ACTA SCIENTIARUM POLONORUM
Acta Sci. Pol. Hortorum Cultus, 24(3) 2025, 39-51

https://czasopisma.up.lublin.pl/index.php/asphc ISSN 1644-0692 e-ISSN 2545-1405 https://doi.org/10.24326/asphc.2025.5486

ORIGINAL PAPER

Received: 17.01.2025
Accepted: 14.05.2025
Issue published: 30.06.2025

EFFICACY OF SEVERAL INSECTICIDES AND PLANT EXTRACTS AGAINST *Ostrinia nubilalis* HÜBNER IN SWEET PEPPER

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ABSTRACT

Pepper (*Capsicum annuum* L.) is a globally important crop, often affected by the European corn borer (*Ostrinia nubilalis* Hübner, ECB), a significant pest causing substantial yield losses. Chemical insecticides, such as chlorantraniliprole and indoxacarb, are commonly used to control this pest; however, their environmental and health risks and potential for resistance development highlight the need for alternative pest management strategies. Biological control methods offer promising alternatives, including natural enemies and plant-derived compounds. This study evaluated the efficacy of neem oil, garlic extract, and chili pepper extracts against ECB larvae on pepper plants, comparing them to the chemical insecticides indoxacarb and chlorantraniliprole. Results from a two-year field experiment indicated that chlorantraniliprole exhibited the highest efficacy in reducing pepper fruit damage and larval survival, with the lowest damage severity and the lowest number of larvae per fruit. In the first year, neem oil and garlic extract showed promising results, effectively reducing fruit damage and performing comparably to indoxacarb. However, in the second year, only chlorantraniliprole showed consistent efficacy, likely due to unfavorable weather conditions that reduced the persistence of other treatments. Compared to the control, plant extracts showed higher efficacy in the first year of the trial, while indoxacarb was equally effective as the plant extracts. These findings suggest that plant-derived products like neem oil and garlic extract may be viable alternatives to chemical insecticides; however, further investigation is needed to optimize their application and efficacy in pest control.

Keywords: *Capsicum annuum*, garlic extract, chili extract, neem oil, European corn borer control, chlorantraniliprole

INTRODUCTION

Pepper (*Capsicum annuum* L.) is one of the most important vegetables and spice crops globally. The world's total cultivation area under pepper was above 2 million hectares in 2023 [FAOSTAT 2024]. Pepper is also one of the major vegetable species in Serbia, and it was grown at 9,915 ha in 2023 [FAOSTAT 2024]. Several major pests affect pepper crops, with the European corn borer (*Ostrinia nubilalis* Hübner, ECB) (Lepidoptera: Crambidae) causing the most substantial damage. Although the primary host plant of ECB is maize [Schmidt-Jeffris and Nault 2017], in recent years, it has gained increasing importance as a pest of pepper [Sekulić et al. 2003]. The main damage is caused by the caterpillars, which tunnel into the stem and fruit, feeding on the pericarp and seeds, weakening the plant and directly reducing yield. Infested pepper fruits eventually rot and drop off; late-infested fruit may exhibit premature reddening [Mason et al. 1996]. The economic losses can reach 50% or more [Sekulić et al. 2003]. The larvae are difficult to detect, and infestations are typically noticed only after significant damage. The larvae

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move among fruits, spreading pathogens such as Pectobacterium carotovorum (Jones) Waldee, and rotten fruits are generally symptoms of ECB infestation [CABI 2021]. Given this species' highly detrimental effect on pepper production, chemical treatments are often used to control the pest. However, insecticide residues in pepper fruits pose a serious threat to both consumers and the environment. Chlorantraniliprole and indoxacarb are the most commonly used chemical insecticides to control ECB infestations.

Chlorantraniliprole is an insecticide belonging to the anthranilic diamide class, first registered for use in 2008. It controls Lepidopteran, Coleopteran, and certain Dipteran pests [Bentley et al. 2010]. Indoxacarb is a highly toxic, broad-spectrum oxadiazine insecticide used against several Lepidopteran pests and certain Hemiptera and Coleoptera [Wing et al. 2000].

Likewise, the excessive use of insecticides may lead to the development of resistance to chemical compounds. Chlorantraniliprole-resistant strains of *Spodoptera littoralis* Boisduval showed obvious cross-resistance to indoxacarb [Moustafa et al. 2024].

On the other hand, biological control-based solutions, as the application of natural enemies, like parasitic wasps (*Trichogramma* sp.) and biological insecticides based on *Bacillus thuringiensis* subsp. *kurstaki*, are promising alternative control measures still underused, primarily due to the challenges associated with their application. A promising alternative is the use of plant-derived oils and extracts. These compounds can potentially reach pest control products' efficacy and remain safe for consumers and the environment [Souto et al. 2021]. Additionally, botanical extracts provide innovative and various modes of action that reduce the probability of developing resistance in pest populations [Isman 2008].

