



Green defense: bioactivity of *Carthamus dentatus* vahl extract against the invasive stink bug *Halyomorpha halys* (Hemiptera: Pentatomidae)

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Abstract

In response to increasing concerns over the ecological and health-related consequences of synthetic pesticide use, this study investigates the insecticidal efficacy of methanolic extracts derived from *Carthamus dentatus* against the invasive agricultural pest *Halyomorpha halys* (Brown Marmorated Stink Bug). Laboratory bioassays revealed a statistically significant, dose- and time-dependent increase in adult mortality over a 10-day exposure period. Notably, Flower Dose 25 (mg/L) consistently induced complete lethality by Day 7 ($100.00 \pm 0.00\%$), while Leaf Dose 25 (mg/L) approached similar efficacy by Day 9 ($96.60 \pm 1.99\%$). Intermediate mortality levels were recorded for Flower Dose 50 (mg/L) and Leaf Dose 50 (mg/L), whereas the control group exhibited negligible mortality ($\leq 0.86 \pm 1.33\%$), underscoring the specificity of the treatment effect. To elucidate the phytochemical basis of this bioactivity, high-performance liquid chromatography (HPLC) was employed to characterise the phenolic composition of the extracts. Rutin was identified as the predominant compound in floral tissues (56.4%), while o-coumaric acid was most abundant in cauline leaves (38.9%). Additional phenolics, including chlorogenic acid, naringin, chrysin, t-ferulic acid, quercetin, and rosmarinic acid, were also detected. These compounds are known to contribute to plant defence through mechanisms such as allelopathy, UV protection, and anti-herbivory activity. Collectively, the findings highlight the potential of *C. dentatus* methanolic extracts as a promising botanical alternative for the sustainable management of *H. halys* populations.

Keywords Botanical biopesticides · Methanolic extracts · Insecticidal activity Sustainable pest management

Introduction

The brown marmorated stink bug *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae) has become an invasive insect pest of many crops. Stink bugs (Hemiptera: Pentatomidae) are important pests of agricultural crops and ornamental

plants in the United States (McPherson and McPherson 2000). *H. halys* is native to China, Japan, Korea, and Taiwan, but it has now been detected in 40 states and the District of Colombia since it was first discovered in North America near Allentown, PA in the late 1990s (Hoebeke and Carter 2003; Leskey et al. 2012). Unfortunately, *H. halys*, a polyphagous insect native to East Asia, has been recorded on more than 300 host plants, encompassing a wide spectrum from agricultural crops to ornamental species (Hoffman 1931; Hoebeke and Carter 2003; Bernon 2004; Nielsen et al. 2009). Since its accidental introduction, *H. halys* has rapidly established itself across vast areas of North America and Europe, where it poses a dual threat: economically, through significant damage to fruit, vegetable, and ornamental plant production; and domestically, as a considerable nuisance in residential settings. Its proclivity for overwintering within human-made structures—particularly homes—can result in severe infestations, occasionally exceeding 20,000 individuals (Watanabe et al. 1994; Nielsen et al. 2008; Sargent et al. 2011; Inkley 2012). The

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species' high reproductive capacity, extensive host range, and strong dispersal ability make it particularly challenging to control using standard pest management approaches. The brown marmorated stink bug, is a destructive, invasive and polyphagous pest that causes significant losses in agricultural production. Its presence in Türkiye was first recorded in 2017. Due to global climate change, this pest has rapidly spread from the Black Sea region to other parts of the country, prompting the implementation of pesticides are often used in its control. *Carthamus tinctorius* L. is an oil crop. It is cultivated mainly in Asia and Eastern countries. 6 *Carthamus* species grow naturally in Turkey. *Carthamus dentatus* Vahl. is an annual herbaceous plant that grows in marginal soils and rocky slopes. It has purple flowers and dent like thistles. Seeds contains long pappuses. Many researchers studied genetic, oil and phenolic composition of *C. dentatus* (Hacıkamiloğlu et al. 2025; Arslan et al. 2010; Konar et al. 2010). The most abundant component in the stem leaf is chrysin, while naringenin was in the flower (Hacıkamiloğlu et al. 2025). Cauline leaf extract was found promising for insecticidal agent against some storage pests (Hacıkamiloğlu et al. 2025).

