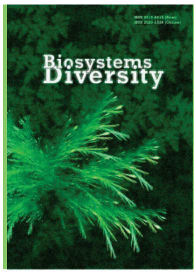

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Managing populations of cyst-forming nematodes in agroecosystems of field crops

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Cyst-forming nematodes have been known since the second half of the 19th century as one of the causes of "soil fatigue" and highly harmful agricultural pests. In Ukraine, the sugarbeet cyst nematode *Heterodera schachtii* Schmidt, 1871; cereal cyst nematode *H. avenae* Wollenweber, 1924; golden potato cyst nematode *Globodera rostochiensis* Wollenweber, 1923; clover cyst nematode *H. trifolii* Goffart, 1932; alfalfa cyst nematode *H. medicaginis* Kirjanova & Krall, 1971; hop cyst nematode *H. humuli* Filipev, 1934 are currently economically significant species. Their distribution mainly coincides with the traditional cultivation of sugar beets, grain cereals, potatoes, clover, alfalfa and hops. Long-term studies of the impact of abiotic, biotic, and anthropogenic factors on their populations made it possible to identify the dominant species and improve the set of protective measures. Anti-nematode crop rotations are the main limiting factor in preventing mass reproduction of cyst-forming nematodes, provided there is scientifically justified crop rotation. To prevent the mass accumulation of alfalfa and clover cyst-forming nematodes, the maximum share of perennial grasses in crop rotations should not exceed 30% (crops under cover of grain cereals + perennial legumes – one-two-year use); oat nematode – 40% of grain cereals; beet nematode – 20% of Chenopodioideae and cruciferous crops; golden potato nematode – 20% of potatoes (10% susceptible + 10% resistant varieties). The rational saturation of modern crop rotations with intermediate crops makes it possible to reduce the level of crop weediness caused by potential host plants of cyst-forming nematodes and to increase their anti-nematode effectiveness in general. The developed ecologically oriented system of phytosanitary control provides mandatory measures, which must be applied regardless of the level of initial population density, and additional measures specific to each culture and species of cyst-forming nematodes. Considering the current high specialization of crop production, the use of biological preparations in modern systems of integrated plant protection will contribute to the greening of agricultural output. Pre-planting treatment of tubers with metabolic biological preparations (*Streptomyces avermitilis*) of multifunctional action ensured the achievement of a higher (79.2–91.7%) efficiency of biological cleaning of the soil from the golden potato nematode, compared to the use of only potato-resistant varieties. A logical combination of various anti-nematode measures makes it possible to effectively keep the density of populations at an economically insignificant level and prevent crop yield losses.

Keywords: Heteroderidae; levels of harmfulness; multifunctional metabolic pesticides; integrated plant protection system.

Introduction

Potential losses of crop production from cyst-forming nematodes range from 6 to 25%, but in high population centers can reach 70–90% (Pylypenko et al., 2016; Sigareva et al., 2017; Darling et al., 2023). However, despite such crop losses, the phytosanitary control of heteroderids is still a difficult problem. This is due to the peculiarities of their biology, the presence in the development cycle of cyst-protected eggs which are resistant to environmental changes and can be stored in the soil for many years (Sigareva et al., 2017; Sasanelli et al., 2021; Litvinova et al., 2023). Therefore, phytosanitary measures should primarily be aimed at preventing the penetration and further settlement of cyst-forming nematodes (Sukhomlin et al., 2019; Borzykh et al., 2021; Darling et al., 2023).

In previous years, the main effective measure to reduce the number of beetroot and several other types of cyst-forming nematodes was scientifically based crop rotation. This protection measure is cheap and easy to apply, so it can be used in large areas (Sigareva et al., 2017). However, regarding the effect of various agricultural crops on the reduction of nematode numbers in crop rotations, the literature data are quite contradictory, which indicates the feasibility of further research (Abbasi et al., 2020; Mhatre et al., 2022). According to the data of Sigareva et al. (2017), non-host plants in the first year of growing reduced the number of potato cyst nematodes in the soil by an average of 46.6%. At the same time, higher efficiency was provided by wheat, cucumbers, lupine, and corn (from 48.7% to 56.6%), lower efficiency by cabbage (33.3%) and red beet (37.5%) (Sigareva et al., 2017; Du Preez et al., 2022).

