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RESEARCH ARTICLE

Chemical control associated with genetic management of *Meloidogyne javanica* in soybean

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ABSTRACT

Integrated management is considered the best strategy to mitigate the damage caused by plant-parasitic nematodes. However, there is still limited information regarding some integrated techniques. Thus, this study aimed to assess the effects of genetic management associated with chemical control of *Meloidogyne javanica* in soybean (*Glycine max* (L.) Merr.) The experiment was installed in a greenhouse according to an 8×4 factorial design with eight replicates. The first factor was soybean cultivar (HO Juruena IPRO, resistant; Foco IPRO, HO Maracaí IPRO, and CZ 58B28 IPRO, moderately resistant; HO Mamoré IPRO, moderately susceptible; and Extrema IPRO, CZ 48B32 IPRO, and HO Aporé IPRO, susceptible). The second factor consisted of an untreated control and commercial nematicides based on abamectin, thiodicarb+imidacloprid, and fluopyram. Plants were inoculated with 2000 nematode eggs, and nematode and vegetative variables were evaluated at 65 d after inoculation. There was an interaction effect on nematode variables. Furthermore, there was an additive effect of genetic management and chemical control, mainly in resistant cultivars treated with thiodicarb+imidacloprid or fluopyram with controls of up to 69.90% and 96.86%, respectively. The application of fluopyram and the use of 'HO Juruena IPRO', 'Foco IPRO', or 'HO Maracaí IPRO' also contributed to the control of *M. javanica*. Vegetative variables were studied by analyzing product effects separately, but results were inconclusive.

Key words: Cultivars, *Glycine max,* integrated management, nematicides, root-knot nematodes.

INTRODUCTION

Nematodes cause losses estimated at US$13.6 billion in Brazilian agriculture, with US$5.8 billion attributed solely to damage to soybean (*Glycine max* (L.) Merr.) crops (Syngenta, 2022). Research has also shown that nematodes are present in 94% of symptomatic soybean-growing areas, and the genus *Meloidogyne* is found in about 40% of samples (Syngenta, 2022). *Meloidogyne javanica* is considered one of the most important species of plant-parasitic nematodes, owing to its high economic impact, wide geographical distribution, and broad range of hosts. Furthermore, *M. javanica* exhibits high aggressiveness and within-species variability, which complicates management (Chidichima et al., 2021). For nematode control, it is recommended to use integrated strategies based on cropping, genetic, chemical, and biological methods (Favoreto et al., 2019).

The use of resistant cultivars is an efficient strategy for nematode control that does not require specific investments, given that seed costs are similar to those associated with susceptible cultivars. Resistant cultivars harbor one or more genes that enable the plant to detect nematode penetration and, via hypersensitivity reactions, prevent the formation of feeding sites. However, an important limitation of this practice is that *Meloidogyne* populations may have different behaviors and levels of aggressiveness

depending on the cultivar; thus, a cultivar may exhibit different responses to different nematode populations (Chidichima et al., 2021; Machado et al., 2022).

Chemical control is applied to protect roots at the initial stages of crop development, when the plant is defining its productive potential. Products based on fluensulfone, fluopyram, fluazaindolizine, abamectin, cadusafos, and thiodicarb + imidacloprid were shown to provide effective control of *Meloidogyne* (Bortolini et al., 2013; Alcebíades et al., 2019; Desaeger and Watson, 2019). Some of the most commonly used compounds for controlling nematodes in soybean crops include thiodicarb, which acts by inhibiting acetylcholinesterase, causing hyperexcitation and nematode death (Guedes et al., 2008); abamectin, which inhibits the opening of glutamate-gated chloride channels, disrupting the nervous system of nematodes (Evans et al., 2021); and fluopyram, which acts on succinate dehydrogenase, inhibiting electron transport and ATP production (Schleker et al., 2023). The efficacy of these products in controlling root-knot nematodes has been confirmed by different studies (Oka and Saroya, 2019; El-Marzoky et al., 2022).

It should be noted that the isolated use of a single control tactic does not provide sufficient crop protection, especially in areas containing high population densities of nematodes. Therefore, it is crucial to use combined strategies to reduce nematode populations throughout the crop cycle. In view of the foregoing, this study aimed to investigate the additive effect of genetic and chemical management on the control of *M. javanica* in soybean.

