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Article

Efficacy of insecticides applied to soybean seeds in controlling *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) under two soil moisture conditions

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Abstract

The present work aimed to evaluate the effectiveness of insecticides applied to soybean seeds aiming to control *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) caterpillars in two soil water conditions. In the 7-day post-emergence assessment (DAE), the fipronil and thiamethoxam treatments provided the highest percentages of control of *S. frugiperda* caterpillars and lower levels of soybean defoliation at 70% FC. At 14 DAE, the highest percentages of caterpillar control and the lowest percentages of soybean defoliation were observed with the insecticide chlorantraniliprole and with the thiamethoxam + cyantraniliprole mixture. In the last two evaluations of the trial, the treatments fipronil and thiamethoxam presented the 21 DAE with higher levels of caterpillar control and lower percentages of soybean defoliation in the condition of 70 % FC. At 28 DAE. the fipronil and thiamethoxam treatments and the imidacloprid + thiodicarb mixture showed higher levels of caterpillar mortality and lower levels of soybean defoliation also in the70% FC. It was concluded that the chemical treatments chlorantraniliprole and thiamethoxam + cyantraniliprole were the most effective in controlling *S. frugiperda* caterpillars, regardless of the level of moisture present in the soil.

Additional keywords: Fall armyworm, field capacity, mortality, defoliation.

Resumen

El presente trabajo tuvo como objetivo evaluar la efectividad de insecticidas aplicados a semillas de soja con el objetivo de controlar las orugas de *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) en dos condiciones hídricas del suelo. En la evaluación post-emergencia (DAE) de 7 días, los tratamientos con fipronil y thiamethoxam proporcionaron los porcentajes más altos de control de orugas de *S. frugiperda* y niveles más bajos de defoliación de la soja al 70% FC. A los 14 DAE, los mayores porcentajes de control de orugas y los menores porcentajes de defoliación de la soja se observaron con el insecticida chlorantraniliprole y con la mezcla thiamethoxam + cyantraniliprole. En las dos últimas evaluaciones del ensayo, los tratamientos fipronil y thiamethoxam presentaron a los 21 DAE mayores niveles de control de orugas y menores porcentajes de defoliación de la soja en la condición de 70 % FC. A los 28 DAE, los tratamientos con fipronil y thiamethoxam y la mezcla imidacloprid + thiodicarb mostraron mayores niveles de mortalidad de orugas y menores niveles de defoliación de la soja también en el 70% FC. Se concluyó que los tratamientos químicos chlorantraniliprole y thiamethoxam + cyantraniliprole fueron los más efectivos para controlar las orugas de *S. frugiperda*, independientemente del nivel de humedad presente en el suelo.

Palabras clave: Gusano cogollero, capacidad de campo, mortalidad, defoliación.

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Introduction

Soybean (*Glycine max* (L.) Merrill) is Brazil's main agricultural export commodity which has great global socioeconomic importance since it represents one of the main inputs of the agro-industrial complex (Costa Neto et al. 2011, Dall'agnol 2016). However, this crop requires technical knowledge and research to guarantee its productivity since it is attacked by different insect pests from sowing to the grain maturation phase. These pests, if not controlled, can reduce both the productivity and the quality of the grains produced (Panizzi et al. 2012, Ávila and Schlick-Souza 2015).

Among the pests that occur in soybean crops, species of defoliating caterpillars such as *Anticarsia gemmatalis* (Hübner, 1818), *Chrysodeixis includens* (Walker, 1858) and *Helicoverpa armigera* (Hübner, 1808) deserve to be highlighted; which are considered initial pests in soybean crops (Hoffmann-Campo et al. 2012, Moscardi et al. 2012). *Spodoptera frugiperda* (Smith, 1797) (Lepidoptera: Noctuidae), although it is a pest most associated with grasses, can also attack soybean plants in their initial stages of development (Araújo et al. 2023). At this stage of development, damage caused by the fall armyworm can significantly reduce the soybean plant stands and directly impact the final yield of the crop (Bernardi et al. 2014).

