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Natural and semi-synthetic insecticides protect onion from wireworms

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SUMMARY

Wireworms, the larval stage of click beetles (Elateridae: *Agriotes* spp.), pose a significant threat to global agriculture, particularly to root vegetables, such as onion. Their subterranean lifestyle, as well as the withdrawal of some traditional synthetic insecticides, make them challenging to control. Therefore, this research aimed to compare the effects of natural, semi-synthetic and synthetic insecticides in controlling wireworm damage in an onion field.

A field trial for testing the effects of different insecticidal treatments on plant density, wireworm damage (%) and total onion yield, was conducted at the Institute for Vegetable Crops (Smederevska Palanka, Serbia) in 2024. The experiment consisted of six treatments: an untreated control, three natural insecticides (two formulations of spinosad a.i. - granular and liquid, and *Beauveria bassiana* ATCC 74040 2.3×107 conidiospores/ml), a semi-synthetic insecticide (a.i. spinetoram) and a synthetic insecticide (a.i. tefluthrin). The insecticides were applied during planting, following their label application rates per hectare. Assessments were conducted 20 and 42 days after treatment (DAT) to determine plant density. Wireworm damage was specifically evaluated 42 DAT, and yield was calculated by weighing the harvested onion bulbs. The results showed that the granular spinosad formulation, applied in furrows at planting, significantly increased plant density 20 DAT, while its liquid formulation, applied as a soil treatment during planting, resulted in the lowest density. Spinetoram showed the highest plant density 42 DAT and the highest percentage of wireworm damage (15%) of all insecticides tested. The control had the highest percentage of damaged plants and the lowest yield. Onion yield was at the maximum after treatment with spinetoram, whereas the lowest yield was achieved after treatment with the granular spinosad formulation.

Field trials show that natural and semi-synthetic insecticides can effectively control wireworms, ensuring adequate crop protection and viable yields. This study supports developing and adopting environmentally conscious soil pest management.

Keywords: Elateridae, biopesticides, insecticides, pest control, yield, onion

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INTRODUCTION

Onion (Amaryllidaceae: *Allium cepa* L) is recognized globally as one of the oldest cultivated vegetable crops, which has been grown for 4000 years. In the Republic of Serbia, onion is cultivated on approximately 4,114 ha, constituting 0.76% of the global onion cultivation area. (Bošnjak et al. 2007; Takač & Vuković 2023). Climate change, with its associated warmer temperatures, droughts, and altered precipitation, has amplified the impact of soil pests, particularly wireworms, on onion yield. A three-year field study investigating wireworm activity in sunflower under these changing conditions underscored this trend (Gvozdenac et al., 2022).

Wireworms, the subterranean larvae of click beetles (Coleoptera: Elateridae, genus *Agriotes* spp. Eschscholtz, 1829), are a significant and persistent challenge to global agricultural productivity. These polyphagous pests are characterized by their extended larval stage, which may last for several years while they reside in soil, which makes them very difficult to detect and control (Parker & Howard, 2001; Sufian, 2013; Stolpe Nordin, 2017; Toscano et al., 2017). *Agriotes* larvae are polyphagous herbivores that specialize in feeding on underground plant structures of a large number of plant species, including field crops, vegetables and ornamentals. Damage to root and tuber vegetables, especially during planting and preharvest stages, is economically significant. The initial signs include small holes and tunnels, which later develop into skin scarring, impacting product marketability (Barsics et al., 2013; Furlan et al., 2017; Antwi et al., 2018; Poggi et al., 2021; Gvozdenac et al., 2022). This feeding behavior leads to significant economic losses for farmers worldwide as damaged crops become unusable or show reduced yields. The impact of wireworms is particularly severe in regions with temperate climate, where their long life cycle and adaptability to different soil types contribute to their prevalence. The economic impact of wireworm infestation on potato crops is substantial, given the high susceptibility of potato tubers to damage, while even minor injuries diminish their market value (Parker & Howard, 2001; Staudacher et al., 2013). Furthermore, sunflower, as well as some other field and vegetable crops, are vulnerable to these pests (Gvozdenac et al., 2019; Gvozdenac et al., 2022). Onion seedlings are also extremely vulnerable to wireworm damage, making early stage protection critical. Therefore, chemical pesticides are often considered essential, especially during planting (Bošnjak et al., 2007; Barsics et al., 2013).