Alfalfa, corn, rye, barley, peas, sunflower, buckwheat, and several other crops are antagonistic plants for the beet nematode (Pylypenko & Sigareva, 2003; Pylypenko et al., 2016). The root secretions of these plants can provoke the release of larvae from cysts, but the larvae cannot complete the development cycle in them (Daub, 2021; Kalatur et al., 2022; Oro et al., 2022). Against the oat nematode, it is recommended to include peas, lupine, vegetables, technical crops, as well as bare fallow in the crop rotation (Sigareva et al., 2017).

The current narrow specialization of crop production, against the background of the decline of the general culture of agriculture, caused the deterioration of the phytosanitary state of agrocenoses (Mezhenskyj et al., 2024a, 2024b). To prevent the degradation of modern agroecosystems, it is necessary to improve both the theoretical foundations of plant protection and the search for new methodological approaches (Ignatenko et al., 2024). Given that the decrease in the level of soil population fluctuated over the years, we consider it necessary to study the influence of abiotic factors on these processes as well. There is also a certain difference in biological cleaning depending on the level of the initial number of cyst-forming nematodes, and in heavily populated areas, the population density decreased to an economically insignificant level only during many years of cultivation of crops that are not susceptible to reproduction. Therefore, to achieve high efficiency, a combination of various anti-nematode measures is necessary (Babich et al., 2020).

In many countries, compounds of carbamic acid derivatives are mostly used to prevent crop losses from nematodes. Due to their potential environmental hazard, chemical nematicides are not included in the current

"List of pesticides and agrochemicals approved for use in Ukraine". Therefore, an alternative to them should be multifunctional biological preparations capable of exhibiting nematicidal properties (Khalil & Darwesh, 2019; Dara, 2021; Li & Zhang, 2023).

Priority is given to scientific research on creation of environmentally safe microbial preparations with multifunctional properties – nematicidal, phytostimulating, immunomodulatory, and anti-stress. However, effective protection can be achieved only with an optimal combination of various anti-nematode measures (Ivanova et al., 2022; Litvinova et al., 2023a, 2023b; Pavlichenko et al., 2023; Voitovyk et al., 2023). In the current conditions, to achieve high anti-nematode efficiency, it is necessary to optimize the existing schemes of crop rotations or individual links without violating the scientific foundations of crop rotation; the wide use of green manure and by-products as one of the reserves of organic matter supply and the activation of natural antagonists, the introduction of immune varieties, and if necessary, the use of ecologically safe biological preparations.

In the protection of plants from phytopathogens, modern science increasingly turns to natural mechanisms of resistance, which enable plants to survive in natural conditions under the negative influence of many stress factors of abiogenic and biogenic nature, including nematodes (Chitwood, 2002; Fadei Tehrani & Fati, 2020; Du Preez et al., 2022; Schleker et al., 2022).

Mycelial soil actinobacteria representatives of the genus *Streptomyces*, which have antibiotic, antiparasitic, growth-stimulating, and other properties, are the source of various biologically active substances with a chemical structure and spectrum of action. Preparations based on biologically active metabolites of streptomycetes are characterized by several advantages, selectivity of action and high activity against phytopathogens at low concentrations, which makes it possible to avoid their excessive accumulation in agricultural products. Compared to chemical preparations, they more intensively penetrate and are metabolized in plant tissues through the leaf surface, stems, and roots, are characterized by lower toxicity, quickly decompose, and do not pollute the environment (Seong et al., 2021).

The versatility of the latest ecologically safe metabolic biological preparations is based on the synergistic action of all their components, which is manifested in the interaction of each element due to their unification into a single system and the strengthening of activity. The use of the latest biological preparations allows full realization of the potential capabilities of the plant laid in the genome by nature and selection, regulation of the ripening period, improvement of the quality of the harvest, and increase in the productivity of the main agricultural crops (Blyuss et al., 2019; Dara et al., 2021). These innovative biopreparations are intended for modern advanced technologies of growing ecologically safe products, they are used for pre-sowing seeds treatment, seedlings, vegetative plants, planting material, and soil remediation. They show a combined biological activity due to both a direct effect on pathogens of various etiologies, and indirectly due to phytoregulatory activity or by increasing plants' resistance to phytopathogens, phytonematodes, pests, and adverse environmental factors (Ahmed et al., 2019; Hallmann et al., 2019; Sasanelli et al., 2020; Kahn et al., 2021).

Therefore, the study of the spectrum of antagonistic activity of representatives of the genus *Streptomyces*, the study of their biosynthetic potential, and the creation of ecologically safe multifunctional metabolic biopreparations (biopesticides) based on them is currently a very relevant issue (Tsygankova et al., 2012).

