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Plant derived formulation *Brahmastra* for the management of peach leaf curl aphid, *Brachycaudus helichrysi* (Kaltenbach, 1843) and its natural enemies under organic orchard conditions

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Abstract

The peach leaf-curl aphid, *Brachycaudus helichrysi* (Kalt.), is a major early-season pest of peach, causing severe leaf curl, stunting and yield loss when left unmanaged. In a two-year field study, the population dynamics of *B. helichrysi* in peach orchard (cv. Shan-e-Punjab) revealed a distinct outbreak pattern, with low infestation until standard meteorological week (SMW) 4, a sharp rise between SMW 7–10 and a clear peak between SMW 11–12, indicating a main risk window of SMW 7–13 under the local climate. The efficacy of *Brahmastra*-based formulations and a homemade neem extract was evaluated on aphid density, coccinellid abundance, predator–prey ratios and yield under organic compatible conditions. *Brahmastra* at 18.0 L ha^{-1} and the homemade neem extract at 5.0 L ha^{-1} produced significant suppression of *B. helichrysi* and the highest percent reduction over control (73.50% and 64–65%, respectively), along with the greatest fruit yields (63.00 and 62.17 t ha^{-1}) and net returns. Treatment T4 also maintained the most favourable predator-prey ratio (0.40), indicating relatively good compatibility with coccinellid populations, whereas lower *Brahmastra* doses and a soap-based treatment provided weaker control and smaller economic gains. Overall, the study suggests that Brahmastra and neem derived inputs, applied at adequate doses and targeted to the SMW 7–13, can effectively suppress peach leaf-curl aphid while supporting conservation-based biological control, and thus constitute promising components of climate-informed, organic-compatible integrated pest management for peach.

1. Introduction

Peach (*Prunus persica* L.) is an important temperate fruit crop cultivated in most major fruit-growing regions of the world, with global harvested area estimated at around 0.87 million ha and annual production of about 27.1 million tonnes in recent years (Anonymous 2026c&d). The Fresh Peaches Market size is estimated at USD 13.46 billion in 2025, and is expected to reach USD 16.22 billion by 2030, at a CAGR of 3.8% (Anonymous 2026d). In India, peach is a niche but valuable fruit of the north-western and Himalayan states, occupying roughly 16.65 thousand ha, with Jammu & Kashmir, Himachal Pradesh and Uttarakhand as the leading producers with a production of 108.28 thousand MT (Govt. of India 2025). Peaches are mainly grown by small and medium orchardists, and the crop plays an important role in income diversification and livelihood security in hill and foothill ecosystems. In Punjab the peach occupies 2940 hectares (Anonymous 2026$_a$) of land contributing 52,723 metric tonnes of raw fruits during 2024-25 (Anonymous 2026$_b$).

Peach plants are susceptible to damage by numerous insect pests in India which includes peach leaf curl aphid, *Brachycaudus helichrysi* (Kaltenbach); peach black aphid, *Pterochlorus persicae* (Cholodkovsky); chaffers and other defoliating beetles (*Adoretus* spp.); hairy caterpillars (*Euproctis* sp.); fruit flies, *Bactrocera dorsalis* (Hendel) and *Bactrocera zonata* (Saunders); flat-headed borer, *Sphenoptera dadkhani* Obenberger; tortrix moth, *Archips micaceana* Walker; Castor capsule borer, *Conogethes punctiferalis* (Guenee) American bollworm, *Helicoverpa armigera* (Hubner) and Bark eating caterpillar *Indarbela* sp. (Singh et al., 2016). Among these, the peach leaf curl aphid, *Brachycaudus helichrysi* (Kaltenbach) (Hemiptera: Aphididae), is recognized as a major pest on peach and other stone fruits in many temperate regions worldwide (Singh and Sharma, 2012; King & Lujan 2025). The pest is highly polyphagous infesting about 175 species belonging to 115 genera and 49 plant families in India (Arora et al. 2009). Colonies of *B. helichrysi* develop on tender shoots and the undersides of young leaves, causing severe curling, chlorosis and premature defoliation, while the honeydew excreted by the aphids promotes sooty-mould growth that reduces photosynthesis and marketable fruit quality (Singh and Kaur 2015; Sharma and Khokhar 2018). Under favourable conditions, high aphid infestations can lead to considerable reductions in shoot growth, fruit set and yield, and the species can also act as a vector of virus diseases in stone-fruit orchards (Singh and Kaur 2015; Sharma and Khokhar 2018).

Control of aphids in conventional fruit production has relied largely on repeated applications of broad-spectrum synthetic insecticides during early shoot growth and fruit development periods (Shaw et al. 2021). However, intensive use of these compounds has resulted in the development of insecticide resistance in several aphid species (Krestonoshina et al., 2022 & Ullah et al. 2023) and has raised concerns regarding residues on fruit (WHO 2022; Ssemugabo et al. 2022 & Tambo et al., 2024), disruption of natural-enemy complexes and wider environmental and human-health risks (Isman 2006; Shaw et al. 2021). In organically managed orchards, where the use of most synthetic insecticides is prohibited, growers depend on cultural measures, conservation of natural enemies and a limited range of approved products, yet aphids remain difficult pests to manage effectively (Shaw et al. 2021; Porcel et al. 2018). These challenges have stimulated interest in plant-derived and other bio-rational products that can provide effective aphid suppression while remaining compatible with organic certification standards and biological control agents (Zehnder et al. 2007; Attra 2022). Globally, a wide array of botanicals, such as neem (*Azadirachta indica*) extracts, *Annona* formulations and various herbal decoctions have shown promising activity against aphids in vegetable, field and horticultural crops (Kassie et al. 2025; Prasannakumar et al. 2021, 2023 & 2025; Biswas 2013). Many of these products act as feeding deterrents, repellents, growth regulators or contact poisons, and they are generally biodegradable, leave minimal residues and are considered less harmful to natural enemies than conventional insecticides (Isman 2006; Dubey et al. 2008). Recent syntheses also emphasize the central role of predators and parasitoids in aphid suppression in diversified and organic systems, and document successful integration of biological control agents with selective inputs in different parts of the world (Porcel et al. 2018; Liu and Chen 2025). For *B. helichrysi* on peach, several coccinellid predators and parasitoids contribute to natural regulation of populations, and targeted conservation of these natural enemies is essential for long-term pest management (Singh and Kaur 2015; Bhandari et al. 2025).