There are several challenges in controlling these pests, including difficulties in diagnosing their presence in the soil, prolonged development and presence of larval stages, and traditional management strategies that rely heavily on treatments with conventional insecticides, including organophosphates, pyrethroids, and neonicotinoids (Van Herk et al., 2008; Furlan & Kreutzweiser, 2015; Traugott et al., 2015). However, there has been in recent years a significant decrease in the use of compounds from the groups of synthetic pesticides, due to strict bans and/or restrictions as a result of concerns over their impact and persistence in the environment, their non-selective action, especially on beneficial organisms, and the development of resistance in wireworm populations to these insecticides. Experimental evidence suggests that sublethal doses of conventional insecticides such as neonicotinoids, pyrethroids, and fipronil result in extended morbidity in wireworm populations. Crucially, the documented recovery of some individuals underscores a significant risk of evolving insecticide resistance (Antwi et al., 2018). As mentioned, many of these traditional insecticides have been consequently withdrawn from the market or subjected to strict regulatory restrictions, necessitating the development of alternative and more sustainable control measures (Wilde et al., 2007; Van Herk et al., 2008; Antwi et al., 2018; de Oliveira Cantao & Mian, 2023).

The lack of effective chemical controls has prompted increased research into integrated pest management (IPM) strategies, including biological control agents, agro-technical measures, and innovative technologies. Biological control approaches, such as the use of entomopathogenic fungi and nematodes, are being explored as environmentally friendly alternatives (Kabaluk et al., 2007; Milosavljevic, 2015; Poggi et al., 2021; Nikoukar & Rashed, 2022). This study evaluated the impact of natural, semi-synthetic and synthetic insecticides on wireworm control in onion crop, comparing the effects of three natural insecticides - two spinosad formulations (granular and liquid), one *Beauveria bassiana* Balsamo-Crivelli (1936) (Ascomycota: Hypocreales) biological preparation, the semi-synthetic spinetoram, and the synthetic tefluthrin insecticide.

A study by Ladurner et al. (2009) evaluated the efficacy of *B. bassiana* in biological control of wireworm populations in organic production systems in Germany and Italy. Naturalis-L, a microbial insecticide containing *B. bassiana* strain ATCC 74040, targets a wide range of arthropod pests, including whiteflies, tetranychid mites, thrips, and wireworms (Ladurner et al., 2009;

Prijović et al., 2011; Paluch, 2022). Its primary mode of action is contact-based, fungal spores adhere to the insect cuticle, germinate, and produce hyphae that penetrate the host. This process is facilitated by the release of cuticle-hydrolyzing enzymes (Vernon & Van Herk, 2022; CBC Europe, 2025). The biological product containing *B. bassiana* shows a promising effectiveness in reducing wireworm damage in potatoes. Application at planting is recommended, especially in non-irrigated fields. While effective against some wireworm species, its efficacy varies, and further research is needed to optimize fungal biocontrol strategies (Ester & Huiting, 2007; Ladurner et al., 2009; Wraight et al., 2009).

Spinosyns (spinosad and spinetoram) have been used for over 25 years against various pests, and despite the IPM guidelines, pests have developed resistance. Spinosad, a naturally derived biopesticide from *Saccharopolyspora spinosa* Mertz and Yao (1990), offers a valuable combination of high selectivity against target insect pests and low toxicity to beneficial arthropods. Registered globally for seed treatment and planting use, it provides effective control both by contact and ingestion of a broad spectrum of pests, including Coleoptera. To date, the unique mechanism of action of nicotinic acetylcholine and gamma-aminobutyric acid (GABA) receptors in the insect nervous system has resulted in no observed cross-resistance (Salgado et al., 1997, 2010; Salgado, 1998; Racke, 2006; Bacci et al., 2016; de Oliveira Cantao & Mian, 2023; Sparks et al., 1995, 2021, 2025). The use of spinosad to protect crops from wireworms and other soil-borne pests has been studied extensively. Studies have consistently shown that spinosad significantly reduces wireworm damage, and seed treatment is a particularly effective method of application (Ericsson et al., 2007; Van Herk et al., 2015; Arrine et al., 2017). In addition, in-furrow applications at planting have shown good results in crop protection (Vernon et al., 2013; de Oliveira Cantao & Mian, 2023). Spinetoram, a ''reduced-risk,'' semi-synthetic analog of spinosad, shares a similar mode of action (Yee, 2018). While spinetoram is effective against a broad spectrum of pests, its ecotoxicological impact, particularly on beneficial insects, remains understudied (Chloridis et al., 2007; Drobnjaković et al., 2023, 2025). Although spinosad has shown some efficacy against wireworms, the effectiveness of spinetoram against this pest varies, as evidenced by mixed results reported in studies using the insecticide Radiant 120 SC (Zhang et al., 2018; Poggi et al., 2021).

