Original Article

TOXICOLOGICAL IMPACT OF LAMBDA-CYHALOTHRIN ON *APIS MELLIFERA*: COMPARATIVE ANALYSIS UNDER SEMI-FIELD AND FIELD CONDITIONS

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Abstract

Lambda-cyhalothrin is the most widely used insecticide worldwide. This study investigates the impact of lambda-cyhalothrin on honeybees (*Apis mellifera*) colonies under semi-field and field conditions utilizing the formulated product (Karate 5% at a concentration of 0.85 ml/l). Considering the application of lambda-cyhalothrin in onion fields, the foraging activities reduced by 27.89 and 29.28% under semi-field and field conditions, respectively. The number of dead workers in the comparison group was three-fold higher than that in the control group under both semi-field and field conditions. Under semi-field and field conditions, reductions were observed in the brood (22.6 and 24.01%), pollen (94.46 and 41.51%), and nectar (69.27 and 44.50%) areas. The effect of lambda-cyhalothrin on the strength of *A. mellifera* under semi-field conditions resulted in a significant decrease until the 14th day (2.20 bee frames/hive) and in field condition it was on the 7th day (4.79 bee frames/hive). This highlights the non-bee-safe nature of lambda-cyhalothrin when applied during flowering, and spraying should be avoided to reduce its contamination of nectar and pollen. Overall, our results show the significance of conducting field trials to accurately assess the risk of pesticides, depicting a more realistic exposure scenario under actual colony conditions.

Keywords: brood area, lambda-cyhalothrin, mortality, toxicity

INTRODUCTION

The use of agricultural inputs in India, particularly agrochemicals, was introduced to the small holder farmers, facilitated by diverse agricultural extension systems since the 1960s (Nedumaran & Ravi, 2019). This shift enhanced crop yields and mitigated losses, increasing the use of agrochemicals on a significant scale, with pesticide usage in India increasing from 154 t in 1954 to a staggering 88,000 t in 2000, representing a 570 times increase in less than half a century (Bonvoisin et al., 2020). As of 2020-2021, the pesticide consumption in India was approximately 62,193 t (FAOSTAT, 2021). Alarming statistics from the United Nations Organization for Food and Agriculture rank India as the second highest consumer of pesticides in Asia, with

a consumption rate of 0.29 kg/ha (Sharma et al., 2020).

Within this surge in agrochemical use, pyrethroids have emerged as the predominant insecticides, overtaking organophosphorus insecticides, and are now the most commonly used insecticides worldwide (Saillenfait et al., 2015). However, the widespread use of agrochemicals in agriculture has caused greater toxicity for bees, resulting in a rise in honeybee colony mortalities globally. This alarming issue has drawn considerable attention from the scientific community, highlighting the potential repercussions of pesticide misuse on the survival of pollinators (Chauzat et al., 2009; VanEngelsdorp et al., 2009). The detection of lambda-cyhalothrin residues in plant nectar and pollen grains indicated the potential impact of its use on honeybee health through natural environmental exposure (He et al., 2008; Abdel-Razik, 2019). Lambda-cyhalothrin targets ion channels that are involved in the functioning of various tissues (including the nervous and muscular systems). Its primary mode of action is known to hinder the normal functioning of voltage-gated sodium channels (Field et al., 2017).

Traditional pesticide regulations typically prioritize poisoning effects, emphasing the acute toxicity and lethal dosages required by regulatory agencies for product registration (OECD, 2017). However, bees often encounter pesticides in sublethal doses within their environment, which affect multiple developmental stages, including foragers, larvae and newly emerged bees (Dively & Kamel, 2012). Sublethal doses pose a significant threat to the survival of the entire bee colony (Wu-Smart & Spivak, 2016) with harmful effects, including reduced responsiveness to sucrose stimulation (Aliouane et al., 2009) and impaired pollination activities (Gill et al., 2012).

Although these studies suggest that the sublethal effects of most insecticides are molecule-specific and cannot simply be extrapolated directly from the LD_{50} values, none of these molecules have collectively been tested in parallel tests in the same experimental conditions. Another aspect of toxicological studies on honeybees is the complexity of the formulation of commercial products. Although several studies have used pure active ingredients, real-world applications of formulated products also contain adjuvants with potential effects on bees. All these compounds have the potential to interact with each other and other ingredients. In this study, we examined the sublethal effects of pesticide exposure on honeybee colonies, which may affect their biology and evaluated two approaches for evaluating the toxicity to honeybees in diverse situations. We employed a two-tier assessment scheme comprising early studies in semi-field and field studies with formulated products (Karate 5%). Similar studies were carried for evaluating Thiamethoxam (Negi et al., 2022). Parameters such as foraging activity, mortality in field conditions, brood area, bee strength, pollen and nectar storage were included for semi- field and field studies.

