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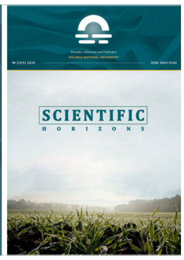

Herbicide impacts on bee pollination and yield interactions in sunflower production

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Abstract. This study aimed to quantify and compare the effects of soil-applied and post-emergence herbicide programmes on bee visitation and seed yield of sunflower hybrids under contrasting seasonal conditions in the Eastern Steppe of Ukraine. Field experiments were conducted during 2022-2024 in Vasylivka (Dnipropetrovsk region), using three hybrids (Biloba CLP, NK Neoma, Suvex), a hand-weeded control, two soil-applied programmes (Primextra TZ Gold + Yastryb; Eclipse + Filder) and several post-emergence options (Helianthex, Stels, Challenge, Pulsar Flex, Granstar) applied according to label instructions. Managed colonies were stocked at 5 hives ha^{-1} with standardised flight distance. Pollinator activity during anthesis was monitored using 24 GoPro cameras (10:00-12:00; four days; three replicates) and expressed as visits head^{-1} 10 min^{-1}, while yield (t ha^{-1} at 7% moisture) was assessed post-harvest. Weather conditions varied markedly, including severe drought in 2024. The control treatment recorded the highest bee visitation (mean 6.11 visits head^{-1} 10 min^{-1}). Soil-applied programmes reduced visitation by 29-56%, with the smallest decrease under Primextra TZ Gold + Yastryb (-29%) and the largest under Eclipse + Filder (-56%). Post-emergence treatments reduced visitation by 33-86%; Challenge (0.4 L ha^{-1}) had the least impact (-33%), whereas Helianthex (45 g ha^{-1}) showed the greatest reduction (-82%). Visitation was strongly influenced by year (≈4.5-5.0 in 2022-2023 vs 1.28 in 2024). Yield responses partially diverged: among soil-applied options, Eclipse + Filder showed the smallest mean reduction (-0.31 t ha^{-1}; -8%), followed by Primextra TZ Gold + Yastryb (-0.35 t ha^{-1}; -9%); among post-emergence options, Stels performed best (-0.58 t ha^{-1}; -15%), outperforming Challenge (-0.76 t ha^{-1}; -20%) and Helianthex (-27%). Overall, soil-applied herbicides were associated with lower risk to pollinator activity and yield compared with post-emergence ALS/imidazolinone chemistries, while drought exerted a dominant limiting effect on both processes. Integrating pollinator-sensitive herbicide selection with seasonal risk management may help sustain ecosystem services and productivity

Keywords: sunflower; bee visitation; herbicide programs; pollinator attractiveness; yield

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INTRODUCTION

Sunflower (*Helianthus annuus* L.) had been recognised as a crop of strategic significance, serving as a major source of vegetable oil and export revenue in Ukraine. Its economic relevance depended not only on genetic improvement and agronomic technologies but also on reliable pollination processes, which determined yield formation and oil quality (Amarilla *et al*., 2025). The increasing climatic instability, intensification of herbicide regimes and fragmentation of pollinator habitats had intensified the vulnerability of pollination services, positioning sunflower cultivation at the intersection of agronomy and ecosystem functioning. Within this context, the need to identify cultivation practices that preserved pollinator activity while ensuring agronomic performance had emerged as a major research priority.

Pollination by insects, primarily *Apis mellifera*, had been shown to markedly improve seed set, oil content and commercial quality parameters. According to the findings of G.J. Brewer *et al*. (2023), bee visitation enhanced seed weight and germination capacity. L.D. Amarilla *et al*. (2025) demonstrated that pollination significantly increased yield components and oil concentration. In Ukraine, analogous patterns were reported: I.M. Kulynych and T.M. Soloviova (2021) observed 20-47% increases in hybrid seed productivity under managed bee pollination, while P. Herasymiuk *et al*. (2025) found that exclusion of pollinators reduced seed weight by up to 2.3 times and decreased overall yield by 57%. These observations confirmed that pollinator presence constituted a critical agronomic factor in sunflower production systems.

Environmental conditions had also been demonstrated as key determinants of pollination efficiency. X. Chen *et al*. (2023) established that moisture deficit and heat stress altered photosynthetic activity, flowering dynamics and nectar secretion, leading to lower visitation rates. Similar effects were reported by Q. Ali *et al*. (2024), who indicated that water deprivation and sowing time jointly affected plant–pollinator relationships and seed yield. Landscape structure further shaped pollinator communities: K. Lajos *et al*. (2021) demonstrated that habitat simplification and monocropping reduced insect diversity and sunflower visitation. This aligned with global assessments suggesting broad dependence of agricultural systems on pollinator-mediated services (Silva *et al*., 2021).