Brahmastra is a farmer-prepared plant derivative extract consisting of fresh cow urine combined with leaves of neem (*A. indica*), karanj (*Millettia pinnata*), guava (*Psidium guajava*), papaya (*Carica papaya*) and castor (*Ricinus communis*) (Devrat 2019; Singh and Sidhu 2025). Chemical characterization of the extract revealed a mixture of flavonoids, terpenoids and fatty acids with documented antifeedant, growth regulating and pesticidal activities, which could explain its broad bio-rational action (Mabry et al. 1970; Koul 2008; Singh and Sidhu 2025). Despite this evidence, there is little information on the performance of *Brahmastra* against aphids in perennial fruit systems, particularly under organic orchard management where canopy structure, microclimate and natural-enemy assemblages differ from those in annual crops (Shaw et al. 2021; Porcel et al. 2018). Therefore, the present investigation was undertaken to evaluate the impact of *Brahmastra* on *B. helichrysi* and associated natural enemies in organically managed peach orchards. The specific objectives were: (i) to assess the efficacy of different field doses of *Brahmastra* in suppressing *B. helichrysi* populations; (ii) to determine its effects on key predators and predator-prey ratios; and (iii) to quantify any resultant changes in fruit yield under organic farming conditions.

2. Materials and methods

2.1 Study site characteristics

Field experiments were conducted during the spring seasons of 2022 and 2023 in an organically managed peach orchard located at Ballowal Saunkhri, district Saheed Bhagat Singh Nagar, Punjab, India (30° 44' and 32° 32' N and 75°52' E at an elevation of 335 m above mean sea level). The site lies in the sub-montane zone of lower Shivalik hills (Fig. 1) characterized with sub humid climate having hot summers, cool winters and an average annual rainfall of approximately 1100 mm, most of which occurs during the monsoon (July to September). The experimental orchard consisted of peach trees Shan-e-Punjab cultivar planted at 6 m × 6 m spacing and maintained without synthetic fertilizers or pesticides for more than three years prior to the study. The experimental field has sandy loam soil texture and is classified as Fluventic Ustochrepts (Soil Survey Staff, 2014) and does not exhibit any salinity issues. Well decomposed farmyard manure at 10 t ha^{-1} and recommended organic inputs were applied before bud break, and standard cultural practices such as pruning, irrigation and weeding were followed uniformly across all plots. The weather data of the experimental site is presented in Fig. 2. The mean monthly minimum and maximum air temperature varied between 3.8 to 21.20 and 7.6 to 42.80°C during the crop year with their respective plateau in January and April *i.e* Standard Meteorological Week (SMW) 1–18.

2.2 Preparation of *Brahmastra*

Brahmastra was prepared following the procedure described by (Devrat 2009; Maru et al., 2021) with minor modifications. Fresh leaves of neem (*A. indica*), lantana (*Lantana camara*), guava (*Psidium guajava*), *akk* (*Calotropis procera*) and *datura* (*Datura stramonium*) were collected from locally available trees. A twenty-litre metallic container was used, into which 10 L of fresh cow urine was added to a paste made from 3 kg neem leaves (27.27% w/v), 2 kg lantana leaves (18.18% w/v), 2 kg guava leaves (18.18% % w/v), 2 kg akk leaves (18.18% % w/v) and 2 kg datura leaves (18.18% % w/v). The mixture was boiled on a low flame three to four times with continuous stirring while keeping the container covered, then allowed to cool for 48 h, being stirred once each morning and evening to facilitate extraction of allelochemicals. The cooled mixture was filtered through a double layer of muslin cloth to obtain the stock *Brahmastra* extract, which was stored in clean, tightly closed container under shade until field application. Homemade neem extract (HMNE) was prepared by boiling 4.0 kg terminal parts of the shoots of neem trees (including leaves, green branches and fruits) in 10 litres of water for 30 minutes and then filtrate was used as per test concentrations (Anonymous 2022).

2.3 Experimental design and treatments

Population dynamics of *B. helichrysi* was monitored on 9 marked peach plants weekly from SMW 1–18 during 2022 and 2023. To assess natural population dynamics without interference from pest management interventions, these trees were maintained without insecticide application throughout the study period (Hall and Hentz, 2011). Nymphal counts were taken from five leaf whorls covering all four canopy directions (1–2 m height). Weekly mean populations were calculated, and the phenology of *B. helichrysi* was depicted by plotting mean adult and nymph counts over time. The field evaluation of *Brahmastra* against *B. helichrysi* was laid out in a Randomized Block Design (RBD) with six treatments and three replications. Each replication comprised of three contiguous peach plants with guard rows between treatments to minimize spray drift. The different treatments used were T1-*Brahmastra* @ 6.0 l^{-ha}, T2- *Brahmastra* @ 12.0 $l^{-ha,}$ T3-*Brahmastra* @ 18.0 $l^{-h,}$ T4-Home-made neem extract @ 5 L ha^{-1}, T5-Soap solution @0.1% and T5- Untreated control.

2.4 Field evaluation of *Brahmastra* and Application of treatments

Sprays were applied with a battery-operated knapsack sprayer (Mohindra GA-914) of 15 litre capacity fitted with a hollow cone nozzle to ensure thorough coverage of the foliage and terminals. Five litre of spray solution was applied to each tree for proper coverage. Peach trees under control treatment were not sprayed at all. In each season, the first application of *Brahmastra* was made when *B. helichrysi* populations levels reached approximately 50–60 aphids per leaf whorl based on preliminary surveys and available recommendations for peach leaf curl aphid (Gupta and Bhatia 2017). A second spray was given 7 days after the first application. All sprays were conducted in the late afternoon (15:00 17:00 h) under calm conditions to reduce drift and avoid direct exposure of natural enemies to fresh deposits.

2.4 Sampling of aphids and natural enemies

Within each treatment, three representative trees were permanently tagged. On each observation date, five current-season leaf whorls per tagged tree were selected at random from the mid-canopy covering all the directions. The number of *B. helichrysi* nymphs and adults was counted visually before spraying (pre-spray) and at 1, 3 and 7 days after each spray. At the same time, the numbers of key natural enemies, primarily coccinellid beetles per tree were counted. Any phytotoxic symptoms such as leaf burn, chlorosis or fruit russeting were noted on treated trees. For ecological interpretation, predator - prey ratios were calculated for each treatment and observation date by dividing the total predator count by the total aphid count pooled over the tagged shoots. Pooled predator - prey ratios across observation dates and seasons were also derived for each treatment.

2.5 Yield and Economic returns assessment

At commercial maturity, all fruits from the tagged trees in each treatment were harvested and weighed to obtain total yield per plot, which was then converted to quintals per hectare. To estimate the economic returns from the peach crop, yield benefits were calculated as the difference between treated and untreated control plots, multiplied by the average price of fruits, and then reduced by the costs of spray preparation and labor for application.