MATERIAL AND METHODS

Our study was conducted between 2020-2022 in the experimental fields of Seed Science and Technology at Dr. Y. S. Parmar University of Horticulture and Forestry, a) colony performance under cage or semi-field conditions, and b) colony performance under field conditions.

Semi-field Studies and Field Studies

To determine the impact of lambda-cyhalothrin spray (0.85 g/l), the Pandah, Khaltoo, and Manhat experimental sites were selected for growing onion crops. Onion (*Allium cepa* var. Palam Lohit) was sown as per the package and practices in the Seed Science and Technology experimental fields, Pandah Farm for semi-field experiments. Khaltoo and Manhat were sown for for field experiments in which one site was exposed to lambda-cyhalothrin and the other was exposed to water spray only (control). The three sites were separated by 2-3 kilometers to prevent bees from foraging in other fields. In the semi- field, nine cages, measuring 40 m^2 (8×5) each were affixed to iron poles, with three cages dedicated to each treatment. Nylon was utilized for constructing these cages. The bee colonies selected for the

study were healthy, devoid of any disease, and had been subjected to no chemical treatment for the prior four weeks. Each cage housed a colony comprising three fully developed frames which contained brood cells at different development stages, as well as a comb containing pollen and nectar. At the entrance of each hive, a dead-bee trap (100×50×10 cm) was installed, and a linen sheet (15 m^2) was spread in front of the hives after the dead-bee trap. The colony was divided into young bees before the bees were placed inside the cages to limit the abundance of active foragers that were subsequently introduced into the cages after 10% bloom of the onion crop. After relocation-related mortality stopped, lambda-cyhalothrin was sprayed at a field application rate of 0.85 ml/l, whereas a control group received water spray, and both treatments were applied onto the blooming onion crop at 17:00 (local time). Throughout the 14-day testing period, the colonies were provided with water. Subsequently, the colonies were transferred to pesticide-free areas. Spray calibration was conducted based on the nozzle output rate and application time according to the methodology of the Bureau of Indian Standards (BIS, 1985). The spray was applied first to the control and then to the insecticide treatments.

In field experiments, the hives included five frames, each containing at least 10,000 bees (three brood frames and two storage frames). At 10% bloom, the bee colonies were transported to the test locations (treated and untreated). The hives were placed on the field boundaries so that the bees could fly over the treated fields. The insecticide dose mentioned above was applied in the evening. The honeybee colonies were exposed to treatments for fourteen days in the field and the impact of insecticides was observed. They were subsequently shifted to pesticide-free sites and further observed for twenty-eight days for post-exposure effects.

Observations recorded for semi-field and field studies

Honeybee mortality was calculated by enumerating the daily number of dead adult bees using dead-bee traps, linen sheets and routes within cages over fourteen days. The foraging activity was recorded by observing a 1 m wide transect along each side of the cage at 10:00, 12:00, and 15:00 h (local times) for fourteen days. The condition of the colonies was evaluated based on colony strength, comb area with pollen and nectar (cm^2), and total brood area (cm^2).