Extracts from several plant species, such as garlic, chili peppers, and neem, have shown strong insecticidal properties [Ngegba et al. 2022]. Garlic (*Allium sativum* L.) has insecticidal, repellent, anti-feeding, and broad-spectrum anti-microbial properties [Mamduh et al. 2017]. It promotes self-defense mechanisms in plants against fungal and bacterial infections, acts as a biostimulant or inducer [Hayat et al. 2022], and could be used as a coating biofungicide before sowing for the disinfection of wheat seeds [Perelló et al. 2013]. Garlic and its extracts have shown high efficacy in controlling insect pests from several orders, such as Coleoptera [Lu and Liu 2003, Mamduh and Movahedi Fazel 2010, Beltagy and Omar 2016, Golubkina et al. 2022], Lepidoptera [Lu and Liu, 2003, Perez-Mendoza and Aguilera-Penã 2004, Oparaeke et al. 2007], Heteroptera [Jaastad et al. 2007, Golubkina et al. 2022], and Diptera [Prowse et al. 2006, Cao et al. 2012]. Capsaicin is the active ingredient in chili peppers. It is used as a bird and insect repellent. Capsaicin has also demonstrated insecticidal activity and can control a wide range of insect pests, but at low levels of insect infestation [Li et al. 2019]. Its main target pests are aphids, loopers, armyworms, spider mites, thrips, leaf miners, and whiteflies [Antonious et al. 2006, Tomita and Endo 2007, Cuadrado et al. 2019]. Capsaicin has also shown anti-microbial activity [Vuerich et al. 2023]. Neem oil is an organic biopesticide extracted from the fruits of the neem tree, *Azadirachta indica* A. Juss. The primary active ingredient of most neem-derived products is azadirachtin. This steroid-like tetranortriterpenoid exhibits a wide range of bioactivity to hundreds of phytophagous insect species from different orders [Shannag et al. 2015], among which it has shown antifeeding effects and increased larval mortality in Lepidoptera [Mancebo et al. 2002]. This study aimed to assess the efficacy of neem oil, garlic, and chili pepper extracts against ECB larvae on pepper plants and compare it with two widely used active ingredients in commercial pesticides, indoxacarb, and chlorantraniliprole, in order to find out if botanicals can provide adequate alternative for chemical insecticides.

MATERIAL AND METHODS

Experimental design

The two-year trial was carried out in 2018 and 2019 on an experimental field of the Institute of Field and Vegetable Crops (Rimski Šančevi, Novi Sad, Serbia). The pepper variety Amfora (NS Seme) was sown on the 4th of April 2018 and 28th of March 2019 in a plastic greenhouse without heating. Amfora is a sweet pepper variety belonging to the "kapia" type, the most preferred pepper fruit type in Serbia [Danojević et al. 2021]. This variety was chosen because it is extensively grown and because the damage of the ECB is more severe in sweet pepper varieties with larger fruits [Sekulić et al. 2003].

A herbicide based on diquat 200 g L^{-1} (3 ml in 1 L of water) was used before the emergence, while during transplants, growing fungicide based on a.i. propamocarb-fosetylate 840 g L^{-1}, in a dose of 3 mL in 2 L of water (5 L solution per 1 m^2) was applied, and 2% solution of water-soluble fertilizer NPK 15:30:15. Plants were transplanted into an open field on the 31st of May 2018 and the 14th of June 2019.

The size of the basic experimental plot was 5×1.4 m. The planting distance was 70 cm between rows and 25 cm within the row. The experiment was established in a randomized block design with 3 replications with 40 plants per replicate. Fertilization with ammonium nitrate was applied at a rate of 200 kg ha^{-1} on the 26th of June 2018 and the 5th of July 2019. The plants were irrigated with sprinklers. No other pesticides were applied after transplanting.

Laboratory egg masses rearing

In order to increase pest pressure, one cluster of ECB eggs (30 eggs on average) per plant was placed onto the inner leaves on the upper third of 10 pepper plants (per replicate) on the 24th of July 2018 and 29th of July 2019. The egg masses were obtained in laboratory conditions from wild-collected specimens. The moths were collected in light traps, and each morning, they were placed in rearing cages. The rearing cages comprised a wooden 50×50×50 cm frame covered with a mesh screen. A special opening for introducing fresh specimens and extracting dead ones was positioned on the side of the cage. The moths were kept at 25 ±2 °C, relative humidity: 45 ±5%, and photoperiod 14:10 (light:dark) and fed daily with a sugary syrup. A 50×50 cm filter paper was placed at the top of the cage on which the females laid eggs. The eggs were collected daily by cutting the paper around the egg masses, then stored at 25 °C for several days to check the eggs' quality before being placed on the pepper plants. Eggs were placed on ten healthy pepper plants (without symptoms of any diseases), one egg mass per plant, and attached with an entomological needle to the leaf. Inoculated plants were marked. In 2019, the egg clusters that dried out before hatching were replaced by fresh ones on the 4th and 5th of August. At the inoculation period, the first fruit on pepper plants has reached typical size and form (stage 701 according to the BBCH scale).