Material and methods

The main research was conducted during 1990–2020 in Vinnytsia, Kyiv, Chernihiv, Sumy, Poltava, Volyn, Chernivtsi, and other regions of Ukraine. Laboratory research was carried out on the basis of the Departments of Phytopathology named after academician V. F. Peresypkin and Integrated Protection and Quarantine of Plants of the National University of Life and Environmental Sciences of Ukraine; laboratory-vegetative – at the D. K. Zabolotny Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine, the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences (NAAS), the Kyiv Seed Plant; field and production – in the Uladovo-Lyulynetsk Research and Breeding Station, the Ukrainian Plant Quarantine Research Station of the National Academy of Sciences, farms of various forms of ownership.

The objects of research are agricultural crops, plants of natural phytocenoses and segetal vegetation, tubers, root crops, plant roots, soil, cysts, eggs, larvae, and adults of cyst nematode are given in Table 1.

Table 1
Systematic position of the most important cyst-forming nematodes prevalent in Ukraine

Taxonomic structure	Title	
	Latin	English
Phylum	Nematodes (Rudolphi, 1808)	nematodes
Class	Secernentea (von Linstow, 1905) Dougherly, 1958	–
Order	Tylenchida (Filipjev, 1934) Thorne, 1949	–
Family	Heteroderidae (Scarbilovich, 1947)	cyst nematodes
Subfamily	Heteroderinae Filip'ev & Schuurmans Stekhoven, 1941	–
Genus	*Heterodera* (Schmidt, 1871)	–
Species	*Heterodera avenae* (Wollenweber, 1924)	cereal cyst nematode
	(Heterodera) hordecalis (Krall et Krall, 1978)	barley cyst nematode
	Heterodera schachtii (Schmidt, 1871)	sugarbeet cyst nematode
	Heterodera medicaginis (Kiryanova, sp.nov., 1954)	alfalfa cyst nematode
	Heterodera trifolii (Goffart, 1932)	clover cyst nematode
	Heterodera cruciferae (Franclin, 1945)	cabbage cyst nematode
	Heterodera humuli (Filipjev, 1934)	hop cyst nematode
	Heterodera filipjevi (Madzhidov, 1981) Stelter, 1984	Filipjev's cereal cyst nematode
	Heterodera galeopsidis (Goffart, 1936)	hemp nettle cyst nematode
	Heterodera ripae (Subbotin, Sturhan, Rumpenhorst & Moens, 2003)	–
Subfamily	Punctoderinae (Krall et Krall, 1978)	–
Genus	*Punctodera* (Mulvey et Stone, 1976)	–
Species	*Punctodera punctata* (Thorne, 1928) Mulvey, Stone,1976	grass cyst nematode
Genus	*Globodera* (Scarbilovich, 1959) Behrens, 1975	–
Species	*Globodera rostochiensis* (Wollenweber, 1923) Behrens, 1975	golden potato cyst nematode
	Globodera pallida (Stone, 1973) Behrens, 1975	–

To investigate the nematicidal effectiveness of pre-planting treatment of planting material, biological pesticides based on *S. avermitilis* were used. In particular, the basic preparation containing an ethanol extract of biomass from the strain *S. avermitilis* IMV Ac-5015 with a concentration of avermectins at 100 μg/mL, and the supernatant of the cultural liquid of the aforementioned strain at a 1:1 ratio, also containing a complex of biologically active substances, including amino acids, lipids (phospholipids, free fatty acids, sterols, etc.), steroids, phytohormones, and the biopolymer chitosan. And its enhanced version with humates, which, in addition to the compounds mentioned above (basic preparation), also contains salts of humic acids with free amino acids and an organo-mineral complex (in a ratio of 1:24).

Phytohematological monitoring was carried out according to standard, improved, and developed methods using telecommunication technologies (Babich et al., 2020). The influence of phytoparasitic nematodes on the growth, development, productivity of plants, and structural yield indicators of major crops was studied in the field in permanent and temporary experimental plots. Repetition of laboratory-vegetation experiments – 8–20 times, small-area field experiments – 4–50 times, stationary and temporary field experiments – 4 times, industrial – 3–4 times.

In the experiments, modern unmanned aerial vehicles were used, which, flying along pre-planned routes in the geographic information system, provided digital aerial photography of the terrain using the boat method at an altitude of 50 meters. The outcome of the photography was high-resolution images taken at programmed GPS coordinates. For each image, a complete set of digital information was obtained, including the geographic coordinates of the central point of the image, shooting altitude, exposure angle, as well as a set of telemetry data for transfer and use in commonly accepted GIS systems. When detecting local inconsistencies in crops, a re-survey was conducted at established coordinates from a height of 10 meters to obtain detailed high-resolution images of focal plant damage.

