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Use of different spray volumes and hydraulic nozzles in air-assisted electrostatic insecticide application technologies to control coffee berry borer (*Hypothenemus hampei*) populations

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ABSTRACT. Chemical control is essential for efficient pest management in coffee crops. Application technologies should safely deliver insecticides to the target whilst protecting the environment, insecticide applicators, and consumers. To achieve these goals, application volumes, hydraulic nozzles, and application techniques should be evaluated. This study assessed the biological efficiency of different spray volumes and spray nozzles used to apply insecticides to control coffee berry borer (*Hypothenemus hampei*) populations. We applied insecticides using a hydropneumatic sprayer with and without an electrostatic spraying system. The experiment followed a randomized block factorial design (2 × 2 + 1) and included two types of spray nozzles [a hollow cone spray nozzle (JA1) and a hollow cone spray nozzle with air induction (TVI)], two spray volumes (200 and 400 L ha^{-1}), one additional treatment (SPE2 nozzle with a 200 system 200 L ha^{-1}), and six replicates. We assessed the control efficiency of the different application methods by evaluating the percentage of fruits damaged 20 and 40 days after the date of application. The spray volume did not affect the biological efficiency of pest control, and the lower spray volume (200 L ha^{-1}) was effective in the control of coffee berry borers. Application of insecticides using coarse droplets was more efficient than the application using very fine and fine droplets. The TVI hydraulic spray nozzle effectively controlled coffee berry borers at 200 and 400 L ha^{-1}. The electrostatic application system performed similarly to the conventional system in terms of the control of the coffee berry borers, and was less efficient than the conventional system under some operational conditions.

Keywords: plant health; agricultural spraying; biological efficiency; spray volume.

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Introduction

Coffee berry borers, *Hypothenemus hampei* (Ferrari, 1867) (Coleoptera: Scolytidae), are recurrent pests in coffee plantations in the Cerrado region of Minas Gerais, Brazil. Coffee berry borers affect the yield and quality of coffee beans. Higher coffee plant densities, which create a humid microclimate, and mechanized harvesting, which leaves beans behind, contribute to maintaining the borer life cycle and its incidence in each harvest.

According to Leiva-Espinoza, Oliva-Cruz, Rubio-Rojas, Maicelo-Quintana, and Milla-Pino (2019), the coffee berry borer is first attracted to coffee crops by secondary metabolites produced by coffee trees during fruit development. Later, it is attracted by the fruit color and shape.

Coffee berry borers naturally occur at different levels of intensity over the year. Rubio (2009) stated that the larvae of the coffee berry borer are adapted to living inside the plant tissues of green and ripe coffee beans, and can reduce harvest yields by up to 30%. Morris and Perfecto (2016) stated that the coffee berry borer is the pest that most harms coffee crops in all coffee-producing countries. Coffee farmers, public and private institutions, and researchers have developed practical, low-cost, and environmentally safe solutions to control coffee berry borers (Jaramillo, Montoya, Benavides, & Góngora B., 2015; Quispe-Condori et al., 2015; Zayas, Piñeda, Gómez, Ortiz, & Chaviano, 2016).

Until 2013, endosulfan was the main and most efficient insecticide used in the chemical control of coffee berry borers in Brazil. However, due to its toxicology, certifying agencies, and later the Brazilian government, banned this product. According to Mota et al. (2017), after the use of endosulfan was banned, rates of coffee berry borer infestation increased in the main Brazilian coffee planting regions. Managing coffee berry borer populations has become more challenging, and is further complicated by increased insecticide resistance.

After endosulfan was banned, companies competed to register products to replace it. New insecticides with greater selectivity and lower environmental impacts have been presented as alternatives. These new insecticides include those in the anthranilic diamide group, such as chlorantraniliprole and cyantraniliprole, as well as acetamiprid and metaflumizone. These insecticides require strategic management and constant monitoring of plots and spray efficiency to guarantee that they reach the target, control the pest, and reduce its impacts. The efficiency and type (hydropneumatic or electrostatic) of insecticide application technologies affect the biological control efficiency, and therefore the ability of insecticides to protect crops.

Electrostatic spraying and different hydraulic nozzles are alternatives to improve insecticide application (Sasaki, Teixeira, Fernandes, & Monteiro, 2013), but data confirming their agronomic effectiveness are lacking. In addition, coffee growers still do not know the advantages and disadvantages of these technologies. Thus, Brazilian research institutions should evaluate the effectiveness of these insecticide application methods.