Plant extract preparation

Plant extracts were prepared as an infusion using an extraction technique reported by Azwanida [2015] and slightly modified. Garlic cloves of Bosut (autumn variety) were measured (10 g), crushed, and boiled in 500 mL water for 15 minutes. After boiling, the extract was cooled for 24 h, filtered, and diluted up to 1 L of water. Water garlic extract was used because the concentration of alicin, one of the main bioagents, is ten times higher than in ethanol extract [Bajac et al. 2018]. The same procedure was used for the preparation extract from physiologically mature fruits of the red Habanero variety of *Capsicum chinense* Jacq., except that 10 g of air-dried fruits cut in pieces were used. Commercial neem oil (concentration 100%) produced by Shree Baidyanath, India, was used for neem plant extract. For the treatment of pepper plants, the concentration of neem plant extract was 1% (10 mL of the neem oil was diluted in 1 L of water). Subsequently, after preparation, extracts were used for plant treatment.

Treatment application

The application of pesticides and plant extracts was done once per year – on the 30th of July 2018 and the 6th of August 2019, during calm weather (without wind). Three biological and two chemical insecticides (Table 1) were applied using a SOLO 417-Li backpack sprayer with a pressure of 2 bar. Untreated plants were used as a control. The amount of solution per replication (plot) was 280 mL.

Assessments

The pepper fruits from the inoculated and control plants were harvested on the 24th of August 2018 and the 4th of September 2019, at BBCH scale 805. The fruits were dissected, and each fruit's number of larvae and damage severity were noted. Five fruits per plant were evaluated according to the damage rating scale (Fig. 1). This scale was purposely designed for ECB damage evaluation on pepper. The values on the scale range from 0 to 5, meaning the rating 0 is given to pepper fruits with no sign of damage. Rating 1 (minimal

Table 1. Insecticides and plant extracts used in the experiment

Insecticide active ingredient	Rate per hectare (L ha^{-1})
chlorantraniliprole 200 g L^{-1}	0.1
indoxacarb 150 g L^{-1}	0.25
Plant extract	**Amount of plant extract per 1 L of water**
neem oil	10 mL
aqueous garlic extract	10 g
aqueous red habanero extract (chili)	10 g

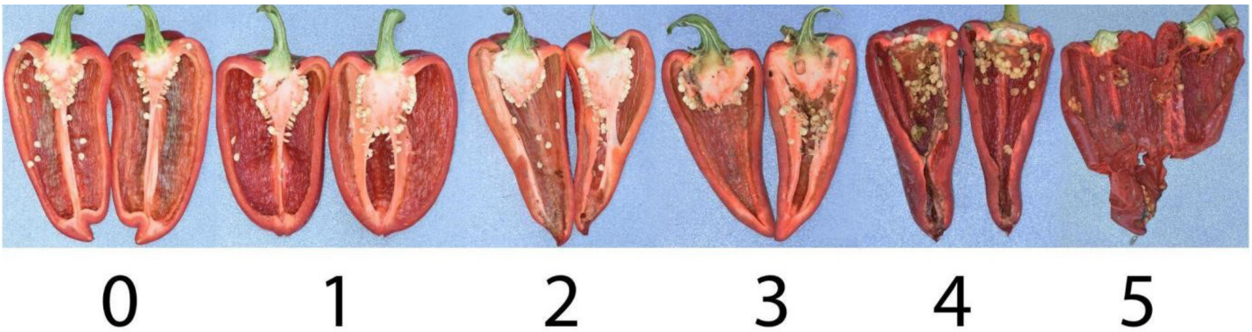

Fig. 1. Damage severity caused by *Ostrinia nubilalis* on pepper fruit (rating scale 0–5): 0 – no damage, 1 – minimal damage, 2 – visible damage, 3 – considerable damage, 4 – severe damage, 5 – destroyed fruit

