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Using a rainfall simulator thrust type to evaluate the efficacy of insecticides in a apple orchard

Uso do simulador de chuvas tipo empuxo na avaliação da eficiência de agrotóxicos em pomar de macieiras

Uso de un simulador de lluvia tipo empuje para evaluar la eficacia de insecticidas en un huerto de manzanos

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ABSTRACT
A rainfall simulator thrust type was evaluated as a novel tool for studying the efficacy of insecticides against pests in apple orchards, compared to traditional laboratory methods. The simulator was installed and calibrated to simulate rainfalls of 50 mm h^{-1} on a 7-year-old apple orchard. The results of *Grapholita molesta* (Lepidoptera: Tortricidae) control in the field differed from those obtained in laboratory. The control efficacy in the orchard was lower than that obtained in laboratory tests. Control percentages varied throughout the simulated rains, with increases at the beginning of rainfall followed by decreases. The use of the push-type rainfall simulator provides advantages to research experiments, as it allows for evaluations under field conditions at different developmental stages of plants in orchards under different management practices, with results closer to field reality than those currently generated by laboratory tests.

Keywords: Rain Effect, Control, Pests, Apples.

RESUMO
Foi avaliado o uso do simulador de chuvas tipo empuxo como nova ferramenta para estudos de eficiência de inseticidas sobre pragas da macieira e comparar os resultados com metodologias de laboratório. O simulador foi instalado e calibrado para lançar chuvas de 50 mm h^{-1} sobre plantas adultas no pomar de macieiras com 7 anos de idade. Os resultados obtidos no controle de *Grapholita molesta* (Lepidoptera: Tortricidae) diferiram daqueles realizados em laboratório. No pomar, a eficiência de controle é inferior à obtida no laboratório e existe variação nos percentuais de controle ao longo da precipitação havendo elevação no início das chuvas com posterior decréscimo. O uso do simulador de empuxo traz ganhos aos experimentos, pois permite que as avaliações sejam realizadas em condições de campo, explorando diferentes estágios de desenvolvimento das plantas, fatores de manejo dos pomares e com resultados mais próximos da realidade no campo do que aquele aplicado atualmente em laboratório.

Palavras-chave: Efeito da Chuva, Controle, Pragas, Maçãs.

RESUMEN
Se evaluó un simulador de lluvia empuje como una nueva herramienta para estudiar la eficacia de las insecticidas contra plagas en huertos de manzanos, en comparación con métodos de laboratorio tradicionales. El simulador fue instalado y calibrado para simular lluvias de 50 mm h^{-1} en un huerto de manzanos de 7 años. Los resultados del control de *Grapholita molesta* (Lepidoptera: Tortricidae) en campo difirieron de los obtenidos en laboratorio. La eficacia del control de plagas en el huerto fue menor que la obtenida en pruebas de laboratorio; los porcentajes de control variaron a lo largo de las lluvias simuladas, con aumentos al inicio de las lluvias seguidos de disminuciones. La utilización del simulador de lluvia tipo empuje ofrece ventajas para los experimentos de investigación, ya que permite evaluaciones en condiciones de campo en diferentes etapas de desarrollo de las plantas en huertos bajo diferentes prácticas de manejo, con resultados más cercanos a la realidad de campo que los generados actualmente por pruebas de laboratorio.

Palabras clave: Efecto de Lluvia, Control, Plagas, Manzanas.

1 INTRODUCTION

Rainfall is a significant factor that affects the efficacy of pesticides for pest control in fruit crops. Rainfall can adversely affect the effectiveness of pesticide treatments, increasing the need for reapplications, consequently increasing production costs and environmental impacts (Fortunato et al., 2011). The effects of rainfall on pesticide application have been studied using rainfall simulators to provide information that contributes to the improvement of application technologies and persistence of pesticide residues on plants (Taylor & Mathews, 1986; Decaro et al., 2016).

Rainfall simulators have been developed since the 1930s (Meyer, 1958, 1960; Meyer and Mccune, 1958; Swanson, 1965) and were primarily used for soil erosion and management studies requiring water sprinkling systems that simulate natural rainfall, particularly in terms of raindrop characteristics. The Swanson rainfall simulator (Swanson, 1965) was the most widely used until the 1980s and is still in use in Brazil. However, it is a large, robust, and heavy device constructed from solid iron, making it difficult to move across experimental areas, especially on sloping terrains.