This study assessed the biological efficiency of different insecticide application methods to control coffee berry borer populations, including using different spray volumes and spray nozzles in a hydropneumatic sprayer, with and without electrostatic application.

Material and methods

We conducted our experiment in a commercial coffee growing area located on the Japão farm in the municipality of Estrela do Sul, state of Minas Gerais, Brazil (18° 43’ 01 N and 47° 47’ 11.30” E), at an elevation of approximately 997 m above sea level.

We started monitoring the coffee berry borer infestation on the farm, 60 days after flowering. After the fruits turned green, we assessed them weekly at the north and south positions of the coffee plants, and at low, medium, and high heights of the coffee tree canopy. Each height and cardinal direction of the canopy consisted of a sampling point, which resulted in six sampling points (three heights × two cardinal directions). We evaluated 10 fruits at each sampling point of each plant, with 30 plants in each plot. Therefore, we analyzed 1,800 fruits following a method adapted from Souza, Reis, Silva, and Toledo (2015). We used a non-destructive testing method in the monitoring stage, i.e. we did not collect the fruits of the plants.

Insecticide application sessions were conducted using a hydropneumatic sprayer, model Arbo 360, brand Montana (São José dos Pinhais, Paraná State, Brazil), which has six nozzle holders at each of its edges, a 300 L tank, a membrane spraying pump with a flow rate of 40 L min.$^{-1}$, and a 615 mm diameter fan with nine fixed angle blades. We connected the equipment to the hydraulic system of a tractor so that the center of the fan was 1,070 mm above the ground. After insecticide application with hydraulic nozzles, we included an electrostatic spray kit comprising six nozzles, which was developed and traded by the company *Sistema de Pulverização Eletrostático* (SPE, Electrostatic Spraying System, Porto Alegre, state of Rio Grande do Sul, Brazil). To reduce the effect of the fan's rotation direction due to the position of its blades, we used the sprayer only on the right side, standardizing the air direction. Application sessions were carried out using a 4 × 2 Massey Ferguson tractor (Canoas, state of Rio Grande do Sul, Brazil), model 275, with 55.16 kW (75 cv) of power.

The experiment followed a randomized block factorial design (2 × 2 + 1), and included two spray volumes (200 and 400 L ha^{-1}), two spray nozzles (TVI-80-0075 and JA 1), and one additional treatment with an SPE2 nozzle (coupled to an electrostatic system and a volume of 200 L ha^{-1}), and six replicates. The JA-1 nozzle (Jacto, Pompeia, state of São Paulo, Brazil) produces a hollow cone jet, and the TVI-80-0075 nozzle (Albuz, Evreux, France) produces a hollow cone jet with air induction. The additional treatment was applied with an SPE 2 hollow cone spray nozzle and an electrostatic spray kit attached to the sprayer boom. The electrical field generated at the bottom of the sprayer is due to the electrification of the ring in the nozzle (Table 1).

Table 1. Insecticide application method descriptions and operational characteristics.

Spray volume (L ha^{-1})	Spray nozzle	Pressure (kPa)	Droplet size*
400	TVI-80-0075	931	Coarse
400	JA-1	1,034	Fine
200	JA-1	414	Fine
200	TVI-80-0075	517	Coarse
200	SPE2	861	Very fine

*Information obtained from manufacturers' catalogs.

The experimental area was composed of 7-year-old Topazio cultivar coffee plants, placed at 3.8 × 0.7 meter spacing, which totals 3,760 plants per hectare. The experimental plots comprised 57 plants (40 m^2). The 25 trees in the center of each plot were included in our evaluations, and 16 trees at the edges of the plots were considered the borders between plots. Plots were 40 m apart from each other in each row, and 7 m apart between rows to reduce drifting effects and contamination between the treatments. According to Baker (1984), this distance minimizes the migration and displacement by wind or flight of adult coffee berry borers between treatments, as these insects travel short distances when food is available, according to Román-Ruiz et al. (2017).

The insecticide contained an active ingredient whose experimental code was SYN200 (dose = 200 mL ha^{-1}; concentration = 200 mL L^{-1}; Syngenta Proteção de Cultivos, state of São Paulo, Brazil). This is a contact and ingestion systemic product formulated in a suspension concentrate (SC) belonging to a recently discovered chemical group. Its locus of action is the allosteric modulator of gamma aminobutyric acid (Gaba)-gated chloride channels.