The influence of chemical inputs – including herbicides – had increasingly been recognised as a constraining factor for pollinator behaviour. Evidence from L. Russo *et al*. (2023) indicated that herbicide use reduced nectar quality and visitation frequency. Sublethal effects of neonicotinoids on wild bees and yield formation were recorded by M.S. Saleem *et al*. (2023), while L.T. Ward *et al*. (2023) reported negative impacts of seed treatments even when chemical residues were not detected in floral tissues. At the broader agroecological scale, S. Boinot *et al*. (2024) identified that herbicide intensity reduced floral diversity and constrained pollinator networks. Although these studies advanced current understanding, most were conducted outside sunflower systems or under controlled conditions, leaving limited evidence on the interaction between herbicide programmes and pollination dynamics under real field conditions.

Research on mitigation strategies highlighted opportunities for preserving pollinator activity within intensive production systems. The establishment of flower strips and semi-natural vegetation had been shown to promote bee visitation and stabilise yield formation in sunflower (Mota *et al*., 2022). More recent work by D. Bertleff *et al*. (2025) demonstrated that organic farming and habitat diversification differentially affected wild pollinators and honeybees, resulting in improved crop performance. N-fertilisation and plant nutrition were also suspected to interact with pollination processes: P. Wu *et al*. (2021) established that soil nitrogen availability and bee abundance jointly modulated fruit quality in high-input agricultural landscapes, suggesting analogous dynamics for sunflower hybrids.

The Eastern Steppe of Ukraine represented a particularly vulnerable production zone. Drought, high temperatures and chemical stress coincided during the growing season, impairing nectar secretion and increasing hybrid sensitivity to herbicide exposure. Niche analyses of keystone pollinators conducted by D. Li *et al*. (2024) further highlighted the climatic risks facing *Apis mellifera* populations. Despite the prevalence of these conditions, few studies had directly examined how contrasting herbicide programmes shaped pollination and yield outcomes in Eastern Europe. Most prior research had investigated either pollination benefits or pesticide effects in isolation, without integrating them in long-term field conditions. Therefore, a clear knowledge gap remained concerning how weed-control chemistry influenced bee behaviour and hybrid-specific yield under diverse hydrothermal regimes.

Given the agronomic dependency of sunflower on pollinators and the operational necessity of herbicide use, identifying safe management strategies had become a critical requirement for sustainable production systems. The study aimed to generate practical evidence supporting herbicide strategies that safeguard pollinator activity while maintaining high agronomic performance.

MATERIALS AND METHODS

Research was conducted during 2022-2024 at the experimental field of the State Institution "Institute of Grain Crops of the National Academy of Agrarian Sciences of Ukraine" (Vasylivka, Dnipropetrovsk Oblast; coordinates: 48.2769004 N, 34.9405689 E). The trial covered three consecutive growing seasons characterised by contrasting hydrothermal conditions. Experimental plots measuring 21.5 m × 2.8 m were established in a randomised block design with three replications. Sowing of the sunflower hybrids Biloba CLP, Suvex, and NK Neoma was carried out simultaneously according to the scheme presented in Table 1.

***Table 1**. Experimental design for evaluating honeybee pollination of sunflower under different herbicide-based weed management technologies*

Herbicide technology	Hybrid
Control (hand weeding)	Biloba CLP
	NK Neoma
	Suvex
Soil-applied herbicide (Primextra TZ Gold (Atrazine, 320gm/l +S-Metolachlor, 400 g L^{-1}) 4,5 L ha^{-1} + Yasryb (Glyphosate potassium salt, 441 g L^{-1})2,0 l/ha	Biloba CLP
	NK Neoma
	Suvex
Soil incorporated: Eclips (Prometrin, 500 g L^{-1}) 2,0 L ha + Filder (propisochlor, 720 g L^{-1}) 2,0 L ha	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Helianthex (galoxyphen-methyl, 68.5 g L^{-1}) 45 g ha^{-1}	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Stels (Flurochloridone, 250 g L^{-1}) 0,35 L ha^{-1}	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Challenge (Aclonifene, 600 g L^{-1}) 0,4 L ha^{-1}	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Pulsar Flex (Imazamox, 25 g L^{-1}) 1.6 L ha^{-1}	Biloba CLP
	NK Neoma
	Suvex
Post-emergence herbicide: Granstar (Tribenuron-methyl, 750 g kg^{-1}) 40 g ha^{-1}	Biloba CLP
	NK Neoma
	Suvex

***Source:** developed by the author*

The study was conducted under conditions including a control treatment (hand weed removal) and the application of various herbicides (soil-applied and post-emergence) that were applied in accordance with the manufacturer's recommendations. Bee colonies were established in the experimental field at a rate of 5 colonies per 1 ha. The colonies were positioned so that the route length from the apiary to all experimental plots was the same. For the purpose of recording bee visits, GoPro video cameras were installed on the plots under study during the sunflower flowering period. A total of 24 cameras were installed. Video recording was carried out from 10:00 to 12:00 (30 min for each replication + 30 min for moving the equipment) and over four days. In total, the cameras were set in three replicates. After analysing the video camera data, indicators of flower attractiveness to bees were analysed and a point-based scoring system was developed (the mean number of visits per head per 10 minutes, where 1 visit was equivalent to 1 point and 10 visits to 10 points), and yield (in t ha^{-1}, 7% moisture) was assessed for the three sunflower hybrids: Biloba CLP, NK Neoma, Suvex.