In 2012, Bertol et al. (2012) improved the Swanson simulator, resulting in a rainfall simulator thrust type; the main advantage of this adapted rainfall simulator is the hydraulically driven movement of arms without the need for extra driving force, maintaining the simulated rainfall and droplets with similar characteristics to natural rainfall. It was built on a steel chassis with four automotive wheels at the base, with an aluminum tower in the center pushing water to 10 rotating arms placed on the tower. The arms (7.5 m long) were built of aluminum, attached to the tower by a quick-connect mechanism, and radially and horizontally distributed (Figure 1). The arms move counterclockwise due to the pressure from the water thrust released by four sprinklers at the ends of the arms. This rainfall simulator maintains characteristics of the Swanson model, mainly those related to the produced rainfall, but the excess weight was minimized and the use of an internal combustion engine to move the arms was eliminated. These new features make it lighter, more economical, quieter, and easier to handle throughout experimental areas. These characteristics enable this device to contribute to other research approaches, including those focused on investigating effects of rainfall on pesticide treatments in orchards.

Currently, researches investigating effects of rainfall on insecticide efficacy have employed stationary rainfall simulators equipped with multiple oscillating sprinkler nozzles mounted on a fixed platform (Arrué et al, 2014; Decaro et al., 2016; Wise et al., 2017; Andika et al., 2019). These studies usually evaluate plants grown in pots or plant parts removed from field-grown plants, which are placed beneath the simulator to receive simulated rainfall. The results have consistently shown a reduction in pest control efficacy with increasing rainfall intensity due to the loss of active ingredients through leaching (Hulbert et al., 2012; Andika et al., 2019). Therefore, rainfall removes pesticides applied to plants, reducing product absorption and protection duration (Dinardo-Miranda et al., 2004). Moreover, the leached pesticide can infiltrate the soil and adversely impact the environment (Casida & Quistad, 1998).

Some studies in Brazil have evaluated insecticide efficacy against pests in fruit crops under laboratory conditions, with results often extrapolated to agricultural fields (Arioli et al., 2007a; Chaves et al., 2014). These laboratory studies usually involve preparing insecticide solutions for immersing the fruits for a few minutes, allowing them to dry, and subsequently offering them to insects in bioassays under controlled conditions (Arioli et al., 2004; Nondillo et al., 2007). However, the results of these studies, as well as those using potted plants or plant parts, may not accurately reflect field conditions, as factors such as canopy architecture, pesticide deposition patterns by spraying devices, and variations in environmental conditions are not properly considered.

Considering that thrust type simulator can produce similar raindrops to natural rainfall on mature orchards, their use for evaluating the performance of insecticides may provide more accurate information for pest control in fruit production areas. In this sense, the objective of this study was to calibrate and evaluate a rainfall simulator thrust type as a novel methodology for assessing the insecticide efficacy for pest control in apple orchards by comparing it to traditional laboratory methods.

2 MATERIAL AND METHODS

2.1 IMPLEMENTATION AND CALIBRATION OF RAINFALL SIMULATOR

The study was conducted at the Embrapa Uva e Vinho - Vacaria, RS, Brazil - in a 0.4-hectare orchard containing 7-year-old apple trees (cultivars Gala and Fuji), during the 2017/2018 production cycle.

A rainfall simulator thrust type was installed and calibrated to simulate rainfall on the orchard. Two water pumps were tested for water collection and simulator operation: a) self-priming gasoline-powered four-stroke water pump (model TFAE3RF70FX2V, Toyama®) with a maximum power of 7.0 HP, cylinder capacity of 212 cubic centimeters, maximum flow rate of 60 m^3 h^{-1}, and maximum head of 28 m; b) electric multistage water pump (RL16/3, Thebe®), voltage of 220/380 – three-phase, 12.5 HP power, final flow rate of 24.7m^3 h^{-1}, and a manometric head of 65 mca. Water was delivered to the simulator through 6-meter-long quick-connect PVC pipes with nominal diameter of 75 mm. Thirty S.S.CO type nozzles (VeeJet® 80/100) were used in the simulator, with 1 to 3 nozzles open per sprinkler arm, helically arranged in a concentric spiral, and simulated rainfall covering an area of 176 m^2. The water spray pattern was formed parallel to the arm, producing large droplets calibrated to 50 mm h^{-1} intensity, simulating the high-intensity, short-duration summer rainfall patterns of Vacaria, RS.

Figure 1: Overview of the rainfall simulator thrust type and rain gauges installed above ground level.

Source: Daniela Fernanda Klesener, 2017.