2.6 Data analysis

Observations on peach leaf curl aphid populations were recorded as the number of aphids per five leaf whorls of 10 cm length per plant from nine randomly tagged plants in each treatment at pre-spray, 3 DAS, and 7 DAS. Data on natural enemies, expressed as the number of coccinellids per plant, were recorded before spraying and at 7 DAS. Aphid and predator counts were square-root transformed before statistical analysis to stabilize variance, whereas yield data

were analyzed on the original scale. Pearson's correlation coefficients were calculated to describe relationships between *B. helichrysi* populations and abiotic variables The pooled data over years were subjected to analysis of variance (ANOVA) and treatment means were separated using the critical difference at the 5% level with OPSTAT online software (Sheoran et al., 1998). Predator - prey ratios were calculated for treated and untreated control plots and analyzed statistically. Fruit yield was recorded on a per-plant basis, converted to a per-hectare basis, and analyzed using the same statistical procedure without transformation. Percent reduction of aphids over the untreated control (PROC) for each treatment and observation date was calculated using:[6]

$$\text{PROC} = \frac{\text{Aphid count in contro - Aphid count in treatment}}{\text{Aphid count in control}} \times 100$$

3. Results

3.1. population dynamics of Brachycaudus helichrysi in peach

The results of the study indicated aphid incidence on peach displayed a pronounced, short early-season outbreak pattern in both years *i.e.* spring of 2022 and 2023, with consistently higher densities in 2023 than in 2022 (Fig. 3). The orchards remained practically free from aphids up to SMW 4, after which small colonies appeared on the apical twigs in SMW 5–6 (6.7–8.4 aphids/10 cm leaf whorl in 2022 and 10.8–12.2 in 2023), followed by a steep increase during SMW 7–10 when populations more than doubled almost every second week and reached 80.0 and 118.2 aphids/10 cm leaf whorl in 2022 and 2023, respectively. The infestation culminated in a distinct peak between SMW 11 and 12, with maximum densities of 195.8 aphids/10 cm leaf whorl in 2022 and 222.7 in 2023, indicating that the latter season offered more favourable conditions for aphid multiplication. Thereafter, numbers declined rapidly by SMW 14–15 they dropped to 82.4–59.9 aphids in 2022 and 98.6–66.5 in 2023, and by SMW 16–18 only low residual populations remained (≤ 23.8 aphids at SMW 16 and ≤ 9.1/6.2 at SMW 18), marking the end of the damaging period. Taken together, the data indicate a main risk window from approximately SMW 7 to 13, with the most critical phase around SMW 10–12, implying that monitoring and need-based, bio-rational interventions should be timed to the rising limb and peak of the curve rather than to the late-season tail of the infestation.

The correlation analysis indicated that weather parameters significantly influenced the population dynamics of *B. helichrysi* on peach during February-April (2022 and 2023). In February, maximum temperature showed a strong positive correlation (r = 0.98*, p < 0.05) with aphid infestation, while minimum temperature was significantly negatively correlated (r = − 0.70, p < 0.05), suggesting that warm days and cooler nights affected population build-up (Table 1). Maximum relative humidity exhibited a strong but non-significant negative association (r = − 0.94). In March, most correlations were weak and non-significant, though maximum relative humidity showed a moderate positive relationship (r = 0.80). In April, maximum temperature had a significant negative correlation (r = − 0.97, p < 0.05), indicating that higher temperatures may suppress aphid populations. Rainfall consistently showed a negative but non-significant association across all months (Table 1). Overall, moderate temperatures favored aphid infestation, while higher temperatures and rainfall tended to reduce population levels, providing useful insights for timing management practices under organic production systems.

Table 1
Relationship between weather variables and mean infestation of *B. helichrysi* on peach during 2022 and 2023

Weather Parameters	February	March	April
Maximum Temperature (T_{max}, °C)	0.98*	0.73	-0.97*
Minimum Temperature ($T_{min,}$ °C)	-0.70*	0.35	-0.21
Maximum Relative Humidity ($RH_{max,}$ %)	-0.94	0.80	0.39
Minimum Relative Humidity ($RH_{min,}$ %)	-0.30	-0.04	-0.03
Rainfall (mm)	-0.68	-0.55	-0.46
**Significant at the 5% level of significance ($p < 0.05$).*			

3.2. Effect of *Brahmastra* on *B. helichrysi* population and yield in peach orchard

The number of *B. helichrysi* per five leaf whorls of 10 cm length was significantly influenced by the *Brahmastra*-based treatments during both 2022 and 2023 growing seasons (Table 2). *Brahmastra*-based treatments significantly reduced the population of *B. helichrysi* in the peach orchard during both growing seasons, while pre-spray counts were non-significant, indicating similar initial infestation levels across all the treatments. The treatment effect was highly significant at all post-spray observations in both years. In 2022, aphid population differed significantly after the first and second sprays, with F-values of 175.72, 492.14, 249.08 and 86.11 at 3 DAFS, 7 DAFS, 3 DASS and 7 DASS, respectively (P < 0.01). Likewise, in 2023, the corresponding F-values were 196.61, 434.21, 237.21 and 153.80, again indicating highly significant treatment differences (P < 0.01). Among the treatments, T3 consistently recorded the lowest aphid population and was therefore the most effective treatment in both years (Table 2). The untreated control consistently harbored the highest aphid density throughout the observation period, confirming the strong suppressive effect of the *Brahmastra*-based treatments. On the basis of pooled mean population, T3 was the best-performing treatment, followed by T4 and T2, whereas T5 showed comparatively weaker control. This trend was further supported by pooled percent reduction over control, where T3 recorded the highest suppression of aphids, followed by T2 and T4. In contrast, T1 and T5 gave lower reductions, indicating moderate efficacy (Table 2). Yield response also showed a highly significant treatment effect, with an F-value of 161.46 (P <

0.01). The highest pooled fruit yield was obtained in T3 (63.00 t ha⁻¹), followed by T4 (62.17 t ha⁻¹) and T2 (61.33 t ha⁻¹), while the control produced the lowest yield (59.83 t ha⁻¹).