The experimental period (2022-2024) was characterised by considerable variability in climatic conditions, particularly in the amount and monthly distribution of precipitation, which directly affected sunflower growth and yield (Table 2). In 2022, the total precipitation during the growing season (April-September) was 209.3 mm, which was significantly lower than the long-term average (by 23.7 mm). The main deficit occurred in May (19 mm) and June (29 mm), causing water stress at critical growth and development stages such as early vegetative growth, flowering, and seed filling. These conditions led to reductions in yield and oil content. In 2023, precipitation for the same period totaled 246 mm, exceeding the long-term average by 13 mm. Precipitation in April (102 mm) substantially exceeded the long-term average by 57 mm, providing adequate moisture for early plant development. However, a pronounced moisture deficit was observed in May and June. July precipitation (42 mm) partially offset the water shortage but simultaneously caused lodging in some plots, which negatively affected yield. In 2022 and 2023, the sums of active temperatures (1559 and 1651°C days) were sufficient for medium-early hybrids (1700-2100°C days).

***Table 2**. Average daily temperature (°C) and total precipitation (mm) during the study period, 2022-2024*

Year	Month						Difference from the long-term average
	April	May	June	July	August	September	
Average daily temperature (°C)							Sum of active temperatures (°C days)
2022	11.8	16.4	21.6	24.3	23.8	17.2	+71 (1559)
2023	12.0	17.2	22.0	25.0	24.5	18.0	+163 (1651)
2024	15.5	16.4	23.2	26.6	24.6	21.0	+610 (2098)
3-year average	12.1	16.7	22.3	24.5	23.8	17.4	+281 (1769)
Long-term average	11.8	16.4	20.2	22.4	21.6	16.2	0 (1488)
Total precipitation (mm)							Precipitation deviation from the long-term average (mm)
Year	April	May	June	July	August	September	
2022	45.3	19.0	29.0	35.0	46.0	35.0	-23.7
2023	102.0	29.0	29.0	42.0	30.0	14.0	+13
2024	14.0	12.0	29.0	44.0	1.6	11.0	-121.4
3-year average	53.8	20.0	29.0	40.3	39.2	29.7	-21
Long-term average	45	29	34	42	45	38	0

Source: *developed by the author*

In 2024, precipitation during the growing season totaled 111.6 mm, which is 121.4 mm below the long-term average. The moisture deficit was especially pronounced in May (12.0 mm) and August (1.6 mm), which are critical periods for vegetative growth and seed filling. The sum of active temperatures reached a level optimal for medium-maturing hybrids (2100-2300°C·days), indicating unfavorable thermal conditions for the medium-early hybrids used in the study. Additionally, the lack of precipitation substantially affected sunflower development, leading to reduced yield and deterioration of quality.

RESULTS AND DISCUSSION

The control treatment (hand weeding) provided the highest average attractiveness to bees (6.11 visits per head per 10 minutes). The application of herbicides reduced this indicator in all treatments, although the magnitude of the effect depended on the product used (Table 3). Thus, soil-applied herbicides generally caused a reduction in bee visitation to sunflower heads by an average of 29–56%. The smallest negative effect was observed with the tank mix of Primextra TZ Gold 4.5 L ha^{-1} + Yastryb 2.0 L ha^{-1}, under which bee visitation decreased by an average of 29% compared with the control. At the same time, the tank mix of Eclipse 2.0 L ha^{-1} + Filder 2.0 L ha^{-1} led to an even more pronounced decrease in attractiveness to bees: in this variant, visitation decreased by an average of 56% compared with the control.

The post-emergence herbicides under study showed an even more negative impact, reducing the attractiveness of sunflower plants to bees by 33-86%. The smallest impact among the post-emergence treatments was recorded with Challenge at 0.4 L ha^{-1}, where bee visitation to heads decreased by an average of 33% relative to the control, whereas the variant with Helianthex at 45 g ha^{-1} had the worst effect – the attractiveness to bees decreased by an average of 82%. It is worth noting that bee visitation of sunflower plants depended greatly on the growing year. In the favorable years 2022 and 2023, average visitation of heads was 4.5-5.0 per 10 minutes, whereas in the drought-prone 2024 season this indicator averaged 1.28 per 10 minutes (Table 3).