Statistical analysis

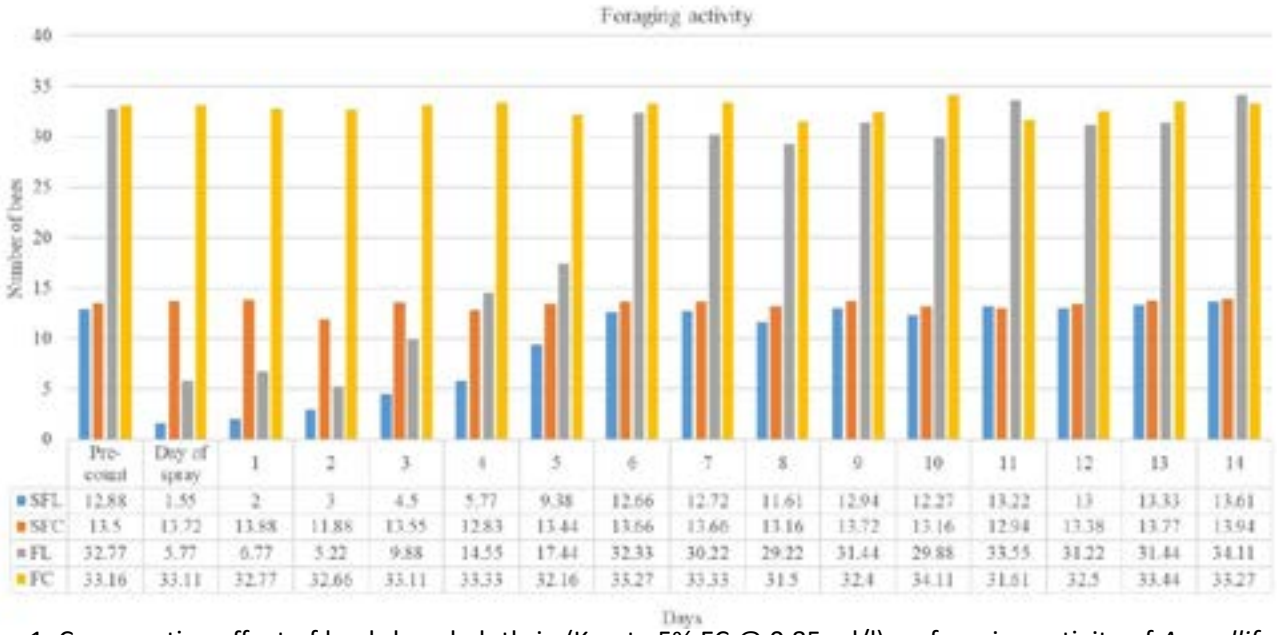
The data recorded for various parameters under field and semi-field conditions was analyzed in OPSTAT with suitable transformation in Randomized Block Design as suggested by Gomez & Gomez (1984). Analysis of variance (ANOVA) was used to compare the treatments at various days after the treatment (Sheoran et al., 1998).

RESULTS

Foraging activity

In the lambda-cyhalothrin-treated plots, a significant decrease was observed in bee count, which reached its lowest on the second day (3.00 bees/m^2/2 min), and the foraging activity remained consistently low up to the sixth day (12.66 bees/m^2/2 min). The overall statistically higher average bee count in the control group (13.39 bees/m^2/2 min) than that in the lambda-cyhalothrin-treated group (9.65 bees/m^2/2 min), indicated a 27.89% reduction in bee count owing to the chemical spray (Fig. 1). The lambda-cyhalothrin-treated *A. mellifera* foragers were confined inside the hive, and little activity was observed at the entrance as lambda-cyhalothrin exhibited a repelling effect on bees.

Under field conditions, after the application of the recommended lambda-cyhalothrin spray, significant decreases were observed in bee count on the day of spraying (4.22 bees/m^2/10 min) and day 1 (5.50 bees/m^2/10 min), followed by a recovery on day 7 (32.00 bees/m^2/10 min). Overall, the foraging activity in lambda-cyhalothrin-treated plots (23.23 bees/m^2/10 min) was significantly lower than that of the control group (32.86 bees/m^2/10 min), which indicated that the foraging activity in the lambda-cyhalothrin treated plots reduced by 29.28% compared with that in the control.



	Pre-count	Day of spray	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SFL	12.88	1.55	2	3	4.5	5.77	9.38	12.66	12.72	11.61	12.94	12.27	13.22	13	13.33	13.61
SFC	13.5	13.72	13.88	11.88	13.55	12.83	13.44	13.66	13.66	13.16	13.72	13.16	12.94	13.38	13.77	13.94
FL	32.77	5.77	6.77	5.22	9.88	14.55	17.44	32.33	30.22	29.22	31.44	29.88	33.55	31.22	31.44	34.11
FC	33.16	33.11	32.77	32.66	33.11	33.33	32.16	33.27	33.33	31.5	32.4	34.11	31.61	32.5	33.44	33.27

Fig. 1. Comparative effect of lambda-cyhalothrin (Karate 5% EC @ 0.85 ml/l) on foraging activity of *A. mellifera* on onion bloom under semi-field and field conditions.

Mortality

The analysis of *A. mellifera* mortality from lambda-cyhalothrin-treated onion blooms (2020-2022, semi-field conditions, Tab. 1) indicated significant mortality on the first (61.50 bees/day) and second (41.83 bees/day) days. During days 1, 2, 3, 4, and 5, mortality due to lambda-cyhalothrin-treated crops exceeded that of the water-sprayed control. The overall average daily mortality of the treated crop was 18.30 bees, significantly higher than that of the control (6.94 bees).