To control the initial pests in agricultural crops, chemical insecticides applied in seed treatments have generally been used (Ávila and Gomes 2003, Nikolova and Georgieva 2015, Portilho et al. 2015); with this practice being widely adopted and efficient since it guarantees the initial stand, and consequently; good development and productivity of the crop (Floss 2022). Among the main products used in the seed treatment to control initial pests are neonicotinoid insecticides and fipronil (Radolinski et al. 2018). The greatest interest in these products among producers is due to their high toxicity to target pests; the persistence and flexibility with which they are used in crops to control insect pests (Bonmatin et al. 2015).

In addition to the direct effect on pests, some neonicotinoid insecticides such as thiamethoxam, for example, can alter the expression of genes related to plants' natural defense; making them more vigorous in response to stress both in the presence and absence of water available in the soil. (Stamm et al. 2014). However, the availability of insecticides applied to seeds for plant defense depends on their rate of leaching and absorption by the roots, as well as their persistence in the soil; parameters that are influenced by the availability of water in the rhizosphere region of plants (Scorza-Júnior and Franco 2013, Radolinski et al. 2018).

During the germination and emergence process of soybean seedlings, the matric potential and soil texture interfere with the rate of absorption of water and chemicals by plant roots (Peske and Delouche 1985). Moist soils, especially in conditions of higher temperatures, tend to increase the rate of degradation of insecticides applied to seeds or in the planting furrow, which consequently reduces their residual effect on pest control (Castillo and Torstensson 2007, Martinez et al. 2008). Scorza-Júnior and Franco (2013) evaluated the influence of humidity on the degradation of the insecticide fipronil in two types of soil; finding that the increase in humidity in the soil accelerated the degradation process of this product. Portilho et al. (2015) evaluated the degradation of pyrethroid insecticides and neonicotinoids in a clayey soil cultivated under crop-livestock integration, direct and conventional planting; finding that thiamethoxam showed slow degradation in the soil, while permethrin, and mainly bifenthrin, showed rapid degradation. Stamm et al. (2016) evaluated the absorption and translocation of the insecticides imidacloprid, clothianidin and flupyradifurone when applied to soybean seeds under water stress conditions and concluded that the absorption and translocation of these insecticides presented different responses depending on the amount of water available in the soil.

Therefore, the present work aimed to evaluate the effectiveness of insecticides applied to soybean seeds aiming to control *S. frugiperda* caterpillars in two soil water conditions.

Material and Methods

The work was carried out by growing soybean plants in a greenhouse and in the laboratory evaluating the mortality of *S. frugiperda* caterpillars and defoliation in soybeans. For this, soybean seeds were previously treated with different insecticides (Table 1) and placed to germinate in plastic pots with a capacity of five liters containing Dystrophic Red Latosol soil with a clayey

texture under two water conditions (30 and 70% of field capacity). Field capacity (FC) is characterized as the maximum water content retained by the soil after the excess has been drained through percolation (Mello *et al.* 2022). The soil water retention curve and its field capacity (FC) were determined using the Richards chamber method (Richards 1965). After determining the FC and placing the equivalent amount of water in the soil (30 and 70% FC), the pots containing soybean plants were weighed twice a week, aiming to replace the water required by evaporation and transpiration of the plants; consequently, returning to the initial condition of the studied FC soil.

To evaluate the chemical treatments applied to the seeds on the *S. frugiperda* caterpillars, leaflets from the median part of the plants from the two humidity conditions of the soil (30 and 70% FC) were collected at 7, 14, 21 and 28 days after emergence (DAE) of the soybean. Next, leaf discs of 4 cm in diameter were prepared from the leaflets of each treatment using a perforator and offered to the 1st to 2nd instar *S. frugiperda* caterpillars kept in Petri dishes which contained 2% agar solution at the base to avoid drying out the leaf discs. The dishes containing the leaf discs and caterpillars were kept under laboratory conditions at a temperature of 25 ºC and a 14-hour photophase. Caterpillar mortality was evaluated daily on the dishes, however, total mortality and the percentage of leaflet defoliation visually (0 to 100%) in each treatment were always computed at the end of the seven days of confinement of the caterpillars on the dishes. After evaluating the final mortality and soybean defoliation in each replication, new 1st to 2nd instar *S. frugiperda* caterpillars and new leaflets were placed on the bioassay dishes, thus starting another evaluation period.

The *S. frugiperda* caterpillars used in the test came from stock breeding at the MT Foundation Entomology Laboratory.