The degree of host plants' population was assessed according to modern nine-point scales.

The agronomic techniques for cultivating agricultural crops were universally adopted for the research area. Harvesting of potatoes, cereal crops, green mass, and seeds of perennial legumes was done using the method of complete harvesting from the entire area of the accounting plots.

The effectiveness of soil purification in the cultivation of resistant-to-reproduction crops was determined by the difference between the initial and post-harvest populations of cyst-forming nematodes using the Abbott formula (1925):

$$E = \frac{100\,(A - B)}{A},$$

where E stands for the effectiveness of purification (%); A – the initial population (eggs, and larvae/100 cm^3 of soil); B – the post-harvest population (eggs, and larvae/100 cm^3 of soil).

The technical efficiency of microbiological preparations, taking into account the correction for changes in the population of cyst-forming nematodes in the control, was calculated using the formula:

$$Te = \frac{100\,(A{*}b - B{*}a)}{A{*}a},$$

where Te is the technical efficiency with adjustment for control (%); A – The population in the experimental variant before treatment (eggs, and larvae/100 cm^3 of soil, eggs/plant); B – the population in the experimental variant after treatment (eggs, and larvae/100 cm^3 of soil); a – the population in the control at the first survey (eggs, and larvae/100 cm^3 of soil, eggs/plant); b – the number of eggs and larvae in the control group at the initial survey (eggs, and larvae/100 cm^3 of soil, eggs per plant).

Statistical analysis of the study data was performed using Statistica 13.1 software (StatSoft, Inc., USA). Results are expressed as means ± standard deviation of three analytical replicates in each year. Data were analyzed using two-way or one-way ANOVA, and significant differences ($P < 0.05$) between the mean values were determined by Duncan's multiple-range test.

Results

During the period of scientific research, 12 species of heteroderids were found in cultural and natural phytocenoses of Ukraine, 10 of them belong to the genus *Heterodera*: sugarbeet cyst nematode *Heterodera schachtii* Schmidt, 1871; alfalfa cyst nematode *H. medicaginis* Kirjanova & Krall, 1971; clover cyst nematode *H. trifolii* Goffart, 1932; cereal cyst nematode *H. avenae* Wollenweber, 1924; Filipjev's cereal cyst nematode *H. filipjevi* (Madzhidov, 1981) Stelter, 1984; barley cyst nematode *H. hordecalis* Andersson, 1975; hop cyst nematode *H. humuli* Filip'ev, 1934; cabbage cyst nematode *H. cruciferae* Franklin, 1945; *H. ripae* Subbotin, Sturhan, Rumpenhorst & Moens, 2003; hemp nettle cyst nematode *H. galeopsidis* Goffart, 1936.

The genera *Globodera* and *Punctodera* include 1 species each: golden potato cyst nematode *Globodera rostochiensis* Wollenweber, 1923 and grass cyst nematode *Punctodera punctata* (Thorne, 1928) Mulvey & Stone, 1976 (Babich et al., 2021).

Currently, the economically significant species are beet, oat, golden potato, and hop nematodes. Their distribution basically coincides with the areas of traditional cultivation of sugar beets, grain cereals, potatoes, and hops, which indicates a high degree of their trophic specialization, acquired during a long co-evolution. Clover and alfalfa cyst-forming nematodes are of economic importance for perennial legumes. The *H. galeopsidis* nematode is also potentially dangerous for clover; wheat and barley cyst-forming nematodes are harmful to cereal grain; cabbage is vulnerable to cabbage cyst-forming nematode; cereal is potentially vulnerable to *H. ripae*, distributed mainly in biocenoses, but they are also found in agrocenoses.

The modern concept of plant protection involves the transition from the application of protection measures to the preventive principle of regulation and management of harmful organisms in agroecosystems.

Prevalence cartograms with a determination of foci area, the level of soil population, and the species composition of cyst-forming nematodes should become the basis for a differentiated choice and planned application of various anti-nematode measures, depending on their economic payback and ecological feasibility. Such nematological cartograms are developed based on plant or soil samples selection and analysis.

We consider the creation of electronic maps of nematode prevalence extremely promising. Entering the survey data into the GPS memory database makes it possible to reproduce in the field the route, the location of previously detected micro-cells of cyst-forming nematodes or even the places of selection of individual nematological samples, and in the future to periodically monitor, specify and, if necessary, adjust the limits of their prevalence.