MATERIALS AND METHODS

The experiment was conducted in a greenhouse on two different occasions (Trials 1 and 2), under controlled humidity conditions, at the Rio Verde Foundation, Lucas do Rio Verde (12°59′49.64″ S, 55°57′46.40″ W), Mato Grosso, Brazil. The first experimental period (Trial 1) lasted from January to March 2022, with minimum, average, and maximum temperatures of 20.1, 25.1, and 35.8 °C, respectively. The second experimental period (Trial 2) took place between November 2022 and January 2023, with minimum, average, and maximum temperatures of 19.7, 24.3, and 31.9 °C, respectively.

Both trials were conducted using the same installation and evaluation procedures, treatments, and number of replicates. The design was completely randomized, with an 8 × 4 factorial arrangement and eight replicates. The first factor comprised eight soybean (*Glycine max* (L.) Merr.) cultivars with varying degrees of genetic resistance to *Meloidogyne javanica*. The second factor comprised an untreated control and three chemical agents. Information on the level of resistance of cultivars against the nematode was obtained from seed companies. The following cultivars were used: Resistant, HO Juruena IPRO; moderately resistant, Foco IPRO, HO Maracaí IPRO, and CZ 58B28 IPRO; moderately susceptible, HO Mamoré IPRO; and susceptible, Extrema IPRO, CZ 48B32 IPRO, and HO Aporé IPRO. Chemical nematicides were based on abamectin (abamectin 50%, 57.5 g a.i. 100 kg^{-1} seed, Avicta 500 FS, Syngenta Proteção de Cultivos Ltda., São Paulo, Brazil), thiodicarb + imidacloprid (thiodicarb 45% + imidacloprido 15%, 90 g a.i. 100 kg^{-1} seed + 270 g a.i. 100 kg^{-1} seed, Cropstar, Bayer S.A., São Paulo, Brazil), and fluopyram (fluopiram 50%, 200 g a.i. ha^{-1}, Verango Prime, Bayer S.A., São Paulo, Brazil) at the intermediate doses cited on the product sheet.

Each experimental unit consisted of an expanded polystyrene cup (8.5 cm diameter) containing 500 cm^3 of a 2:1 mixture of medium-textured soil and sand. The substrate was previously sterilized by autoclaving for 2 h at 121 °C. Liming and fertilization were performed by applying 2 g dolomitic limestone and 3 g Osmocote fertilizer (NPK 15-09-12 + micronutrients, Forth Jardim, Cerquilho, São Paulo, Brazil) 30 d before sowing. Abamectin and thiodicarb + imidacloprid were applied via seed treatment. For this, 50 g seed of each cultivar were weighed, placed in a plastic bag, and mixed with the respective product at a volume of 0.5 L 100 kg^{-1} seed. Subsequently, manual agitation was performed, bags were opened, and seeds were left to dry at room temperature. Seed treatment was carried out on the day of sowing. Fluopyram was applied in the sowing hole at 176 L ha^{-1} by using a pipette.

Seeds were sown at a density of one seed per pot in a hole about 3 cm deep. Subsequently, the hole was closed and a 2 cm layer of autoclaved commercial substrate (HT Hortaliças, Grupo Provaso, Mogi Mirim, São Paulo, Brazil) was added to reduce water loss. At 11 d after sowing, plants were inoculated with 2000 eggs and eventual second-stage juveniles (J2) of *M. javanica*. For this, two holes were opened in the soil,

about 1 cm away from the plant, and 1 mL inoculum was deposited in each hole. The inoculum was obtained from a pure population maintained on tomato at the Rio Verde Foundation. Nematodes were extracted according to the method of Hussey and Barker as adapted by Boneti and Ferraz (1981). Samples were clarified as described by Coolen and D'Herde (1972), and nematodes were quantified in a Peters chamber under an optical microscope. The suspension was adjusted to 1000 eggs + J2 mL^{-1}. Plants were irrigated manually on a daily basis.