The experiment was conducted in a completely randomized experimental design with four replications with treatments allocated in a 6 x 2 factorial scheme (six seed treatments x two soil moisture conditions). The percentages of caterpillar mortality and soybean visual defoliation observed in each treatment were transformed to arcsine $(\frac{\sqrt{x}}{100})$ aiming to obtain normality and homoscedasticity of the data according to Shapiro and Wilk (1965). This transformation is recommended when there are discrepant mortality values as obtained in this paper. The transformed data were subjected to analysis of variance and when a significant effect was verified by the F test ($p < 0.05$), the means of the treatments were compared by the Scott-Knott test at 5% probability. The original data for this article will be available if any reader is interested.

Table 1. Treatments applied to soybean seeds aiming to control *Spodoptera frugiperda* caterpillars in soil with two water conditions (30 and 70% FC). Rondonópolis, MT.

Active ingredient	**Dose[1](g a.i. Kg of seeds^{-1})**
Control	-
Chlorantraniliprole	0.625
Imidacloprid + thiodicarb	0.75 + 2.25
Fipronil	1.25
Thiamethoxam	1.75
Thiamethoxam + cyantraniliprole	0.35 + 1.20

[1]Dose equivalent to the recommended product/hectare

Results

In the evaluation at 7 DAE, a significant interaction between the seed treatment factors and soil water capacity was found (Table 2), with the fipronil and thiamethoxam treatments showing a different effect on caterpillar mortality and defoliation of soybeans in the two water conditions studied in the test (Table 3). The highest percentages of control of the *S. frugiperda* caterpillars, and consequently, lower defoliation in these two treatments were observed in the 70% FC condition when compared to the 30% FC condition (Table 3). In the other treatments from the same evaluation period, the two variables behaved similarly in the two soil moisture conditions (Table 3). The simple effects of the seed treatment factor were significant by the F test for the two variables studied, while for the FC soil factor, no significance was observed by the F test for the two variables (Table 2). The highest percentages of control of the *S. frugiperda* caterpillars and lowest soybean defoliation in this evaluation were found with the chlorantraniliprole and thiamethoxam + cyantraniliprole treatments, which differed from the other chemical treatments of the test for the two variables studied, especially in the 30% water condition of the FC soil (Table 3). In the imidacloprid + thiodicarb treatment, intermediate levels of caterpillar mortality and defoliation were found, although they differed from the value found in the control for both varieties studied (Table 3).

In the evaluation at 14 DAE, no interaction was observed between the seed treatment factors and soil water conditions, although the simple effects of both factors were significant in the analysis of variance using the F test (Table 2). Since the factors behaved independently, the variables studied were analyzed separately within each factor. Therefore, it was observed that the highest percentages of caterpillar control and the lowest percentages of soybean defoliation were observed in treatments with the insecticide chlorantraniliprole and with the thiamethoxam + cyantraniliprole mixture, which differed from the other chemical treatments in the test and the control treatment (Table 4). Regarding the effects of soil moisture levels on the two variables studied, it was found that the 30% FC soil condition presented higher caterpillar mortality and lower levels of soybean defoliation when compared to the 70% FC condition (Table 5).

Table 2. Calculated F values (Fc) and probability (*p*) for the interaction and simple effects of seed treatment factors (**ST**) and soil field capacity (**FC**) of the variance analysis table considering the control variables and defoliation of *Spodoptera frugiperda* caterpillars in soybeans. Rondonópolis, MT.

Assessment period	Variable	Interaction	ST	FC
7 DAE	**Control**	Fc = 4.749 ($p < 0.0022$)	Fc = 34.962 ($p < 0.0001$)	Fc = 3.749 ($p > 0.0614$)
	Defoliate	Fc = 5.107 ($p < 0.0014$)	Fc = 48.189 ($p < 0.0001$)	Fc = 3.486 ($p > 0.0708$)
14 DAE	**Control**	Fc = 1.168 ($p > 0.3455$)	Fc = 19.100 ($p < 0.0001$)	Fc = 5.010 ($p < 0.0320$)
	Defoliate	Fc = 1.451 ($p > 0.2322$)	Fc = 22.460 ($p < 0.0001$)	Fc = 6.652 ($p < 0.0145$)
21 DAE	**Control**	Fc = 4.139 ($p < 0.0049$)	Fc = 36.536 ($p < 0.0001$)	Fc = 4.020 ($p > 0.0532$)
	Defoliate	Fc = 4.327 ($p < 0.0038$)	Fc = 41.690 ($p < 0.0001$)	Fc = 4.558 ($p < 0.0402$)
28 DAE	**Control**	Fc = 6.600 ($p < 0.0002$)	Fc = 40.013 ($p < 0.0001$)	Fc = 66.000 ($p < 0.0001$)
	Defoliate	Fc = 6.573 ($p < 0.0002$)	Fc = 48.127 ($p < 0.0001$)	Fc = 62.259 ($p < 0.0001$)