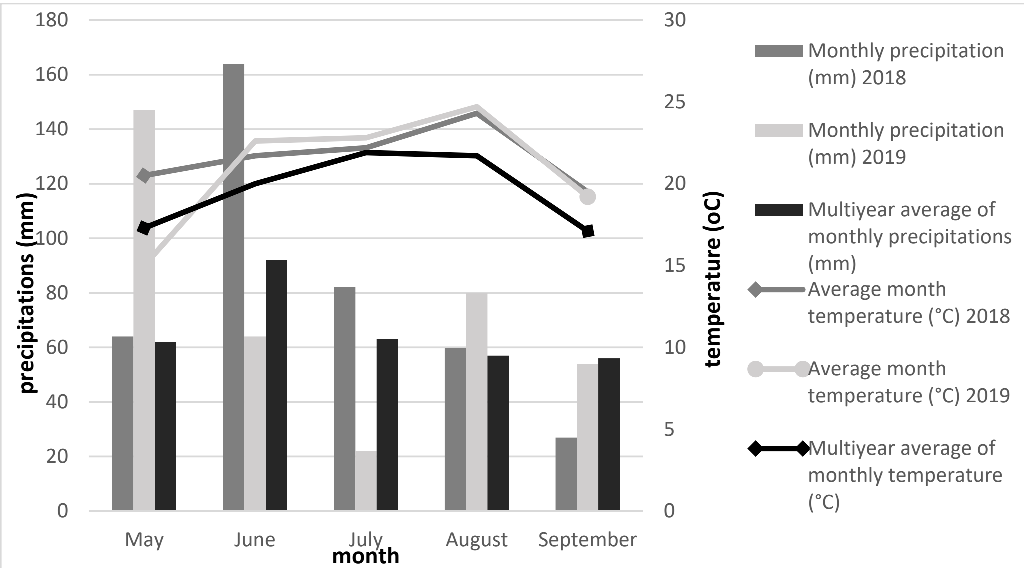

Fig. 2. Meteorological data for 2018 and 2019, compared with the 30-year climatic average (1989–2019) [Republic Hydrometeorological Service of Serbia]

Table 2. Analysis of variance (ANOVA) for the effects of active ingredient and year on damage severity and number of larvae in pepper fruits

Effect	df	Damage severity			Number of larvae		
		MS	F	*p*	MS	F	*p*
Intercept	1	1045.207	518.064	0.000	51.615	340.163	0.000
Active ingredient	6	33.308	16.510	0.000	2.294	15.120	0.000
Year	1	0.597	0.296	0.586	0.036	0.237	0.627
Active ingredient * year	4	2.147	1.064	0.373	0.071	0.470	0.758
Error	1755	2.018	–	–	0.151	–	–

df – degree of freedom, MS – mean square, F – value, *p* – probability

damage) is given to fruits with barely visible damage, rating 2 (clearly visible damage) is given to fruits showing visible but limited damage without the presence of frass, rating 3 (considerable damage) is given to fruits with a large amount of damage and visible frass, while rating 4 (severe damage) is given to fruits that not only exhibit extensive damage and frass but also show signs of decomposition visible externally, without the need for dissection. The highest rating (5) is given to fruits with such an extent of damage, already in an advanced stage of decomposition, and can be classified as destroyed. The commonly used tunnel length assessment method [Butron et al. 2014] for stem-boring insects in maize could not be applied to pepper fruits due to the complex tunneling patterns created by ECB larvae as they feed on them. Therefore, the authors devised an alternative method that has demonstrated ease of use and produced reliable results.

Statistical analysis

A two-factorial experimental design was applied, with year and active ingredient as fixed factors. The experiment was conducted over 2 years to assess the impact of various insecticides and plant extracts on damage severity and the number of larvae in pepper fruits. The data were analyzed using ANOVA with type I sum of squares and sigma-restricted parameterization due to many zero values in the dataset. The model included an intercept term, as it was found to be necessary for accurate estimation. The results were presented graphically for each year separately to enhance clarity and facilitate comparison. Post-hoc comparisons were conducted using the Bonferroni test at a significance level 0.05. Statistica software version 13.2 (Dell Inc., USA) was applied for these analyses.

Meteorological conditions

Meteorological conditions during the two experimental years varied considerably compared to the 30-year climatic average (1989–2019), as officially reported by the Republic Hydrometeorological Service of Serbia. In the first experimental year, 2018, a large amount of precipitation was recorded in June, and the temperatures were above average. During the experimental setup in August, the average temperatures were above the multiyear average for that month (Fig. 2). In the second experimental year, 2019, a significant amount of rainfall was recorded in May, while there was a notable lack of rainfall in July. The average temperature in August was almost 3 °C higher than the multiyear average.

RESULTS

The ANOVA results indicate that the active ingredient had a highly significant effect on both damage severity and number of larvae ($p < 0.001$), suggesting that the treatments differed significantly in their effectiveness. However, year and the interaction between active ingredient and year did not show statistically significant effects for either parameter ($p > 0.05$), implying that the treatments produced consistent results across both years and that seasonal variation (likely due to meteorological conditions) did not significantly influence the outcomes (Table 2). This suggests that the active ingredients tested in this study were effective regardless of the year or the environmental conditions.