A reliable forecast of potential crop losses from the initial level of cyst-forming nematodes' soil population makes it possible to economically substantiate and differentiate protection measures, depending on their payback. Summarized economic thresholds of harmfulness, calculated for a 3–5% level of crop loss from cyst-forming nematodes, for modern resource-saving technologies for growing the main crops, are given in Table 2.

Table 2
Economic thresholds of harmfulness (ETH) of cyst-forming nematodes dominant species

Cyst-forming nematodes	Crops	ETH (eggs + larvae in 100 cm^3 of soil)
	Grain cereals	
Oat	Oats	100–125
	Spring wheat	200–225
	Winter wheat	275–300
	Spring barley	225–250
	Winter barley	325–350
	Winter rye	300–325
	Beets and cruciferous oil crops	
Beet	Sugar, fodder, and red beets	175–225
	Spring rape (seeds)	250–300
	Winter rape (seeds)	300–350
	Red clover	
Clover	Green mass	350–400
	Seeds	200–250
	Alfalfa	
Alfalfa	Green mass	450–550
	Seeds	300–350

In modern conditions, the main effective measure of population density control of the cyst-forming nematodes should be scientifically based crop rotations. It has been established that in order to prevent the mass accumulation of alfalfa and clover cyst-forming nematodes, the maximum share of perennial grasses in crop rotations of various purposes should not exceed 30% (sowing under the cover of grain cereals + perennial legumes – one-two-year use); oat nematode – 40% of grain cereals; beet nematode – 20% of Chenopodioideae and cabbage; golden potato nematode – 20% of potatoes (10% susceptible + 10% resistant varieties).

When growing crops unfavorable to nematode reproduction, the reduction to an economically insignificant level of golden potato nematode initial population – ≥50,000 eggs and larvae in 100 cm^3 of soil – was achieved after 9 years, ≥40,000 – 8 years, ≥30,000 – 7 years, ≥20,000 –

6 years, ≥10,000 – 5 years, ≥5000 – 4 years, ≥2500 – 3 years, ≥1000 – 2 years; and numbers of beet, oat, alfalfa, and clover nematodes – ≥3000 – 5 years, ≥2,000 – 4 years, ≥1,000 – 3 years; ≥500 eggs and larvae in 100 cm^3 of soil – 1–2 years. At the same time, since the complete soil cleaning from cyst-forming nematodes did not occur, even during the long-term cultivation of non-susceptible crops, this indicates the expediency of combining various anti-nematode measures.

Considering that modern cultivation technologies of many crops provide sowing at the final density, a necessary condition should be the provision of reliable protection, especially in the initial, most vulnerable phases of plant growth and development. Pre-sowing treatment is one of the rational means of plant protection, because of the minimal consumption of active substances and the low cost of protective measures. Among the modern range of anti-poisoners, microbiological preparations must meet the requirements of environmental safety, which ensures their wide practical application. It was established that among the microbiological preparations, the highest anti-nematode efficiency was provided by the rapeseed treatment with *S. avermitilis* + humates (1.0 L/t).

The duration of protective effect of biological preparations was on average about two weeks, and thereafter it gradually decreased. However, the decrease in the level of infestation by larvae in the initial phases of plant growth ensured the formation of optimal seedling density, and the penetration of the root system into deeper horizons, thanks to the growth-stimulating effect of metabolic biological preparations and the overall positive effect on their development, ensured prolonged resistance to heteroderosis.

On potatoes, the pre-planting treatment of tubers with biological preparations with regulating properties had a positive effect on the root system development and hatching activation of larvae from cysts that inhabited the seedlings but did not complete the full cycle of development in plants of the resistant variety. As a result of the combination of methods with the use of metabolic preparations of multifunctional action (phytoprotective, restregulatory, adaptogenic), a higher efficiency of biological soil purification from the golden potato nematode was achieved, compared to the use of resistant varieties only (Table 3).

The average yield in the version of the experiment with potato tubers treatment with *S. avermitilis* + humates exceeded the control indicators (with no use of microbiological preparations) by 1.96–2.79 t/ha, and *S. avermitilis* – by 0.78–1.52 t/ha, respectively.

A logical combination of various anti-nematode measures makes it possible to effectively control population density at an economically insignificant level and prevent crop yield losses (Table 4).

