

INTEGRATION OF GENOTYPES OF MAIZE (*Zea mays* L.) AND PLANT POWDERS AGAINST *Sitophilus zeamais* Motschulsky (COLEOPTERA: CURCULIONIDAE)

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ABSTRACT

The objective of this study was to determine the combined effect of maize (*Zea mays* L.) genotypes with the application of epazote (*Dysphania ambrosioides* L.), castor oil plant (*Ricinus communis* L.), Mexican pepperleaf (*Piper auritum* Kunth), moringa (*Moringa oleifera* Lam.), neem (*Azadirachta indica* A. Juss.), and Pacific Coast mahogany (*Swietenia humilis* Zucc.) as an alternative to control the maize weevil (*Sitophilus zeamais* Motschulsky). It was hypothesized that combining certain maize genotypes with specific plant powders would significantly reduce *S. zeamais* damage without affecting germination. Three bioassays were conducted. In the first, the biological activity of six plant powders to control weevil populations and their impact on seed germination was evaluated; in the second, the effect of the hardness of three maize hybrids and the “Ancho Pozolero” variety on weevil was determined; and in the third, the interaction between genotypes and the most effective powders was explored. With five replicates per treatment and a control without application, 100 g of maize and 1 % plant powder were placed in 250 mL glass containers using a fully randomized design. Mortality, emergence, insect damage, and maize germination were assessed. In the evaluation of plant powders, *D. ambrosioides* and *S. humilis* stood out for their insecticidal and insectistatic effects and protection of maize, although they affected germination by 6.5 and 7.2 %, respectively. *P. auritum* showed good insecticidal and insectistatic effects without affecting germination. The hybrid “Tlaoli Puma,” classified as hard, reduced the damage caused by *S. zeamais* by one third. The combination of the hybrid “Tlaoli Puma” with 1 % plant powder of *D. ambrosioides* or *S. humilis* reduced the chances of attack and damage by *S. zeamais*, contributing to reducing post-harvest losses of stored maize and thus validating the hypothesis.

Key words: maize weevil, plant insecticides, pest management in storage.

INTRODUCTION

Sitophilus zeamais Motschulsky (Coleoptera: Curculionidae), known as the maize weevil, is one of the most economically important insect pests of stored grains in the world. In storage, it directly consumes the grain, reducing its quality and contaminating it (Matías-Oregán *et al.*, 2022). In addition, the damage promotes susceptibility to plant pathogens and leads to market rejection (Nwosu *et al.*, 2015). This insect is a pest of wheat, barley, sorghum, rice, and millet in storage, but its main host is maize (*Zea mays* L.). If the grain is 10 % infested at the time of harvesting and is not controlled, it can result in total losses after six months. Post-harvest losses caused by *S. zeamais* in subsistence maize producers can reach up to 80 % if no control measures are implemented (Rangel-Fajardo *et al.*, 2020a).

Synthetic fumigants such as aluminum phosphide and insecticides such as deodorized malathion are used to combat *S. zeamais*, which pose a risk to human health (Silveira-Gramont *et al.*, 2018), promote the selection of resistance genes in target populations, and contaminate the environment while accumulating residues in grains and leading to technological dependence. In view of this situation, agro-ecological and sustainable strategies are being sought to help combat this pest.

Improved maize varieties with resistance to grain-attacking insects are one of the most desirable factors in preventing pest damage (López-Castillo *et al.*, 2018). The physical, chemical, and biochemical characteristics of the grain are closely related to resistance, which is based on the hardness, amount of protein, moisture, and phenols in the grain (Nwosu *et al.*, 2015). For example, hardness is a type of mechanical-structural resistance considered to be antigenic and is negatively correlated with damage and susceptibility to insects. Another type of resistance is antibiosis, with the performance of compounds such as phenolic acids concentrated in the pericarp of the grain (Cabrera-Soto *et al.*, 2009). These compounds can act as an anti-feed and anti-nutritional factor, causing the insect to reduce its ability to digest and absorb nutrients from the maize grains.