***Table 3**. Effect of herbicide programs on attractiveness to bees (2022-2024)*

Herbicide technology (A)	Hybrid (B)	Attractiveness to bees, visits per head (10 min) each year (C)				Mean increase relative to the control	
		2022	2023	2024	average	ct/head	%
Control (hand weeding)	Biloba CLP	7.00	9.00	2.00	6.00	-	-
	NK Neoma	7.00	9.00	5.00	7.00	-	-
	Suvex	6.00	9.00	1.00	5.33	-	-
	Average	6.67	9.00	2.67	6.11	-	-
Soil-applied herbicide (Primextra TZ Gold 4.5 L ha^{-1} + Yastryb 2.0 L ha^{-1})	Biloba CLP	6.00	6.00	2.00	4.67	-1.33	-22
	NK Neoma	5.00	8.00	2.00	5.00	-2.00	-29
	Suvex	5.00	4.00	1.00	3.33	-2.00	-37
	Average	5.33	6.00	1.67	4.33	-1.78	-29

Table 3. Continued

Herbicide technology (A)	Hybrid (B)	Attractiveness to bees, visits per head (10 min) each year (C)				Mean increase relative to the control	
		2022	2023	2024	average	ct/head	%
Soil-applied herbicide: Eclipse 2.0 L ha^{-1} + Filder 2.0 L ha^{-1}.	Biloba CLP	4.00	3.00	1.00	2.67	-3.33	-56
	NK Neoma	4.00	3.00	1.00	2.67	-4.33	-62
	Suvex	5.00	3.00	0.00	2.67	-2.66	-50
	Average	4.33	3.00	0.67	2.67	-3.44	-56
Post-emergence herbicide: Helianthex 45 g ha^{-1}.	Biloba CLP	3.00	1.00	0.00	1.33	-4.67	-78
	NK Neoma	2.00	1.00	0.00	1.00	-6.00	-86
	Suvex	1.00	1.00	1.00	1.00	-4.33	-81
	Average	2.00	1.00	0.33	1.11	-5.00	-82
Post-emergence herbicide: Stels 350 mL ha^{-1}.	Biloba CLP	4.00	4.00	1.00	3.00	-3.00	-50
	NK Neoma	4.00	5.00	3.00	4.00	-3.00	-43
	Suvex	4.00	4.00	0.00	2.67	-2.66	-50
	Average	4.00	4.33	1.33	3.22	-2.89	-47
Post-emergence herbicide: Challenge 0.4 L ha^{-1}.	Biloba CLP	5.00	6.00	1.00	4.00	-2.00	-33
	NK Neoma	4.00	8.00	1.00	4.33	-2.67	-38
	Suvex	5.00	6.00	1.00	4.00	-1.33	-25
	Average	4.67	6.67	1.00	4.11	-2.00	-33
Average	Biloba CLP	4.83	4.83	1.17	3.61	-	-
	NK Neoma	4.33	5.67	2.00	4.00	-	-
	Suvex	4.33	4.50	0.67	3.17	-	-
	Average	4.50	5.00	1.28	3.59	-	-
Post-emergence herbicide: Pulsar Flex 1.6 L ha^{-1}.	Biloba CLP	4.00	6.00	0.00	3.33	-2.67	-44
	NK Neoma	4.00	7.00	1.00	4.00	-3.00	-43
	Suvex	-	-	-	-	-	
	Average	-	-	-	-	-	
Post-emergence herbicide: Granstar 40 g ha^{-1}.	Biloba CLP	-	-	-	-	-	
	NK Neoma	-	-	-	-	-	
	Suvex	3.00	7.00	0.00	3.33	-2.00	-37
LSD_{05}		A – 0.24; B – 0.19; C – 0.21; AB – 0.46; AC – 0.44; BC – 0.41; ABC – 0.66					

Source: *developed by the author*

The reduction in bee visitation observed after soil-applied herbicides likely reflects indirect physiological and ecological effects rather than acute toxicity. Primextra TZ Gold (containing S-metolachlor and atrazine) and Yastryb (metolachlor + terbuthylazine) act primarily through inhibition of photosynthetic and lipid-synthesis pathways in weeds. Their relatively low volatility and limited translocation explain why the decline in bee visitation (-29%) remained moderate – these products rarely cause visible phytotoxicity or changes in sunflower floral morphology. In contrast, the Eclipse + Filder combination includes active ingredients with higher persistence and stronger systemic uptake (metazachlor + dimethenamid-P + clomazone), which can temporarily influence plant metabolism, especially under limited soil moisture. Clomazone, known for its vapour-phase activity and bleaching effect, may reduce nectar secretion and pigment synthesis, making the flowers less visually attractive to bees.

The pronounced decline in bee visitation after post-emergence herbicide use (Helianthex, Pulsar Flex, Challenge, Stels, Granstar) is likely associated with foliar absorption and short-term physiological stress on the sunflower plants. Helianthex (a sulfonylurea herbicide) inhibits acetolactate synthase (ALS), a key enzyme for amino acid synthesis, and even sublethal phytotoxic stress can reduce nectar and pollen production. Additionally, sulfonylureas are known for residual activity on non-target species, which can slightly modify floral scent profiles important for bee orientation. Conversely, Challenge (aclonifen) has low volatility and limited systemic mobility, explaining its relatively smaller effect (-33%). It acts through inhibition of carotenoid biosynthesis but with minimal impact on floral physiology at label rates. Climatic conditions also played a critical role. The strong decline in bee visits during 2024 corresponded with high air temperatures (>32°C) and a Selyaninov hydrothermal coefficient below 0.5, which constrained nectar secretion and reduced overall pollinator activity. Under drought, both nectar volume and sugar concentration in sunflower florets decrease sharply, which may explain why differences between herbicide treatments were less distinct that year.