Pyrethroids, typically applied as foliar sprays, have also been explored for in-furrow wireworm control with varying results (Traugott et al., 2015). In wheat, tefluthrin seed treatments have provided good stand and yield protection under heavy *Agriotes obscurus* L pressure, although, like neonicotinoids, it did not reduce wireworm populations (Vernon et al., 2009). Laboratory studies suggest that tefluthrin acts as a repellent rather than a lethal agent to wireworms when applied to wheat seeds, potentially explaining the observed stand protection in both wheat and maize crops (Van Herk and Vernon, 2014). In Serbia, tefluthrin-based soil insecticides are registered for protecting various field and vegetable crops, including maize, sugar beet, potato, carrot, celery, parsley, and onion (Plant Protection Directorate, 2025). Specifically, Saturn Terra New, a granular formulation (GR) containing tefluthrin, is used to control wireworms in maize, potato, onion and carrot (Agrosava, 2025).

This research aimed to evaluate the efficacy of environmentally friendly insecticides against synthetic alternatives, establishing precise application rates, so as to optimize onion yield and quality, while minimizing ecological impact. Ultimately, this study sought to equip onion growers with effective and sustainable tools for long-term wireworm management, thereby enhancing the stability of onion production.

MATERIAL AND METHODS

The 'Stuttgarter Yellow' Dutch yellow onion variety, commercially known as 'Stuttgarter Riesen', was selected for this experiment. This variety is characterized by round yellow bulbs and excellent storage capacity, and is suitable for sowing over the period from March to April.

Wireworms, the larval forms of various click beetles *Agriotes* spp., were used as test organisms to assess the effects of insecticides. The risk of wireworm infestation was assessed by soil sampling. Wireworm density was estimated per m^2 based on the number of specimens found in spring soil samples collected before the experiment was established. Samples were collected using the standard square method (50 × 50 cm, approximately 40 cm deep) with 10 replicates distributed across the experimental field (Čamprag, 1983; Štrbac, 2005).

Experimental field and treatments

The trial was conducted in an experimental field specifically designed for controlled pest management studies of the Institute for Vegetable Crops (Smederevska

Palanka, Serbia; 44^0 22' N, 20^0 57' E) in 2024. This field allowed for precise treatments and monitoring of wireworm populations, as well as onion crop responses (Photo 1). The experimental field soil was a vertisol (alluvial loam), which was significantly influenced by the nearby Kubršnica and Jasenica rivers. A multiannual crop rotation with moderate fertilization ensured an adequate macroelement supply. Winter wheat was used as a preceding crop. Prior to sowing, the soil received a mixed mineral fertilizer of 46 kg/ha N, P_2O_3 and K_2O. Following winter plowing and seedbed preparation, sowing was conducted with crop-specific interrow spacing and plant density.

The Dutch yellow onion variety 'Stuttgarter Yellow' was sown directly in the field on March 29, 2024.

The experimental design, including treatment arrangement and plot size, was based on EPPO (2005) guidelines and was implemented in four replicates.