Another viable alternative for the control of *S. zeamais* is the use of botanical insecticides in the form of powders, extracts, or oils, which are generally biodegradable and have a low impact on the ecosystem (Ileke *et al.*, 2020). These powders have been used especially by small producers where maize is produced for self-consumption, and are a renewable, accessible, and inexpensive resource compared to synthetic insecticides (Quiñones-Dena *et al.*, 2017). Their secondary metabolites with insecticidal and insectistatic effects can protect grain in storage (García-García *et al.*, 2019). Some experiments conducted on maize grains treated with plant powders were effective against *S. zeamais*, such as *Piper nigrum* L. and *Ruta graveolens* L. powder, which caused 68.8 and 60.4 % mortality, respectively (Quiñones-Dena *et al.*, 2017).

Although there is previous work on maize grain resistance or the use of plant powders to combat storage pests, few combine the two technologies. The objective of this work was to determine, under laboratory conditions, the effect on the grain of four maize genotypes in combination with different plant powders for the control of *S. zeamais*.

MATERIALS AND METHODS

Location of the experiment

The study was conducted in the insectary of the Entomology and Acarology Program of the Postgraduate College, Campus Montecillo, in Texcoco, State of Mexico, Mexico, during the summer-autumn period of 2023.

Maize genotypes tested

Maize grains of three hybrids were used: H-50 (MAZ-427-030904), one of the most commercially used in the High Valleys of Mexico; Tlaoli Puma (MAZ-1844-231117) and Tsiri Puma (MAZ-1571-290514), which have prospects for commercial use (Tadeo-Robledo *et al.*, 2016, 2021; SNICS, 2023); and the open-pollinated variety of broad maize “Ancho Pozolero.” The hybrids were provided by Dr. Alejandro Espinosa Calderón and Dr. Margarita Tadeo Robledo from the National Institute of Forestry, Agriculture, and Livestock Research (INIFAP-CEVAMEX) and the National Autonomous University of Mexico (UNAM, Faculty of Higher Education (FES) Cuautitlán Campus), respectively. The Ancho pozolero variety was obtained from Catalina Armendáriz Guzmán, a producer in the municipality of Ozumba, State of Mexico, Mexico.

In order to have sufficient material for testing, hybrids were grown in the spring-summer 2021 cycle in experimental plots at Rancho Almaraz, UNAM FES-Cuautitlán. Harvesting was done by hand when the maize cobs reached physiological maturity. The grain was sieved to separate impurities. It was then exposed to -4 °C for 48 h to kill pathogens and insects. Grain hardness was determined indirectly with its volumetric weight (kg hL⁻¹) using the GAC 2100 grain analysis equipment (Dickey-John®, USA).

Insect breeding

Mass reproduction of *S. zeamais* started with around 2000 individuals from an infested storage. Insects were kept in quarantine and without selection pressure to insecticides for four generations. Adults (150) were placed in 1 L glass containers with 750 g of Ancho Pozolero maize, previously washed and disinfected. The lid of each container was perforated and covered with organza cloth to allow ventilation. Adults were kept on the grain for 15 d to oviposit and then removed with an aspirator. The infested jars were kept in a rearing chamber at 26 ± 2 °C, relative humidity (RH) of 37 ± 2 % and a 12 h photoperiod. This process was carried out periodically in order to have biological material during the experiment.

Plant powders

Plant species were selected based on history of previous use as insecticides, their abundance in regions of Mexico, and history of use in stored grains (Table 1). For each plant species, 10 kg of fresh plants were collected, and five specimens were mounted in presses for taxonomic identification, which was carried out by Dr. Monserrat Vázquez Sánchez, head of the Botanical Herbarium-Hortory of the Postgraduate College.

Table 1. Species, family, organ used and collection place of plants tested against the maize weevil (*Sitophilus zeamais* Motschulsky) under laboratory conditions.

Scientific name	Common name	Family	Organ used	Place of collection
<i>Azadirachta indica</i> A. Juss.	Neem	Meliaceae	Leaf	Veracruz, Ver.
<i>Dysphania ambrosioides</i> L.	Epazote	Amaranthaceae	Leaf	Texcoco, Mexico
<i>Moringa oleifera</i> Lam.	Moringa	Moringaceae	Seed	Veracruz, Ver.
<i>Piper auritum</i> Kunth	Mexican pepperleaf	Piperaceae	Leaf	Veracruz, Ver.
<i>Ricinus communis</i> L.	Castor oil plant	Euphorbiaceae	Leaf	Texcoco, Mexico
<i>Swietenia humilis</i> Zucc.	Pacific Coast mahogany	Meliaceae	Seed	Culiacán, Sin.