Although the interaction between active ingredient and year was not statistically significant, the results were presented separately for each year to allow a more straightforward interpretation of treatment per-

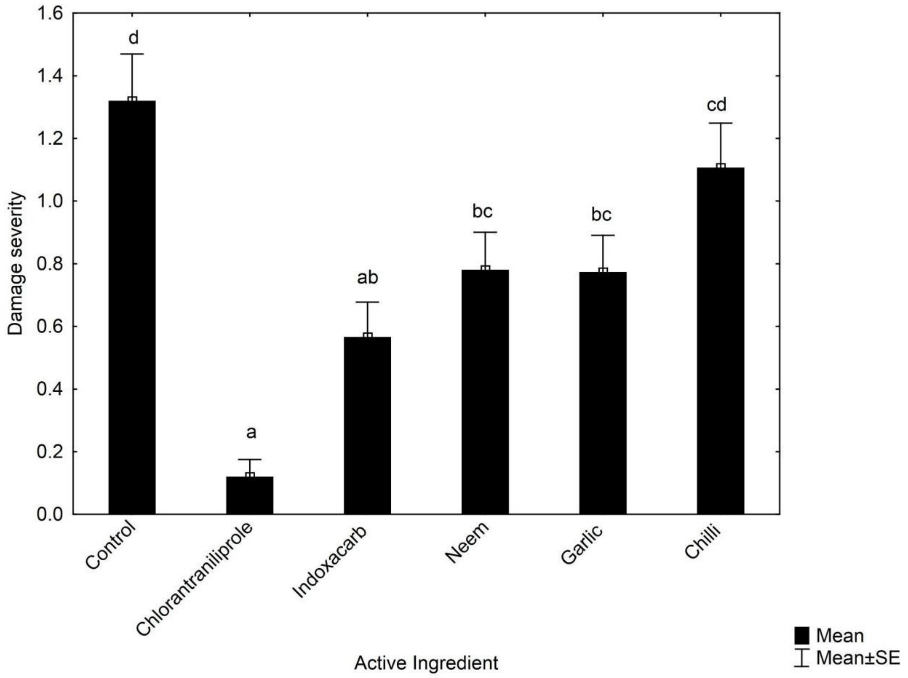

Fig. 3. Effects of different active ingredients on pepper fruit damage severity caused by *O. nubilalis* in 2018. Different letters indicate a significant difference, as determined by the Bonferroni test ($p < 0.05$)

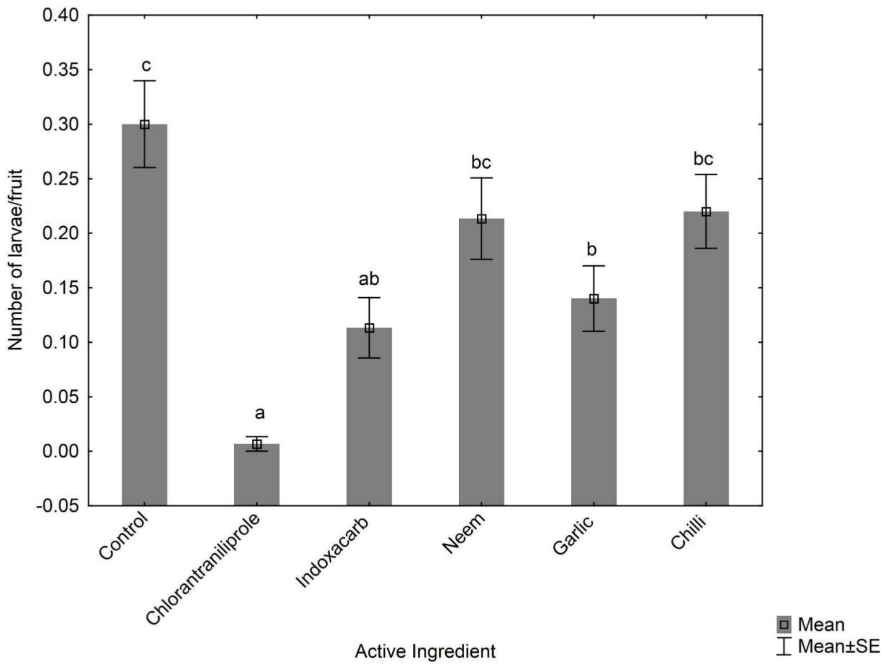

Fig. 4. Effects of different active ingredients on the number of larvae in pepper fruit in 2018. Different letters indicate a significant difference, as determined by the Bonferroni test ($p < 0.05$)