Six treatments were tested as follows: untreated control, three insecticides of natural origin, a semi-synthetic and a synthetic insecticide (Table 1). The insecticides were applied directly to furrows at planting following the label application rates per hectare. A pre-emergence herbicide application significantly reduced weed density. To eliminate the risk of phytotoxic effects on onion plants, residual weeds were manually removed. Manual weed control and crop hoeing were consistently implemented throughout the experimental period with no other pesticides used, ensuring that the wireworm response was solely attributable to the tested insecticides.

a b

Photo 1. Experimental onion field during planting (a) and second assessment (b)

Plant density and wireworm damage (%)

Owing to a lack of specific method for assessing the impact of wireworms on onion crops, assessment methods for maize and cereals were adapted for use in this study. The efficacy of the applied insecticides was estimated based on plant density and wireworm damage (%) on onion plants, observed 20 and 42 days after treatment (20 DAT and 42 DAT). For both evaluations, plant density was assessed by randomly selecting ten 1-meter sections within a row per plot and counting the number of emerged plants within each section. The first assessment was conducted at the time of emergence after approximately 75% of onion plants have emerged, and the second assessment was conducted at the stage of 5-6 leaves. The number of plants showing symptoms of wireworm infestation was recorded during the second assessment and transformed into %.

Onion yield

Bulb mass per replicate was measured on an analytical balance upon harvest (July 25, 2024) and converted to average onion yield (t/ha) for each treatment. The percentage yield change, indicating insecticide effects, was calculated relative to the untreated control and synthetic insecticide.

Statistical analysis

Wireworm density was expressed as a total number of individuals per square meter (m^2).

Plant density, expressed as the mean number of plants per linear meter, was used to estimate the effects of insecticides. The difference in mean plant density between the insecticide-treated plots and untreated control plots was used to calculate the percentage effect of each insecticide.

The mean onion bulb yield was determined by measuring the total bulb yield per experimental plot for each treatment. Insecticide effects were expressed as a percentage relative to both the untreated control and the synthetic insecticide treatment.

The results were statistically analyzed using STATISTICA 10. Fisher's least significant difference test (Fisher's LSD) was employed to determine significant differences in mean values at a 95% confidence level ($p < 0.05$).

RESULTS

The results of the present study demonstrated significant differences in all measured variables (the efficacy of different insecticide treatments expressed as plant density, wireworm damage, and total onion yield) across experimental treatments.

Table 1. List of insecticides tested in the experimental onion field

Product	A.i.	Concentration (F)	Company name	Rate (ha)	Rate (fr)
Natural origin insecticides					
Gestikal 001GR	Spinosad	1 g/kg (GR)	Agrosava, Serbia	48 kg	16 g
Laser 240 SC	Spinosad	240 g/l (SC)	Corteva Agriscience, Switzerland	0.3 l	0.1 ml
Naturalis-L	*Beauveria bassiana* ATCC74040	2.3×10^7 conidiospores/ml(l)	CBC (Europe) S.r.l. Biogard division, Italy	3 l	1 ml
Semi-synthetic insecticide					
Radiant 120 SC	Spinetoram	120 g/l (SC)	Corteva Agriscience, Switzerland	0.4 l	0.13 ml
Synthetic insecticide					
Saturn Terra New	Tefluthrin	5 g/kg (GR)	Agrosava, Serbia	15 kg	5 g
Untreated Control	–	–	–	–	–

A.i. - active ingredient; F – formulation of prodact; GR – granules; SC - concentrated suspension; L – liquid; ha – per hectare; fr – per furrow

Baseline soil sampling confirmed wireworm population density of 3 larvae/m^2 per experimental plot (Photo 2), a level exceeding the economic threshold requiring insecticidal treatment for effective crop protection (Čamprag, 1983; Furlan, 2014; Bažok et al., 2018).

Plant density and wireworm damage (%)

An analysis of plant density data indicated significant differences in the efficacy of applied insecticides (Table 2). Treatment with Gestikal 001 GR at 48 kg/ha resulted in a plant density increase by 202.5%, 20 DAT, compared to the control, thereby demonstrating a substantial positive impact on plant emergence and plant density. Conversely, treatment with Laser 240 SC (0.3 l/ha) achieved the lowest plant density increase (165.0%, 20 DAT) compared to the control, considering all insecticides tested. Over the longer period of 42 DAT, Radiant 120 SC (applied at a rate of 0.4 l/ha) resulted in a statistically significant increase in plant density of 121.1% relative to the control, whereas Gestical 001 GR showed the smallest increase (110.2 %), compared to the other insecticides.