Among the soil-applied herbicides, the smallest reduction in yield compared with the control was observed with the combination Eclipse 2.0 L ha^{-1} + Filder 2.0 L ha^{-1}. The decrease in mean yield for this treatment was 0.31 t ha^{-1} (8%), which was the lowest among the soil-applied herbicide schemes studied (Table 4). Under this treatment, hybrid yields were close to the control: for NK Neoma the mean was 3.83 t ha^{-1} (-0.21 t ha^{-1} relative to the control), for Suvex 3.61 t ha^{-1} (-0.12 t ha^{-1}), and for Biloba CLP 3.17 t ha^{-1} (-0.59 t ha^{-1}). The second most effective soil-applied herbicide was the combination Primextra TZ Gold 4.5 L ha^{-1} + Yastryb 2.0 L ha^{-1}, which resulted in an average yield reduction of 0.35 t ha^{-1} (9%) compared with the control. Among the post-emergence herbicides, the best results were obtained with Stels 0.35 L ha^{-1}, where mean yield decreased by only 0.58 t ha^{-1} (15%) relative to the control. For Suvex the yield was 3.45 t ha^{-1} (-0.28 t ha^{-1} vs. control), for NK Neoma 3.34 t ha^{-1} (-0.69 t ha^{-1}), and for Biloba CLP 2.99 t ha^{-1} (-0.77 t ha^{-1}). The second most effective post-emergence treatment was Challenge 0.4 L ha^{-1}, which caused an average yield reduction of 0.76 t ha^{-1} (20%). The treatment with Helianthex at 45 g ha^{-1} had the most negative effect on the yield of all sunflower hybrids among the post-emergence herbicides studied (-27%) (Table 4).

***Table 4**. Yield of sunflower hybrids as affected by herbicide application, t ha^{-1} (2022-2024)*

Herbicide technology (A)	Hybrid (B)	Year (C)				Mean increase relative to the control	
		2022	2023	2024	Average	t ha^{-1}	%
Control (hand weeding)	Biloba CLP	4.53	4.25	2.50	3.76	–	–
	NK Neoma	4.10	5.10	2.90	4.03	–	–
	Suvex	4.07	5.05	2.07	3.73	–	–
	Average	4.23	4.80	2.49	3.84	–	–
Soil-applied herbicide (Primextra TZ Gold 4.5 L ha^{-1} + Yastryb 2.0 L ha^{-1})	Biloba CLP	4.13	3.80	1.97	3.30	-0.46	-12
	NK Neoma	3.93	4.70	2.33	3.66	-0.38	-9
	Suvex	4.03	4.60	1.93	3.52	-0.21	-6
	Average	4.03	4.37	2.08	3.49	-0.35	-9
Soil-applied herbicide: Eclipse 2.0 L ha^{-1} + Filder 2.0 L ha^{-1}	Biloba CLP	3.73	3.50	2.27	3.17	-0.59	-16
	NK Neoma	3.77	4.65	3.07	3.83	-0.21	-5
	Suvex	3.73	4.90	2.20	3.61	-0.12	-3
	Average	3.74	4.35	2.51	3.54	-0.31	-8
Post-emergence herbicide: Helianthex 45 g ha^{-1}	Biloba CLP	3.00	3.05	1.30	2.45	-1.31	-35
	NK Neoma	3.17	4.20	2.07	3.14	-0.89	-22
	Suvex	3.07	4.00	1.53	2.87	-0.86	-23
	Average	3.08	3.75	1.63	2.82	-1.02	-27
Post-emergence herbicide: Stels 350 mL ha^{-1}	Biloba CLP	3.60	3.05	2.33	2.99	-0.77	-20
	NK Neoma	3.37	4.45	2.20	3.34	-0.69	-17
	Suvex	3.53	4.65	2.17	3.45	-0.28	-7
	Average	3.50	4.05	2.23	3.26	-0.58	-15
Post-emergence herbicide: Challenge 0.4 L ha^{-1}.	Biloba CLP	3.40	3.75	1.63	2.93	-0.83	-22
	NK Neoma	3.23	4.45	2.03	3.24	-0.79	-20
	Suvex	3.23	4.25	1.70	3.06	-0.67	-18
	Average	3.29	4.15	1.79	3.08	-0.76	-20
Average	Biloba CLP	3.73	3.57	2.00	3.10	–	–
	NK Neoma	3.60	4.59	2.43	3.54	–	–
	Suvex	3.61	4.58	1.93	3.37	–	–
	Average	3.65	4.24	2.12	3.34	–	–
Post-emergence herbicide: Pulsar Flex 1.6 L ha^{-1}	Biloba CLP	3.47	3.75	1.87	3.03	-0.73	-19
	NK Neoma	3.20	4.55	2.43	3.39	-0.64	-16
	Suvex	–	–	–	–	–	–
	Average	–	–	–	–	–	–
Post-emergence herbicide: Granstar 40 g ha^{-1}	Biloba CLP	–	–	–	–	–	–
	NK Neoma	–	–	–	–	–	–
	Suvex	3.60	4.55	1.72	3.29	-0.44	-12
	Avrerage	–	–	–	–	–	–
LSD_{05}	A – 0.15; B – 0.10; C – 0.21; AB – 0.29; AC – 0.40; BC – 0.38; ABC – 0.51						