Tabla 3. Average values of mortality of *Spodoptera frugiperda* caterpillars and defoliation in the different treatments applied to soybean seeds at seven days after plant emergence (DAE) in clay soil with 30 and 70% of its field capacity (FC). Rondonópolis, MT.

Treatments (g/kg of seeds)[1]	FC (30%)		FC (70%)	
	Mortality (%)	Defoliate (%)	Mortality (%)	Defoliate (%)
Control	18.8 ± 4.7 Ab	82.2 ± 4.5 Aa	0.0 ± 0.0 Ac	100.0 ± 0.0 Aa
Chlorantraniliprole (0,625)	100.0 ± 0.0 Aa	0.0 ± 0.0 Ac	100.0 ± 0.0 Aa	0.0 ± 0.0 Ad
Imidacloprid + thiodicarb (0.75 + 2.25)	43.8 ± 2.3 Ab	59.7 ± 1.9 Ab	37.5 ± 6.3 Ab	65.4 ± 5.7 Ab
Fipronil (1.25)	31.3 ± 2.3 Bb	75.3 ± 1.9 Ab	81.3 ± 4.7 Aa	28.5 ± 4.3 Bc
Thiamethoxam (1.75)	43.8 ± 2.3 Bb	60.9 ± 1.9 Ab	75.0 ± 0.0 Aa	36.9 ± 2.7 Bc
Thiamethoxam + cyantraniliprole (0.35 + 1.20)	100.0 ± 0.0 Aa	0.33 ± 1.9 Ac	100.0 ± 0.0 Aa	0.33 ± 0.1 Ad

[1]Dose equivalent to the recommended product/hectare

Means followed by the same uppercase letter in the row for the same parameter and lowercase in the column do not differ statistically from each other by the Scott-Knott test ($p < 0.05$).

Table 4. Average values of mortality of *Spodoptera frugiperda* caterpillars and defoliation in the different treatments applied to soybean seeds at fourteen days after plant emergence (DAE). Rondonópolis, MT.

Treatments (g/kg of seeds)[1]	Mortality (%)	Defoliate (%)
Control	12,5 ± 1.6 c	88,6 ± 1.5 a
Chlorantraniliprole (0,625)	100,0 ± 0.0 a	1,43 ± 0.5 c
Imidacloprid + thiodicarb (0.75 + 2.25)	54,4 ± 3.9 b	45,5 ± 3.6 b
Fipronil (1.25)	62,5 ± 3.1 b	40,8 ± 3.1 b
Thiamethoxam (1.75)	62,5 ± 3.1 b	38,6 ± 2.7 b
Thiamethoxam + cyantraniliprole (0.35 + 1.20)	100,0 ± 0.0 a	1,59 ± 0.2 c

[1]Dose equivalent to the recommended product/hectare

Means followed by the same letter in the column do not differ statistically from each other by the Scott-Knott test ($p < 0,05$).

Table 5. Average mortality values of *Spodoptera frugiperda* caterpillars and soybean defoliation in the two soil moisture conditions (30 and 70% FC) at 14 days after plant emergence (DAE). Rondonópolis, MT.

Water condition\Variable	Mortality (%)	Defoliate (%)
FC (30%)	72.9 ± 6.5 a	28.9 ± 6.6 b
FC (70%)	59.4 ± 8.6 b	43.3 ± 8.4 a

Means followed by the same letter in the column do not differ statistically from each other by the Scott-Knott test ($p < 0,05$).