Table 3
Technical and economic efficiency of pre-planting tubers treatment of potato varieties resistant to the golden potato nematode with metabolic biological preparations ($x \pm SD$, n = 4)

Varieties	Rate, L/t	Population, eggs + larvae / 100 cm^3 of soil		Decrease, %	Average yield, t/ha
		before seeding	after harvest		
Dnipryanka (early)	With no treatment (control)	8037 ± 324	2588 ± 217***	67.80 ± 1.84^{f}	14.43 ± 0.26^{h}
	S. avermitilis 0.04 L/t	8262 ± 258	1719 ± 176***	79.17 ± 2.07^{d}	15.21 ± 0.32^{g}
	S. avermitilis + humates 1.0 L/t	7983 ± 191	1326 ± 231***	83.37 ± 2.50^{c}	16.39 ± 0.24^{f}
Zabava (middle-early)	With no treatment (control)	7812 ± 267	2218 ± 146***	71.58 ± 1.92^{e}	15.74 ± 0.35^{fg}
	S. avermitilis 0.04 L/t	8156 ± 309	1459 ± 183***	82.12 ± 1.74^{c}	17.26 ± 0.28^{e}
	S. avermitilis + humates 1.0 L/t	7974 ± 232	987 ± 162***	87.61 ± 1.81^{b}	18.53 ± 0.41^{d}
Slovyanka (medium-ripe)	With no treatment (control)	8353 ± 241	1812 ± 194***	78.29 ± 1.96^{d}	19.68 ± 0.31^{c}
	S. avermitilis 0.04 L/t	8192 ± 187	1293 ± 159***	84.23 ± 1.50^{c}	20.94 ± 0.39^{b}
	S. avermitilis + humates 1.0 L/t	8218 ± 215	682 ± 127***	91.69 ± 1.46^{a}	22.07 ± 0.37^{a}

Note: * – P < 0.05, **– P < 0.01, ***– P < 0.001, significant differences inside one line of the table according to the results of ANOVA.

Table 4
The developed system of integrated crop protection for regulating the population of cyst-forming nematodes in agroecosystems (developed based on the results of long-term research)

Dates of implementation	Purpose	Implementation technology	Population density, eggs, and larvae / 100 cm^3 of soil	Protective measures
1 time per crop rotation of all crop rotation fields	clarification of oat nematode soil population level	soil sample selection and analysis	the economic threshold of harmfulness is 100–350 (depending on the type of cereal crop)	to prevent the mass reproduction of the oat nematode, the saturation of crop rotation with cereal grain crops should not exceed 40%
– // –	of clover and alfalfa nematodes	– // –	for fodder clover crops, ETH – 350–400, seed crops 200–250; alfalfa – 450–550 and 300–350, respectively	the saturation of crop rotations with perennial leguminous grasses should not exceed 30% (field covered with grain cereals + perennial grasses – one-two year use)
Pre-planting, post-harvest, vegetation periods	detection of golden potato nematode foci	soil and plant samples selection	regardless of the initial population level	imposition of quarantine; development of protective measures plan
Rotation period	eradication of golden potato nematode foci	growing of non-susceptible crops: perennial leguminous grasses, cereals, corn, legumes, beets, etc.)	initial number: >5,000 1,000–5,000 <1,000 >5,000 1,000–5,000 <1,000	*In agricultural enterprises:* Lupine, winter wheat, sugar beets, vetch oats, corn Barley with clover seeding, clover, winter wheat, fodder beets Peas, winter wheat, corn *On private farms of villagers:* Strawberries, green crops, red beets, resistant varieties of potatoes Carrots, cabbage, cucumbers, green peas, resistant varieties of potatoes Onions, garlic, beans, resistant varieties of potatoes
– // –	reduction of soil population to an economically imperceptible level: oat nematode	growing of non-susceptible cultures: legumes, beets, potatoes, legumes, sunflower	initial number: 500 1,000 2,000 3,000	Approximate dates for host plants' return to the previous place, years: 1–2 3 4 5
– // –	of clover and alfalfa nematodes	cereals, beets, potatoes, corn, sunflower	initial number: 500 1,000 2,000 3,000	Approximate dates for host plants' return to the previous place, years: 1–2 3 4 5