Conventional pest management strategies have long relied on synthetic chemical insecticides; however this approach has led to several adverse consequences, including environmental contamination, mortality of non-target species and the development of insecticide resistance. Moreover, the indiscriminate use of chemical pesticides raises serious concerns about food safety and ecological sustainability. In response to these challenges, there has been a growing interest in alternative, eco-friendly pest control methods, particularly methods based on plant-derived compounds. Botanical insecticides, derived from plant extracts and essential oils, have gained considerable attention as viable alternatives in Integrated Pest Management (IPM) programs. These natural compounds often exhibit insecticidal, repellent, antifeedant or growth-regulating effects on a broad range of pests species, while generally posing reduced risks to the environment and human health (Matyjaszczyk 2023). Among the botanical sources, *Carthamus tinctorius* L. (safflower) is a valuable oilseed crop predominantly cultivated in Asia and other Eastern regions. Renowned for its traditional applications in both agriculture and medicine, this species is rich in bioactive compounds that have demonstrated potential insecticidal activity. In addition to cultivated varieties, several wild species of the genus *Carthamus* grow naturally in Turkey. Notably, *C. dentatus* is an annual herbaceous plant typically found in areas with limited or negligible agricultural or industrial value, such as rocky slopes and low-fertility soils. It is distinguished by its purple flowers, thistle-like dentate structures, and seeds bearing long pappuses. Recent studies have explored the genetic characteristics, oil composition,

and phenolic content of *C. dentatus*, highlighting its potential value in both agronomic and biochemical contexts (Hacıkamiloğlu et al. 2025; Arslan et al. 2010; Konar et al. 2010). The genus *Carthamus*, known as safflower, consists of herbaceous, annual plants in the *Asteraceae* family, typically with a thorny structure. *Carthamus* species grow naturally on slopes, rocky terrains, and in areas up to an altitude of approximately 2300 m above sea level (Arslan et al. 2010). Historically safflower flowers were used in ceremonial and ritual practices in ancient Egypt, and served as a source of red dye in traditional textile applications in India. These flowers have also been employed for medicinal purposes across various cultures. Researchers investigating their pharmacological properties have identified a range of phenolic compounds within the flower composition. Previous studies have reported that these compounds possess antimicrobial properties similar to commercial chemicals, acting against various pathogenic microorganisms (Rafiq et al. 2020; Abuova et al. 2022). In contemporary agricultural practices, synthetic chemicals are commonly employed to mitigate the impact of pests. However, the intensive use of pesticides has raised growing concerns among consumers due to its detrimental effects on environmental and human health. Consequently, there has been a marked shift towards natural alternatives, particularly within the frameworks of organic farming and Good Agricultural Practices (GAP). Interest in herbal remedies, plant extracts, and preparations obtained without intensive industrial processes is rising. Health-conscious consumers opt for organic products to maintain a healthy lifestyle and reduce their exposure to synthetic substances.

In response to escalating concerns regarding the environmental degradation and health risks associated with the widespread use of synthetic pesticides, this study explores the insecticidal efficacy of botanical extracts derived from the phyllary and floral leaves of *C. dentatus* (wild safflower) against the invasive agricultural pest *Halyomorpha halys* (brown marmorated stink bug). The research specifically evaluates both lethal effects and sublethal behavioral responses following exposure to these plant-based extracts. By doing so, it aims to contribute to the advancement of sustainable and eco-friendly pest management strategies that align with Integrated Pest Management principles.

The primary objective of this study is to assess the potential of *C. dentatus* as a natural source of bioactive compounds with insecticidal properties, thereby offering a viable alternative to conventional chemical pesticides. This investigation not only enhances our understanding of the bioactivity of safflower-derived phytochemicals but also represents the first documented attempt in Türkiye to utilize *C. dentatus* extracts in the context of biopesticide development. The findings are expected to support future efforts in

the formulation of green pesticides and promote the adoption of environmentally responsible agricultural practices.

Materials and methods

Plant collection and extract preparation

Carthamus dentatus Vahl. plants identified and collected from Ondokuz Mayıs University Kurupelit campus site, Samsun/Türkiye, at 190 m altitude. Plants collected at the flowering stage in mid July 2025. Cauline leaves and flower heads separated and dried in oven at 36 °C for 48 h. Completely dried plant parts well grinded with electric mill.