Table 2
Effect of *brahmastra* on *B. helichrysi* population in peach orchard

Treatment	2022 (No. of aphids /5 leaf whorls of 10 cm length)							2023 (No. of aphids /5 leaf whorls of 10 cm length)					
	BS	3 DAFS	7 DAFS	3 DASS	7 DASS	Mean	PROC (%)	BS	3 DAFS	7 DAFS	3 DASS	7 DASS	M
T1	118.33	126.67^{a} (11.25)	91.33^{c} (9.56)	46.00^{c} (6.78)	22.67^{c} (4.76)	71.67^{c} (8.47)	49.20	143.67	140.00^{b} (11.83)	106.00^{c} (10.30)	62.00^{c} (7.87)	34.00^{c} (5.83)	8 (9
T2	116.67	101.33c (10.07)	76.00^{d} (8.72)	29.67^{d} (5.45)	10.33^{d} (3.21)	54.33^{d} (7.37)	61.49	146.67	116.00^{d} (10.77)	96.00^{d} (9.80)	40.33^{d} (6.35)	23.00^{d} (4.80)	6 (8
T3	117.67	91.33^{d} (9.56)	40.67^{f} (6.38)	8.00^{f} (2.82)	3.00^{f} (1.72)	35.75^{f} (5.98)	74.66	144.33	104.00^{e} (10.20)	66.00^{f} (8.12)	14.67^{f} (3.83)	5.00^{f} (2.23)	4 (6
T4	118.33	106.00^{b} (10.30)	70.33^{e} (8.39)	18.67^{e} (4.32)	8.67^{e} (2.94)	50.92^{e} (7.14)	63.91	145.00	120.00^{c} (10.95)	85.00^{e} (9.22)	30.00^{e} (5.48)	14.00^{e} (3.74)	6 (7
T5	118.00	127.33^{a} (11.28)	111.33^{b} (10.55)	75.33^{b} (8.68)	38.33^{b} (6.19)	88.08^{b} (9.39)	37.57	141.67	140.00^{b} (11.83)	122.00^{b} (11.05)	98.67^{b} (9.93)	52.33^{b} (7.23)	1 (1
T6 (Control)	117.67	125.67^{a} (11.21)	147.33^{a} (11.93)	171.33^{a} (13.09)	200.00^{a} (14.14)	161.08^{a} (12.48)	-	141.67	167.67^{a} (12.95)	178.67^{a} (13.40)	206.67^{a} (14.41)	224.00^{a} (14.99)	1 (1
F-statistic	NS	175.72**	492.14**	249.08**	86.11**	127.01**		NS	196.61**	434.21**	237.21**	153.80**	1
CD (P = 0.05)	NS	0.18	0.12	0.23	0.26	0.06		NS	0.07	0.04	0.25	0.27	0.
SE(m)	0.66	0.06	0.04	0.07	0.08	0.02		1.22	0.02	0.01	0.08	0.09	0.
CV (%)	0.98	0.91	0.67	1.85	3.13	0.38		1.29	0.34	0.19	1.70	2.67	0.

Note: Values in parentheses are square root transformed. Means followed by the same letter within a column do not differ significantly at P = 0.05. **BS** = Before spray; **DAFS** = Days after first spray; **DASS** = Days after second spray; **PROC** = Percent reduction over control, **= indicate their significant correlation at P < 0.01; NS= not significant.

3.3. Effect of *Brahmastra* on *coccinellid* population in peach orchard

The coccinellid predator population per plant responded significantly to *Brahmastra* based treatments in both seasons, whereas pre-spray counts were statistically comparable across treatments (Table 3). In 2022, treatment effects were highly significant at 7 DAFS and 7 DASS, with F-values of 127.02 and 347.68, respectively, and the pooled mean also differed significantly among treatments ($F_{5,2}$ = 136.80), indicating pronounced post-spray variation in predator abundance. A similar pattern was recorded in 2023, with even stronger treatment effects at 7 DAFS ($F_{5,2}$ = 399.79), 7 DASS ($F_{5,2}$ = 773.14), and for the pooled mean ($F_{5,2}$ = 195.60). In 2022, the untreated control (T6) supported the highest coccinellid density at 7 DAFS and 7 DASS, with 42.00 and 12.33 predators per plant, respectively, and a pooled mean of 27.17 predators per plant. Among the treated plots, T5 and T1 maintained relatively higher predator populations, with pooled means of 25.00 and 22.50 predators per plant (Table 3), respectively, whereas T3 recorded the lowest abundance (10.17 predators per plant). In 2023, the control again registered the highest mean predator population (31.83 predators per plant), followed by T5 and T1, while T3 remained the least supportive treatment for coccinellid abundance, with a pooled mean of 14.83 predators per plant. Across both years, the control consistently showed the highest predator population (29.50 predators per plant), followed by T5 (27.17) and T1 (25.50), while T2 and T3 recorded lower means of 19.00 and 12.50 predators per plant, respectively. The pooled prey population showed the opposite trend, being highest in the control (160.00 aphids per five leaf whorls) and lowest in T3 (41.58), followed by T2 (61.58) and T1 (78.58). The predator - prey ratio was highest in T4 (0.40), suggesting a comparatively more favorable balance between natural enemies and prey, whereas the control recorded the lowest ratio (0.18), reflecting greater aphid pressure relative to predator abundance (Table 3).

Table 3
Effect of *brahmastra* on coccinellid population and predator-prey ratio of peach leaf curl aphid in peach orchard

Treatment	2022 (No. of coccinellids per plant)				2023 (No. of coccinellids per plant)				Pooled Mean Predator	Pooled Prey Population	Predator: Prey ratio
	BS	7DAFS	7DASS	Mean	BS	7DAFS	7DASS	Mean			
T1	26.67	39.00 (6.24)	6.00 (2.45)	22.50 (4.74)	31.33	45.00 (6.71)	12.00 (3.46)	28.50 (5.34)	25.50 (5.05)	78.58 (8.86)	0.32
T2	27.00	30.00 (5.48)	3.33 (1.82)	16.67 (4.08)	32.67	35.33 (5.94)	7.33 (2.71)	21.33 (4.62)	19.00 (4.36)	61.58 (7.85)	0.31
T3	27.00	18.33 (4.28)	2.00 (1.41)	10.17 (3.19)	30.33	24.33 (4.93)	5.33 (2.31)	14.83 (3.85)	12.50 (3.54)	41.58 (6.45)	0.30
T4	27.00	37.33 (6.11)	3.00 (1.73)	20.17 (4.49)	31.00	43.33 (6.58)	6.33 (2.51)	24.83 (4.98)	22.50 (4.74)	56.58 (7.52)	0.40
T5	28.00	39.67 (6.30)	10.33 (3.21)	25.00 (5.00)	32.00	44.33 (6.66)	14.33 (3.79)	29.33 (5.42)	27.17 (5.21)	95.67 (9.78)	0.28
T6	27.00	42.00 (6.48)	12.33 (3.51)	27.17 (5.21)	30.33	47.33a (6.88)	16.33a (4.04)	31.83a (5.64)	29.50a (5.43)	160.00a (12.65)	0.18
F-statistic	NS	127.02**	347.68**	136.80**	NS	399.79**	773.14**	195.60**	228.38**	161.46**	
CD (P = 0.05)	NS	0.07	0.14	0.06	NS	0.04	0.08	0.05	0.05	0.05	
SE(m)	0.38	0.02	0.05	0.02	0.57	0.01	0.03	0.01	0.01	0.02	
CV (%)	2.40	0.69	3.36	0.77	3.18	0.32	1.43	0.52	0.53	0.34	