Dates of implementation	Purpose	Implementation technology	Population density, eggs, and larvae / 100 cm^3 of soil	Protective measures
During crop rotation	natural antagonists' activation	organic farming system	regardless of the initial population level	saturation of crop rotations with perennial legumes, systematic application of traditional organic fertilizers, use of non-marketable by-products and green manure
Vegetation period	destruction of weeds-reservoirs	on all fields	regardless of the initial population level	avoiding repeated sowing of related crops, saturation of crop rotations with intermediate crops
Preseeding period	yield losses prevention	selection of the species of perennial legumes	regardless of the initial population level	when the clover nematode is detected-alfalfa is sown, the clover nematode – alfalfa, and sainfoin are sown when the fields are colonized by both types.
– // –	reducing seedlings infestation level by larvae	pre-sowing tuber treatment with protective and stimulating substances	with the pre-sowing number, which does not exceed the ETH by more than 3 times	sowing (planting) in the early optimal period with seeds (tubers) treated with biological preparations based on metabolites of soil streptomycetes (*S. avermitilis*, 0.04 L/t and *S. avermitilis* + humates, 1.0 L/t)
Vegetation period	mass reproduction prevention	interruption of the biological cycle (at the initial phase of females' ontogenesis)	>50 females/plant of clover or alfalfa nematodes; >100 females/plant of golden potato nematode	plowing of thinned crops of perennial grasses (after harvesting); local and selective digging of potato bushes of early ripening susceptible varieties (at the beginning of flowering) affected by globoderosis.
Spring-summer next year	– // –	phytocleaning of crops	regardless of initial population level	removal of seedlings of unwanted vegetation: potato bushes; from overwintered tubers; in soil, bushes of perennial legumes

The ecologically oriented system of phytosanitary control developed by us provides for mandatory measures that must be applied regardless of the level of initial population density, and additional measures specific to each culture and species of cyst-forming nematodes.

It was established that the greatest decrease or accumulation of the level of cyst-forming nematodes' soil population occurred in the years with optimal humidity and temperature regime (hydrothermal coefficient (HTC)) (∑t) for the same time, reduced by 10 times) in the range of 1.0–1.6), and their limiting effect was manifested in dry periods (HTC – 0.4–0.9) and less so in cool wet years (HTC – 1.7–2.2).

In the predominantly facultative type of parasitism, abiotic conditions also significantly influenced the effectiveness of natural antagonists. The activation of the vital activity of regulatory factors was facilitated by the saturation of crop rotations with perennial leguminous grasses and the use of green manure.

The use of the organo-mineral nutrition system is one of the effective factors influencing the growth and development of plants, however, the optimization of their nutrition conditions provided in most experiments a higher reproduction potential of cyst-forming nematodes.

Pre-sowing seeds treatment with biological preparations of multifunctional action reduces the population of the initial phases of plant organogenesis, increases their resistance to phytonematodes, and ensures the formation of optimal seedling density. At the same time, the use of seed material treated with protective and stimulating substances was most effective at pre-sowing densities of cyst-forming nematodes that did not exceed the economic thresholds of harmfulness by more than three times.

The direct and indirect influence of climatic conditions on plants' growth and development and the duration of the protective effect of poisons were also revealed. To achieve high anti-nematode efficiency, it is advisable to sow seeds treated with protective-stimulating substances in the early optimal times for each soil-climatic zone with correction for the weather conditions of the current year.

We believe that with the high specialization of crop production, the use of biological preparations in modern systems of integrated plant protection will contribute to the greening of agricultural production.

Cyst-forming nematodes of cereal and root crops, potatoes, and other agricultural crops are among the most problematic pests (Dababat et al., 2015; Pulavarty et al., 2022). The presence of cyst stages in their life cycle enables the offspring to survive under various adverse conditions, including prolonged absence of susceptible host plants for reproduction. Therefore, high nematode control efficacy through crop rotation is achieved only through the long-term cultivation of non-host crops (Müller, 1999; Singh et al., 2009). Specifically, to prevent the mass accumulation of sugar beet and other species of cyst-forming nematodes in several countries in Europe and worldwide, it is recommended to observe a 4–5-year break between the repeated placement of host plants (Mokrini et al., 2017).

However, such recommendations are not always feasible, especially for farms with narrow specialization (Dababat et al., 2015). Therefore, it was advisable to determine the optimal timing for the return of susceptible crops to their previous locations depending on the level of soil infestation. We found that depending on the initial population density of cyst-forming nematodes, the duration of the break between the repeated cultivation of certain host plants can range from 1–2 years for low, 3–4 years for moderate, and 5–6 years – for high population densities, and even longer in heavily infested areas. The practical application of the research results allows one to optimize the structure of crop rotations, favoring the cultivation of economically viable agricultural crops in areas prone to phytoparasitic nematode infestations. Thus, through the differentiated saturation of crop rotations with certain host plants and their optimal rotational combination with non-host crops, biological soil cleansing from cyst-forming nematodes is ensured.

However, achieving effective control of nematodes is only possible through the integration of various anti-nematode measures (Hauer et al., 2016). Nevertheless, the use of chemical agents – nematicides – is prohibited in many countries around the world (Viaene et al., 2013), including Ukraine (Babich et al., 2020). Resistant varieties are developed only for certain crops, and natural antagonists are unable to effectively control nematode population densities (Müller, 1999).