Modified method from Hacıkamiloğlu et al. (2025) used for extract preparation. 5 g of dried and well grinded plant parts added in methanol and stirred for 12 h in orbital shaker. In this study, it was aimed to increase the original value of the study by using methanol instead of ethanol in the old method. The solution transferred to eppendorf tubes then evaporated at rotary evaporator at 1000 rpm at 40 °C. Dry extracts kept in +4 °C until use. The dry weights of leaf and flower extracts were determined by subtracting the weight of empty Eppendorf tubes from the total weight after drying. Each extract was dissolved in 1000 ml of methanol to obtain two concentrations: 25 mg/L (Dose 2) and 50 mg/L (Dose 1). Stock solutions were freshly prepared prior to bioassays and stored under dark conditions at room temperature until use. **Phenolic analysis.**

High performance liquid chromatography method used for phenolic analysis. Agilent 1260 Infinity at ALUM laboratory (İğdır University) deployed. Flow rate 0,8 ml/min, wavelength 300/200 nm, column temperature 30 °C, detector DAD selected.

Insect

Adult *Halyomorpha halys* (Brown Marmorated Stink Bug) (1–2 day old) were collected in 2025 from various gardens and orchards in the Tekkeköy district of Samsun, Türkiye, and maintained in the laboratory. No specific permissions were required for the collection of the stink bugs because the collections occurred on private properties with the owners' consent. The collection of these insects did not involve endangered or protected species. *H. halys* were kept in a growth chamber at 24 °C with a 16:8 h light: dark cycle. Insects were provided with water, organic carrots, grape tomatoes, and green beans purchased from a local grocery store, as well as green bean seedlings. Adults typically laid eggs on the underside of bean leaves, and nymphs were reared in the same manner. Laboratory colonies were

continuously maintained by rearing successive generations from eggs laid by laboratory adults.

Experimental design

The bioassay was conducted using four replications per treatment. Each replicate consisted of 10 adult individuals of *Halyomorpha halys* (Stål), which were randomly selected and placed into individual plastic containers (10×10 cm) with perforated lids to allow ventilation. The insects were acclimatized for 24 h prior to treatment application. Each treatment group received 2 mL of the respective plant extract, applied uniformly using a precision hand sprayer to ensure consistent coverage. Control groups were treated with the same volume of distilled water. All bioassays were performed under controlled environmental conditions maintained at 20±5 °C and 60±5% relative humidity, with a photoperiod of 16:8 (light: dark) hours.

Post-treatment observations were recorded daily for a period of 10 days. Mortality and behavioral responses were monitored, and dead individuals were removed and recorded at each interval. Data were statistically analyzed to evaluate the insecticidal efficacy of the tested extracts. Ten replicates were performed for each treatment and all applications were performed in duplicate.

Statistical analysis

The experimental data were statistically analyzed using Minitab® software (version 16) to evaluate the insecticidal efficacy of *Carthamus dentatus* methanolic extracts on adult *Halyomorpha halys* mortality. A one-way analysis of variance (ANOVA) was conducted to assess differences in mean mortality rates (%) among treatment groups and the control. To further quantify the time-dependent toxicity of the extracts, probit analysis was performed to estimate the median lethal time (LT₅₀) and 90% lethal time (LT₉₀) values for each concentration. These parameters provided insight into the speed and potency of the extract's insecticidal action. Significant differences among treatment means were determined using Tukey's post hoc test at a significance level of $p < 0.05$.

Results

Methanolic extracts of *C. dentatus* exhibited pronounced insecticidal activity against adult *H. halys*, as evidenced by a statistically significant increase in mortality rates compared to the control group. Mortality was observed to escalate in a dose-dependent manner throughout the 10-day exposure

period, indicating a clear correlation between extract concentration and toxic effect (Table 1).

* Different lowercase letters within a column indicate significant differences among treatments ($p < 0.05$). Identical letters denote no significant difference.