The results obtained under field conditions revealed that mortality reached statistical equivalence with the pre-count (12.66 bees/day) on the sixth day. Day-wise comparisons of mortality with that of the control revealed higher mortality up to the sixth day in the sprayed field; subsequently, no significant observed difference was indicated that lambda-cyhalothrin caused significant bee mortality up to the seventh day under field conditions. The overall average bee mortality in bee colonies foraging on the lambda-cyhalothrin-treated onion crop (18.77 bees/day) was significantly higher than that on the water-sprayed control crop (6.16 bees/day), which indicated that the mortality in the lambda-cyhalothrin-treated group was approximately three-fold higher than that in the control.

Brood area, bee strength, and pollen and nectar areas (cm²) of *Apis mellifera* foraging on the onion bloom under semi-field conditions during 2020-2022

Lambda-cyhalothrin resulted in a significant decline in the brood area of *A. mellifera* colonies foraging on onion crops on the seventh and fourteenth days (823.16 and 639.00 cm^3, respectively, Tab. 2) compared with that one day before the introduction (1056.33 cm^3) of colonies. The day-wise brood areas in the hives within the treated crops consistently showed lower values than that of the control group throughout the study period. Based on the overall comparison, the brood area in the unsprayed onion crop (953.67 cm^2) was significantly higher than that of the lambda-cyhalothrin-treated crop (737.90 cm^2), which reduced by 22.6%. The observed decline in the *A. mellifera* hive brood area may be attributed to variations in foraging activity, as evidenced by data presented in the foraging activity table.

The effect of lambda-cyhalothrin on the strength of *A. mellifera* under semi-field conditions during 2020-2022 (Fig. 2) resulted in a significant decrease until the 1 day (2.20 bee frames/hive) compared with that during the pre-count. Thereafter, a significant increase in colony strength was observed on the 28th day (2.54 bee frames/hive),

Table 1.

Pooled data on mortality of bees in Lambda-cyhalothrin treated onion bloom under field and semi-field conditions during 2020-2022

Number of dead bees/DBT and Linen sheet/ Day				
	Semi-field		Field	
DAS**	Lambda-cyhalothrin	Control	Lambda-cyhalothrin	Control
Pre-count (One day before spray)	11.66 (3.53)*	11.33 (3.49)	12.66 (3.68)	10.50 (3.38)
1	61.50 (7.88)	9.50 (3.16)	58.83 (7.65)	6.00 (2.60)
2	41.83 (6.53)	10.50 (3.34)	49.50 (7.05)	5.16 (2.42)
3	39.16 (6.33)	10.66 (3.39)	34.66 (5.93)	7.50 (2.87)
4	33.00 (5.80)	10.83 (3.38)	28.00 (5.34)	7.83 (2.93)
5	23.33 (4.90)	7.66 (2.94)	17.66 (4.26)	4.00 (2.23)
6	13.33 (3.76)	8.66 (3.10)	14.16 (3.88)	6.33 (2.67)
7	13.16 (3.74)	3.83 (2.18)	9.16 (3.17)	6.83 (2.75)
8	7.83 (2.96)	2.00 (1.72)	10.16 (3.32)	4.00 (2.22)
9	5.50 (2.51)	3.33 (2.05)	7.33 (2.87)	6.83 (2.76)
10	5.50 (2.50)	6.83 (2.73)	9.50 (3.23)	3.16 (2.03)
11	5.50 (2.52)	6.00 (2.60)	7.50 (2.88)	4.16 (2.26)
12	2.66 (1.90)	5.66 (2.53)	10.00 (3.29)	7.16 (2.83)
13	5.33 (2.50)	4.16 (2.25)	5.33 (2.48)	7.50 (2.91)
14	5.16 (2.47)	3.16 (2.02)	7.16 (2.85)	5.50 (2.54)
Mean	18.30 (3.99)	6.94 (2.73)	18.77 (4.13)	6.16 (2.63)
C.D. $_{(p=0.05)}$	Treatment (0.26), Treatment × Days (1.01)		Treatment (0.26), Treatment × Days (1.01)	

*Figures in parentheses are √n+1 transformation values

** DAS (days after spray)

Table 2.