Photo 2. Visual confirmation of wireworms (*Agriotes* spp.) in a soil sample from an experimental plot (original photo)

Table 2. The number of emerged onion plants in different insecticidal treatments and plant density (%) in comparison to untreated control

Insecticides (Rates liters/ha or kg/ha)	Mean number (± SE)	Plant density (%)	
		Ec	Es
20 DAT			
Gestikal 001 GR 48 kg/ha	4.05 (0.83) **a**	202.5	108.6
Laser 240 SC 0.3 l/ha	3.30 (0.61) **ab**	165.0	88.5
Radiant 120 SC 0.4 l/ha	3.60 (0.79) **ab**	180.0	96.5
Naturalis-L 3 l/ha	3.40 (0.58) **ab**	170.0	91.2
Saturn Terra New 15 kg/ha	3.73 (0.69) **ab**	186.5	100.0
Untreated Control	2.00 (0.68) **b**	100.0	–
	F=1.16; p<0.37		
42 DAT			
Gestikal 001 GR 48 kg/ha	7.33 (0.61) **ab**	110.2	94.6
Laser 240 SC 0.3 l/ha	7.68 (0.39) **ab**	115.5	99.1
Radiant 120 SC 0.4 l/ha	8.05 (0.42) **a**	121.1	103.9
Naturalis-L 3 l/ha	7.90 (0.52) **ab**	118.8	102.0
Saturn Terra New 15 kg/ha	7.75 (0.09) **ab**	116.5	100.0
Untreated Control	6.65 (0.32) **b**	100.0	–
	F=1.48; p<0.25		

DAT = days after treatment; Mean values marked by different letters are significantly different (Fisher's LSD test, p < 0.05); Ec – efficacy compared to untreated control; Es – efficacy compared to synthetic insecticide

The frequency of wireworm damage, quantified as the percentage of plants with wireworm damage 42 DAT showed significant treatment effects. Laser 240 SC showed the lowest incidence of damage (10%), indicating superior protection. Radiant 120 SC, which enabled the highest plant density, recorded the highest incidence of damage (15%) of all insecticide treatments. The untreated control showed a statistically significant increase in the frequency of damage (26%) compared to all treatments, indicating a significant impact of wireworm infestation. Figure 1 provides a graphical representation of these data.

Photo 3 shows a comparison of healthy onion plants and plants with symptoms. Plants on the left, originating from the Laser 240 SC-treated field, exhibited healthy growth. In contrast, plants on the right from the untreated control displayed characteristic wireworm damage symptoms, including stunting, underdeveloped root systems, chlorosis, and dried outer leaves.

Photo 3. Symptoms of wireworm damage in onion plants: left - healthy plants, and right - plants with symptoms (original photo)

Onion yield

The maximum average onion yield (21.80 t/ha) was obtained from plots treated with Radiant 120 SC. As anticipated, the untreated control exhibited the lowest yield (15.23 t/ha). All insecticide treatments significantly enhanced yield, relative to the control.