By the fifth day of exposure, mortality rates demonstrated a clear dose-dependent pattern. The highest mortality was recorded in Leaf Dose 50 ($56.42 \pm 2.38\%$), followed by Flower Dose 50 ($52.01 \pm 0.38\%$) and Flower Dose 25 ($47.59 \pm 1.10\%$), with no statistically significant differences among these three treatments. In contrast, Leaf Dose 25 induced significantly lower mortality ($26.02 \pm 0.56\%$), while no mortality was observed in the control group ($0.00 \pm 0.00\%$), indicating a pronounced divergence between treated and untreated groups. These findings are consistent with previous reports, such as Yeşilayer and Aslan (2018) on thyme-derived essential oils, and Yeşilayer et al. (2025) evaluating nano-silver and lavender extract efficacy against *Tetranychus urticae*. At the seventh day, mortality in Flower Dose 50 reached $100.00 \pm 0.00\%$, significantly exceeding all other treatment groups. Flower Dose 50 exhibited a high but statistically distinct mortality rate ($86.86 \pm 1.33\%$), whereas Flower Dose 25 ($60.00 \pm 1.18\%$) and leaf Dose 2 ($40.00 \pm 0.00\%$) formed separate statistical groupings. The control group continued to exhibit negligible mortality ($0.86 \pm 1.33\%$), further supporting the specificity of the treatment effect. By Day 9, complete lethality was sustained in Flower Dose 50 ($100.00 \pm 0.00\%$) and nearly achieved in Leaf Dose 50 ($96.60 \pm 1.99\%$), with no statistically significant difference between them. Although mortality rates in Flower Dose 25 ($72.50 \pm 0.46\%$) and Leaf Dose 25 ($60.00 \pm 1.18\%$) were significantly lower, they remained markedly elevated compared to the control ($0.86 \pm 1.33\%$). Overall, these results provide robust evidence of a statistically significant, dose- and time-dependent increase in mortality across the treatment groups. These findings suggest a strong dose- and time-dependent increase in mortality, with flower Dose 1 consistently inducing the highest lethality

across all time points. The statistical groupings indicate significant differences among treatments, particularly between higher and lower doses, as well as between treated and control groups.

**LT₅₀ and LT₉₀ indicate the time (days) required to reach 50% and 90% adult mortality, respectively ($p < 0.05$).

Recent studies in Türkiye have demonstrated the insecticidal potential of various botanical and biological agents against *H. halys*. For instance, Göktürk (2024) reported that extracts of *Prunus laurocerasus* induced high adult mortality within 96 h, while Aşkın et al. (2022) documented the efficacy of entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*, *Verticillium lecanii*) with LT₅₀ values ranging between 5 and 8 days. In a related acaricidal study, the ethanol extract of *Lavandula* and silver nanoparticles (AgNPs) exhibited the highest toxicity against *Tetranychus urticae* adults, with peak effects observed on Days 7 and 9, respectively. These results revealed a clear positive correlation between dose and exposure time, whereby increased concentrations and prolonged contact significantly enhanced mortality rates. Comparable findings have been reported internationally: Cira et al. (2017) demonstrated that pyrethroid insecticides achieved rapid mortality in *H. halys* adults (LT₅₀: 1–3 days; LT₉₀: 5–7 days), whereas botanical extracts such as neem (*Azadirachta indica*) and essential oils of *Mentha* and *Thymus* species exhibited slower but significant lethal effects (Lee et al. 2013; Zhang et al. 2020). In the present study, methanolic extracts of *C. dentatus* revealed dose- and tissue-specific bioactivity, with Flower Dose 50 inducing complete lethality by Day 7 (LT₅₀: 2.86 days; LT₉₀: 4.75 days), thereby outperforming several previously tested plant-derived treatments (Table 2; Fig. 1).

In the second phase of the study, high-performance liquid chromatography (HPLC) analysis confirmed the presence of phenolic constituents within the extracts, which are likely contributors to the observed bioactivity. As a results are given in Table 3; Fig. 2. rutin was identified as the predominant compound in the flower (56.4%), whereas o-coumaric

Table 1 Mortality (%) of *Halyomorpha halys* adults exposed to methanolic flower and leaf extracts of *Carthamus dentatus* over 10 days