The collected plant material was subjected to dehydration in the shade for 20 d. It was then pulverized by structures in an electric mill (Dakota®, model 1500) and sieved on a 0.25 mm mesh, 24 h before setting up the bioassays. The powder obtained was stored in properly labelled plastic containers.

Bioassays

Three bioassays were conducted to evaluate the effects of plant powders, maize genotypes, and their interaction against *S. zeamais*. In the first, the biological activity of the six plant powders to control *S. zeamais* populations and their impact on seed germination was evaluated. The second bioassay was to determine the effect of the hardness characteristics of the genotypes (three maize hybrids and the variety Ancho Pozolero) on the weevil. In the third bioassay, the interaction between genotypes and the most effective powders was explored.

Effect of plant powders on *S. zeamais*

In this bioassay, each treatment was evaluated at a dose of 1 % (1 g of plant powder per 100 g of grain). For these tests, 250 mL glass containers were used, in which 100 g of Ancho Pozolero maize with a moisture content of 13 % were placed and the corresponding plant powder was added. It was mixed uniformly by oscillatory and vertical movements for 1 min and infested with 10 pairs (females and males) of adults *S. zeamais* from 1 to 10 d of age. Treatments were kept in a chamber under brood-like conditions for 15 d to allow adults to copulate and oviposit. At the end of this time, the adults were extracted to quantify mortality, considering as dead the one that, after being touched with a brush, did not respond to the stimulus.

To assess the effect of powders on emergence and level of damage, the same procedure was followed as for the mortality tests, except that first-generation adults were counted 55 d after infestation. Adult emergence and grain damage in the control group were considered to be 100 %.

Finally, treatments that showed promise (≥ 40 % mortality and/or ≥ 50 % reduction in emergence) were selected to determine the effect of powders on germination. For this purpose, 500 seeds per treatment were randomly selected to establish five replicates of 100 seeds each. The seeds were arranged in groups of 20 and wrapped in folded paper towels, moistened with distilled water, and placed in plastic bags. Treatments were randomized and placed in a germination chamber at 25 °C and a 12 h photoperiod for 7 d. After this time, the germination percentage was determined according to ISTA criteria (ISTA, 2024).

Effect of genotypes on *S. zeamais*

The objective of the second bioassay was to determine the effect of the hardness characteristics of the maize hybrids (H-50, Tlaoli Puma, and Tsiri Puma, and the variety Ancho Pozolero) on the weevil. The same procedure was followed as in the previous trial to maintain the experimental unit, and the same variables (mortality, emergence, damage, and germination) were determined without using plant powder impregnation. Five replicates were carried out for each genotype to ensure consistency of results and minimize random variability.

Powder-genotype interaction on *S. zeamais*

In the third bioassay, the interaction between the best plant powders and genotypes was analyzed using similar experimental units to the second bioassay. A total of 1 g of powder from the best treatments of the first bioassay was added, and a control group without powder was included, with five replicates each. This configuration allowed a specific evaluation of the effect of the interaction between powder and genotype under controlled conditions.

Experimental design and statistical analysis

The design was completely randomized. The data obtained were tested for assumptions of normality and homogeneity of variances ($p \leq 0.05$); when these were met, analysis of variance (ANOVA) was performed. Means were compared using Tukey's test ($p \leq 0.05$). When the assumptions were not met, the data were analyzed with the Kruskal-Wallis test, and a comparison of means and ranks was performed with the InfoStat software version 2020 (InfoStat, 2020).

RESULTS AND DISCUSSION

Effect of plant powders against *S. zeamais*

The evaluated plant powders caused an insecticidal and insectistatic effect on *S. zeamais* ($p \leq 0.05$) (Table 2). The best results were obtained with the impregnation of plant powders of *D. ambrosioides* (leaf), *S. humilis* (seed), and *P. auritum* (leaf). These caused more than 90 % mortality and reduced adult emergence and grain damage by

Table 2. Results of the application of 1 % plant powders against *Sitophilus zeamais* Motschulsky adults in maize stored in Montecillo, Texcoco, State of Mexico, Mexico.