The water source from which the water was collected was 100 meters from the apple orchard, at a 10-meter lower altitude than the orchard (Figure 2).

Figure 2: Satellite image showing the water source, flat area and the apple orchard where the rainfall simulator was installed.

Source: Google Earth, adapted by Regis Sivori Silva dos Santos, 2024.

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Forty apple trees of each experimental plot were pruned to a height of 2 m. The rainfall simulator's arms were positioned at 3.5 m above ground level. Therefore, the rainfall was produced 1.5 m above the tree canopies. Eight experimental plots were evaluated, consisting of two insecticides and four drying times, moving the simulator device between plots after each rainfall.

The rainfall simulator was leveled according to the lateral slope of the land. Rainfall intensity was measured using 20 rain gauges (capacity of 150 mm) placed under the simulator. Each rain gauge was mounted on a wooden stake at a height of 60 cm above the ground, arrangement as follows: ten rain gauges in the central span of the simulator, in two rows of five gauges; five on the right side span; and five on the left side span (Figure 3A and B).

Fifteen-minute rainfalls were simulated and the water volume in each rain gauge was recorded to calculate the mean value and the rainfall intensity for one hour. The simulated rainfalls were repeated five times, with readings on a pressure gauge at the last pipe in the system before reaching the simulator, until the desired rainfall for the study (50 mm h^{-1}) was achieved (Figure 3C).

Figure 3: Rain gauge used to measure rainfall (A), rainfall simulator leveled with planks and wooden blocks (B), and pressure gauge to check system pressure (C).

Source: Daniela Fernanda Klesener, 2017.

2.2 EVALUATION OF INSECTICIDE EFFICACY

The effect of simulated rainfall on insecticide efficacy for pest control was evaluated by applying the insecticides phosmet (Imidan®) at a rate of 200 g 100 L^{-1} and chlorantraniliprole (Altacor®) at a rate of 10 g 100 L^{-1}, based on the control of larvae of *Grapholita molesta* (Lepidoptera: Tortricidae). The insecticides were applied to the orchard using an axial turbo atomizer set to a solution volume application of 1000 L ha^{-1}, following technical recommendations for apple orchards at fruiting stage. Four drying times of the products on the plants after insecticide application were evaluated: 30 minutes, and 2, 6, and 24 hours before the beginning of simulated rainfalls (Figure 4B and C).

The control efficacy of insecticides applied to the field was compared with laboratory tests; 20 L of the prepared insecticide solutions were taken for the laboratory tests. Apples harvested from the orchard were placed in net-type fruit bags and dipped in the insecticide solution for five seconds. This procedure was called "perfect application". The fruits subjected to treatment in the insecticide solutions were taken to the field and placed on benches at a height of 1.5 m from the simulator's arms for exposure to rainfall (Figure 4A).

Four one-hour rainfalls with intensity of 50 mm h^{-1} were carried out for each insecticide and application method (field and laboratory). These rainfalls had four repetitions, at the following times: before the rainfall event (control - 0 mm); and during the rainfalls at 5 minutes (5 mm), 15 minutes (13 mm), 30 minutes (25 mm), and 60 minutes (50 mm - end of rainfall). These different rainfall volumes were obtained by calculating the means of the readings from the field rain gauges.

The insecticide efficacy was determined by evaluating the internal damage caused by *G. molesta* to 100 fruits collected from apple trees in the orchard (field) and from the benches under the rainfall simulator (laboratory).

The collected fruits were taken to the laboratory and kept under refrigeration until the end of the last rainfall event. Subsequently, two first-instar larvae of G. *molesta* were carefully placed onto each fruit, specifically on the upper third of the fruit, near the peduncle, using a paintbrush, following the methodology described by Arioli et al. (2007b). The larvae were obtained from a rearing colony maintained by the Entomology Laboratory at the Embrapa Uva e Vinho. Each infested fruit was then individually placed into a plastic bag (18 × 30 cm), which was sealed and maintained under controlled conditions (25 °C and a 16-hour photoperiod) for 10 days. Subsequently, all the fruits were cut and evaluated for internal damage caused by the larvae.

Figure 4: Apples packed in net-type fruit bags for dipping in the insecticide solution (perfect application) (A). Rainfall produced by the push-type rainfall simulator on the benches with treated apples in the perfect application test (B). Rainfall produced by the push-type rainfall simulator on apple trees in the field (C).

Photograph: Daniela Fernanda Klesener, 2018.