% Death $\pm$ SE*					
Dose (mg/L)	1 d	2 d	3 d	4 d	5 d
Flower 50	7.54 $\pm$ 1.99 a	47.99 $\pm$ 9.02 a	69.58 $\pm$ 5.47 a	75.01 $\pm$ 0.38 a	76.01 $\pm$ 0.38 a
Flower 25	1.48 $\pm$ 0.00 b	5.18 $\pm$ 3.20 ab	31.54 $\pm$ 0.46 b	47.59 $\pm$ 1.10 b	52.01 $\pm$ 0.38 b
Leaf Dose 50	5.18 $\pm$ 3.20 ab	1.87 $\pm$ 2.87 b	35.33 $\pm$ 2.41 b	52.41 $\pm$ 2.51 ab	56.42 $\pm$ 2.38 a
Leaf Dose 25	0.10 $\pm$ 0.36 c	2.18 $\pm$ 0.02 bc	23.65 $\pm$ 0.31 bc	23.65 $\pm$ 0.31 c	26.02 $\pm$ 0.56 cb
Control	0.00 $\pm$ 0.00 d	0.00 $\pm$ 0.00 d	0.00 $\pm$ 0.00 d	0.00 $\pm$ 0.00 d	0.00 $\pm$ 0.00 d
	6 d	7 d	8 d	9 d	10 d
Flower Dose 50	100.00 $\pm$ 0.00 a	100.00 $\pm$ 0.00 a	100.00 $\pm$ 0.00 a	100.00 $\pm$ 0.00 a	100.00 $\pm$ 0.00 a
Flower Dose 25	60.00 $\pm$ 1.18 c	60.00 $\pm$ 1.18 c	68.46 $\pm$ 0.46 B	72.50 $\pm$ 0.46 c	76.35 $\pm$ 0.31 c
Leaf Dose 50	87.15 $\pm$ 3.64 b	86.86 $\pm$ 1.33 b	87.00 $\pm$ 0.00 B	96.60 $\pm$ 1.99 b	99.79 $\pm$ 0.75 b
Leaf Dose 25	35.71 $\pm$ 0.30 d	40.00 $\pm$ 0.00 d	52.01 $\pm$ 0.38 C	60.00 $\pm$ 1.18 d	68.66 $\pm$ 1.68 d
Control	0.00 $\pm$ 0.00 e	0.86 $\pm$ 1.33 e	0.86 $\pm$ 1.33 D	0.86 $\pm$ 1.33 e	0.86 $\pm$ 1.33 e

Table 2 Lethal time (LT₅₀ and LT₉₀, days) of *Halyomorpha halys* adults exposed to methanolic flower and leaf extracts of *Carthamus dentatus*

Dose (mg/L)	LT ₅₀ (day)	LT ₉₀ (day)
Flower 50	2,86	4,75
Flower 25	5,25	11,75
Leaf 50	3,2	7,92
Leaf 25	7,25	13

acid was found in the highest concentration in the cauline leaf (38.9%). The HPLC results also revealed the presence of other phenolic compounds, including chlorogenic acid, naringin, chrysin, t-ferulic acid, quercetin, and rosmarinic acid.

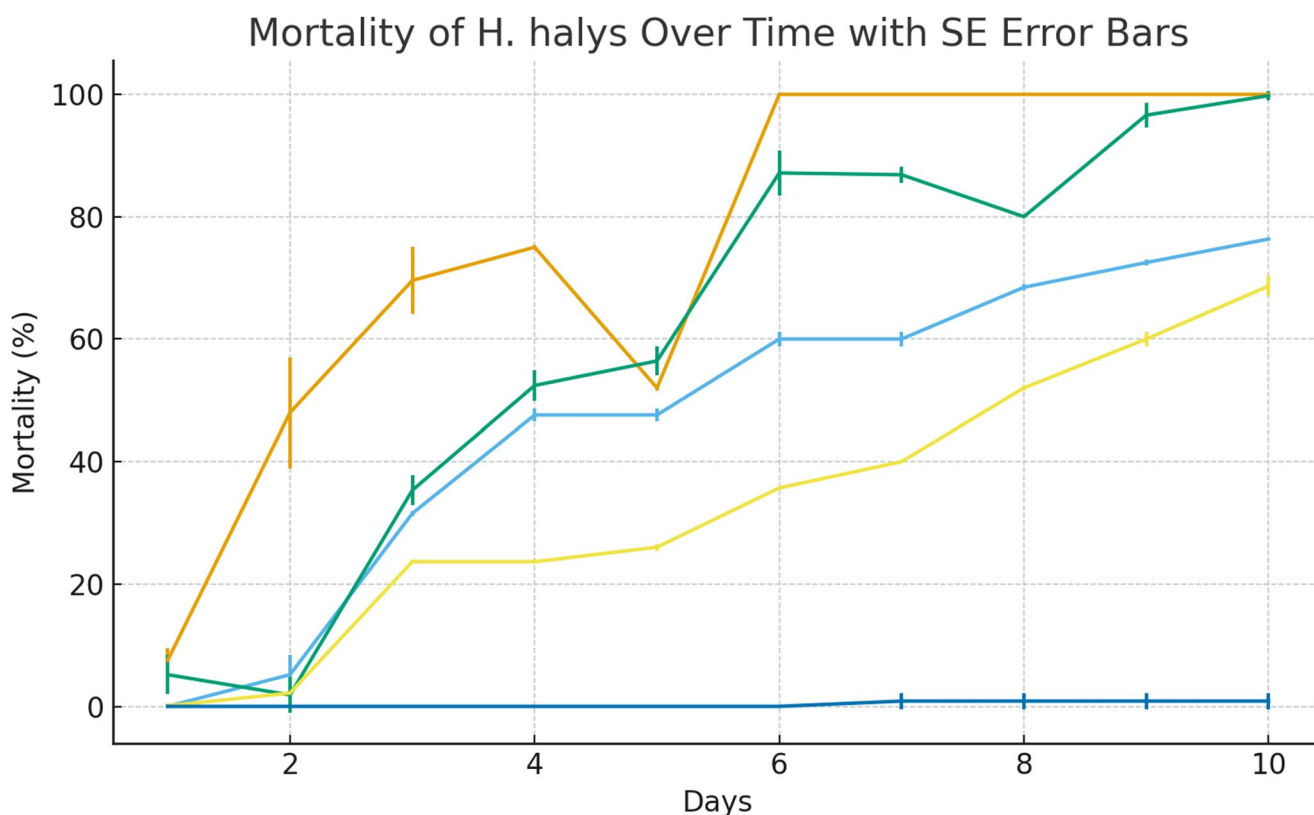
Rutin, a citrus flavonoid glycoside, is widely distributed among various plant species. Its name originates from the plant *Ruta graveolens* (Atanassova and Bagdassarian 2009). The biosynthesis of rutin begins with phenylalanine and proceeds through a series of enzymatic conversions involving phenylalanine ammonia-lyase, 4-coumarate-CoA ligase, and chalcone synthase, leading to the formation of naringenin chalcone, naringenin, dihydrokaempferol, dihydroquercetin, quercetin, and isoquercitrin, which is finally converted into rutin (Yu et al. 2020). Rutin and its derivatives play a crucial role in chelating cations to facilitate the supply of essential elements to plants, as well as in binding iron (Fe) to prevent the formation of reactive free radicals. Kreft et al. (1999) mentioned rutin in buckwheat mostly found