Fertilizer and fungicides were applied to the aboveground parts of plants whenever necessary, ensuring vigorous growth and protection from fungal attack. In Trial 1, foliar fertilization with monoammonium phosphate (MAP) was performed at 1 g L^{-1} at 15 d after inoculation (DAI). Fluxapyroxad + pyraclostrobin (50.1 and 99.9 g ha^{-1}, respectively) and picoxystrobin + tebuconazole + mancozeb (66.5, 83.32, and 1000 g ha^{-1}, respectively) were applied at 11 and 28 DAI for fungal control. In Trial 2, two foliar fertilizations with MAP were carried out at 1 g L^{-1} at 15 and 43 DAI, in addition to one application of fluxapyroxad + pyraclostrobin at 50.1 and 99.9 g ha^{-1}, respectively, at 25 DAI.

At 65 DAI, plants were harvested and separated into shoots and roots for analysis. Roots were washed under running water, placed on absorbent paper to remove excess moisture, weighed, and measured for length. Then, nematode extraction was performed by the above-mentioned methods. *Meloidogyne javanica* eggs and J2 were counted in a Peters chamber under a light microscope to obtain the total number of nematodes. This parameter was divided by the root fresh weight to obtain the nematode population density, expressed in number of nematodes per gram of root. The reproduction factor (RF) was determined according to Oostenbrink (1966), as follows: RF = Final population/Initial population.

Nematode data were subjected to ANOVA. In the case of significant interaction effects, factors were combined for analysis. In the case of non-significance of interaction effects, factors were studied separately. When significant, means were compared by the Scott-Knott test at the 5% significance level. Vegetative data were also subjected to ANOVA. Only the effects of the product factor were analyzed within each cultivar, given that each cultivar possesses specific morphological characteristics associated with its genetic background. When significant, means were compared by the Scott-Knott test at the 5% significance level. Analyses were performed using Sisvar software (Ferreira, 2019).

RESULTS

There were significant interaction effects on nematode variables in both trials. In analyzing the effects of cultivar within nematicide treatments, it was found that in Trial 1 (Table 1), *M. javanica* showed variable reproduction factor (RF) in non-treated cultivars (control). The highest means were observed in 'CZ 48B32 IPRO' (RF = 22.40, susceptible) and 'HO Aporé IPRO' (RF = 13.86, susceptible). Among plants treated with abamectin, the same cultivars and Extrema IPRO (susceptible) exhibited the highest RF values. In the thiodicarb + imidacloprid treatment, the RF on 'HO Aporé IPRO' was high. In general, HO Juruena IPRO' (resistant) and 'CZ58B28 IPRO', 'Foco IPRO', and 'HO Maracaí IPRO' (moderately resistant) showed the lowest RF values in the control, abamectin, and thiodicarb + imidacloprid treatments. On the other hand, RF values did not differ between cultivars treated with fluopyram, being lower than 1 in all plant genotypes.

In Trial 2, 'HO Aporé IPRO' exhibited the highest RF among untreated plants and plants treated with thiodicarb + imidacloprid. The other plants did not differ from each other within these treatments (Table 1). Among plants treated with abamectin, RF was highest on 'HO Aporé IPRO' and lowest on 'Extrema IPRO' (susceptible) and 'HO Juruena IPRO' (resistant). Different from the first trial, RF differed between plants in the fluopyram treatment, with the highest nematode reproduction being observed in 'HO Aporé IPRO' (RF = 9.84); the other plants exhibited RF close to 1 ('Extrema IPRO', RF = 1.11; 'Foco IPRO', RF = 1.05; and 'HO Maracaí IPRO', RF = 0.78) or lower than 0.5 (Table 1).

Analyzing the effect of nematicides within cultivars, it was found that RF did not differ according to nematicide in 'HO Juruena IPRO' and 'Foco IPRO' in either trial, 'HO Maracaí IPRO' in Trial 1, and 'Extrema IPRO' in Trial 2 (Table 1). On the other hand, in Trial 1, in the case where nematicide application reduced nematode reproduction, fluopyram treatment was effective in controlling *M. javanica*, with reductions of 98.12% to 99.73%. Abamectin resulted in lower RF values than the control in 'CZ 48B32

IPRO' (60.36% improvement compared with the control), as did thiodicarb + imidacloprid in 'CZ 48B32 IPRO' (82.50%), 'Extrema IPRO' (61.72%), and 'HO Mamoré IPRO' (69.90%). In Trial 2, fluopyram was again the most effective in controlling *M. javanica*, with reductions ranging from 71.29% to 81.90% in relation to the control. Abamectin and thiodicarb + imidacloprid were also more effective than the control in 'CZ 58B28 IPRO', 'HO Maracaí IPRO', and 'HO Mamoré IPRO' (Table 1).

