suggesting a shift toward a high-oleic oil profile.

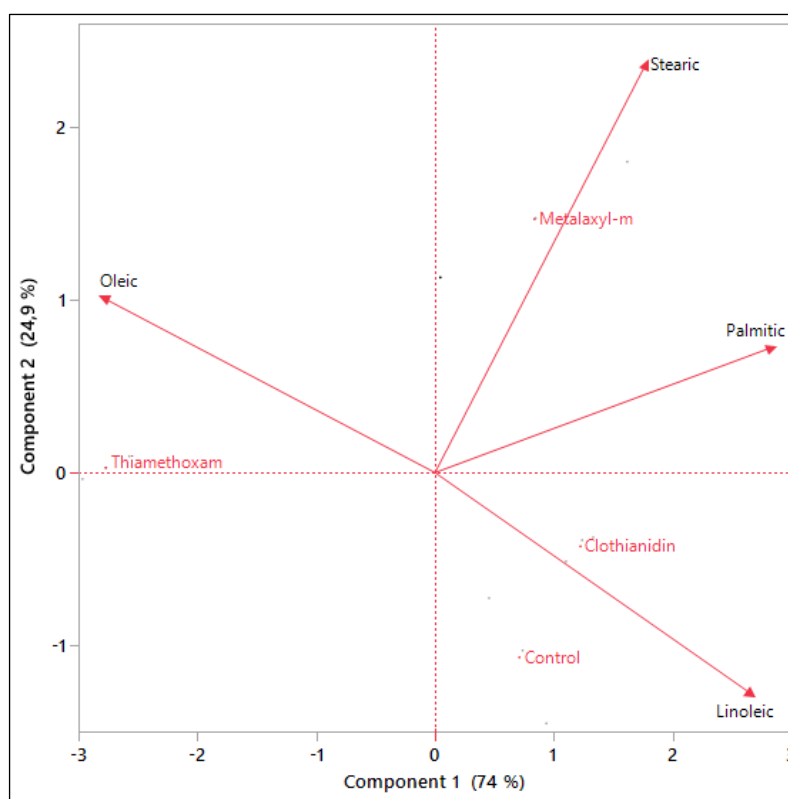


Figure 2. Bi-plot graph based on PCA for seed treatments × fatty acid composition

In contrast, linoleic acid showed a stronger association with the control and clothianidin treatments, reflecting a more linoleic-dominant composition. Palmitic and stearic acids were primarily aligned with the metalaxyl-m treatment, indicating that this fungicidal seed coating influenced the accumulation of saturated fatty acids. Overall, the direction and magnitude of the vectors demonstrate that seed treatments exerted distinct and treatment-specific effects on sunflower oil composition.

CONCLUSION

The findings of this study demonstrate that the effects of systemic seed treatments on sunflower agronomic traits are strongly influenced by environmental conditions, with treatment-specific responses varying between years. Different active ingredients were associated with distinct seed yield-related traits, highlighting the importance of multi-season evaluations to accurately assess their agronomic performance.

In addition to these effects, seed-applied pesticides induced significant changes in fatty acid composition, with thiamethoxam promoting a high-oleic profile and metalaxyl-m increasing saturated fatty acids. These results indicate that seed treatments can influence lipid metabolism during seed development. Overall, pesticide seed treatments affect not only seed yield-related traits but also oil quality through metabolic processes, emphasising the importance of integrating biochemical parameters into sunflower production strategies.

Ethical Statements and Declarations

Conflict of Interest

The author declares that there is no conflict of interest.

Author Contribution

The author solely conducted the study, including experimental design, execution of the experiment, analysis, interpretation, and manuscript preparation.

Ethics Committee Approval

Ethics committee approval was not required for this study.

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