Note: Values in parentheses are square root transformed. Means followed by the same letter within a column do not differ significantly at P = 0.05. **BS** = Before spray; **DAFS** = Days after first spray; **DASS** = Days after second spray; **= indicate their significant correlation at P < 0.01; NS= not significant.

3.4. Yield and economic returns:

Economic analysis revealed clear differences among treatments in their profitability for managing peach leaf curl aphid (Table 4). All treatments improved yield relative to the untreated control (59.83 q ha^{-1}), but the magnitude of gain varied with dose and formulation. The *Brahmastra* @ 18.0 L ha^{-1} (T3) recorded the highest mean yield (63.00 q ha^{-1}) over the untreated control (59.83 q ha^{-1}) in 'Shan-e-Punjab' peach, and realized the maximum net additional return of Rs. 20,470 ha^{-1} (Table 4). The next best treatment was the home-made neem extract @ 5.0 L ha^{-1} (T4), which produced a comparable increase in yield (62.17 q ha^{-1}) and generated a substantial net additional return of Rs. 15,230 ha^{-1}, exceeding the profitability of the lower *Brahmastra* doses (12.0 and 6.0 L ha^{-1}) and the soap solution treatment. Overall, the economic data indicate that the highest dose of *Brahmastra* (18.0 L ha^{-1}) is the most profitable option, combining the greatest yield increase with the largest net return over control, followed by home-made neem extract and the medium dose of *Brahmastra*; lower *Brahmastra* dose and soap solution, although better than the untreated control, offer comparatively smaller economic benefits.

Table 4
Economic benefits in managing peach leaf curl aphid in peach orchards

Treatment	Dose (L^{-ha})	Mean Yield (q^{-ha})	Additional yield over control (q^{-ha})	Percent increase in yield over control	Income from additional yield (Rs.$^{-ha}$)	Cost of treatment (Rs.$^{-ha}$)	Net additional returns over control (Rs.$^{-ha}$)
T1-*Brahmastra*	6.0	60.50	0.67	1.12	4690	1240	3450
T2-*Brahmastra*	12.0	61.33	1.5	2.51	10500	1480	9020
T3-*Brahmastra*	18.0	63.00	3.17	5.30	22190	1720	20470
T4-Home-made neem extract	5.0	62.17	2.34	3.91	16380	1150	15230
T5-Soap solution	0.1%	60.83	1.0	1.67	7000	1100	5900
T-6 Untreated Control	-	59.83					
Price (*peach*) = Rs. 7000/q; Spray labour = Rs 500/ha; brahmastra preparation cost @ Rs.20/litre; home-made neem extract preparation cost: 12/litre							

Discussions

The population dynamics of peach leaf curl aphid, *B. helichrysi* observed in the present study align closely with the early-season, spring outbreak pattern reported for this leaf curl aphid in peach growing regions worldwide (Sharma and Khokhar 2018, Arora et al., 2009). Aphid populaion appeared on the leaf whorls 4–6 standard meteorological weeks (SMW) after petal-fall and then increased rapidly between SMW 7–10, peaking sharply between SMW 11–12, a pattern consistent with strong dependence on succulent foliage and favourable spring temperatures (Sririvatsava 2009, Estay et al., 2014). Arora et al. (2009) and Sharma and Khokhar (2018) similarly reported a rapid population buildup and a distinct spring peak of *B. helichrysi* coinciding with rising temperature and humidity in Himalayan peach orchards, underscoring the role of climate in governing the timing and intensity of outbreaks. The higher aphid densities in 2023 compared with 2022 likely reflect marginally warmer and more humid conditions during the key growth phase, echoing recent findings that minor shifts in weather parameters can amplify aphid population growth in prunus-based systems (Arora et al., 2009; Piyaratne et al., 2014; Bala, 2026; Zia & Haseeb 2019). The rapid decline after SMW 14–15 and the low residual populations by SMW 16–18 are consistent with the transition to less suitable foliage and intensified natural enemy pressure, as noted by Stary (2003), Arora et al. (2009) and Bhat et al., (2020) for peach aphid systems. Together, these data reinforce that the main risk window for *B. helichrysi* lies in SMW 7–13, with the most critical phase around SMW 10–12, highlighting the need for targeted, early-season monitoring and need-based interventions.

B. helichrysi is favoured by moderate early-spring temperatures and declines when maximum temperatures rise and rainfall increases, which is highly relevant for designing weather-based management in organic peach orchards. The strong positive correlation of aphid infestation with maximum temperature in February and its significant negative correlation in April suggest a relatively narrow thermal window for rapid colony build-up, consistent with reports that aphids generally increase under warm (Almogdad et al., 2024) but suboptimal conditions and are suppressed and rapid induction of winged morphs by short-term heat stress and very high temperatures (Arora, 2009; Kairo, 1995). The consistently negative association with rainfall supports the view that wet weather events can act as a natural regulatory factor through mechanical wash-off and microclimatic changes unfavourable to dense colonies (). This climatic stress, coupled with the nutritional hardening of peach tissues, typically triggers the production of winged morphs (*alates*) that migrate away from peach trees to alternate summer hosts (Arora, 2009; Godefroid, 2020). For organic systems, these relationships imply that intensive scouting should start in late winter and continue through early spring, with action thresholds set before the onset of severe leaf curling; early removal and destruction of infested shoots, maintenance of open canopy structure, and conservation of ground cover that enhances natural enemies form the backbone of cultural control. Under climate change, rising temperatures and altered precipitation regimes are expected to shift aphid phenology, advance spring emergence, and potentially increase voltinism, while also shortening favourable windows when temperatures exceed optimal limits, making calendar-based control less reliable and reinforcing the need for flexible, weather-informed IPM that integrates organic control tools with conservation of natural enemies and plant resistance strategies.