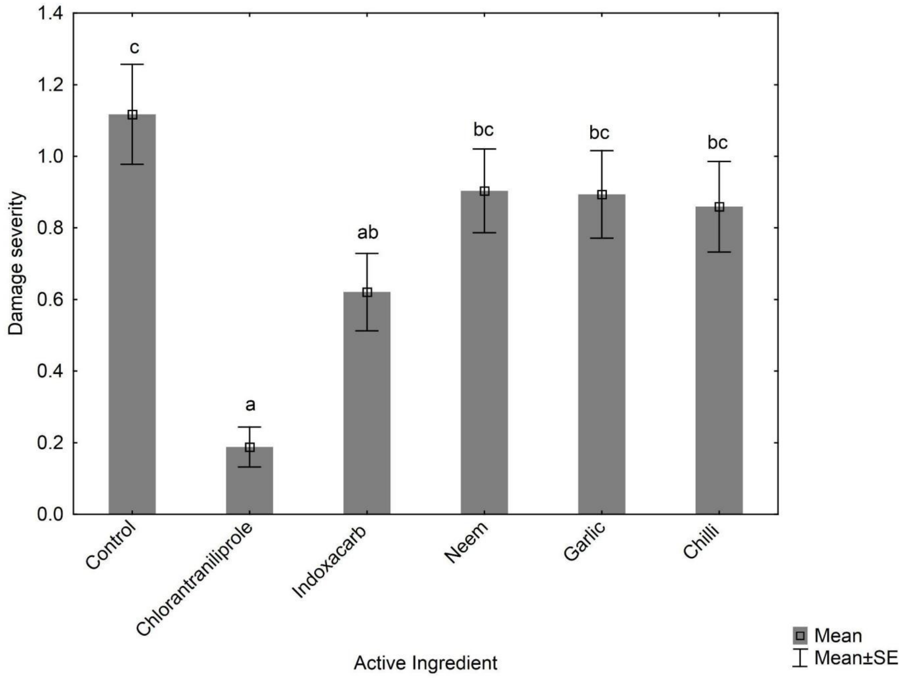

Fig. 5. Effects of different active ingredients on pepper fruit damage severity in 2019. Different letters indicate a significant difference, as determined by the Bonferroni test ($p < 0.05$)

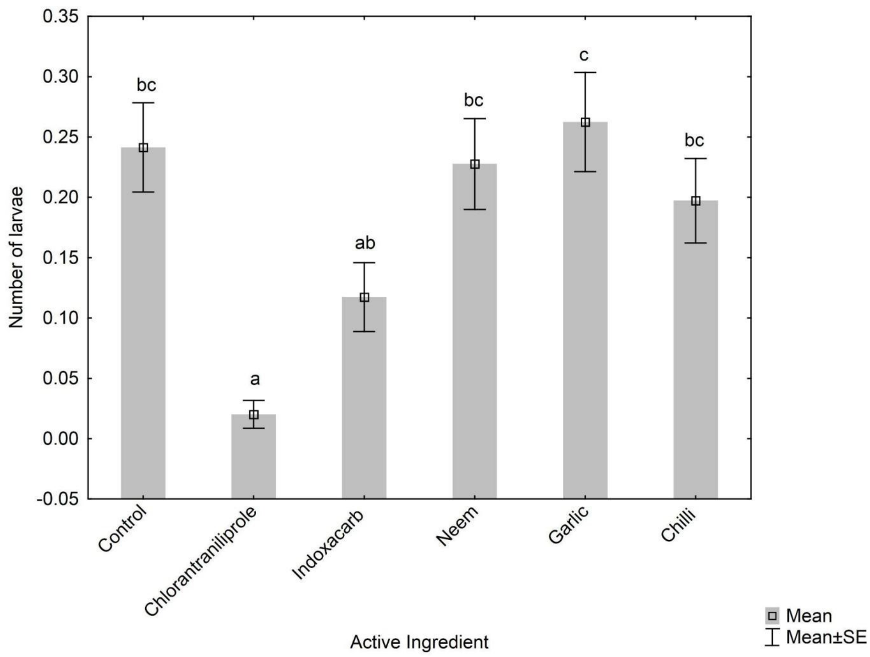

Fig. 6. Effects of different active ingredients on the number of larvae in pepper fruit in 2019. Different letters indicate a significant difference, as determined by the Bonferroni test ($p < 0.05$)

formance under differing environmental conditions. This approach provides insight into potential year-specific trends or anomalies, such as the observed reduction in efficacy during the second year, likely due to unusual weather patterns.

Results from 2018

The results for the first year of the trial showed that the lowest damage severity caused by ECB larvae was observed on pepper fruits treated with chlorantraniliprole (0.12), while the highest was in the control treatment – 1.32 (Fig. 3). All treatments, except chili treatment, showed statistically significant differences compared to the control; however, there was no significant difference between chlorantraniliprole and indoxacarb. Furthermore, the chemical insecticide based on indoxacarb did not show a significant difference in fruit damage severity compared to neem oil and garlic aqueous extract. Analyzing the effects of used plant solutions (neem oil, garlic, and chili aqueous extracts), the highest damage severity in 2018 was noted on pepper fruits treated with chili extract – 1.11 (Fig. 3).