***Source:** developed by the author*

The moderate yield reduction under soil-applied herbicides indicates that these treatments primarily affected early vegetative development rather than reproductive success. The relatively higher yield under

Eclipse + Filder compared with Primextra TZ Gold + Yastryb is consistent with its shorter residual activity and partial selectivity for broadleaf weeds. Because soil-applied herbicides are incorporated before sowing, they interact less with floral organs and pollinator behavior, explaining the weaker correlation between bee visitation and yield reduction. In contrast, the post-emergence herbicides act directly on the green tissue during active growth stages (V8-R1), potentially disrupting photosynthesis and assimilate transport at critical periods of head and seed formation. Helianthex (ALS inhibitor) and Pulsar Flex (imidazolinone group) can transiently slow chlorophyll biosynthesis and carbon fixation, leading to smaller heads and fewer filled achenes. Challenge (aclonifen) and Stels (a PPO inhibitor) caused less physiological stress because of their contact-type mode of action and limited translocation within the plant. However, repeated exposure to such herbicides may still lower pollen viability and nectar secretion, indirectly reducing pollination efficiency and seed fill.

Overall, yield responses followed the same trend as pollinator activity: treatments that least disturbed plant physiology (Primextra + Yastryb, Stels, Challenge) maintained both higher bee visitation and higher yield. This suggests that maintaining floral integrity and minimising post-emergence stress is critical for balancing weed control efficiency with pollination-dependent productivity in sunflower cultivation. Differences in bee visitation and yield among herbicide programs demonstrate how weed-control chemistry can mediate sunflower-pollinator interactions through both plant-physiological and environmental pathways. The pattern observed – highest bee activity under mechanical weeding and progressively lower visitation under chemical treatments – parallels the conclusions of L. Russo *et al.* (2023), who found that common herbicide and fertilizer inputs altered floral rewards and reduced visitation in multiple crops. The moderate reduction under the soil-applied mix Primextra TZ Gold + Yastryb corresponds with reports that pre-emergence chloroacetamide-based programs exert limited short-term stress on floral tissues, while the sharper decline under Eclipse + Filder is consistent with the higher volatility and residual action of clomazone, which can transiently bleach petals and alter nectar secretion. Such plant-mediated effects likely explain why differences in bee activity persisted even under standardised hive density. Post-emergence herbicides showed the steepest visitation losses, a result comparable with those of M. Saleem *et al.* (2023), who documented reduced pollinator activity and seed production under intensive pesticide regimes in sunflower. The pronounced decline under Helianthex (ALS inhibitor) matches the mechanism-based expectation that interference with amino-acid biosynthesis and photosynthetic metabolism suppresses nectar and pollen formation. Challenge (aclonifen) and Stels (a PPO inhibitor) caused smaller penalties, reflecting their limited systemic mobility. These chemical-specific outcomes reinforce the view that physiological selectivity and timing relative to reproductive stages are decisive for pollinator safety.

The outcomes of the present research closely aligned with recent advances in pollinator-pesticide interaction studies. According to P. Basu *et al.* (2024), the impact of pesticide use on pollinators depended not only on active ingredients but also on application timing, mobility and the sensitivity of floral tissues. This concept supported the clear distinction observed between soil-applied programmes and post-emergence chemistries: the former exerted limited physiological stress, whereas the latter strongly interfered with nectar and pollen formation. The multiscale perspective proposed by O. Catrice *et al.* (2023) further reinforced the need to assess sunflower-pollinator interactions across physiological, agronomic and landscape levels. Their findings mirrored the current results by indicating that pollination outcomes could not be explained solely by floral traits but must integrate management regimes and environmental stressors. Physiological mechanisms underlying bee-herbicide interactions were also evident. W.M. Farina *et al.* (2019) demonstrated that glyphosate exposure impaired sensory perception and cognitive performance of *Apis mellifera*, even in the absence of lethal doses. This observation corresponded with the steeper reduction in bee visitation recorded under post-emergence ALS inhibitors, where disruption of amino acid synthesis and photosynthetic metabolism likely suppressed nectar secretion. Comparable trends were reflected in the current study, where lower systemic mobility of Stels and Challenge resulted in smaller penalties, supporting earlier claims regarding the role of herbicide selectivity in pollinator safety.