We determined the control effectiveness of the insecticide application methods by counting damaged coffee fruits following a method adapted from Souza et al. (2015). We randomly collected 1 L of coffee fruits in each sampling portion, from which we randomly selected 500 fruits. We then cut the fruits open to determine the percentage of fruits damaged by borers, following a method adapted from Castaño-Sanint, Benavides-Machado, and Baker (2005) and Suárez, Arrieche, and Paz (2013). We performed this procedure 20 and 40 days after insecticide application (DAA). We calculated the percentage of control using Abbott's formula.

We monitored the weather conditions during insecticide application with a digital portable Thermo-Hygro-Anemometer (Instrutherm, model AD-250, state of São Paulo, Brazil). The temperature ranged from 25 to 31°C, the relative humidity ranged from 60 to 67%, and the wind speed ranged from 3 to 7 km $hour^{-1}$.

We performed statistical analyses using the statistical software R. The data met the assumptions of normal distribution of residuals [evaluated using the Shapiro-Wilk test (W)], and homogeneity of variances (evaluated using the Anscombe and Tukey's test). We applied Dunnett's test to compare the averages with the additional treatment. The level of significance was set at 5% in all tests performed.

Results and discussion

Before insecticide applications, the coffee berry borer infestation rate was 6.7%, which is slightly higher than the maximum percentage recommended for insecticide application (between 3 and 5%; Souza, Reis, Silva, Carvalho, & Pereira, 2013).

The analysis of variance indicated differences between the treatments of the factorial design and the additional treatment. However, the spray volumes (200 or 400 L ha^{-1}) did not affect the biological efficiency of the control. The efficiency of the TVI-80-0075 nozzle was higher than that of the JA-1 nozzle on both evaluation days (20 and 40 days after insecticide application). There was no interaction between the factors 'nozzle' and 'spray volume'. With respect to the additional treatment with the SPE2 nozzle, only the TVI-80-0075 nozzle had a significant effect at a volume of 400 L ha^{-1} 20 days after application and at both volumes (200 and 400 L ha^{-1}) 40 days after application (Tables 2 and 3).

Table 2. Effectiveness of insecticide application to control coffee berry borers (*Hypothenemus hampei*) in Estrela do Sul, state of Minas Gerais, Brazil, in 2019, using different hydraulic nozzles and spray volumes, with and without electrostatic application, 20 days after application.

Nozzle	Spray Volume (L ha^{-1})		Average
	200	400	
	Control Effectiveness (%)		
TVI-80-0075	69.0 α	76.0 β	72.5 A
JA-1	59.4 α	67.0 α	63.2 B
SPE2	57 α		
C.V. (%)	14.7		
DMS	14.1		

Averages followed the same letters (capital letters in the columns and Greek letters related to the additional treatment) do not differ according to the F and Dunnett's test, respectively (p > 0.05).

Table 3. Effectiveness of insecticide application to control coffee berry borers (*Hypothenemus hampei*) in Estrela do Sul, state of Minas Gerais, Brazil, in 2019, using different hydraulic nozzles and spray volumes, with and without electrostatic application, 40 days after application.

Nozzle	Spray Volume (L ha^{-1})		Average
	200	400	
	Control Effectiveness (%)		
TVI-80-0075	64.9 β	69.6 β	67.3 A
JA-1	51.0 α	59.0 α	55.1 B
SPE2	50.0 α		
C.V. (%)	13.1		
DMS	11.1		

Averages followed by the same letters (capital letters in the columns and Greek letters related to the additional treatment) do not differ according to the F and Dunnett's test, respectively ($p > 0.05$).

The average control effectiveness was considered satisfactory due to the high prevalence of the borers (Reis, 2007). We found a high incidence of untreated damaged fruits in areas neighboring the experimental area. In these untreated areas, the incidence of damaged fruits was seven to nine times the economic damage threshold (Souza et al., 2013), around 18% 20 days after application, and 27% 40 days after application.

The TVI-80-0075 nozzle was more efficient than the JA-1 nozzle 20 days after application. Theoretically, the JA-1 nozzle has a higher capacity for product penetration and deposition in the target because of its small droplet size, which can reach the fruits through the leaves and protect them (Butts et al., 2019).