In the evaluation at 21 DAE, a significant interaction between the factors was again observed, which shows that the seed treatment factor had a different effect on the two variables depending on the level of the moisture factor considered (Table 2). Therefore, it was found that the fipronil and thiamethoxam treatments presented higher levels of caterpillar control and lower percentages of soybean defoliation at 70% FC (Table 6). In the other seed treatments, the effects on the two variables were similar under the two FC soil conditions. The simple effects of the seed treatment factor have been verified for both variables in this evaluation, while the moisture factor proved to be significant only for the soybean defoliation variable (Table 2). However, the highest levels of control of the *S. frugiperda* caterpillars and protection against soybean defoliation in the present evaluation were again observed with the chlorantraniliprole insecticide and with the thiamethoxam + Cyantraniliprole mixture considering both soil water conditions (Table 6). In the imidacloprid + thiodicarb treatment, intermediate levels of caterpillar mortality and soybean defoliation were found, although they showed difference from the control for the two humidity conditions studied (Table 6).

At 28 DAE, an interaction was verified between seed treatment factors and soil water conditions using the F test, as well as for the simple effects of both factors studied (Table 2). Therefore, in addition to the fipronil and thiamethoxam insecticides, the imidacloprid + thiodicarb mixture also had a different effect on caterpillar mortality and defoliation intensity; depending on the water availability in the soil (Table 7). Similar to the results in the 21 DAE evaluation, the highest levels of caterpillar mortality and the lowest levels of soybean defoliation were observed in these three chemical treatments in the 70% FC soil water condition when compared to the 30% FC level. However, the chlorantraniliprole insecticide and the thiamethoxam + cyantraniliprole mixture showed the highest levels of caterpillar control and the lowest levels of soybean defoliation in both soil moisture conditions at this assessment period (Table 7).

Tabla 6. Average values of mortality of *Spodoptera frugiperda* caterpillars and defoliation in the different treatments applied to soybean seeds at twenty-one days after plant emergence (DAE) in clay soil with 30 and 70% of its field capacity (FC). Rondonópolis, MT

Treatments (g/kg of seeds)[1]	**FC (30%)**		**FC (70%)**	
	Mortality (%)	**Defoliate (%)**	**Mortality (%)**	**Defoliate (%)**
Control	18,8 ± 2.3 Ac	84,7 ± 1.9 Aa	18,8 ± 2.3 Ac	83,5 ± 2.1 Aa
Chlorantraniliprole (0,625)	100,0 ± 0.0 Aa	0,0 ± 0.0 Ac	100,0 ± 0.0 Aa	0,95 ± 0.2 Ac
Imidacloprid + thiodicarb (0.75 + 2.25)	62,5 ± 12.5 Ab	41,9 ± 11.3 Ab	43,8 ± 4.7 Ab	58,5 ± 4.6 Ab
Fipronil (1.25)	12,5 ± 3.1 Bc	89,0 ± 2.7 Aa	43,8 ± 5.5 Ab	57,2 ± 5.4 Bb
Thiamethoxam (1.75)	43,8 ± 4.7 Bb	57,8 ± 4.5 Ab	87,5 ± 3.1 Aa	15,7 ± 3.0 Bc
Thiamethoxam + cyantraniliprole (0.35 + 1.20)	100,0 ± 0.0 Aa	2,0 ± 0.1 Ac	100,0 ± 0.0 Aa	3,2 ± 1.3 Ac

[1]Dose equivalent to the recommended product/hectare

Means followed by the same uppercase letter in the row for the same parameter and lowercase in the column do not differ statistically from each other by the Scott-Knott test ($p < 0.05$).

Tabla 7. Average values of mortality of *Spodoptera frugiperda* caterpillars and defoliation in the different treatments applied to soybean seeds at twenty-eight days after plant emergence (DAE) in clay soil with 30 and 70% of its field capacity (FC). Rondonópolis, MT.

Treatments (g/kg of seeds)[1]	FC (30%)		FC (70%)	
	Mortality (%)	Defoliate (%)	Mortality (%)	Defoliate (%)
Control	0,0 ± 0.0 Bc	100,0 ± 0.0 Aa	37,5 ± 3.1 Ac	66,0 ± 3.0 Ba
Chlorantraniliprole (0,625)	100,0 ± 0.0 Aa	0,0 ± 0.0 Ac	100,0 ± 0.0 Aa	1,9 ± 0.2 Ac
Imidacloprid + thiodicarb (0.75 + 2.25)	25,0 ± 3.1 Bb	75,3 ± 3.1 Ab	68,8 ± 2.3 Ab	35,6 ± 2.1 Bb
Fipronil (1.25)	18,8 ± 4.7 Bb	82,2 ± 4.5 Ab	87,5 ± 3.1 Aa	19,1 ± 2.4 Bc
Thiamethoxam (1.75)	25,0 ± 0.0 Bb	75,0 ± 0.0 Ab	68,8 ± 4.7 Ab	34,4 ± 4.2 Bb
Thiamethoxam + cyantraniliprole (0.35 + 1.20)	93,8 ± 2.3 Aa	6,3 ± 2.3 Ac	100,0 ± 0.0 Aa	0,0 ± 0.0 Ac