Considering the negative impact of chemical protection agents on beneficial fauna and the environment as a whole, in recent years, many countries have been paying increasing attention to environmentally safe plant protection methods against nematodes (Zhang et al., 2014; Abd-El-gawad, 2021; Mhatre et al., 2022). One of the alternatives to chemical agents currently is modern long-lasting multifunctional bio-preparations, which combine properties of biostimulants, nematicides, insecticides, stress relievers, adaptogens, and more (Biliavska et al., 2016; Loboda et al., 2024). In particular, a bacterium widely used to combat nematodes belongs to the genus *Bacillus* (*Bacillus subtilis*), while other commercially available biopesticides for nematode control include Bio-Act® (*Paecilomyces lilacinus*), Botanigard® (*Beauveria bassiana*), Bioarc® (*Bacillus megaterium*), Bio Zeid® (*Trichoderma album*), and brown algae Algaefol® (*Ascophyllum nodosum*) (Roopa & Gadag, 2020).

According to data from Nicola et al. (2020), the application of the biopesticide abamectin (based on *S. avermitilis*) to the soil also provided significant control of *Globodera pallida* with LD_{50} and $LD_{99.9}$ of 14.4 and 131.3 µg/mL, respectively. These results indicate the high effectiveness of abamectin against *G. pallida* in potato crops and its potential use in organic farming (Mhatre et al., 2022). The combination of different methods of population regulation, such as the use of biological preparations and crop rotation, may be an effective approach for integrated protection of potatoes against *G. rostochiensis* (López-Lima et al., 2020).

This indicates the promising prospect of further scientific research to study their effectiveness on various agricultural crops (Sasanelli et al., 2020). Specifically, the use of metabolic bio-preparations containing macrolide antibiotics – avermectins, in our studies for pre-planting treatment of seedlings, resulted in a reduction in the population level of *Globodera rostochiensis* during the initial phases of plant growth and development, contributing to an overall increase in potato yield.

Considering the high anti-nematode effectiveness of multifunctional bio-preparations on other agricultural crops as well (along with their safety for humans and the environment), we consider it advisable to widely implement them in modern integrated plant protection systems.

Conclusion

During the research period, 12 types of cyst-forming nematodes were identified. The degree of accumulation of dominant harmful species mainly depended on the initial soil population, the species composition of host plants, their share in crop rotations, and the duration of the break between returning to the previous place.

When growing crops unfavorable to nematode reproduction, the reduction to an economically insignificant level of the initial population of golden potato nematode – ≥50,000 eggs and larvae in 100 cm^3 of soil – was achieved after 9 years, ≥40,000 – 8 years, ≥30,000 – 7 years, ≥20,000 – 6 years, ≥10,000 – 5 years, ≥5,000 – 4 years, ≥2,500 – 3 years, ≥1,000 – 2 years; and numbers of beet, oat, alfalfa, and clover nematodes – ≥3,000 – 5 years, ≥2,000 – 4 years, ≥1,000 – 3 years; ≥500 eggs and larvae in 100 cm^3 of soil – 1–2 years.

The economic threshold of oat nematode damage for oats is 100–125, spring wheat – 200–225, spring barley – 225–250, winter wheat – 275–300, winter rye – 300–325, winter barley – 325–350 eggs and larvae in 100 cm^3 of the soil before sowing cereal crops. For beets, the economic threshold of harmfulness is within 175–225, spring rape seed crops 250–300, and winter rape 300–350 beet nematode eggs and larvae. A statistically significant decrease in the productivity of meadow clover in the first year of vegetation occurred with an initial population of about 400, in the second year – 350, seed crops of 200–250 eggs and larvae per 100 cm^3 of soil. For alfalfa fodder crops of the first and second years, these indicators are 450 and 550, respectively, and for seeds – 300–350 eggs and larvae in 100 cm^3 of soil.

Pre-sowing seeds treatment of cereal grains, rape, and perennial leguminous grasses with multifunctional biological preparations (phytoprotective, regulatory, adaptogenic action) reduced the level of seedling infestation by larvae. At the same time, higher technical efficiency was achieved after the use of metabolic biological preparations *S. avermitilis* + humates (1.0 L/t) and *S. avermitilis* (0.04 L/t), which contain macrolide antibiotics – avermectins.

A logical combination of various anti-nematode measures makes it possible to effectively control the density of populations at an economically insignificant level and prevent crop yield losses.

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The authors declare there are no conflicts of interest.

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