Table 3 Quantitative distribution of phenolic compounds (ng/μl, %) in flower and cauline leaves of *Carthamus dentatus*

Component	Flower		Cauline	
	Amount [ng/ul]	%	Amount [ng/ul]	%
Rutin	18,50	56,4	1,07	0,9
o-Coumaric acid	2,27	6,9	47,47	38,9
Chlorogenic acid	5,88	17,9	28,47	23,3
Naringin	0,80	2,4	16,28	13,3
Chrysin	-	-	12,56	10,3
t-Ferulic acid	2,18	6,7	3,60	3,0
Quercetin	1,69	5,2	5,46	4,5
Rosmarinic acid	0,77	2,4	0,84	0,7
Naringenin	0,30	0,9	1,58	1,3
4-Hydroxy benzoic acid	0,28	0,9	1,45	1,2
Resveratrol	0,10	0,3	0,40	0,3
t-Cinamic acid	0,00	0,0	0,21	0,2
Salicylic acid	-	-	1,80	1,5
Hydroxy sinamic	-	-	0,78	0,6
Total	32,78	100,0	121,97	100,0

*-: absent or unavailable

in inflorescence, protects plant from (UV)-B and increase nutritional value. Coumaric acid is derivative of cinnamic acid and it has 3 types, para, meta and orto (p-coumaric, m-coumaric and o-coumaric acid, respectively) (Boz 2015). O-coumaric acid is accepted as phytotoxin that inhibits seed

**Fig. 1** Mortality progression of *Halyomorpha halys* adults treated with *Carthamus dentatus* extracts, with standard error bars