[1]Dose equivalent to the recommended product/hectare

Means followed by the same uppercase letter in the row for the same parameter and lowercase in the column do not differ statistically from each other by the Scott-Knott test ($p < 0.05$).

Discussion

The significant interactions of the factors observed in the evaluation periods at 7, 21 and 28 DAE imply a different action of the seeds on treatments in the two soil moisture conditions studied which acted in a dependent way on the two response variables. In these cases, the effects of each factor need to be analyzed within the other factor through splitting. In evaluations at 7 and 21 DAE, the fipronil and thiamethoxam treatments showed better control of *S. frugiperda* caterpillars and a lower level of soybean defoliation in the water condition of the 70% FC soil. At 28 DAE, in addition to these two treatments, this effect was also extended to the imidacloprid + thiodicarb mixture (Tables 3, 6 and 7). The other treatments in the trial were not influenced by the soil moisture level in these three evaluations.

Before the insecticide is absorbed by the plant roots it needs to enter the soil solution with the absorption intensity depending on the water level in the soil (Zhang et al. 2019). The superiority of these treatments, observed with 70% FC soil, were probably due to better absorption and translocation of products applied to the seeds to the aerial part of soybean plants. With this, it was possible to promote a better level of control of *S. frugiperda* caterpillars which also resulted in greater protection of soybeans against defoliation. This effect of improving control levels of *S. frugiperda* caterpillars under the condition of 70% FC can be further enhanced, especially in clayey soil such as the one used in the present study; which has a greater water retention capacity compared to sandy soil; which has a lower retention capacity (Conte *et al.* 2017). Peske and Delouche (1985) argue that in the process of germination and emergence of soybean plants, the matric potential of the soil interferes with the rate of water absorption of chemicals by the soybean roots and their translocation to the aerial part of the plants.

In the evaluation at 14 DAE, when the factors did not show a significant interaction, the effects of seed treatment and soil water level acted independently on the two response variables studied. However, in the four control evaluations of *S. frugiperda* caterpillars and defoliation carried out after soybean emergence, it was found that the chlorantraniliprole and thiamethoxam + cyantraniliprole treatments presented, in general, the greatest control efficiencies of this pest which,

consequently, ensure the lowest levels of soybean defoliation in practically all evaluations carried out in the trial (Tables 3, 4, 6 and 7). The best caterpillar control efficiencies of these active ingredients were probably due to the higher absorption rates by the roots of soybean plants and/or the greater persistence of these products in the soil (Radolinski et al. 2018). The insecticide chlorantraniliprole has a high half-life (DT50) in the soil of 597 days (Lewis et al. 2016), a characteristic of this active ingredient that probably explains its greater performance in controlling *S. frugiperda* caterpillars and consequently; guaranteed greater protection of soybeans against defoliation.

Although the thiamethoxam + cyantraniliprole mixture showed good levels of control of *S. frugiperda* caterpillars, the insecticide thiamethoxam, when tested alone, showed only moderate levels of effectiveness in controlling this pest. Triboni *et al.* (2019) evaluated thiamethoxam (105 g a.i. 100 kg^{-1}) in a treatment of soybean seeds aiming to control *S. frugiperda* caterpillars and found that this insecticide presented low efficiency in controlling this pest; partially corroborating the findings in the present work. The moderate effectiveness of the insecticide thiamethoxam in controlling *S. frugiperda* caterpillars may have been due to its high solubility in water which is 4100 mg/L (Lewis et al. 2016). This probably favored its absorption by soybean plants in pot soil, especially in the 70% FC condition (Tables 3, 6 and 7). Thrash *et al.* (2013) evaluated different insecticides in the treatment of soybean seeds aiming to control *S. frugiperda* caterpillars; finding that both cyantraniliprole (8.99 g a.i. ha^{-1}) and chlorantraniliprole (65.4 g a.i. ha^{-1}) significantly reduced the survival of second instar caterpillars of this pest in the field; in line with the results obtained in the present work. In another study, Triboni *et al.* (2019) studied the effect of treating soybean seeds to control *S. frugiperda* in initial infestations in the crop, concluding that the insecticides chlorantraniliprole (62.5 g a.i. 100 kg^{-1}) and cyantraniliprole (120 g a.i. 100 kg^{-1}) also showed good effectiveness in controlling this pest; which consequently resulted in less defoliation in plants similar to what was observed in the present work.