Interactions between droplet sizes, product deposition in the target, and nozzle type have been reported (Chen et al., 2020). However, we found different results: the TVI-80-0075 nozzle had a biological efficiency 13% higher than that of the JA-1 nozzle at 400 L ha^{-1}, and 25% higher than that of the additional treatment with the SPE2 nozzle. The distance between the sprayer and the target may reduce the droplet attraction (Appah, Wang, Ou, Gong, & Jia, 2019), which is common because of the semicircular sprayer boom of hydropneumatic sprayers in the lower and, mainly, upper positions of the plant canopy.

Forty days after insecticide application, the efficiency of the TVI-80-0075 nozzle was 18% higher than that of the JA-1 nozzle, which is higher than that found 20 days after application. Twenty days after application, the efficiency of the TVI-80-0075 nozzle was 23 and 28% higher at volumes of 200 and 400 L ha^{-1}, respectively, than that of the additional treatment with an SPE2 nozzle. Theoretically, electrostatic spraying systems deposit a greater spray volume on both leaf faces (Appah et al., 2019). However, the electrostatic spraying system was not found to have a greater biological efficiency in this study. Salcedo et al. (2020) obtained different results when analyzing grape crops, and found that electrostatic application was more efficient than the traditional system, which may be due to the different morphology of the plants.

Our results contradict the idea that fine droplets are more suitable for insecticide application. Thus, the resistance to using coarse droplets for insecticide application in coffee crops is unfounded. We suggest that future studies investigate the use of coarse droplets to control pests by using a hydropneumatic sprayer.

The results obtained 20 and 40 days after application demonstrate an interaction between the droplet size produced by both nozzle models and the spray volumes applied. This corroborates the results of Melo et al. (2019). Although the JA-1 nozzle has a higher capacity to penetrate and deposit the product on the target, the coarse droplets produced by the TVI nozzle had greater control effectiveness at both volumes. When we analyzed both hydraulic nozzles under specific meteorological conditions, which are common in the research region, the use of coarse droplets proved to be an efficient alternative, mainly at 400 L ha^{-1}, which is the more commonly used volume in coffee-producing farms in the Cerrado region of Minas Gerais State, Brazil.

Farmers often use fine droplets (American Society of Agricultural and Biological Engineers [Asabe], 2009) to apply insecticides with hydropneumatic sprayers in the studied coffee-producing region. Hollow cone nozzles are often used even in winter, when the relative air humidity is below 20%. However, we demonstrated that nozzles that produce coarse droplets are more efficient for controlling pests than the nozzles that produce fine droplets.

Insecticide application with coarse droplets is an environmentally safe solution, as it reduces drifting effects, and the exposure of both applicators and pollinating insects to insecticides. This corroborates the results found by Cunha, Reis, Assunção, and Landim (2019) and Locatelli et al. (2019). However, coarse droplets require extra caution to prevent runoff and loss of insecticide to the soil (Cação, Moreira, Raetano, Carvalho, & Prado, 2019).

The airflow probably increased the penetration capacity of coarse droplets in the coffee canopy. This occurred because of the distance between the launch point and the fruits inside the coffee canopy, resulting in an efficient control of coffee berry populations. Salcedo et al. (2020) also highlighted the importance of air flow in spray deposition during hydropneumatic spraying.

We did not find any studies on the use of electrostatic insecticide application technologies to control coffee berry borer populations published in scientific journals in the last 10 years (which is around the time when this technique started to be used in coffee crops). The difficulty in monitoring and evaluating pests may be the reason for the lack of available data. We suggest that future studies further investigate the efficiency of this technique to control coffee berry borer populations.

Conclusion

The insecticide spray volume (200 or 400 L ha^{-1}) did not affect the biological efficiency of pest control, as the lowest volume (200 L ha^{-1}) was efficient in the control of coffee berry borers.

The application of insecticide using coarse droplets resulted in a better biological efficiency than that with very fine and fine droplets.

The TVI hydraulic hollow cone spray nozzle with air induction is an efficient alternative to control coffee berry borers at insecticide spray volumes of 200 and 400 L ha^{-1}.

The electrostatic spraying system was not more efficient than the conventional system for the control of coffee berry borers, and it was even less efficient under some operational conditions.

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