Brahmastra, as used in the present study, is a fermented, cow urine-based extract prepared from neem, lantana, papaya, guava, castor and Datura leaves, each contributing distinct insecticidal or deterrent phytochemicals. Neem (*Azadirachta indica*) leaves supply azadirachtin and related limonoids that act as potent antifeedants, anti-inflamatory, growth regulators, repellents, against aphids and other soft-bodied insects and relatively good compatibility with natural enemies under field and semi-field conditions (Yu et al., 2013, Singh & Sidhu, 2025; Mutua, 2013; Vangansbeke et al., 2014; Santos et al., 2023). Lantana (*Lantana camara*) leaves are rich in triterpenes, sesquiterpenes and other secondary metabolites (e.g. lantadenes, phytol, β-caryophyllene and related compounds) that have been associated with insecticidal, antifeedant and repellent activity against a range of agricultural and stored-product pests (Prasanthi et al. 2019; Silva et al. 2024; Karahacane and Kaci Zakia 2021; Kumarr et al., 2024; Natchiappan et al., 2024). Karanj (*P. pinnata*) tree leaves are rich in furanoflavonoids such as karanjin also shown significant toxic, antifeedant, anti-inflammatory and repellent effects on sucking pests (Stevenson and Kauffman 2013, Sheela and Uthayakumari 2013, Silva et al. 2014, Kukarni et al., 2010; Raghav et al., 2019, Singh & Sidhu 2025) and similar plant-based mixtures are incorporated in Neemastra and *Brahmastra* like formulations evaluated for non-chemical pest management in India (Subha et al., 2025; Maneesha et al., 2025; Surpura et al., 2026, Singh and Sidhu 2025). Leaves of papaya, guava, castor and Datura contribute alkaloids, acetogenins, tannins, phenolics and proteins or enzyme-based inhibitors; phytols present in papaya leaf extracts have shown promising insecticidal and antifeedant activity in recent biopesticide studies (Silva et al. 2014), Leaf extract of guava is rich in flavonoids, flavanols, proanthocyanidins, dihydrochalcones and anthocyanidins, benzophenones, tannins, saponins, polyphenols, steroids, terpenoids, triterpenoids, and glycosides (Tousif et al., 2022; Kumar et al., 2023) which possess larvicidal properties and can be used to control mosquito populations both in the laboratory and in the field (Muema et al., 2016; Arunthirumeni et al., 2023), castor leaf extracts contain trypsin inhibitors with demonstrated antifeedant, feeding deterrent and pesticidal activities to lepidopteran larvae (Kumar et al 2011, Alli and Mangamoori 2014 Poudel et al. 2023, Rossi et al., 2012) and Datura species possess tropane alkaloids with contact and fumigant action contributing antifeedant, growth inhibitor, larvicidal and oviposition deterrent activities against different insect groups (Sharma et al., 2021; Ramesh and Chinnammal 2016; Ullah & Wiedmer 2025). These botanicals are boiled and fermented in cow urine, which functions as an extraction and fermentation medium. *Brahmastra* has shown that cow urine enhances the stability, leaf adhesion and penetration of active compounds and itself contributes mild repellent and bio-enhancing effects, resulting in significant reductions in sucking-pest populations and improved yields in several crops (Gahukar 2013, Anonymous 2019; Kumar et al. 2020; Maurya et al., 2024; Sangma et al., 2025). Together, the combined action of neem limonoids, lantana-derived terpenoids, furanoflavonoids, alkaloids, tannins and the cow-urine fermentation matrix provides a plausible mechanistic basis for the strong suppression of *B. helichrysi* observed in our *Brahmastra* treatments, in line with the broad-spectrum efficacy against aphids, whiteflies, jassids and lepidopteran larvae reported for similar *Brahmastra* formulations in natural-farming and organic systems (Sangma et al. 2025; Kumar & Sarda 2020; Maru et al., 2021; Subha et al., 2025; Maneesha et al., 2025; Surpura et al., 2026).

Brahmastra-based treatments, especially at 18.0 L ha⁻¹ (T3) and the home-made neem extract at 5.0 L ha⁻¹ (T4), induced highly significant suppression of *B. helichrysi* across all post-spray intervals ($F > 100$, $p < 0.01$; Table 1). The untreated control plots recorded the highest aphid densities, confirming that organic orchards left without bio-rational intervention are highly vulnerable to severe aphid outbreaks, as shown in several studies on unsprayed peach and plum systems (Arora et al., 2009; Rahm et al., 2012 & Sharma and Khokhar, 2018). The superior performance of T3 and T4, with PROC values of 73.50% and ~ 64–65%, indicates that these formulations can achieve knockdown comparable to or better than many conventional and neem-based products reviewed for aphid control in stone fruits (Desneux et al., 2007). The relatively weaker control by the lower *Brahmastra* dose plus soap solution (T5) follows the

dose-response pattern widely reported for plant-based oils and botanical sprays, where sub-optimal concentrations permit faster population recovery (Gontijo et al., 2013). The marked yield increases under T3 (63.00 t ha^{-1}) and T4 (62.17 t ha^{-1}), exceeding the untreated control (59.83 t ha^{-1}), parallel findings in integrated-management studies where timely aphid control during the early growth phase significantly improved fruit set and size (Arora at al., 2009 and Gupta et al., 2017). These results underscore that organic-compatible sprays must be applied at adequate doses and precisely timed to the SMW 7–13 window to prevent yield losses arising from leaf-curl-induced physiological stress.

The impact of *Brahmastra* on coccinellid populations reflects the trade-off between rapid aphid suppression and conservation-based biological control, a central theme in modern organic IPM (Desneux et al., 2007). The control plots, despite supporting the highest aphid densities and coccinellid numbers, showed the lowest predator-prey ratio (0.18), indicating that intense aphid pressure can overwhelm even sizeable predator populations, a pattern described in aphid-predator systems in many recent findings (Stary, 2003; Desneux et al., 2006; Boivin et al., 2012; De Backer et al., 2012; Zhang et al., 2022). Treatments T3 and T4 strongly reduced aphid numbers but also lowered coccinellid abundance, particularly T3, mirroring the limited contact harm that plant-based oils and neem-related inputs can exert on non-target predators, as documented in low-impact IPM guidelines for organic horticulture (Desneux et al., 2006 & 2007; Boivin et al., 2012; De Backer et al., 2012; Zhang et al., 2022). In contrast, T4 yielded the highest predator-prey ratio (0.40), suggesting that the home-made neem extract, at the applied dose, maintains a relatively favourable balance between pest control and predator conservation. This is consistent with broader evidence that neem-based products, including azadirachtin-rich formulations, often remain compatible with coccinellids and other beneficial arthropods in organic systems (Schmutterer, 2002). The intermediate ratios for T1, T2 and T3 (0.30–0.32) indicate that moderate doses of *Brahmastra* and combinations can still support a functional predator population while limiting aphid outbreaks, thus promoting more stable, longer-term regulation and reduced spray frequency (Desneux et al., 2007).