Table 1. Reproduction factor of *Meloidogyne javanica* on soybean cultivars with varying levels of resistance subjected or not to chemical nematicide treatment, as determined at 65 d after nematode inoculation. Trials 1 and 2, Lucas do Rio Verde, Mato Grosso, Brazil, 2023. Means within columns followed by the same lowercase letter and means within rows followed by the same uppercase letter are not significantly different from each other (Scott-Knott test, $p < 0.05$). Data were transformed by $\sqrt{(x + 0.5)}$ before analysis. R: Resistant; MR: moderately resistant; MS: moderately susceptible; S: susceptible; CV: coefficient of variation.

Cultivar	Response	Untreated control	Abamectin	Thiodicarb + imidacloprid	Fluopyram
Trial 1					
HO Juruena IPRO	R	1.59^{dA}	0.52^{cA}	0.50^{bA}	0.05^{aA}
Foco IPRO	MR	1.36^{dA}	0.41^{cA}	0.82^{bA}	0.11^{aA}
HO Maracaí IPRO	MR	1.02^{dA}	0.41^{cA}	1.16^{bA}	0.10^{aA}
CZ 58B28 IPRO	MR	2.43^{dA}	2.66^{bA}	2.20^{bA}	0.04^{aB}
HO Mamoré IPRO	MS	4.02^{cA}	2.24^{bA}	1.21^{bB}	0.07^{aB}
Extrema IPRO	S	4.65^{cA}	5.47^{aA}	1.78^{bB}	0.07^{aB}
CZ 48B32 IPRO	S	22.40^{aA}	8.88^{aB}	3.92^{bB}	0.06^{aC}
HO Aporé IPRO	S	13.86^{bA}	18.50^{aA}	15.27^{aA}	0.26^{aB}
CV, %			45.34		
Trial 2					
HO Juruena IPRO	R	1.08^{bA}	0.27^{cA}	0.40^{bA}	0.17^{cA}
Foco IPRO	MR	1.68^{bA}	1.21^{bA}	1.02^{bA}	1.05^{bA}
HO Maracaí IPRO	MR	1.67^{bA}	1.47^{bB}	1.25^{bB}	0.78^{bB}
CZ 58B28 IPRO	MR	1.72^{bA}	1.23^{bA}	0.97^{bA}	0.33^{cB}
HO Mamoré IPRO	MS	1.24^{bA}	0.96^{bA}	0.71^{bA}	0.25^{cB}
Extrema IPRO	S	1.51^{bA}	0.63^{cA}	0.66^{bA}	1.11^{bA}
CZ 48B32 IPRO	S	2.21^{bA}	1.06^{bB}	1.15^{bB}	0.40^{cC}
HO Aporé IPRO	S	34.27^{aA}	18.44^{aB}	14.87^{aC}	9.84^{aD}
CV, %			20.53		

The results for nematode population density were similar to those for RF. In Trial 1, the highest mean population density among untreated plants was observed in 'HO Aporé IPRO' (4326 nematodes g^{-1} root) and 'CZ 48B32 IPRO' (6006 nematodes g^{-1} root). Among plants treated with abamectin and thiodicarb + imidacloprid, the highest means were found in 'HO Aporé IPRO' (6713 and 5383 nematodes g^{-1} root, respectively) (Table 2). Nematode population density did not differ between plants treated with fluopyram (range of 20 to 122 nematodes g^{-1} root). In Trial 2, 'HO Aporé IPRO' exhibited the highest nematode population density, regardless of whether or not the plant was treated with nematicides (Table 2). In the control and thiodicarb + imidacloprid treatments, no differences were observed between cultivars. Among plants treated with abamectin, the lowest population density was observed in 'Extrema IPRO' (124 nematodes g^{-1} root) and 'HO Juruena IPRO' (46 nematodes g^{-1} root). In the fluopyram treatment, the lowest means were found in 'CZ 58B28 IPRO' (74 nematodes g^{-1} root), 'CZ 48B32 IPRO' (98 nematodes g^{-1} root), 'HO Mamoré IPRO' (37 nematodes g^{-1} root), and 'HO Juruena IPRO' (40 nematodes g^{-1} root) (Table 2).