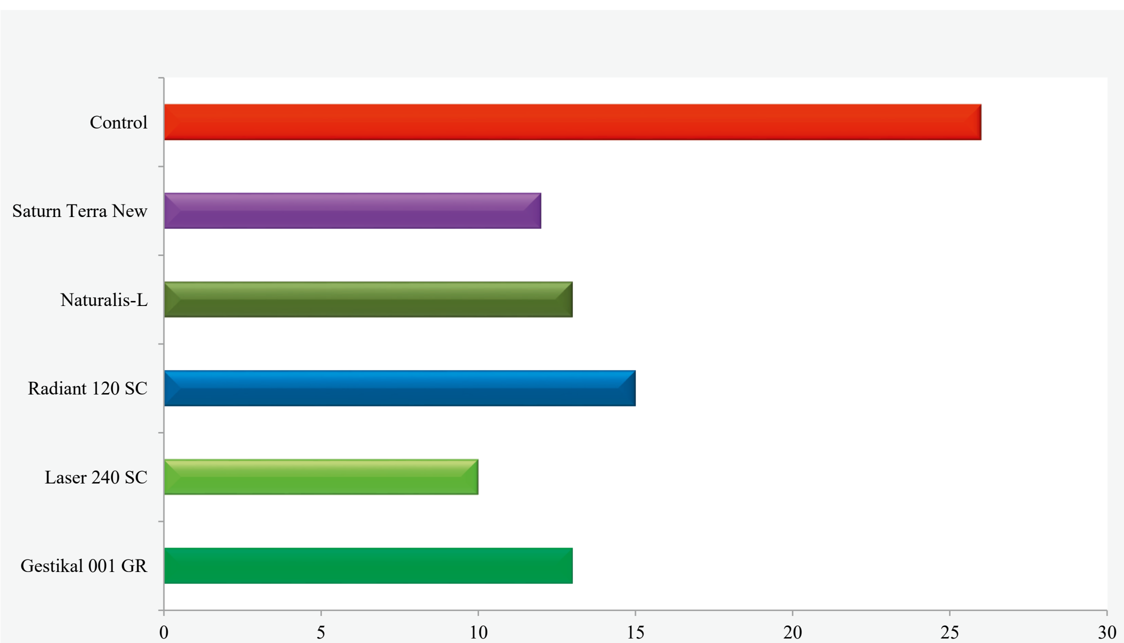

Figure 1. Percentage of wireworm-damaged onion plants

Table 3. Onion yield (t/ha) after different insecticidal treatments and effects of insecticide treatments on onion yield (%) in comparison to untreated control

Insecticides (Rates liters/ha or kg/ha)	Repeats				Mean yield (SE)	Onion yield (%)	
	I	II	III	IV		Ec	Es
Gestikal 001 GR 48 kg/ha	18.1	18.8	20.5	19.5	19.23 (0.51) **c**	126.3	89.4
Laser 240 SC 0.3 l/ha	19.9	18.3	20.6	19.0	19.45 (0.51) **bc**	127.7	90.4
Radiant 120 SC 0.4 l/ha	24.3	21.1	21.5	20.3	21.80 (0.87) **d**	143.1	101.3
Naturalis-L 3 l/ha	22.0	20.7	21.7	20.6	21.25 (0.35) **bd**	139.5	98.8
Saturn Terra New 15 kg/ha	23.3	22.5	19.1	21.1	21.50 (0.92) **d**	141.2	100.0
Control	14.5	14.7	15.9	15.8	15.23 (0.37) **a**	100.0	–
					$F=17.17$; $p<0.01$		

Mean values marked by different letters are significantly different (Fisher's LSD test, $p < 0.05$); Ec – efficacy compared to untreated control; Es – efficacy compared to synthetic insecticide

The 6.57 t/ha yield increase observed with Radiant 120 SC correlated with its peak plant density result 42 DAT. In contrast, Gestical 001 GR resulted in the lowest yield of all insecticides (19.23 t/ha) and also demonstrated the lowest plant density in the second assessment (Table 3).

DISCUSSION

Wireworms, well-known for their polyphagous nature, are globally recognized as major agricultural pests that inflict substantial economic damage across a wide range of crops (cereals, vegetables, including onion, maize, potato, sugar beet and ornamentals), weeds and non-crop plants (Poggi et al., 2021). Their complex biology and ecology, coupled with resistance to numerous insecticide classes, pose significant challenges for effective control (Hays, 1933; Parker & Howard, 2001; Gvozdenac et al., 2022). Implementation of Directive 128/2009/EC (European Commission, 2009), which has resulted either in a ban or restricted use of a substantial number of effective synthetic insecticides, presents significant obstacles for the protection of major field and vegetable crops from soil pests, including wireworms. Consequently, the limitations imposed on traditional chemical control have spurred a surge in research focused on the development and refinement of IPM strategies. These comprehensive approaches encompass a diverse range of tactics, including the implementation of biological control agents, optimization of agronomic practices, and integration of innovative technologies, aimed at achieving sustainable and effective pest control, while minimizing environmental impact (Kabaluk et al., 2007; Ladurner et al., 2009; Poggi et al., 2021; Nikoukar & Rashed, 2022).

Pre-treatment population density assessments are crucial for accurate evaluation of insecticide effects on wireworm populations. Wireworm samples can be collected by soil sampling, bait traps or sex pheromone traps (Traugott et al., 2015). Conversely, bait traps offer a more rapid assessment, and sex pheromone traps are preferred for long-term population monitoring (Burgio et al., 2012; Traugott et al., 2015). Therefore, the current study employed soil sampling, which is labor-intensive but provides reliable estimates of wireworm abundance per unit area (Parker, 1994; Parker & Howard, 2001; Sufian, 2013; Stolpe Nordin, 2017; Toscano et al., 2017). Based on the economic risk assessment of wireworm infestation (Čamprag, 1983; Štrbac, 2005), which identified the harmful abundance threshold for onion crops, the application of tested insecticides in these studies was justified.