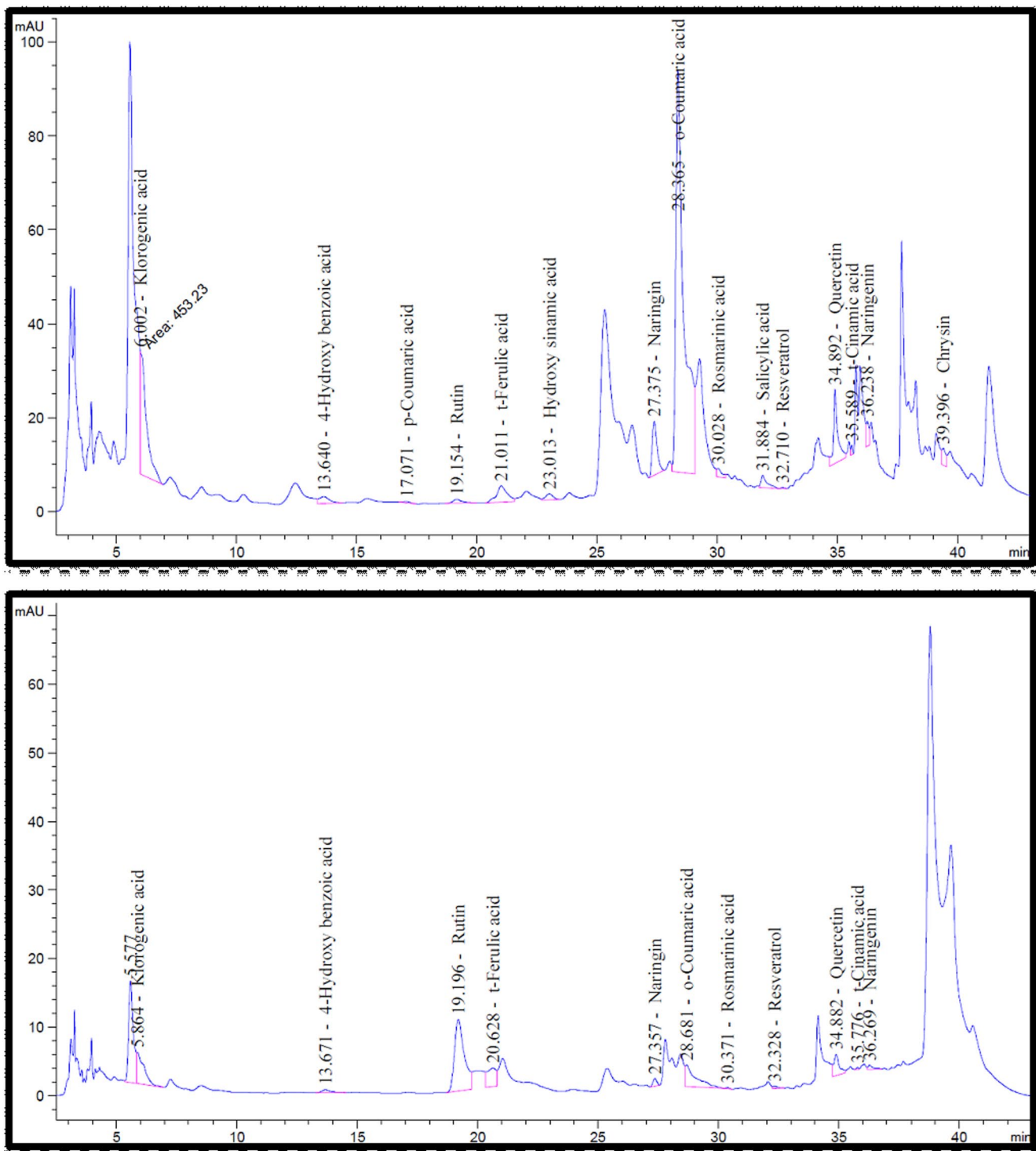


Fig. 2 HPLC chromatogram of *Carthamus dentatus* extract showing retention times and peak profiles of identified phenolic acids and flavonoids

germination and plant growth, damages photosynthesis, causing cell death and oxidative stress. Researchers believe it has important role for plant competition and weed invasion (Zheng et al., 2012).

Chlorogenic acid is an ester formed between caffeic acid and quinic acid (Gil and Wianowska 2017). It is widely distributed across various plant species. Previous studies have shown that elevated levels of chlorogenic acid are associated with insect herbivory (Kundu et al. 2018; Lee et al. 2017).

This compound is therefore considered to play a role in the plant's defense mechanisms against insect attack. Several researchers found chlorogenic acid mechanism in different plants; *Spodoptera litura* at *Arachis hypogea*, *Spodoptera exigua* at *Solanum tuberosum*, *Spodoptera litura* at *Solanum lycopersicum* (Kundu and Vadassery 2018).