Table 2. Number of *Meloidogyne javanica* per gram of root in soybean cultivars subjected or not to chemical control, as determined at 65 d after nematode inoculation. Trials 1 and 2, Lucas do Rio Verde, Mato Grosso, Brazil, 2023. Means within columns followed by the same lowercase letter and means within rows followed by the same uppercase letter are not significantly different from each other (Scott-Knott test, $p < 0.05$). Data were transformed by $\sqrt{(x + 0.5)}$ before analysis. R: Resistant; MR: moderately resistant; MS: moderately susceptible; S: susceptible; CV: coefficient of variation.

Cultivar	Response	Untreated control	Abamectin	Thiodicarb + imidacloprid	Fluopyram
Trial 1					
HO Juruena IPRO	R	515^{cA}	153^{dA}	158^{bA}	20^{aA}
Foco IPRO	MR	697^{cA}	278^{dA}	411^{bA}	95^{aA}
HO Maracaí IPRO	MR	454^{cA}	219^{dA}	530^{bA}	63^{aA}
CZ 58B28 IPRO	MR	890^{cA}	850^{cA}	618^{bA}	21^{aB}
HO Mamoré IPRO	MS	1.479^{bA}	1.086^{cA}	386^{bB}	54^{aB}
Extrema IPRO	S	1.653^{bA}	1.934^{bA}	550^{bB}	35^{aC}
CZ 48B32 IPRO	S	6.006^{aA}	2.762^{bB}	1.277^{bB}	25^{aC}
HO Aporé IPRO	S	4.326^{aA}	6.713^{aA}	5.383^{aA}	122^{aB}
CV, %			53.14		
Trial 2					
HO Juruena IPRO	R	186^{bA}	46^{cB}	91^{bB}	40^{cB}
Foco IPRO	MR	346^{bA}	232^{bA}	204^{bA}	221^{bA}
HO Maracaí IPRO	MR	347^{bA}	311^{bA}	269^{bA}	215^{bA}
CZ 58B28 IPRO	MR	371^{bA}	268^{bA}	174^{bB}	74^{cB}
HO Mamoré IPRO	MS	222^{bA}	176^{bA}	135^{bA}	37^{cB}
Extrema IPRO	S	323^{bA}	124^{cA}	155^{bA}	217^{bA}
CZ 48B32 IPRO	S	424^{bA}	231^{bA}	224^{bA}	98^{cB}
HO Aporé IPRO	S	7.680^{aA}	3.858^{aB}	3.713^{aB}	2.152^{aC}
CV, %			29.21		

Investigating the effect of nematicides within cultivars, it was observed that, in Trial 1 there were no differences between treatments (with and without nematicides) in ‘Foco IPRO’, ‘HO Maracaí IPRO’, or ‘HO Juruena IPRO’. In Trial 2, nematicides had no influence on nematode population density in ‘Extrema IPRO’, ‘Foco IPRO’, or ‘HO Maracaí IPRO’ (Table 2). In treatments where nematicides exerted significant effects, the best nematode control was conferred by fluopyram, with reductions of 96.37% (‘HO Mamoré IPRO’) to 99.58% (‘CZ 48B32 IPRO’) in Trial 1 and of 71.97% (‘HO Aporé IPRO’) to 83.49% (‘HO Mamoré IPRO’) in Trial 2 compared with the control.

In Trial 1, abamectin reduced nematode population density in ‘CZ 48B32 IPRO’ by 54.02% compared with the control. Thiodicarb + imidacloprid promoted reductions of 66.70% (‘Extrema IPRO’), 73.88% (‘HO Mamoré IPRO’), and 78.73% (‘CZ 48B32 IPRO’). In Trial 2, abamectin reduced population densities by 49.77% and 75.46% in ‘HO Aporé IPRO’ and ‘HO Juruena IPRO’, respectively. Thiodicarb + imidacloprid decreased the parameter by 53.02%, 51.65%, and 51.05% in ‘CZ 58B28 IPRO’, ‘HO Aporé IPRO’, and ‘HO Juruena IPRO’, respectively (Table 2).