The current findings confirm a significant efficacy of the entomopathogenic fungus *B. bassiana*-based bioinsecticide Naturalis-L in controlling wireworms in onion plants. The other tested bioinsecticides also demonstrated satisfactory results in terms of enabling good plant density, reducing wireworm damage, and enhancing yield relative to untreated controls. Numerous studies have explored the impact of natural insecticides on soil pests, including wireworms. Specifically, the entomopathogenic fungi *B. bassiana* and *Metarhizium anisopliae* Metschnikoff (1879) (Ascomycota: Clavicipitaceae) are known to infect larval and adult

Agriotes spp, and have been employed in biocontrol experiments against these pests (Parker & Howard 2001; Wraight et al. 2009; Poggi et al., 2021; Paluch, 2022). Zacharuk and Tinline (1968) conducted initial laboratory studies on the effects of the entomopathogenic fungi *M. anisopliae* and *B. bassiana* on larvae and adults of *Agriotes* spp. They observed increased wireworm mortality, reduced crop damage, and higher yields when the spores were applied directly to adult cuticles, feeding larvae with inoculated crop seeds or spreading into soil furrows at planting. In a later study, Kleespies et al. (2013) investigated the effects of microbial antagonists on wireworm larvae in soil and concluded that *B. bassiana* caused the highest fungal infestation and increased wireworm mortality in Germany. In addition, laboratory and field tests were conducted using various strains of *B. bassiana* and *M. anisopliae* at different application rates, and with different wireworm species. In potato field trials in northern Italy, Naturalis-L achieved 54%-94% efficacy against *Agriotes* spp. (Ladurner et al., 2009). The results of Kölliker et al. (2011), who evaluated the efficacy of the Swiss *M. anisopliae* strain ART-2825 and Naturalis against three wireworm species in laboratory, greenhouse and field plots, indicated a higher efficacy under laboratory conditions than in field settings, suggesting a need for further research on wireworm control in potato crops grown in Northern Switzerland. A research in spring wheat against wireworms in Montana, where the efficacy of 10 biopesticides, applied alone, in mixtures or in combination with imidacloprid was tested, showed that the *B. bassiana* ANT-03 biopesticide, its combination with imidacloprid and *B. bassiana* GHA, and combinations of *Metarhizium brunneum* F52 with spinosad or imidacloprid provided significant wireworm control (Antwi et al., 2018). Plots treated with biopesticide-imidacloprid combinations showed significantly higher yields, which highlights the potential of combined biopesticide and insecticide treatments and identifies promising candidates for further research.

In the present study, both spinosad formulations applied (granular, spread in furrows during planting, and liquid, applied as a soil treatment at planting) significantly improved plant density and yield, and reduced plant damage. Similarly, de Oliveira Cantao & Mian (2023) monitored wireworm impact on maize yield in northern Italy and found that spinosad application at planting significantly increased yield, compared to untreated plots, leading them to conclude that spinosad can be incorporated into IPM strategies. Additionally, Arrine et al. (2017) evaluated a microgranular spinosad-based product for the control of *Agriotes* spp. pests in maize and potatoes, and the product showed good efficacy against wireworms in both crops, with favorable environmental behavior. In a study assessing wheat seed treatments, Van Herk et al. (2015) evaluated the efficacy of 11 treatments against two economically significant wireworm species, and high-dose spinosad treatments resulted in high wireworm mortality within 24 h, whereas tefluthrin did not induce significant mortality.

Research on the efficacy of spinetoram against wireworms and soil pests is scarce. Our findings demonstrated that spinetoram-based insecticides positively influenced onion yield and plant density. Nevertheless, the impact of spinetoram on wireworm-induced damage to onions showed inconsistent results. According to Kuhar et al. (2013), spinetoram shares activity against similar pest groups as spinosad and may offer comparable benefits in controlling various pests, including those residing in soil.