Plant powder	Mortality (%)	Emergence (%)	Damage (%)	Germination (%)
<i>Dysphania ambrosioides</i> (leaf)	100 ± 0.0 ^a *	0.0 ± 0.0 c	0.0 ± 0.0 c	93.5 ± 8.0 bc
<i>Moringa oleifera</i> (seed)	2.2 ± 0.8 c	81.2 ± 18.1 b	88.9 ± 4.1 b	88.4 ± 10.2 c
<i>Swietenia humilis</i> (seed)	95.5 ± 1.0 a	1.3 ± 1.7 c	1.4 ± 0.6 c	92.8 ± 9.4 bc
<i>Piper auritum</i> (leaf)	90.0 ± 3.3 a	5.8 ± 6.7 c	4.8 ± 1.9 c	98.2 ± 2.6 a
<i>Ricinus communis</i> (leaf)	28.0 ± 4.4 b	99.0 ± 31.8 ab	104.8 ± 8.9 ab	94.0 ± 4.6 c
<i>Azadirachta indica</i> (leaf)	6.0 ± 1.6 c	156.7 ± 38.9 a	152.4 ± 9.5 a	98.6 ± 4.0 a
Control	3.5 ± 0.7 c	100 ± 22.7 ab	100 ± 8.7 b	100 ± 6.5 a

^aMeans ± standard error. *Same letters in the columns indicate no significant difference among means of the ranges (Kruskal-Wallis, $p \leq 0.05$).

94.2 %. In contrast, the application of *M. oleifera* seed powder, *A. indica* leaf, and *R. communis* leaf did not affect *S. zeamais* and did not protect the grain; on the contrary, *A. indica* leaf favored emergence and damage. In addition, the impregnation of the latter three powders affected germination (Table 2).

The insecticidal effect caused by *D. ambrosioides*, *S. humilis*, and *P. auritum* was reported by several authors on various pests due to the action of secondary metabolites (Ortega-Arenas *et al.*, 2014; Rangel-Fajardo *et al.*, 2020a). These species are characterized by alkaloids, steroids, flavonoids, phenols, and saponins, distributed in different organs of the plant, mainly in roots, leaves, and seeds. These compounds can interfere with the metabolism of organisms, causing variable effects, such as phagorepellency, sterilization, blockage of metabolism, interference with metamorphosis, and death.

In this research, *D. ambrosioides* leaf caused total mortality in *S. zeamais*; however, there are reports indicating that the effect may be minor and/or variable, depending on the plant part evaluated, phenological stage, and prevailing environmental conditions where the plant developed (Rangel-Fajardo *et al.*, 2020b). The leaf and stem powder mixture of *D. ambrosioides*, for example, caused only 10.5 % mortality in *S. zeamais*, while 1 % *P. auritum* powder caused 6.7 % mortality (Gómez-Herrera *et al.*, 2018).

The null biological activity of *M. oleifera* seed powder at 1 %, as found in this study, was also evidenced previously, even at concentrations ranging from 10 to 100 % (Emeka *et al.*, 2020; Asare *et al.*, 2023). The results found with *P. auritum* leaf powder coincide with those reported by Agüero-Cabrera *et al.* (2020); however, these authors point out that greater effectiveness can be obtained when the plants are harvested in cold weather because they contain a higher concentration of secondary compounds. Effectiveness can decrease by up to 6.7 % (Gómez-Herrera *et al.*, 2018).

In this research, it was evident that the treatments with the highest mortality also significantly inhibited emergence ($p \leq 0.05$) (Table 2). *D. ambrosioides* leaf (0 %), followed

by *S. humilis* seed (1.3 %) and *P. auritum* leaf (5.8 %). This is in agreement with the work of Aros *et al.* (2019), who found a reduction of 82.8 and 38.6 %, respectively, in weevil emergence with 1 % leaf and stem powder and 1 % essential oil of *D. ambrosioides*.

The decrease in emergence in this work was probably due to the fact that females were removed before they laid their normal load of eggs, which had a direct effect on female mortality. It is also possible that secondary metabolites in these structures caused a rapid toxic effect in the adult, which prevented copulation from occurring and thus decreased oviposition. Another aspect that may have influenced reproduction was the possible sterility of females or the death of insects in the immature stages, which made insect emergence impossible (Gómez-Herrera *et al.*, 2018).