For vegetative parameters, it was analyzed the effect of nematicides within each cultivar. Thus, cultivars were not compared with each other, as differences between plants may be attributed to genetic factors. In Trial 1, root length was highest in ‘CZ 58B28 IPRO’ treated with abamectin (40.46 cm) and ‘CZ 48B32 IPRO’ treated with abamectin or fluopyram (35.02 and 37.35 cm, respectively) (Table 3). In Trial 2, ‘HO Mamoré IPRO’ treated with abamectin or fluopyram had lower means (22.61 and 24.06 cm, respectively) than the control (32.53 cm).

Table 3. Root length (cm) of soybean cultivars subjected or not to chemical nematicide treatment. Trials 1 and 2, Lucas do Rio Verde, Mato Grosso, Brazil, 2023. Means within rows followed by the same uppercase letter are not significantly different from each other (Scott-Knott test, $p < 0.05$).

Cultivar	Untreated control	Abamectin	Thiodicarb + imidacloprid	Fluopyram	CV (%)
Trial 1					
HO Juruena IPRO	30.92^{A}	31.00^{A}	28.27^{A}	33.45^{A}	14.38
Foco IPRO	25.62^{A}	25.02^{A}	30.67^{A}	29.38^{A}	25.73
HO Maracaí IPRO	30.47^{A}	28.32^{A}	28.67^{A}	26.34^{A}	31.57
CZ 58B28 IPRO	33.57^{B}	40.46^{A}	28.60^{B}	29.25^{B}	23.52
HO Mamoré IPRO	32.53^{A}	32.45^{A}	33.02^{A}	31.00^{A}	19.66
Extrema IPRO	49.70^{A}	34.55^{A}	43.82^{A}	36.07^{A}	32.30
CZ 48B32 IPRO	30.27^{B}	35.02^{A}	28.67^{B}	37.35^{A}	19.92
HO Aporé IPRO	30.00^{A}	26.60^{A}	29.10^{A}	29.82^{A}	23.15
Trial 2					
HO Juruena IPRO	26.47^{A}	26.00^{A}	25.63^{A}	26.86^{A}	14.02
Foco IPRO	25.70^{A}	27.43^{A}	26.86^{A}	25.88^{A}	15.10
HO Maracaí IPRO	26.03^{A}	23.78^{A}	27.14^{A}	25.65^{A}	13.41
CZ 58B28 IPRO	23.88^{A}	23.73^{A}	24.60^{A}	25.15^{A}	17.97
HO Mamoré IPRO	30.60^{A}	22.61^{B}	27.83^{A}	24.06^{B}	15.90
Extrema IPRO	26.00^{A}	27.05^{A}	30.60^{A}	24.65^{A}	24.65
CZ 48B32 IPRO	23.18^{A}	24.60^{A}	26.06^{A}	24.10^{A}	12.28
HO Aporé IPRO	26.38^{A}	25.26^{A}	26.13^{A}	26.11^{A}	15.47

Root fresh weight was the vegetative parameter that differed the most in Trial 1. In general, fluopyram afforded the lowest means in comparison with the control (Table 4). 'CZ 58B28 IPRO' showed greater accumulation of root fresh weight when treated with abamectin or thiodicarb + imidacloprid (6.16 and 7.24 g, respectively). On the other hand, 'CZ 48B32 IPRO', 'Foco IPRO', and 'HO Mamoré IPRO' showed reductions in root fresh weight when treated with abamectin or fluopyram. There were nonsignificant differences in root fresh weight between nematicide treatments in Trial 2 (Table 4).

Table 4. Root fresh weight (g) of soybean cultivars subjected or not to chemical nematicide treatment. Trials 1 and 2, Lucas do Rio Verde, Mato Grosso, Brazil, 2023. Means within rows followed by the same uppercase letter are not significantly different from each other (Scott-Knott test, $p < 0.05$).