Pooled effect of lambda-cyhalothrin (Karate 5% E.C @ 0.85 g/l) on brood, pollen and nectar (cm^2) of *A. mellifera* on onion bloom under semi-field conditions during 2020-2022

DAS**	Brood area (cm^2)		Nectar area (cm^2)		Pollen area (cm^2)	
	Treatment	Control	Treatment	Control	Treatment	Control
Pre-count (one day before introduction)	1056.33	1025.00	258.00	262.33	226.33	267.83
	(32.48)*	(31.97)	(15.91)	(16.18)	(15.07)	(16.38)
7th day	823.16	919.33	148.33	276.50	108.83	266.50
	(28.67)	(30.30)	(12.11)	(16.63)	(10.45)	(16.35)
14th day	639.00	886.83	129.50	250.00	93.33	231.16
	(25.29)	(29.76)	(11.40)	(15.80)	(9.68)	(15.22)
21st day	534.16	974.00	128.83	289.33	104.50	241.83
	(23.08)	(30.08)	(11.37)	(17.02)	(10.26)	(15.57)
28th day	636.83	1033.50	157.83	313.50	122.83	267.66
	(25.23)	(31.98)	(12.55)	(17.70)	(11.10)	(16.38)
Mean	737.90	953.67	164.50	278.33	131.16	255.00
	(26.95)	(30.82)	(12.67)	(16.67)	(11.31)	(15.98)
CD(p=0.05)	Treatment (1.27), Treatment × days (2.84)		Treatment (1.13), Treatment × days (2.53)		Treatment (0.49), Treatment × days (1.11)	

*Figures in parentheses are √n+1 transformation values
** DAS (days after spray)

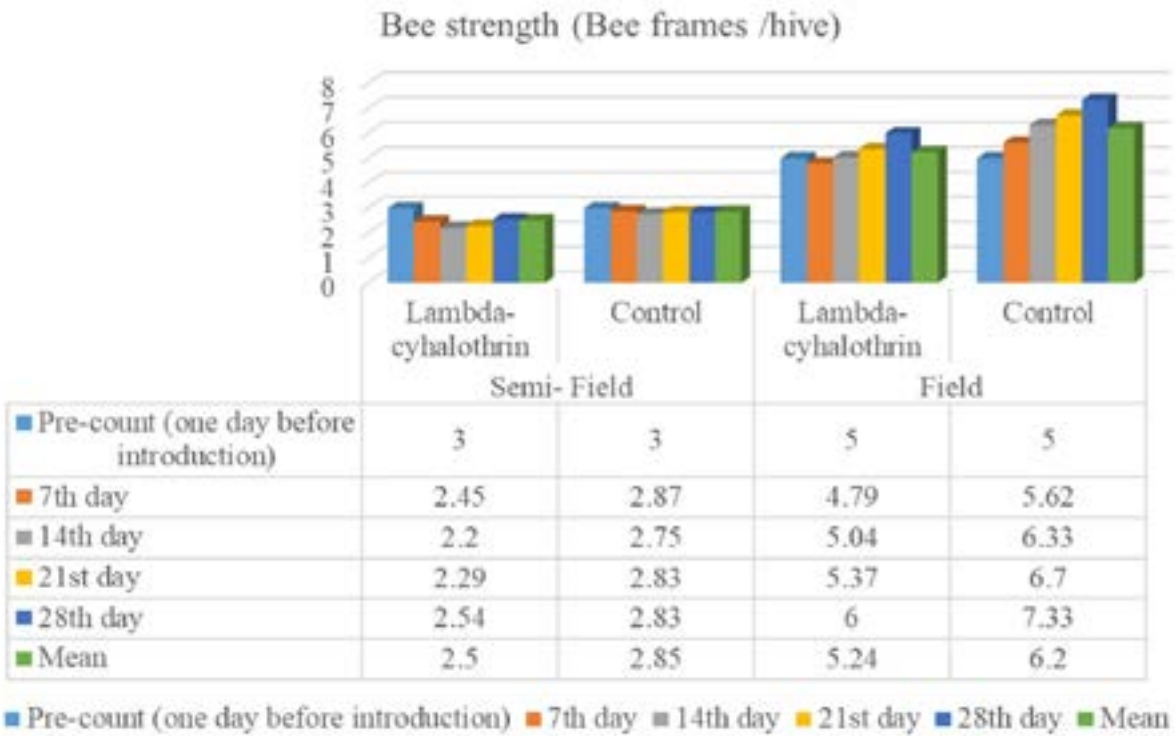


Fig. 2. Comparative effect of lambda-cyhalothrin (Karate 5% EC @ 0.85 ml/l) on bee strength of *A. mellifera* on onion bloom under semi-field and field conditions.

which was still less than that during the pre-count. Irrespective of the day, the bee strength differed significantly between the treatments. Significantly higher bee strength was observed in the control group (2.85 bee frames/hive), followed by the lambda-cyhalothrin group (2.50 bee frames/hive). The *A. mellifera* nectar stores significantly reduced in the lambda-cyhalothrin-treated group (148.33 cm^2) on the seventh day compared with that during the pre-count, which further decreased in both till the 21st day but with no significant differences. This interaction effect indicated that the nectar stores significantly reduced by 69.27% in hives placed in both the chemically sprayed plots compared with that in the control group.