The influence of pollinator density had previously been examined by M. Reyes *et al.* (2024), who showed that increased hive numbers significantly shaped sunflower yield components. Their findings implied that physiological stress from chemical treatments may alter pollination efficiency even under equal hive distribution, which corresponded with the observed differentiation in visitation among herbicide programmes despite standardised stocking rates. This highlighted the sensitivity of sunflower–bee systems to both chemical and ecological contexts. Climatic variability further moderated treatment effects. The precision-agronomy framework developed by M. Zalai *et al.* (2025) demonstrated that sowing accuracy, water availability and microenvironment regulation were decisive for reproductive stability in sunflower. These conclusions corresponded with the narrowing differences between treatments under the drought conditions of 2024, suggesting that hydrothermal stress could override management-based effects. The current findings therefore indicated that herbicide compatibility must be interpreted in relation to seasonal variability and agronomic environment, rather than solely through crop protection objectives.

Seasonal patterns underline the sensitivity of bee-sunflower systems to hydrothermal stress. The drought year 2024 produced a decline in visits, aligning with the results of Q. Ali *et al.* (2024), who showed that water shortage curtails floral reward production and modifies pollination efficiency. The narrowing of treatment differences during this season suggests that climatic stress can override management effects – an increasingly relevant factor under continental climate variability. The yield data broadly followed visitation trends yet did not coincide perfectly, an outcome typical of pollination-limited crops. L. Mota *et al.* (2022) emphasised that final yield integrates both pollinator supply and crop physiological status; where herbicides induced only mild stress, assimilating flow during grain filling buffered yield losses. The relatively small reductions observed with Eclipse + Filder and Primextra + Yastryb confirm that soil-applied programs primarily affect early growth rather than reproductive success. Conversely, foliar ALS and imidazolinone treatments act during active photosynthesis, disturbing carbon allocation and head development – hence the larger penalties under Helianthex and Pulsar Flex. Such partial decoupling between bee visitation and yield has been noted previously in hybrid trials where reproductive compensation mitigated the effects of reduced pollination. The magnitude of pollination benefit implied by control versus herbicide contrasts fits well within the empirical range reported for sunflower in Europe and Ukraine. I. Kulynych and T. Soloviova (2021) observed yield increase of 20-47 % with managed bees, while P. Herasymiuk *et al.* (2025) reported yield losses up to 57 % when pollinators were excluded. Three-year average differentials between the control and chemical variants fall squarely within this range, confirming the robustness of the pollination effect across climatic zones. Treatment-specific insights, however, extend earlier Ukrainian work by identifying which herbicide groups exert the smallest interference with bee activity, thereby bridging agronomic weed management and ecological outcomes. Landscape and habitat conditions may further modulate these relationships. S. Boinot *et al.* (2024) and C. Siopa *et al.* (2024) demonstrated that herbicide intensity and habitat simplification reduce overall pollinator abundance. Even though the present study equalised hive distance, the simplified vegetation of the Steppe region likely accentuated the influence of floral stress from foliar treatments. Incorporating habitat buffers, as recommended by L. Mota *et al.* (2024), could mitigate these effects and sustain visitation in chemically managed fields.

The collective evidence from this and other studies points toward an integrative management framework. Herbicide programs differ markedly in their compatibility with pollination processes: pre-emergence mixtures with moderate persistence (e.g., Primextra + Yastryb) and low-mobility post-emergence products (Challenge, Stels) appear most pollinator-safe. Programs relying on high-systemicity ALS inhibitors near anthesis pose greater risks to bee visitation and potentially to colony activity. Such distinctions are crucial for balancing weed control efficacy with the ecosystem services that underpin sunflower productivity. Climatic variability remains a dominant constraint. Under drought and high temperatures, even the most bee-friendly programs cannot fully maintain pollination rates, underscoring the need for adaptive scheduling of herbicide applications, supplemental irrigation where feasible, and hybrid selection with stronger floral resilience. Long-term sustainability will depend on integrating chemical choice with ecological infrastructure – flower strips, staggered bloom resources, and colony management – to stabilise both pollinator activity and yield in sunflower agroecosystems of the Eastern Steppe.

CONCLUSIONS

Across three-year field experiment (2022-2024) was demonstrated that the interaction between herbicide program, hybrid genotype, and seasonal weather strongly determines both bee visitation and sunflower yield. Across all treatments, the hand-weeded control remained the most favorable for pollinators, recording an average of 6.11 bee visits per head per 10 minutes and the highest yields (3.84 t ha^{-1}). Among the studied hybrids – Biloba CLP, NK Neoma, and Suvex – clear differences in pollinator attractiveness and productivity were observed. NK Neoma maintained the highest mean yield (4.03 t ha^{-1} in control plots) and relatively stable bee visitation across herbicide programs, confirming its better tolerance to both chemical and drought stress. Biloba CLP achieved slightly lower yields (3.76 t ha^{-1}) and showed moderate sensitivity to herbicide application, whereas Suvex proved the most susceptible, with average yields declining from 3.73 t ha^{-1} in the control to 2.87 t ha^{-1} under post-emergence treatments. A distinct pattern emerged between herbicide categories. Soil-applied herbicides caused moderate decreases in bee visitation (-29 to -56%) and yield (-8 to -9%) relative to the control. Within this group, the combination Primextra TZ Gold + Yastryb produced the smallest reduction in pollinator activity (average 4.33 visits $head^{-1}$ 10 min^{-1}) and yield (-0.35 t ha^{-1}). Eclipse + Filder showed slightly stronger effects, especially under low moisture, but remained less detrimental than any post-emergence treatment.