In the first experimental year, pepper fruits treated with insecticide based on chlorantraniliprole were free of ECB larvae – 0.0, while the highest number was observed in the control plot – 0.3 (Fig. 4). Similar to the damage severity stage (level), there was no significant difference between chlorantraniliprole and indoxacarb in the number of larvae per fruit. Moreover, differences between indoxacarb, neem, garlic, and chili were not significant, but the difference between garlic – 0.14, and indoxacarb – 0.11, was very low (Fig. 4).

Results from 2019

In the second year of the experiment (2019), similar to the previous year, the lowest damage severity on pepper fruits was observed in the chlorantraniliprole treatment, while the control treatment showed the highest damage (Fig. 5). The treatment with indoxacarb (0.62) showed greater damage on pepper fruits than chlorantraniliprole (0.19). Extracts made from plants (neem, garlic, chili) showed similar effects on damage severity in 2019, with no significant differences compared to the control.

The lowest number of larvae was observed in the treatment with chlorantraniliprole, the only treatment that exhibited significant differences compared to the control, while the highest was noted with garlic extract (Fig. 6). According to the Bonferroni test, there was no difference between chlorantraniliprole and indoxacarb. Additionally, there were no significant differences between the indoxacarb treatment, the neem and chili treatments, and the control.

Based on the presented results, chlorantraniliprole exhibited the highest efficacy in both years. Using this insecticide resulted in the lowest damage severity and number of larvae per fruit. Compared to the control, plant extracts showed higher efficacy in the first year of the trial, while indoxacarb was equally effective as the plant extracts.

DISCUSSION

The excessive use of synthetic pesticides in Europe is leading to a series of environmental concerns, such as water quality problems [Hüesker and Lepenies 2022], soil contamination [Medić-Pap et al. 2023], which affects soil functions, biodiversity, and food safety overall [Silva et al. 2019]. The intake of raw and cooked vegetables, such as peppers, is one of consumers' most common pesticide exposure routes [Keikotlhaile et al. 2010]. Developing insecticides that precisely target the main pest species is imperative; however, even those active ingredients accumulate in the environment and, over time, exhibit detrimental effects on many non-target organisms [Aktar et al. 2009]. For these reasons, it is essential to identify practical solutions for managing harmful insect species using the safest control methods available. Following the European Union Directive 2009/128/EC [Official Journal of the European Union 2009], the spreading of biological methods based on the sustainable use of pesticides is one of the main objectives aimed at limiting the risks caused by the use of pesticides on the environment and human health. Insecticides based on chlorantraniliprole and indoxacarb exhibit good efficacy in the control of a wide variety of lepidopteran pests [Ghidiu et al. 2009, Vuković et al. 2018, Moustafa et al. 2021]. However, although chlorantraniliprole has low toxicity to mammals, birds, fish, and most soil invertebrates [USEPA 2020], the study conducted by Abdel-Mobdy et al. [2017] revealed its role in pathological parameters of sub-acute and sub-chronic liver, kidneys and protein profile changes in albino rats. Additionally, potentially harmful effects on the development of chicken embryos (*Gallus gallus domesticus* L.) have been reported, even at very low concentrations [Abbas et al. 2018]. It has also been reported to be highly toxic to bees and aquatic invertebrates and persistent in the environment [USEPA 2020]. Similarly, several insecticides with a high pesticide load per hectare, including indoxacarb, have been banned since 2018 [Gensch et al. 2024]. Many formulations containing indoxacarb have been banned in the EU due to unacceptably high risks to bees, beneficial arthropods, birds, and small mammals or because such risks could not be excluded [European Commission 2019, 2021]. However, indoxacarb's approval in biocidal use stretches to December 2026 [Official Journal of the European Union 2024]. It has been shown that several chemical insecticides are difficult to remove from fruits and vegetables. The removal rate of chlorantraniliprole by washing pepper fruits was the lowest (24.8%) among all other applied pesticides, which might be related to its low water solubility [Li et al. 2023].

Plant extracts offer significant advantages in sustainable agriculture and represent a feasible alternative against weeds and pests. Garlic is known for its stimulating properties on plant growth and also protects plants due to its bactericidal and fungicidal activity [Rinaldi et al. 2019]. The demonstrated insecticidal activity of *A. sativum* is based on the presence of allicin [Wanyika et al. 2011]. Aqueous and hydroalcoholic garlic extracts are effective in agriculture [Rinaldi et al. 2019]. Garlic aqueous extract showed a higher efficacy against *Sitophilus zeamais* Motschulsky, which recorded the highest mortality of 98% when comparing its efficacy against *Callosobruchus maculutus* Fabricius, which recorded an 86% mortality. In the first year of our experiment, the garlic solution showed a statistically significant reduction of pepper fruit damage severity and number of ECB larvae in fruits compared to the control and had no significant differences when compared with indoxacarb. Similarly to our findings, Dougoud et al. [2019] reported that in field application, garlic aqueous extracts resulted in a varying level of control of hemipteran, lepidopteran pests, and mites. Compared with positive controls, the efficacy of garlic aqueous extracts was statistically lower in half of the cases [Dougoud et al. 2019].