Considering the pollen area, the pollen stores remained significantly low up to the seventh day (108.83 cm^3), followed by the those on 14th day (93.33 cm^3) with no significant difference. A significantly lower pollen area was recorded in the lambda-cyhalothrin-treated group than in the control group on all observation days (7, 14, 21, and 28th days, Tab. 2). Moreover, the treated onion crops resulted in a 94.46% reduction in pollen area.

Brood, nectar, and pollen areas of *A. mellifera* foraging on the onion bloom under field conditions during 2020-2022

As presented in Tab. 3, the average *A. mellifera* brood area one day before lambda-cyhalothrin exposure (pre-count) was not as prominent, although the brood area decreased on the seventh day (1572.00 cm^2) and subsequently increased, but with a non-significant difference between the days with respect to the pre-count; thus, the effect of lambda-cyhalothrin on the brood area was not evident under field conditions. The overall brood area was found to be the highest (2225.83 cm^2) in the control group, followed by that in the lambda-cyhalothrin group (1691.53 cm^2), which showed a reduction of 24.01%. In this study, the average brood area of *A. mellifera* was significantly reduced on the seventh day post spraying. Under field conditions, a significant decline was observed in the nectar area on the seventh day (388.16 cm^2). A consistent significant decrease was observed in the nectar area from the 7th to 28th days after exposing the hives to lambda-cyhalothrin. Irrespective of the days, the maximum overall nectar stores (610.30 cm^2) were observed in the control group, and the nectar stores of the treated field showed a reduction of 44.50% (338.73 cm^2) compared with those of the control group.

As presented in Tab. 3, the average pollen collection by *A. mellifera* during 2020-2022 under the influence of lambda-cyhalothrin was statistically insignificant in all treatments throughout the study period. The average pollen stores in *A. mellifera* ranged from 279.33 to 452.50 cm^2 and 473.66 to 627.33 cm^2 in the lambda-cyhalothrin-treated and control groups, respectively, during the period of 28 days. The overall pollen area was the highest (565.60 cm^2) under controlled conditions, whereas the lowest pollen area was observed in the lambda-cyhalothrin-treated crop, which reduced by 41.51% (330.83 cm^2). This indicates that the lambda-cyhalothrin spray did not affect the average pollen stores in *A. mellifera*, possibly due to the normal bee activity at the hive entrance, and bees, instead of being confined to the hive, started foraging on alternate flowering areas around the colony. This was also evident from personal observations, wherein incoming *A. mellifera* specimens were observed with pollen loads during periods of low activity in the treated plots.

Figure 2 presents the effect of lambda-cyhalothrin spray on the strength of *A. mellifera* under field conditions during 2020-2022. The initial bee strength of *A. mellifera* one day before spraying lambda-cyhalothrin was 5.00 frames/ hive. Decreased bee strength was observed on the 7th day (4.79 bee frames/hive) but without a significant difference from the bee strength before spraying. Thereafter, increases were observed in colony strength on the 14th (5.04 bee frames/hive), 21st (5.37 bee frames/hive), and 28th days (6.00 bee frames/ hive), with a significant difference from that during the pre-count. In the hives placed in the water-sprayed onion crop, bee strength increased from 5.00 bee frames/hive during the pre-count to 5.62 bee frames/hive on the seventh day and 6.33 bee frames/hive on the 14th day, indicating significant differences. On the

Table 3.