Contrary to what was found with most plant powders, the 1 % *A. indica* leaf powder did not cause a toxic effect on *S. zeamais*, which is in line with what is reported in the literature (Erenso and Berhe, 2016), but had an unusually increased emergence of individuals in the first generation (and thus the damage to the grain). This can be attributed to the chemical composition of the leaf, which stimulates the insects' reproductive capacity and development. This finding is in contrast to that reported by Erenso and Berhe (2016), who found significant weevil mortality when applying *A. indica* powder at doses of 1 to 3 %. However, it is likely that the differences in activity compared to what was found in this study are due to the fact that they used seed powder, which concentrates the highest amount of azadirachtin, the compound to which the insecticidal properties are attributed. The least grain damage was also recorded with *D. ambrosioides* (0 %), followed by *S. humilis* (1.4 %) and *P. auritum* (4.8 %). This reduction could be a consequence of the insecticidal effect on the adult or the growth-regulating or antifeedant effect of the metabolites present in the plant powders studied (Shiberu and Negeri, 2017).

Regarding the effect of powders on seed germination, differences between treatments were found ($p \leq 0.05$) (Table 2). The most evident reduction was recorded with 1 % *M. oleifera* seed powder (11.6 %) and *R. communis* leaf (4 %). In the rest of the treatments, no adverse effect was observed, which suggests that the compounds in the powders of the different organs of the species studied exert biological activity against weevils but have no effect on the germination of the grains studied. This is in line with other studies on species of the same family, which is important as it represents a good alternative for use in seed storage (Yuya, 2017; Aros *et al.*, 2019).

For the assessment of the 1 % plant powders, *D. ambrosioides* and *S. humilis* showed insecticidal, insectistatic, and protective effects on maize, although they affected germination. *P. auritum* is noted for its insecticidal, insectistatic, and grain-protecting effect without reducing germination. In contrast, *R. communis* showed a slight toxic effect against *S. zeamais*, affecting germination. *M. oleifera* does not impact *S. zeamais* or protect the grain and also affects germination. *A. indica* does not kill the weevil but increases emergence and damage without influencing germination. Among these treatments, *D. ambrosioides* leaf achieves total mortality in *S. zeamais* and shows the best performance compared to other treatments and previous studies.

Effect of genotypes on *S. zeamais*

The results of *S. zeamais* development on the four maize genotypes (Table 3) show that they were suitable substrates for feeding and reproduction of the insect since they did not cause significant mortality ($p \leq 0.05$), and that, on the contrary, the hybrids Tsiri Puma and H-50 favored the increase of the adult population in the first generation. Out of the three hybrids evaluated, only Tlaoli Puma reduced damage to maize (29.5 %) ($p \leq 0.05$). All three hybrids showed higher germination percentages compared to the control treatment (Ancho Pozolero) (Table 3).

Table 3. Effect of maize genotype on *Sitophilus zeamais* Motschulsky adults and its outcome on damage and germination in bioassays evaluated in Montecillo, Texcoco, State of Mexico, Mexico.

Genotype	Mortality (%)	Emergence (%)	Damage (%)	Germination (%)
Tlaoli Puma	3.0 ± 1.0 [†] a [‡]	150.5 ± 11.6 a	70.5 ± 8.4 b	118.4 ± 5.5 a
Tsiri Puma	0.0 ± 0.0 a	179.4 ± 8.3 a	92.0 ± 7.5 a	111.8 ± 1.3 b
H-50	4.0 ± 2.0 a	160.8 ± 11.5 a	104.5 ± 10.2 a	[†] 118.7 ± 0.5 a
Ancho Pozolero	2.0 ± 1.0 a	100.0 ± 5.3 b	100.0 ± 10.1 a	100.0 ± 0.9 c

[†]Means ± standard error. [‡]Different letters in columns indicate significant differences between means (Tukey, $p \leq 0.05$).