Post-emergence herbicides, by contrast, exerted a greater negative impact, reducing bee visitation by 33-86 % and yields by 15-27 %. Among them, Challenge (0.4 L ha^{-1}) and Stels (0.35 L ha^{-1}) were the least harmful, maintaining bee visitation around 3.1-4.1 visits head^{-1} 10 min^{-1} and yields close to 3.1-3.3 t ha^{-1}, while Helianthex (45 g ha^{-1}) caused the sharpest decline in both metrics (-82% bee activity; -27 % yield). These results indicate that pre-emergence programs are inherently safer for pollinators because they act before flowering and do not directly affect floral physiology, whereas foliar ALS-inhibiting or imidazolinone herbicides applied near anthesis impose greater physiological stress on plants and reduce nectar secretion. The drought year 2024 amplified yield losses and reduced bee activity to 1.28 visits head^{-1} 10 min^{-1} on average, confirming that climatic stress can override chemical effects. Still, the relative ranking of treatments remained consistent, supporting the robustness of these trends. Overall, the findings show that soil-applied herbicides are significantly less risky for pollinators than post-emergence ones, and that hybrid selection can mitigate or exacerbate chemical stress effects. For sustainable sunflower production in Ukraine's Eastern Steppe, integrating pre-emergence programs with pollinator-friendly, low-mobility post-emergence products (such as Challenge or Stels) and drought-resilient hybrids like NK Neoma will provide the best compromise between weed control efficiency, pollination safety, and yield stability.

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Вплив гербіцидів на запилення бджолами та взаємозв'язок із урожайністю у виробництві соняшнику

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Анотація. Метою дослідження було кількісно оцінено та порівняно вплив ґрунтових і післясходових гербіцидних програм на відвідуваність соняшника бджолами та урожайність різних гібридів за контрастних сезонних умов у Східному Степу України. Польові експерименти проводилися у 2022–2024 рр. в селі Василівка (Дніпропетровська область) із використанням трьох гібридів (Biloba CLP, NK Neoma, Suvex), ручного прополювання як контролю, двох ґрунтових програм (Primextra TZ Gold + Yastryb; Eclipse + Filder) та кількох післясходових варіантів (Helianthex, Stels, Challenge, Pulsar Flex, Granstar), застосованих згідно з етикетковими нормами. Кількість бджолосімей становила 5 вуликів на гектар з вирівнюванням дистанції льоту. Активність бджіл у період цвітіння фіксувалася за допомогою 24 камер GoPro (10:00–12:00; чотири дні; три повторення) та виражалася як кількість візитів на кошик$^{-1}$ за 10 хв$^{-1}$, тоді як урожайність (т га$^{-1}$ при 7 % вологості) визначалась після збирання. Погодні умови істотно різнилися, зокрема 2024 рік характеризувався вираженою посухою. У контролі зафіксовано найвищу відвідуваність бджолами (у середньому 6,11 візитів кошик$^{-1}$ за 10 хв$^{-1}$). Ґрунтові програми знижували відвідуваність на 29–56 %, причому найменше зниження спостерігалося за Primextra TZ Gold + Yastryb (-29 %), а найбільше – за Eclipse + Filder (-56 %). Післясходові програми зумовили зниження на 33-86 %: Challenge (0,4 л га$^{-1}$) спричинив найменший вплив (-33 %), тоді як Helianthex (45 г га$^{-1}$) – найбільший (-82 %). Відвідуваність бджолами була виражено залежною від року проведення експерименту (≈4,5-5,0 у 2022-2023 рр. проти 1,28 у 2024 р.). Урожайність демонструвала часткове розходження з динамікою візитів: серед ґрунтових варіантів найменше зниження зафіксовано для Eclipse + Filder (-0,31 т га$^{-1}$; -8 %), за ним слідував Primextra TZ Gold + Yastryb (-0,35 т га$^{-1}$; -9 %); серед післясходових програм найкраще проявив себе Stels (-0,58 т га$^{-1}$; -15 %), перевищивши Challenge (-0,76 т га$^{-1}$; -20 %) та Helianthex (-27 %). Загалом ґрунтові гербіциди продемонстрували нижчий ризик для активності запилювачів та урожайності порівняно з післясходовими ALS/імідазоліноновими сполуками, тоді як посуха залишалася домінуючим обмежувальним чинником обох процесів. Інтеграція гербіцидного вибору з урахуванням запилювачів та сезонних ризиків розглядається як шлях до підтримання екосистемних послуг і продуктивності агроценозу

Ключові слова: соняшник; відвідуваність бджолами; гербіцидні програми; привабливість для запилювачів; урожайність