Pooled effect of lambda-cyhalothrin (Karate 5% E.C @ 0.85 g/l) on brood area of *Apis mellifera* on onion bloom under field conditions during 2020-2022

DAS**	Brood area (cm^2)		Nectar (cm^2)		Pollen (cm^2)	
	Lambda-cyhalothrin	Control	Lambda-cyhalothrin	Control	Lambda-cyhalothrin	Control
Pre-count (one day before introduction)	1838.66	1951.16	497.00	502.83	452.50	473.66
	(42.67)*	(44.18)	(22.23)	(22.42)	(21.16)	(21.76)
7th day	1572.00	2154.00	388.16	591.33	321.66	540.33
	(39.31)	(46.33)	(19.62)	(24.32)	(17.57)	(23.20)
14th day	1619.67	2361.83	314.16	640.66	299.83	594.16
	(40.16)	(48.31)	(17.73)	(25.32)	(17.24)	(24.37)
21st day	1675.33	2332.17	257.16	647.83	279.33	627.33
	(40.88)	(48.06)	(16.04)	(25.47)	(16.67)	(25.04)
28th day	1752.00	2330.00	237.16	668.83	301.33	592.50
	(41.82)	(48.05)	(15.40)	(25.88)	(17.38)	(24.36)
Mean	1691.53	2225.83	338.73	610.30	330.83	565.60
	(40.97)	(46.99)	(18.21)	(24.68)	(18.00)	(23.75)
CD(p=0.05)	Treatment (1.72), Treatment × days (NS)		Treatment (1.06), Treatment × days (2.37)		Treatment (1.30), Treatment × days (2.92)	

*Figures in parentheses are √n+1 transformation values
** DAS (days after spray)

28th day, we observed a significantly higher bee strength of 7.33 bee frames/hive. Irrespective of the day, the overall average bee strength of water-sprayed fields (control) was the highest (6.20 bee frames/hive), followed by that of lambda-cyhalothrin-treated fields (5.24 bee frames/hive). The bee strength between treatments differed significantly when the hives were placed in lambda-cyhalothrin- and water-sprayed onion blooms under field conditions.

DISCUSSION

The obtained results of foraging are consistent with those reported by Tahir et al. (2017), who observed a significant decline in plant pollinators until the tenth day after lambda-cyhalothrin application to marigold fields. Similar findings were also reported by Ingram et al. (2015), who observed that bees treated with lambda-cyhalothrin travelled 30-71% less than control bees. Similar results were observed by Melisie et al. (2015), who studied the foraging activity of honeybees on onion flowers and observed a 77.43% reduction in foraging.

Differences in behavior were observed between semi-field and field conditions, with normal hive entrance activity in the field and foraging of bees in alternating flowering areas around the colony. This was also evident from personal observations, wherein incoming *A. mellifera* were observed with pollen loads during periods of low activity in the treated plots. Lambda-cyhalothrin exhibited repellency for four days. This is consistent with the results of previous studies which indicate the repellent nature of pyrethroids,

as observed in the studies of Thompson (2003) and Fries & Wibran (1987), who, for the first time, demonstrated that lambda-cyhalothrin exhibited repellency for 4-5 h post oilseed rape treatment. This study supports earlier research by Charreton et al. (2015), wherein the negative impact on bee locomotor abilities due to pyrethroids was found to be 71%. Similarly, Zhang et al. (2017) demonstrated that the contact exposure of honeybees to lambda-cyhalothrin dissolved in acetone led to a reduced lifespan, reduced proboscis extension reflex, and impaired homing ability. Havstad et al. (2019) also observed a 40% decline in honeybee population during the first week after spraying lambda-cyhalothrin.