When comparing all treatments, the resistance of the hybrid Tlaoli Puma stands out for reducing *S. zeamais* damage by almost a third without affecting the pest; however, the increase in germination, which is presumably related to the hardness (76.6 kg hL⁻¹) presented by this material (Palacios-Rojas, 2018). This differs from the hybrids Tsiri Puma and H-50, with “intermediate” hardness (75 and 73.9 kg hL⁻¹), and from the variety Ancho Pozolero, with “soft” hardness (63.8 kg hL⁻¹). This coincides with the work of several authors, who found that hard maize inhibited 47 % (López-López *et al.*, 2023), 75.8 % (López-Castillo *et al.*, 2018), and 78.3 % (Rodríguez-Cobos and Iannacone, 2012) of the insect damage.

Hardness is negatively correlated with damage and susceptibility to insects (López-Castillo *et al.*, 2018) and can be mechanical-structural or due to the action of secondary metabolites such as phenolic acids that are concentrated in the grain pericarp (Cabrera-Soto *et al.*, 2009). These compounds can act as an anti-feed and anti-nutritional factor, causing the insect to reduce its ability to digest and absorb nutrients from the maize grains.

Effect of genotype-plant-powder interaction-*S. zeamais*

In the interaction of *D. ambrosioides* (leaf), *P. auritum* (leaf), and *S. humilis* (seed) powders with the hybrid Tlaoli Puma (Table 4), it is observed that *D. ambrosioides* caused total mortality and complete inhibition of emergence and damage. This could

Table 4. Effect of genotype-powder interaction against *Sitophilus zeamais* Motschulsky adults and its result on damage and germination in bioassays evaluated in Montecillo, Texcoco, State of Mexico, Mexico.

Treatment	Mortality (%)	Emergence (%)	Damage (%)	Germination (%)
Tlaoli Puma- <i>Dysphania ambrosioides</i> (leaf)	100 ± 0.0 ^a	0.0 ± 0.0 b	0.0 ± 0.0 b	97.3 ± 2.3 a
Tlaoli Puma- <i>Piper auritum</i> (leaf)	70.0 ± 4.6 a	20.8 ± 9.5 b	21.4 ± 2.8 b	97.0 ± 1.6 a
Tlaoli Puma- <i>Swietenia humilis</i> (seed)	100 ± 0.0 a	0.0 ± 0.0 b	0.0 ± 0.0 b	97.0 ± 2.7 a
Tlaoli Puma-Control	3.0 ± 0.5 b	100 ± 21.0 a	100 ± 4.2 a	100 ± 2.5 b
Tsiri Puma- <i>Dysphania ambrosioides</i> (leaf)	100 ± 0.0 a	0.0 ± 0.0 b	0.0 ± 0.0 b	81.3 ± 4.3 bc
Tsiri Puma- <i>Piper auritum</i> (leaf)	94.0 ± 1.6 a	2.3 ± 3.0 b	2.8 ± 0.9 b	86.6 ± 1.6 ab
Tsiri Puma- <i>Swietenia humilis</i> (seed)	96.0 ± 0.8 a	3.5 ± 2.7 b	5.8 ± 0.8 b	76.6 ± 2.0 c
Tsiri Puma-Control	0.0 ± 0.0 b	100 ± 15.0 a	100 ± 3.8 a	100 ± 1.9 a
H-50- <i>Dysphania ambrosioides</i> (leaf)	100 ± 0.0 a	0.0 ± 0.0 b	0.0 ± 0.0 b	97.5 ± 1.3 b
H-50- <i>Piper auritum</i> (leaf)	95.0 ± 0.8 a	1.0 ± 1.8 b	1.1 ± 0.9 b	97.5 ± 1.5 b
H-50- <i>Swietenia humilis</i> (seed)	93.0 ± 1.1 a	0.0 ± 0.0 b	0.0 ± 0.0 b	97.1 ± 1.3 b
H-50-Control	4.0 ± 0.8 b	100 ± 20.8 a	100 ± 5.0 a	100 ± 1.1 a
Ancho Pozolero- <i>Dysphania ambrosioides</i> (leaf)	100 ± 0.0 a	0.0 ± 0.0 b	0.0 ± 0.0 b	92.7 ± 1.0 c
Ancho Pozolero- <i>Piper auritum</i> (leaf)	100 ± 0.0 a	0.0 ± 0.0 b	0.0 ± 0.0 b	99.1 ± 3.4 a
Ancho Pozolero- <i>Swietenia humilis</i> (seed)	93.0 ± 1.1 a	1.4 ± 0.5 b	1.8 ± 0.5 b	94.3 ± 2.6 bc
Ancho Pozolero-Control	2.0 ± 0.5 b	100 ± 9.7 a	100 ± 4.6 a	100 ± 2.5 a