The data obtained were tabulated, the mean mortality percentages were calculated, and graphs were plotted with estimates of trend curves and equations for each insecticide and drying time.

3 RESULTS

3.1 CALIBRATION AND OPERATION OF THE RAINFALL SIMULATOR IN THE ORCHARD

Ten calibration tests were conducted to adjust the rainfall simulator to the conditions established for the study. The Toyama® water pump showed efficiency during the simulator's water intake tests in a flat area near the water source (Figure 1 and 2). However, when the simulator was placed at the study orchard, the differences in distance and altitude between the orchard and the water source resulted in a head loss of approximately 33.3%, preventing the system from functioning properly (Figure 2). This was identified by the difference between the pressure gauge at the water pump outlet (indicating a pressure of 24 psi) and that installed near the simulator, which registered 16 psi. This head loss and consequent reduction in thrust prevented the simulator's arms from moving, making the use of this water pump impractical for the study. Therefore, it was replaced with a higher-power electric multistage water pump.

The use of the electric multi-stage water pump, maintaining the same previous pressure on the pressure gauges, resulted in the production of rainfall exceeding the 50 mm h^{-1} established for the study. Therefore, a gradual reduction was necessary by incorporating a bleed valve in the piping system to remove water and reduce the flow rate at the simulator inlet without losing pressure (Figure 5), which is responsible for the movement of the simulator's arms. Several tests were conducted to define the balance between the amount of water removed from the system and the pressure on the pressure gauge at the base of the rainfall simulator.

Therefore, an electric multi-stage water pump should operate at its minimum capacity, generating a pressure between 11 and 12 psi on the pressure gauge installed at the base of the simulator to produce rainfall with an intensity of 50 mm h^{-1}. A pressure below 10 psi is not sufficient to rotate the device's arms, and a higher pressure can potentially generate rainfall intensities higher than 50 mm h^{-1}.

Figure 5: Valve installed to remove water from the system and reduce the flow rate for producing rainfall with an intensity of 50 mm h^{-1}.

Source: Daniela Fernanda Klesener, 2018.

The adjustments and calibration of the system allowed the push-type rainfall simulator to operate perfectly, delivering the desired rainfall intensity (50 mm h^{-1}) to mature apple trees at production stage in the orchard.

3.2 EFFICACY OF INSECTICIDES UNDER SIMULATED RAINFALL

The results of efficacy tests for the two insecticides, two application methods (field and laboratory), and different drying times are shown in Figures 6 and 7. The insecticide phosmet showed 100% control of *G. molesta* larvae in apples treated in the laboratory by dipping them in the insecticide solution (perfect application), regardless of the drying time and rainfall exposure after treatment (Figure 6). Pest control was lower

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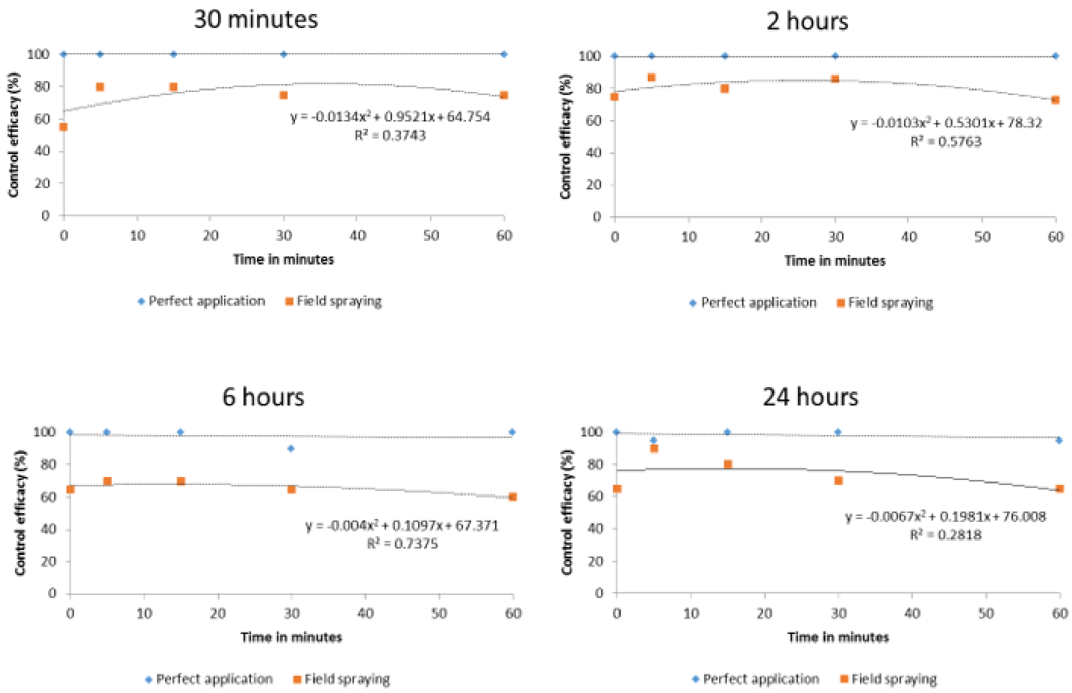
in apples treated by insecticide spraying in the orchard, and followed a different pattern, with a tendency of increased control at the beginning of rainfall followed by a decrease.