Cultivar	Untreated control	Abamectin	Thiodicarb + imidacloprid	Fluopyram	CV (%)
Trial 1					
HO Juruena IPRO	6.50^{A}	7.13^{A}	6.63^{A}	5.35^{A}	25.18
Foco IPRO	3.61^{A}	3.15^{B}	4.18^{A}	2.82^{B}	23.32
HO Maracaí IPRO	4.01^{A}	3.89^{A}	4.16^{A}	3.62^{A}	25.58
CZ 58B28 IPRO	5.42^{B}	6.16^{A}	7.24^{A}	4.56^{B}	21.09
HO Mamoré IPRO	5.92^{A}	4.54^{B}	6.30^{A}	3.66^{B}	19.83
Extrema IPRO	5.85^{A}	5.71^{A}	6.75^{A}	4.22^{B}	26.13
CZ 48B32 IPRO	6.82^{A}	5.54^{B}	6.19^{A}	4.95^{B}	20.39
HO Aporé IPRO	6.19^{A}	6.28^{A}	5.84^{A}	5.37^{A}	25.16
Trial 2					
HO Juruena IPRO	11.33^{A}	12.20^{A}	9.90^{A}	9.54^{A}	21.73
Foco IPRO	11.04^{A}	10.39^{A}	10.83^{A}	9.89^{A}	24.76
HO Maracaí IPRO	9.41^{A}	10.12^{A}	9.40^{A}	8.14^{A}	22.56
CZ 58B28 IPRO	9.81^{A}	11.50^{A}	11.12^{A}	9.13^{A}	26.01
HO Mamoré IPRO	11.72^{A}	11.17^{A}	11.30^{A}	12.17^{A}	23.45
Extrema IPRO	9.71^{A}	9.73^{A}	8.82^{A}	10.71^{A}	21.83
CZ 48B32 IPRO	10.54^{A}	10.46^{A}	10.88^{A}	8.37^{A}	33.68
HO Aporé IPRO	9.37^{A}	9.88^{A}	7.97^{A}	9.15^{A}	19.69

DISCUSSION

Soybean cultivars had distinct and sometimes variable reactions to the same population of *M. javanica*. Similarly, chemical nematicides showed variable effects according to plant genotype. One hypothesis is that cultivars have different types of exudates, directly or indirectly influencing the soil environment and, consequently, affecting the distribution of chemical molecules and root-nematode dynamics. Rocha et al. (2015) studied the nematicidal effect of root exudates from two soybean cultivars on *M. incognita* and observed that dialyzed exudates exhibited different activities.

Despite the variability of data, it was confirmed that 'HO Aporé IPRO' is susceptible to *M. javanica*, with RF values of 13.86 and 34.27 in Trials 1 and 2, respectively. 'CZ 48B32 IPRO', known to be susceptible, exhibited high RF (22.40) only in Trial 1, whereas 'Extrema IPRO' (susceptible) had an RF of 4.65 in Trial 1 and 1.51 in Trial 2. These results are in line with a previous study evaluating 37 soybean cultivars susceptible to *M. javanica*. The referred study showed that plant genotypes reacted differently to the nematode (Balardin et al., 2022).

Here, 'HO Juruena IPRO, considered resistant to the nematode, had low RF in both trials, as also observed for 'Foco IPRO' and 'HO Maracaí IPRO', which are considered moderately resistant. Such findings may be associated with genetic characteristics that confer resistance to *M. javanica*. Independent of the reaction of plants, *M. javanica* was recovered from all roots. Plant resistance is a post-infectious event; resistant plants recognize the presence of nematodes via elicitor-receptor reaction. Elicitors are substances produced by the esophageal gland of nematodes and released into the host cell during parasitism (Silva, 2001). After detection of these molecules, resistant plants initiate the hypersensitivity reaction, leading to disruption or malformation of nematode feeding sites (Machado et al., 2022).

The variable responses to *M. javanica*, combined with the fact that resistance is a post-infectious event, demonstrate the importance of protecting cultivars with nematicides, regardless of their degree of resistance. Fluopyram was effective in protecting 'CZ 58B28 IPRO' and 'HO Mamoré IPRO' in both trials, and abamectin and thiodicarb + imidacloprid were effective for 'CZ 48B32 IPRO'. The other nematicides did not confer significant protection, or did so in only one of the trials. The results allow us to infer that the reduction of initial nematode populations provided by nematicides contributes to minimizing the pressure of virulent individuals on soybean cultivars with resistance genes. With regard to integrated management, even cultivars that exhibit resistance may suffer damage from nematode penetration, possibly affecting plant development. Such effects are even more pronounced when plants are exposed to high nematode populations, emphasizing the importance of integrated strategies combining genetic management with other techniques (Favoreto et al., 2019).