Our results clearly show that mortality in lambda-cyhalothrin-treated onion blooms was lower than that in cage conditions, possibly owing to field repellence. Peak mortality during the first two days after spraying is consistent with the results of Belsky et al. (2022) who observed 80% mortality in *A. mellifera* during continuous thiamethoxam + lambda-cyhalothrin exposure. Our findings align with those of Arca & Saruhan (2022), who observed a significant mortality rate of 97.5% within the first five days of exposure to thiamethoxam + lambda-cyhalothrin. Additionally, we also found that mortality was reduced after seven days due to the dilution of the insecticidal spray, which is supported by the results of Akça & Saruhan (2022), who reported that the lethal time of lambda-cyhalothrin was 8.10 days. In accordance with these findings, Abdel-Razik (2019), observed a peak in mortality (66.9%) after seven days of lambda-cyhalothrin application. Under field conditions, mortality remained low compared with that under semi-field conditions, possibly owing to the reduced foraging activity of bees as opposed to being confined to the hive; the bees started foraging on alternate flowering areas around the onion fields. The mortality of bees was maximal after spraying owing to the residual action of insecticides. This result is supported by that of Nadaf et al. (2013), who observed 40% mortality after 2 h and 100% mortality after 4 h. Despite the repelling effect of lambda-cyhalothrin, bees that visited the sprayed flowers may have died from direct contact with the insecticide. Our results are consistent with those of Gill et al. (2012), who observed maximum mortality in lambda-cyhalothrin-exposed bees (51.6%), and those of Akca et al. (2009), who found that the mortality rate of bees treated with lambda-cyhalothrin at a concentration of 6.2 mg/l for 24 h was 37.20%. Similarly, the results of Bailey et al. (2005) also indicated that residual contact toxicity of tassels treated with lambda-cyhalothrin caused significant mortality one day after treatment (19.3%). These results are consistent with those of Abdel-Razik (2019), who recorded a decrease in foraging worker bees in the lambda-cyhalothrin-treated field (48.89%), attributed to the consumption of insecticide-contaminated pollen. Choudhary & Sharma (2008) reported the presence of lambda-cyhalothrin residues in mustard plant pollen immediately after spraying. Lambda-cyhalothrin exposure significantly affected the bee strength and resulted in the reduction of the colony strength of *A. mellifera* in terms of the number of bee frames. The reduction in bee frames is ascribed to the significant mortality of bees; another reason for the reduction in bee strength may be attributed to the consumption of contaminated nectar and pollen. These findings were corroborated by Desneux et al. (2007) and Koskor et al. (2009), who reported that bee larvae and adults may be killed or suffer from diverse sublethal effects when placed in contact with pollen and nectar contaminated with insecticides.

The significant decline in the nectar area could be ascribed to the significant mortality observed during the first week of spraying and the decrease in the number of worker bees collecting nectar. Another possible reason for the reduction in nectar area could be the aversion to collecting nectar from the treated field, as the bees remained confined inside the hive and were sustained by the available food stores. These results are consistent with those by Cox & Wilson (1984), Fries & Wibran (1987), Rieth & Levin (1988), and Decourtye et al. (2004), who reported a reduction in the foraging behavior of honeybees treated with pyrethroids, where as low pollen stores could be confinement and low foraging activity, as discussed above in Tab. 1 (comparative foraging

activity). Whitehorn et al. (2012) reported that pesticide-exposed *A. mellifera* colonies collected less pollen than control colonies. This result is consistent with those of Abdel-Razik (2019), who found that *A. mellifera* colonies exposed to lambda-cyhalothrin treatment demonstrated the highest decrease in the collection of pollen grains by workers (50.0%). Similarly, Dolezal et al. (2015) reported that hives fed with lambda-cyhalothrin-contaminated pollen consumed significantly less pollen over time than bees fed with pollen containing 140 ppb of cyhalothrin.

Similarly, Abdel-Razik (2019), found a reduction in the brood area of *A. mellifera* foraging on fields contaminated with lambda-cyhalothrin, and reported a decrease of 22.92% in the area of worker brood due to other pesticides (Sandrock et al., 2014; Meikle et al., 2016). In our study, the reason for normal brood rearing after lambda-cyhalothrin treatment under field conditions was possibly because of the shifting of foragers from the target to alternate foraging crops available in the surroundings, ascribed to the repellency of lambda-cyhalothrin. A possible explanation for this result is that when provided with a range of foraging opportunities, honeybees may reduce their foraging visits to food sources containing pesticides (Mayer & Lunden, 1997; Colin et al., 2004; Mullin, 2010; Johnson, 2010). The reduction in bee frames was attributed to the significant mortality of the bees, as discussed above. Moreover, the reduction in bee strength may also be because of the harmful nectar and pollen procured by bees feeding on contaminated fields, including pesticide-polluted plants, that affect the honeybee colony. Newly emerged bees are particularly affected by this phenomenon (Girolami et al., 2009; Pohorecka et al., 2012).

In conclusion, the two methods employed in the experiments revealed different effects on honeybees. The residual effects of lambda-cyhalothrin were determined to be significant in both semi-field and field conditions even after five days. The findings suggest that lambda-cyhalothrin has adverse effects on the foraging activity, colony parameters and mortality of *A. mellifera* under semi-field conditions. There was a marked reduction in bee activity, the colony parameters of brood area, nectar, pollen stores and overall bee strength following lambda-cyhalothrin application in onion crop. Furthermore, evidence of crop avoidance behavior by honey bees further supports the detrimental impact of lambda-cyhalothrin on foraging activities. The effect of lambda-cyhalothrin under field conditions was less pronounced with respect to bee mortality and colony parameters.

Ethics approval and consent to participate

All the methods were performed in accordance with the relevant guidelines/regulations/legislation.

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