The current experiments demonstrated that the tested tefluthrin-based insecticide provided high efficacy in protecting onion from wireworm damage, leading to increased yields and reduced plant damage. This aligns with the findings of a three-year study by Vernon et al. (2009), in which tefluthrin and neonicotinoid seed treatments (imidacloprid, clothianidin and thiamethoxam) effectively protected wheat, probably by wireworm intoxication or repulsion/morbidity, without significantly decreasing wireworm populations in subsequent spring sampling. In addition, a significant wireworm repellency of tefluthrin was recorded (Van Herk et al., 2015). Furthermore, Gvozdenac et al. (2022) compared a *Metarhizium brunneum* Cb15-III-based bioinsecticide to some conventional insecticides, including a tefluthrin-based one, for wireworm control in sunflower, employing an 'Attract and Kill' strategy. Three-year trials demonstrated that tefluthrin treatments consistently yielded the highest plant density and lowest damage, while bioinsecticides exhibited comparable efficacy to conventional insecticides in low wireworm populations.

The onion yields obtained in this study notably surpassed the established two-year average of 18.83 t/ha for the Dutch Yellow onion variety under comparable cultivation conditions, as previously reported (Brdar-Jokanović et al., 2011). This marginal yield increase suggests that the experimental conditions and tested treatments did not detrimentally impact the overall productivity of onion crop relative to previous data for this variety.

Our research demonstrated that natural and semi-synthetic insecticides significantly enhanced onion plant density, vigor, and overall yield. Furthermore, these compounds exhibited comparable levels of efficacy to synthetic insecticides, while offering notable environmental advantages. Consequently, we recommend further investigation of the potentials of biopesticides for wireworm control to improve integrated pest management strategies.

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Prirodni i polusintetički insekticidi u zaštiti luka od šteta koje izazivaju žičnjaci

REZIME

Larve žičnjaka (Elateridae: *Agriotes* spp.), predstavljaju značajnu pretnju globalnoj poljoprivredi, posebno korenasto-krtolastom povrću kao što je luk. Njihov podzemni način života čini ih izazovnim za suzbijanje koji je dodatno komplikovan povlačenjem tradicionalnih sintetičkih insekticida iz upotrebe. Stoga, ova studija upoređuje efekte prirodnih, polusintetičkih i sintetičkih insekticida u kontroli oštećenja od žičnjaka na usevu luka.

Terenski ogledi efikasnosti različitih insekticidnih tretmana na gustinu biljaka, oštećenje od žičnjaka (%) i ukupan prinos luka sprovedeni su 2024. godine u Institutu za povrtarstvo (Smederevska Palanka, Srbija). Eksperiment je podrazumevao šest tretmana: netretirana kontrola, tri prirodna insekticida (dve formulacije a.s. spinosada: granule (GR) i koncentrovana suspenzija (SC), i *B. bassiana* ATCC 74040 2,3×107 konidiospora/ml), polusintetički insekticid (a.s. spinetoram) i sintetički insekticid (a.s. teflutir). Tretiranje je rađeno u vreme sadnje crnog luka prema preporučenoj količini primene po hektaru. Ocene su urađene 20 i 42 dana posle tretmana (DPT) da bi se odredila gustina biljaka. Oštećenja biljaka luka od žičnjaka zabeležena su 42 DPT, a prinos je izračunat vaganjem ubranih lukovica luka nakod žetve. Rezultati su pokazali da je spinosad formulacija GR, razbacana u brazde pri sadnji, značajno povećala gustinu biljaka nakon 20 DPT, dok je formulacija SC, primenjena kao tretman zemljišta pri sadnji, rezultirala najnižom gustinom. Spinetoram je pokazao najveću gustinu biljaka 42 DPT i najveći procenat oštećenja od žičnjaka (15%) od svih testiranih insekticida. Kontrola je imala najveći procenat oštećenih biljaka i najmanji prinos. Spinetoram je dao maksimalan prinos luka, dok je spinosad formulacija GR dala najmanji prinos među insekticidima.

Poljski ogledi su pokazali da prirodni i polusintetički insekticidi efikasno suzbijaju žičnjake, obezbeđujući adekvatnu zaštitu useva i održive prinose. Ova studija podržava razvoj i usvajanje ekološki svesnog upravljanja štetočinama u zemljištu.

Ključne reči: Elateridae, biopesticidi, insecticidi, suzbijanje štetočina, prinos, crni luk