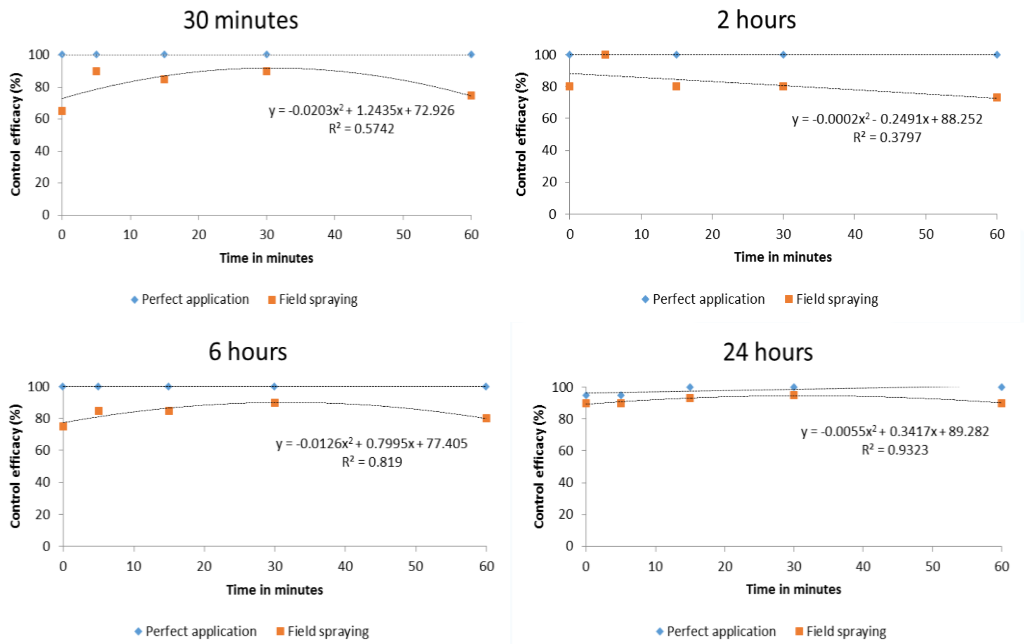
Figure 6: Control efficacy (%) of *Grapholita molesta* damage on apples subjected to application of the insecticide phosmet (Imidan®) to apple trees in the orchard and by fruit treatment in the laboratory (perfect application).



Source: Vacaria, RS, Brazil, 2018.

The pest control pattern of the insecticide chlorantraniliprole was similar to that observed for phosmet. The laboratory fruit treatment (perfect application) also resulted in 100% control of *G. molesta*, whereas field applications resulted in increased control at the beginning of rainfall followed by a decrease, regardless of the drying time (Figure 7).

Figure 7: Control efficacy (%) of *Grapholita molesta* damage on apples subjected to application of the insecticide chlorantraniliprole (Altacor®) to apple trees in the orchard and by fruit treatment in laboratory (perfect application).



Source: Vacaria, RS, Brazil, 2018.

4 DISCUSSION

The results found showed that the pest control evaluation methodology using fruit dipping in insecticide solutions (perfect application) overestimates the efficacy of pesticides. Moreover, this methodology does not allow for assessing the effect of rainfall-induced insecticide removal from fruits, even when considering a drying time of only 30 minutes. The insecticide coverage on fruits obtained through fruit dipping in insecticide solutions is significantly greater than that obtained by field applications, where only droplets of the solution reach the target. This may explain the highest pest control found under laboratory conditions. Similarly, Arioli et al. (2007a) found *G. molesta* control of approximately 90% to 95% when treating apples with neonicotinoid insecticides in the laboratory. Additionally, Chaves et al. (2014) reported pest control of 97% in apple trees for phosmet and 79% for chlorantraniliprole, both applied using the methodology of dipping fruits in insecticide solutions.