As a natural compound derived from the neem tree, azadirachtin represents a sustainable alternative to conventional chemical insecticides. During the fruiting of pepper plants, neem-based products should be used to ensure food safety and promote the activities of beneficial arthropods [Adom et al. 2024]. Azadirachtin (0.3% w/w EC) was effective against the false codling moth (FCM) and fruit flies and reduced whitefly populations in chili peppers. Therefore, this promising biopesticide could be used in integrated pest management [Adom et al. 2024]. It has also been reported that at extremely low concentrations of 1 and 10 ppm, azadirachtin proved to be an effective botanical insecticide for controlling *O. nubilalis* [Arnason et al. 1985]. Our results showed that the neem-based treatment in the first experimental year significantly reduced pepper fruit damage severity compared to the control and performed almost equally well as indoxacarb. Gagnon [1992] reported similar findings against the ECB. This author stated that a neem seed kernel extract sprayed before the artificial infestation of the sweet corn plants provided excellent protection against European corn borer damage and significantly reduced larval populations [Gagnon 1992]. Meisner et al. [1985] reported that they observed no pupation of ECB larvae with fresh residues on sweet corn seedlings of 1.0, 0.5, and 0.25% neem extract; only 7% and 16% of the larvae pupated at 0.1% and 0.05% concentration, respectively. According to Meisner et al. [1985], larval weight on the treated leaves was significantly lower at all observation times than on untreated ones, and no pupation occurred even on 8-day-old residues. The high and consistent efficacy of neem-based products against many insect pests could be explained by the fact that the active ingredient azadirachtin possesses multiple modes of action, including antifeedant, deterrent, and growth disruption effects [Mordue and Nisbet 2000]. However, it has been reported that exceptional weather conditions (high temperatures, dry conditions) may harm the efficacy of foliar-applied neem products [Gagnon 1992]. This statement follows the results obtained in our experiment.

Low toxicity to humans and animals and very low environmental risk make chili pepper extracts promising alternatives to chemical insecticides in sustainable pest management strategies. Capsaicin showed high efficacy against the green peach aphid *Myzus persicae* Sulzer in pepper [Koleva Gudeva et al. 2013], and chili pepper (*Capsicum frutescens* L.). Aqueous extract demonstrated high insecticidal potential in the control of pink hibiscus mealybug *Maconellicoccus hirsutus* Green. Even at low concentrations, the mortality was reported to be higher than 70% [Marchiori et al. 2023]. In addition to that, caterpillars of *Spodoptera latifascia* Walker (Lepidoptera: Noctuidae) reared on highly pungent fruits of the Habanero variety had longer development time, reduced pupation success and lower adult emergence [Chabaane et al. 2022]. Our study on chili extracts showed no significant efficacy expressed through pepper fruit damage severity, and the number of surviving larvae was compared with the control in any of the two experimental years. According to Dougoud et al. [2019], the results of chili pepper aqueous extract application in field experiments against insect pests from various orders were inconsistent, underlining that further research is needed to draw reliable conclusions.

In our experiment, in both years, the treatment with the highest efficacy expressed through pepper fruit damage severity and the number of surviving larvae was chlorantraniliprole, while indoxacarb did not differ from the control treatment only in 2019 for the number of larvae. The plant extracts and neem oil treatment did not exhibit statistically significant efficacy in 2019. It may be attributed to the abnormally high rainfall at the beginning of August 2019, coinciding with the application of the treatments. Therefore, the above-average precipitation in August 2019 likely negatively affected the persistence of the active ingredients on the pepper leaves and fruit, resulting in reduced efficacy across nearly all treatments. The damage severity scale has proven helpful for a reliable infestation assessment and effective pest management decision-making.

CONCLUSION

While synthetic insecticides such as chlorantraniliprole and indoxacarb are effective against *O. nubilalis* in pepper production, their associated environmental and health risks, environmental persistence, and regulatory restrictions underline the urgent need for safer alternatives. The two-year study results demonstrate that among the tested plant extracts, garlic, and neem-based extracts showed promising efficacy, particularly under favorable weather conditions, and in some cases, performed comparably to indoxacarb. In contrast, chili extract did not significantly reduce fruit damage or larval presence in either experimental year. The damage severity rating scale proved effective for assessing infestation levels and guiding pest management decisions. These findings support the possible integration of plant extract insecticides, particularly garlic and neem, into sustainable pest management strategies, per EU directives on reducing synthetic pesticide use. Further studies are needed to optimize application methods in different agroecological conditions.

SOURCE OF FUNDING

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, grant number 451-03-136/2025-03/200032 and the Autonomous Province of Vojvodina, Serbia, as part of a short-term project of special interest for sustainable development in the AP Vojvodina (Project No. 000882611 2024 09418 003 000 000 001 01 001 04 002).

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