Based on the results obtained in the present work, it can be inferred that the insecticide chlorantraniliprole and the thiamethoxam + cyantraniliprole mixture when applied constitute effective alternatives for the management of *S. frugiperda* caterpillars if this pest occurs during the initial stages of crop development.

The insecticide fipronil showed a moderate level of control of *S. frugiperda* caterpillars and protection of soybeans against defoliation, especially in soil with 70% FC (Tables 3, 6 and 7). This active ingredient is considered a non-systemic product with relatively low solubility in water (Lewis et al. 2016); a characteristic that probably makes its absorption and translocation to the aerial part of plants difficult. This moderate efficiency in controlling caterpillars occurred especially in soil with 70% FC. This insecticide has been most commonly used in seed treatment or sprayed on the soil to control initial soybean pests, such as white grubs, anteaters and the Lesser cornstalk borer (Ávila and Gomes, 2003, Viana 2020), or even aiming to control soil termites in sugarcane and forests (Raetano *et al.* 1997, Almeida *et al.* 2000).

The imidacloprid + thiodicarb treatment with the exception of the last evaluation carried out in the study (28 DAE), did not have a significant influence of the soil water condition on the variables studied. This mixture generally presented intermediate levels of control of *S. frugiperda* caterpillars and protection against soybean defoliation. However, in the last evaluation carried out (28 DAE), the lower availability of water in the soil (30% FC) impaired the effectiveness of this treatment in relation to caterpillar mortality and soybean defoliation. Imidacloprid is considered a systemic product that provides good levels of control of sucking insects such as aphids, whiteflies, thrips, stink bugs and (Alves et al. 2001, Carvalho et al. 2011). However, this active ingredient tends to leach into the soil profile into groundwater when applied to seeds or in the planting furrow of different crops (Adak et al. 2012). This fact explains its moderate efficiency in controlling caterpillars, and consequently, protecting soybeans from defoliation. The other insecticide in this mixture (thiodicarb), which belongs to the carbamate group, has a very low average life in the soil (DT50), less than 1 day (Lewis et al. 2016); which contributes to explaining the moderate efficiency of this mixture to control *S. frugiperda* caterpillars. The insecticide thiodicarb is a product that has good solubility in water (Lewis et al. 2016) which favors its absorption and translocation to plants. However, this

product has been used more to treat soybean seeds in order to control nematodes in the crop (Monfort et al. 2006). In addition, this insecticide is considered a good caterpillar killer when sprayed on the aerial part of plants, in addition to being a recommended product for integrated pest management (IPM) since it presents selectivity to natural enemies, especially insect pest predators of soybeans (Boyd and Boethel 1998). Triboni et al. (2019) tested the insecticide fipronil (50 g a.i. 100 kg^{-1}) and the imidacloprid + thiodicarb (52.5 + 105.0 g a.i. 100 kg^{-1}) mixture when applied to soybean seeds and obtained low efficiency in control of *S. frugiperda* caterpillars; partially corroborating the results obtained in the present study.

Conclusions

The treatment of soybean seeds with the insecticides chlorantraniliprole and the thiamethoxam + cyantraniliprole mixture constitute effective alternatives for controlling *S. frugiperda* caterpillars and prevent defoliation of the plants during the initial stages of development of that crop;

Treatments with fipronil, thiamethoxam and the imidacloprid + thiodicarb mixture only present moderate to good levels of control of *S. frugiperda* caterpillars, and the effectiveness of these treatments depends on the level of moisture available in the soil, as well as the time in which this variable is evaluated after soybean emergence.

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