^aMeans ± standard error. ^{*}Same letters in the columns indicate no significant difference between the means of the ranges (Kruskal-Wallis, $p \leq 0.05$).

be attributed to the effectiveness of the plant powder, which has no effect on the hybrid, supporting the inappropriateness of this interaction, particularly the reduction in germination, in contrast to *P. auritum* (leaf), where the insecticidal effect is reduced and the insectistatic effect of the powder dominates the interaction, and the protective effects of both strategies on maize do not add up. On the other hand, antagonism is evident in the sum of both measures, even with a reduction in germination.

Treatment of the hybrid Tlaoli Puma with *S. humilis* seed achieved total elimination of the infesting adult population and totally inhibited emergence and damage. This interaction represents an excellent alternative as an enhancement with a slight reduction in germination caused by the plant. The other treatments (Table 4) showed no significant effects, as there is no natural resistance in Tsiri Puma, H-50, and Ancho Pozolero, so the insect is not affected and the maize is not protected. There is no contribution of these materials to the interaction, manifesting the full activity of the plant powders.

Impregnation of 1 % *D. ambrosioides* leaf powder on any maize hybrid or variety eliminates infesting adults within 15 d and prevents their offspring and damage to the grain before death; however, germination is affected by 2.5 to 18.7 %. In the treatment with Tlaoli Puma and *S. humilis*, the resistance effect of the maize is combined with the

effect of the plant powder; however, *S. humilis* does not cause total mortality in other non-resistant maize; even germination is always affected. The interaction of Ancho Pozolero with *P. auritum* eliminates adults, prevents emergence and damage, and does not affect germination; however, *P. auritum* at 1 % does not always cause total mortality.

In view of the incipient interaction of plant powders and resistant maize, 1 % *D. ambrosioides* leaf powder impregnated into any maize genotype should be used to cause total elimination of adults, prevent the development of the first generation, and fully protect the maize at the risk of a 2.5 to 18.7 % decrease in germination. These findings support the notion that by combining the right maize genotype with an effective plant powder, it is possible to achieve satisfactory results in controlling *S. zeamais*, as corroborated by Rangel-Fajardo *et al.* (2020b), who mention that some maize varieties are less affected by the presence of *S. zeamais* and show less damage when treated with specific doses of plant powders.

It is important to note that there are several strategies for the control of *S. zeamais*. In cultural control, emphasis is placed on preventive measures aimed at avoiding damage in the field, such as early harvesting, given that delayed harvesting significantly increases the percentage of maize cobs affected by *S. zeamais* and early infestations in storage (Rangel-Fajardo *et al.*, 2020a). Another effective strategy is biological control, which focuses on the introduction of natural enemies to combat pests. Although this method has shown positive results in laboratory settings, it has not yet achieved widespread implementation in silos and storage rooms. Finally, physical control relies on proper moisture management, as most damaging insects do not thrive in grains with balanced moisture levels, especially below 40 %. Each of these activities contributes to the reduction of maize postharvest losses, and together, it is estimated that they could reduce losses by up to 60 % (López-Castillo *et al.*, 2018).

CONCLUSIONS

In the evaluation of six 1 % plant powders, *Dysphania ambrosioides* and *Swietenia humilis* stand out for their excellent insecticidal, insectistatic, and protective effects on maize, although they slightly affect germination. *Piper auritum* shows good insecticidal and insectistatic effects, protecting the grain without affecting germination. The hybrid Tlaoli Puma, classified as hardy, proves to be tolerant to *Sitophilus zeamais* attack, as it reduced one third of the normal damage caused by this pest. The combination of the hybrid Tlaoli Puma impregnated with 1 % plant powder of *D. ambrosioides* or *S. humilis* reduces the chances of attack and damage by *S. zeamais* and contributes to reducing post-harvest losses of stored maize.

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