From an economic perspective, *Brahmastra* at 18.0 L ha^{-1} (T3) generated the largest net additional return (Rs. 20,470 ha^{-1} over control), combining the highest yield gain with the greatest profitability within the constraints of an organic-compatible regime. The home-made neem extract (T4) followed closely, with a substantial net return (Rs. 15,230 ha^{-1}), reinforcing findings that locally prepared botanical inputs can be cost-effective and sustainable components of organic aphid management, as emphasized by Schmutterer (2002) and more recent syntheses on Brahmastra and neem utilization (Singh & Sidhu, 2025). Lower *Brahmastra* doses and the soap-based combination provided only modest economic benefits, despite exceeding the untreated control, which echoes the observation that sub-optimal rates may fail to fully recover the yield and quality losses associated with early-season aphid damage, even under organic protocols. Overall, integrating *Brahmastra* and neem-derived formulations into a need-based IPM framework targeted to the narrow SMW 7–13 risk window, with attention to dose, timing, and natural-enemy conservation can reconcile effective aphid control with the ecological and economic goals of organic peach production, as advocated in recent reviews on organic aphid management in horticulture.

5. Conclusion

This study demonstrates that peach leaf curl aphid, *B. helichrysi*, exhibits a pronounced, short early season outbreak in organically managed peach orchards, with rapid population build-up from SMW 7–10, a sharp peak around SMW 11–12, and a main risk window confined to SMW 7–13; moderate spring temperatures favoured aphid multiplication, whereas higher temperatures and rainfall contributed to rapid decline, underscoring the potential of weather-based forecasting for timing interventions. *Brahmastra*-based treatments, particularly *Brahmastra* at 18.0 L ha^{-1} and home-made neem extract at 5.0 L ha^{-1}, provided highly significant suppression of aphid densities, the largest percent reduction over the untreated control, and clear gains in fruit yield and net returns, thereby confirming the bio-efficacy and economic viability of these farmer-prepared botanicals under organic peach production. Although the untreated control supported the highest coccinellid numbers, its very low predator-prey ratio revealed that intense aphid pressure can overwhelm natural enemies, whereas neem-based and intermediate *Brahmastra* doses maintained more favourable predator-prey balances, illustrating that dose and timing strongly condition the compatibility of plant-derived inputs with biological control. Taken together, the findings indicate that integrating *Brahmastra* and neem formulations into a climate informed, early season, threshold based IPM framework centred on careful monitoring during SMW 7–13, timely cultural measures, and conservation of natural enemies can deliver robust, residue-free control of B. *helichrysi* while meeting the ecological and economic objectives of organic peach orchards.

Declarations

Authorship contribution statement

UV and MP conceived and designed the research. UV conducted the experiments and recorded data. MP and UV analyzed data and wrote the manuscript. All authors read and approved the manuscript.

Ethical approval

Not applicable

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The authors received no financial assistance for the research.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Data availability

Data will be made available on request.

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Figures

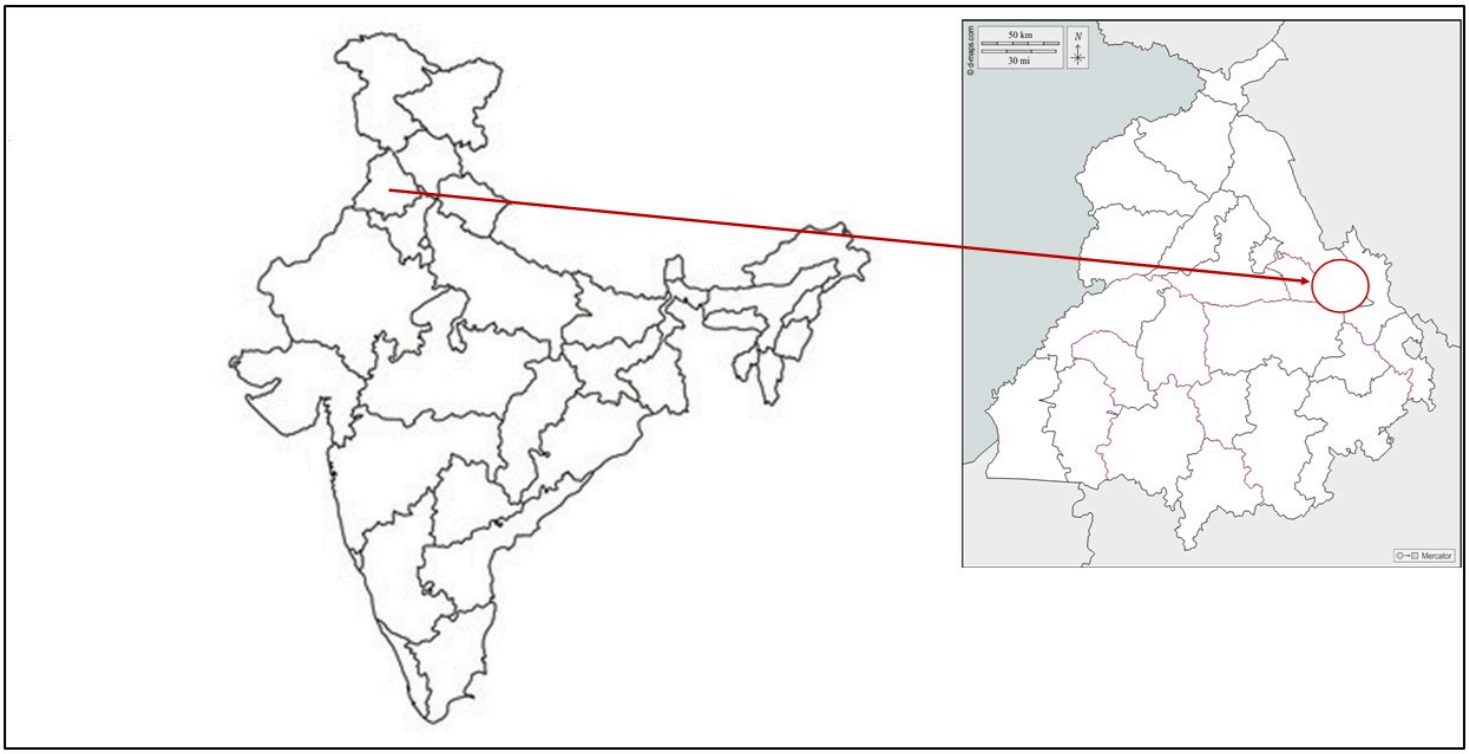


Figure 1

Study area (Shivalik foothills of Punjab, India)