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Field results were similar to those of laboratory treatments only when using chlorantraniliprole and a 24-hour drying time on apple trees (Figure 7). This result can be attributed to factors of product absorption and translocation in the plant. Studies evaluating insecticides have shown that the performance of a molecule varies depending on several factors, including toxicity, persistence, and penetration of the insecticide into plant tissues (Hulbert at al., 2011 and 2012). The insecticides phosmet and chlorantraniliprole act by contact and ingestion on *G. molesta*, and even though they are not systemic, they have a depth effect on fruits, potentially increasing their resistance to rainfall. Wise et al. (2017) established patterns of rainfall effect on insecticide performance for pest control in apple trees, and reported chlorantraniliprole resistance and phosmet susceptibility to rainfall. Thus, high control efficiency is only possible due to the amount of active ingredient deposited on fruits through perfect application, which maintains 100% control even with rainfall.

The architecture of apple trees, the use of a turbo atomizer for insecticide application, and the effect of rainfall in the field resulted in pest control different from that obtained with perfect application in the laboratory. The increase in control observed at the beginning of rainfall for both pesticides can be explained by the redistribution of the products on the plants. This could only be observed with the use of the rainfall simulator thrust type, as it delivered rainfall to mature apple trees in the orchard. According to Arrué et al., (2014) the performance of the insecticide chlorantraniliprole on soybean crops was affected by 20 mm of rainfall due to the washing of the molecule from the plant, reducing control efficacy. Similarly, Wise et al. (2017) and Andika et al. (2019) reported loss of molecule efficacy due to the removal of insecticides from plants by rainfall. These studies involved the use of stationary rainfall simulators, delivering rainfall to potted plants or plant parts, not allowing for the assessment of product redistribution patterns on the plants. Pesticides applied to plants under such conditions are washed from the plant surface and directed to the soil. In an orchard with adult trees, the architecture of the canopy, leaf and fruit densities, insecticide load deposited by the spraying device, atmospheric conditions, and product redistribution by rainfall affect insecticide control efficacy.

The rainfall simulator used in the present study allowed us to observe these effects on *G. molesta* control by insecticide application. Rainfall acted as a dispersing agent for the pesticide on the canopy, removing the unabsorbed portion from the plant surface and repositioning it to other parts of the plant, such as fruits. The peduncular region of apples is the preferred site of entry for *G. molesta* (Nava et al., 2014); therefore, greater deposition of the pesticide in this region increases pest control. However, rainfall events remove the pesticide from this region of the fruits over time, carrying it to the soil, causing the control efficacy to return to the levels before the beginning of the rainfall (Figures 6 and 7).

Furthermore, the use of the rainfall simulator provides several advantages for experiments, as it enables researchers to conduct evaluations under field conditions and at different stages of plant development in orchards under different management practices. Additionally, it facilitates studies on environmental contamination due to pesticide runoff and deposition in the soil.

Therefore, studies on pesticide efficacy using rainfall simulator thrust type can provide more realistic information about the performance patterns of insecticides in apple trees. This methodology allows to evaluate the impact of natural and operational factors more closely representing actual field conditions and agricultural production conditions, with potential to improve current levels of pest control, differing from the results obtained using perfect application in laboratory and stationary rainfall simulators.

5 CONCLUSIONS

The rainfall simulator thrust type is effective in delivering rainfall to apple trees at production stage in orchards, provided that the equipment is calibrated and adjusted to the conditions established for the study and the experimental area.

The pressure required on the pressure gauge installed at the base of the simulator to generate a rainfall of 50 mm h^{-1} is 16 psi, when using a self-priming gasoline-powered four-stroke water pump (model TFAE3RF70FX2V, Toyama®), and 11 to 12 psi, when using an electric multistage water pump (RL16/3, Thebe®). A pressure lower than 10 psi on the pressure gauge at the base of the device prevents the simulator's arms from moving as expected, regardless of the water pump.

The efficacy of the insecticides phosmet and chlorantraniliprole in controlling *G. molesta* larvae in apples differs depending on the application method (laboratory and field). Dipping fruits in insecticide solutions in the laboratory (perfect application) and using stationary rainfall simulators on a benchtop with treated fruits do not represent the control obtained in the field. The rainfall produced by the simulator tested in this study allows for evaluations of insecticide redistribution effects on plants.

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