Phenolic profiling revealed a distinct accumulation of bioactive compounds in cauline leaves compared to floral tissues of *C. dentatus*. The total phenolic content reached 121.97 ng/ μ L in cauline leaves, markedly higher than the 32.78 ng/ μ L detected in flowers. Rutin was the predominant compound in flowers (56.4%), whereas o-coumaric acid dominated in cauline leaves (38.9%). Chlorogenic acid emerged as the second most abundant phenolic in both tissues, indicating its widespread distribution across plant organs. Several of these compounds are known for their insecticidal and deterrent properties, particularly against brown marmorated stink bug and other agricultural pests. Recent studies have demonstrated that polyphenol-based formulations, including chlorogenic acid and flavonoids, significantly reduce *H. halys* feeding activity and survival rates under laboratory conditions (Lowenstein and Walton 2018). O-coumaric acid, highly concentrated in cauline leaves, is recognized for its toxic and repellent effects. Zeng et al. (2012) reported its efficacy as an insect deterrent, particularly against hemipteran pests. Although direct evidence against *H. halys* is limited, its structural similarity to other coumaric derivatives suggests potential cross-species activity.

Chlorogenic acid is a well-characterized antioxidant and defense metabolite. Kundu and Vadassery (2018) demonstrated its role in deterring herbivores and enhancing resistance to pathogens. Santi et al. (2020) further confirmed its insecticidal potential by showing that chlorogenic acid-rich microencapsulated extracts significantly reduced *H. halys* populations. Flavonoids such as naringin, quercetin, and chrysin are multifunctional compounds involved in stress adaptation, anti-herbivory, and defense signaling. Rutin, in particular, has been highlighted for its strong antioxidant activity (Atanassova and Bagdassarian 2009), while naringin and quercetin interfere with insect feeding and reproduction (Kumar et al., 2021). Chrysin contributes to abiotic stress responses and may enhance plant resilience.

Confined to cauline leaves, salicylic acid plays a central role in systemic acquired resistance. It enhances immune responses and reduces palatability to herbivores (Klessig et al. 2018), indirectly affecting *H. halys* and similar pests. The elevated phenolic content in cauline leaves suggests a strategic biochemical defense mechanism against herbivores, particularly piercing-sucking insects. The occurrence of diverse insecticidal bioactive compounds substantiates the

hypothesis that cauline tissues are inherently conditioned for pest resistance.

Discussion and conclusion

This study presents the first comprehensive evaluation of the insecticidal potential of *C. dentatus* methanolic extracts against the invasive pest *H. halys* in Türkiye. Laboratory bioassays revealed a clear dose- and time-dependent increase in adult mortality, with Flower Dose 50 achieving complete lethality by Day 7 and Leaf Dose 50 approaching full mortality by Day 9. The LT_{50} and LT_{90} values further confirmed the rapid toxicological response of *H. halys* to higher extract concentrations, indicating strong and fast-acting insecticidal activity.

These toxicological outcomes are consistent with the phytochemical profile revealed by HPLC analysis. Both floral and cauline tissues contain diverse phenolic compounds with established defensive and bioactive roles. Rutin dominated the flower extract, whereas o-coumaric acid was the major component of cauline leaves. Other phenolics—chlorogenic acid, quercetin, naringin, chrysin, and rosmarinic acid—were also detected and are widely recognized for their involvement in anti-herbivory, oxidative stress regulation, and allelopathic interactions. The higher total phenolic content in cauline leaves suggests a naturally intensified defense signature that aligns with their substantial bioactivity. Overall, the findings strongly support the potential of *C. dentatus* as a promising botanical resource for developing environmentally friendly biopesticides targeting *H. halys*. Given its natural distribution in Türkiye, low ecological impact, and rich phytochemical composition, *C. dentatus* extracts may offer a sustainable alternative to synthetic chemical insecticides. Future research should focus on formulation development, field-scale validation, and assessment of non-target safety to advance this plant toward practical applications in Integrated Pest management Programs. At present, there are no published data on the cost-effectiveness of *C. dentatus* extracts as biopesticides. However, based on general trends in plant-based biopesticides, production costs are typically higher at small scale but can be reduced through optimized extraction and formulation methods. Given the natural distribution of *C. dentatus* in Türkiye, local availability may lower raw material costs compared to imported biopesticides. The ecological and regulatory advantages—such as low residue and environmentally friendly profile—could also offset higher upfront expenses. Nevertheless, dedicated economic analyses and field-scale trials are required to determine the true cost-effectiveness of *C. dentatus* extracts.

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Data availability All relevant data are included in the manuscript, and additional dataset details can be obtained from the corresponding author upon reasonable request.

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