As previously mentioned, fluopyram conferred the greatest reduction in nematode populations in both trials. The product is described as having acute toxicity to *M. javanica*. It acts by inhibiting ATP biosynthesis, impairing nematode muscle contraction, motility, penetration, and infection, in addition to causing pathogen death in the case of irreversible cell damage resulting from extremely low ATP levels (Schleker et al., 2023). In agreement with our results, a previous study demonstrated the effect of this nematicide on *M. javanica* motility; at 48 h after exposure to the compound, nematodes suffered irreversible immobilization, leading to a decrease in infection rate (Oka and Saroya, 2019). Control of *M. incognita* in soybean by fluopyram was attributed to the reduction in J2 penetration (Hawk and Faske, 2020).

Unlike fluopyram, abamectin acts by inhibiting glutamate-gated chloride channels in nematodes, thereby causing ionic imbalance in the nervous system, resulting in paralysis and, ultimately, death (Faske and Starr, 2006). Here, abamectin was effective in reducing *M. javanica* populations in cultivars exhibiting high RF values (Table 1), confirming its efficacy in controlling this root-knot nematode (Almeida et al., 2017; Otoboni et al., 2021; El-Marzoky et al., 2022). However, in some cultivars, the effects of abamectin did not differ from those of the control, agreeing with previous research. A study found that *M. incognita* populations were higher in cotton plants treated with abamectin than in control plants, as evaluated at 50 and 100 d after emergence (Bessi et al., 2010). Abamectin promoted intermediate control in cotton plants infected with *Pratylenchus brachyurus* (Ribeiro et al., 2012). Some characteristics of abamectin might explain the differences in nematode control, such as low mobility, binding with soil particles, and

susceptibility to microbial degradation (Corte et al., 2014). Thus, further studies are needed to elucidate the relationship between abamectin and cultivars with distinct genetic characteristics, as well as its efficiency against different population levels of *M. javanica*.

Thiodicarb + imidacloprid effectively controlled *M. javanica* when associated with resistant cultivars and provided protection to two susceptible cultivars (Table 1). These compounds act by causing nematode hyperexcitation, followed by paralysis and death (Omoto, 2000; Guedes et al., 2008). Other studies reported effective nematode control in susceptible soybean cultivars with the application of thiodicarb + imidacloprid: *M. javanica* egg and J2 numbers decreased compared with the control (Santana et al., 2016). The product was also effective in controlling *M. graminicola* in rice, leading to reduced nematode penetration and population density compared with the control (Soares et al., 2021).

Integrated management practices are fundamental for preserving the genes of cultivars resistant to *M. javanica*, as different populations of this nematode can exhibit varied degrees of aggressiveness (Chidichima et al., 2021). Extensive use of a few resistance genes in a given plant species may promote the selection of virulent nematode populations capable of parasitizing and reproducing in such cultivars (Machado et al., 2022). It should be noted that most soybean cultivars with resistance to *M. javanica* descend from a single source of resistance, the cv. Bragg (Li et al., 2018).

In general, there was no consistency in the results of vegetative parameters. Nematicides both contributed to and negatively affected vegetative development. It is worth noting that experiments under controlled conditions may provide information on the potential of each agent in nematode control, but this may not be true for vegetative development, given physical space limitations and changes in the distribution and interaction of compounds in the soil. Previous studies have shown positive, neutral, or even negative effects of the tested nematicides on vegetative variables (Crow et al., 2020; Watson et al., 2020; Almeida Júnior et al., 2021; El-Ashry et al., 2021; El-Marzoky et al., 2022). Given that this is one of the first studies on the action of chemical nematicides against nematodes in soybean cultivars with different levels of resistance, some hypotheses need to be further elucidated. Future studies are necessary to explain the relationship between cultivars, nematicidal compounds, and nematode populations and gain insight into the underlying causes of differences in reactions.

CONCLUSIONS

There was an additive effect of genetic and chemical management on *Meloidogyne javanica* control, in particular when resistant cultivars were associated with thiodicarb + imidacloprid or fluopyram. Fluopyram treatment and the use of ‘HO Juruena IPRO’, ‘Foco IPRO’, and ‘HO Maracaí IPRO’ also contributed to *M. javanica* control. The results of vegetative development were inconclusive.

Author contributions

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