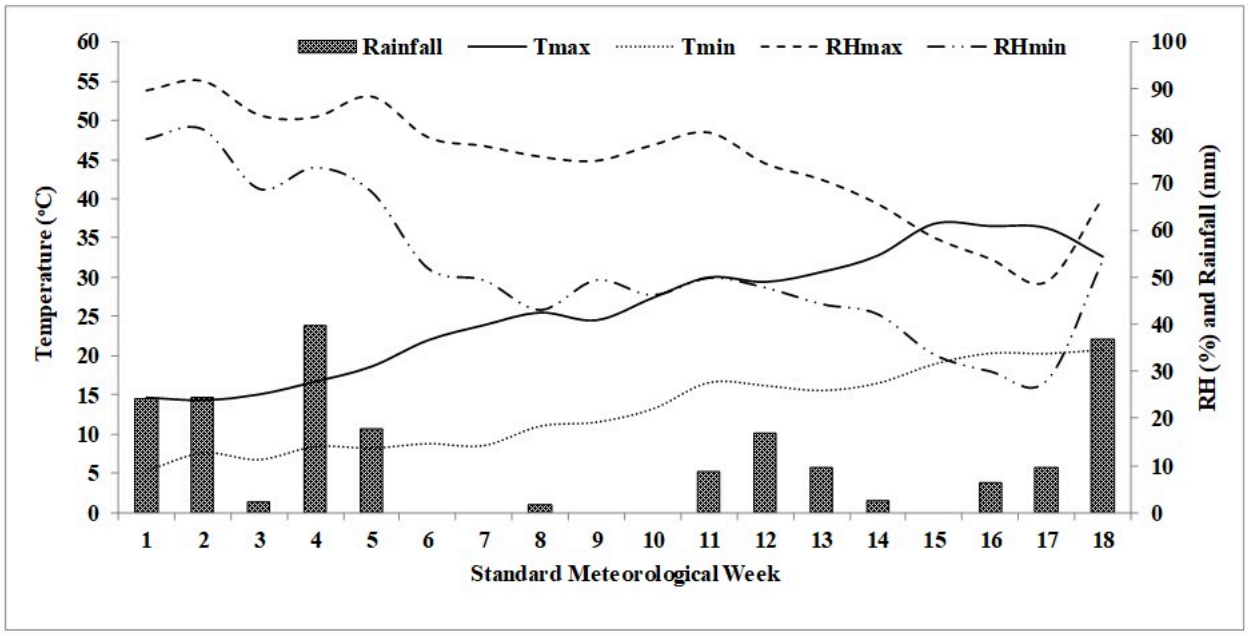


Figure 2

Weather data of the study site (pooled 2022-2023)

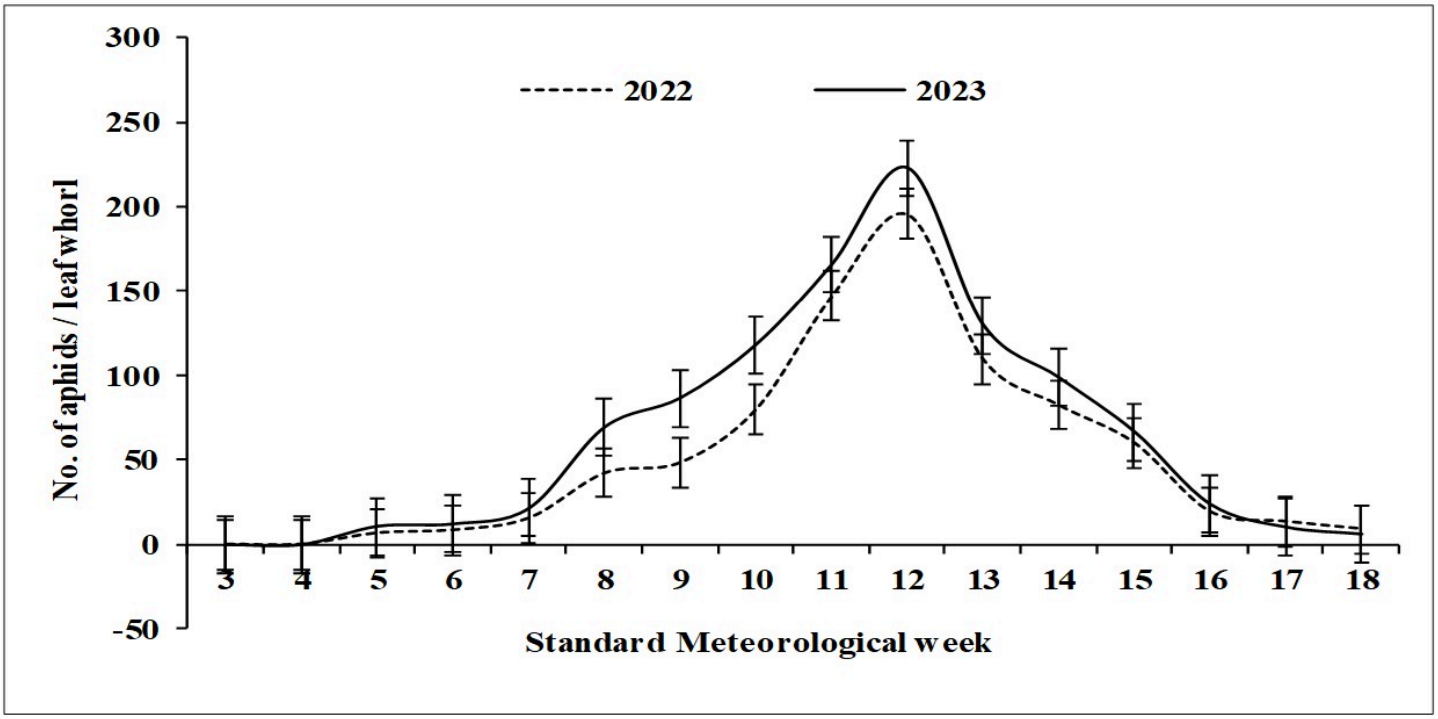


Figure 3

Population dynamics of *B. helichrysi* on peach (pooled 2022-2023)