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The insecticidal activity of azadirachtin against the Indian meal moth (*Plodia interpunctella*), and its influence on nutritional indices of the larvae fed on the kernels of five maize varieties

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Abstract

The Indian meal moth, *Plodia interpunctella* (Hübner), is a destructive pest damaging various stored products including cereals; thus, it is necessary to ascertain the susceptibility of different host varieties. This study assessed the effect of treating broken kernels of five maize varieties (Simon, Valbom, 703, BK, and BC678) with azadirachtin (concentration of 4 ppm a.i.) on mortality and nutritional performance of *P. interpunctella* larvae. The highest mortality percentage was observed on the treated kernels of BK variety which did not exceed 22%. Larval weight was the highest in the 703 variety with the lowest larval weight found in the BK and Simon varieties. Kernel treatments with azadirachtin, compared to the control, resulted in a decline in the larval weight ranging from 9.85 to 10.77 mg in different varieties. In the control group, the larvae reared on 703 followed by BC678 and Valbom had the highest frass and pupal weights, which were significantly different from the means of the azadirachtin-treated kernels. The greatest approximate digestibility and relative growth rate were observed in BC678, while the highest relative consumption rates were recorded in BC678 and 703. According to the oviposition patterns, the highest number of eggs was laid on 703 followed by BC678. Notably, the emergence of normal adults from larvae reared on azadirachtin-treated maize was significantly lower than in controls. Based on the cluster analysis results, BC678 and 703 were identified as the preferred varieties for this moth, while Simon and Valbom revealed tolerance traits, indicating their potential sustainability in this pest management. Further, azadirachtin was significantly effective on disrupting the nutritional efficiency and egg hatching rate of this pest, suggesting its potential as a botanical in *P. interpunctella* management strategies.

Keywords: Nutritional indices, Development, Food consumption, Indian meal moth, Mortality

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فعالیت حشره‌کشی آزادیراختین علیه شب‌پره هندی (*Plodia interpunctella*) و اثر آن روی شاخص‌های تغذیه‌ای لاروهای تغذیه شده از دانه‌های پنج رقم ذرت

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چکیده

شب‌پره‌ی هندی، *Plodia interpunctella* (Hübner) یک آفت مخرب است که به فرآورده‌های انباری مختلفی از جمله غلات خسارت وارد می‌آورد، لذا ارزیابی حساسیت رقم‌های مختلف میزبان به آن ضروری می‌باشد. در این مطالعه، تأثیر تیمار دانه‌های شکسته شده پنج رقم ذرت (سیمون، والبوم، ۷۰۳، BK و BC678) با آزادیراختین (غلظت ٤ پی‌پی‌ام ماده موثر) روی تلفات و چند شاخص زیستی لاروهای این آفت ارزیابی شد. بیشترین درصد تلفات روی دانه‌های تیمارشده رقم BK مشاهده شد که از ۲۲ درصد تجاوز نکرد. وزن لاروها روی رقم ۷۰۳ بیشترین مقدار و روی دو رقم BK و سیمون کمترین مقدار بود. در مقایسه با شاهد، تیمار دانه‌ها با آزادیراختین منجر به کاهش وزن لاروها شد که از ۹/۸۵ تا ۱۰/۷۷ میلی‌گرم در رقم‌های مختلف متغیر بود. در تیمار شاهد، لاروهای پرورش یافته روی رقم ۷۰۳ و پس از آن BC678 و والبوم بیشترین وزن فضولات و وزن شفیره را داشتند که با میانگین‌های دانه‌های تیمار شده با آزادیراختین دارای تفاوت معنی‌دار بودند. بیشترین میزان گوارش‌پذیری تقریبی و نرخ رشد نسبی روی رقم BC678 مشاهده شد، در صورتی‌که بیشترین نرخ مصرف نسبی نیز روی رقم‌های BC678 و ۷۰۳ ثبت شد. طبق الگوهای تخم‌گذاری، بیشترین تعداد تخم روی رقم ۷۰۳ و پس از آن BC678 گذاشته شدند. به شکلی قابل توجه، ظهور حشرات کامل طبیعی از لاروهای پرورش یافته روی دانه‌های ذرت تیمار شده با آزادیراختین به طور قابل توجهی کمتر از تیمار شاهد بود. طبق نتایج تجزیه و تحلیل خوشه‌ای، BC678 و ۷۰۳ به عنوان رقم‌های مطلوب برای این شب‌پره شناسایی شدند، در صورتی‌که سیمون و والبوم ویژگی‌های تحمل را نشان دادند که نشان‌دهنده پتانسیل آن‌ها برای مدیریت پایدار این آفت است. علاوه بر این، آزادیراختین در مختل کردن کارایی تغذیه و درصد تفریخ تخم این آفت اثربخشی قابل توجهی داشت که پتانسیل آن را به عنوان یک آفت‌کش زیستی در راهبردهای مدیریت شب‌پره هندی نشان می‌دهد.

کلید واژه‌ها: شاخص‌های تغذیه، رشد، مصرف غذا، شب‌پره هندی، تلفات

دبیر تخصصی: دکتر محسن یزدانیان

Introduction

Cereals serve as a crucial source of human nutrition and energy, necessitating effective storage solutions such as silos and warehouses to ensure their availability throughout the year. Nevertheless, grain losses along storage are an inevitable challenge, primarily attributed to biotic and abiotic factors (Kumar et al., 2021). Among these, insects represent the most significant biotic threat, causing extensive damage and substantial stored-products losses (Guru et al., 2022). The Indian meal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), stands out as one of the most invasive stored-products pests, infesting a diverse array of stored products including cereals, dried fruits, oilseeds, legumes, and even animal collections. The larvae of this pest not only compromise product quality but can render them entirely unusable (Hill, 2002).

Previous studies have highlighted the varying susceptibility of kernels of different maize varieties to post-harvest infestations by Indian meal moth (Mbata, 1990; Arbogast, 2007; Limonta et al., 2013; Predojević et al., 2017; Gvozdenac et al., 2018), underscoring the need for targeted pest management strategies. Stored-products insect pests infest stored products, including flour, cereals, dried fruits, tobacco, leather, wool, fur, etc., while lowering the quantitative, qualitative, and consumption value of products (Stathas et al., 2023).

Traditionally, the control of stored-products pests has heavily relied on chemical insecticides and fumigants, which are widely utilized owing to their immediate effectiveness (Zettler & Arthur, 2000). Nevertheless, the extensive use of these chemical agents has led to significant resistance among insect populations (Arthur & Subramanyam, 2012). Moreover, concerns regarding chemical residues in food products have raised concerns about potential health risks and the nutritional integrity of these commodities (Anaduaka et al., 2023). As a result, there is an urgent need for alternative pest control methods that are both effective and environmentally sustainable. Botanical insecticides have emerged as a promising solution in this context. They offer a safer alternative to conventional chemicals, offering reduced risks to human health and the environment (Campos et al., 2019). Botanicals not only provide effective protection against insect and mite infestations but also support the establishment of sustainable agricultural practices (Anaduaka et al., 2023; Rajabpour, 2024; Yazdanian & Rajaei, 2024). Among various botanical options, azadirachtin—a natural insecticide derived from the seeds of the neem tree (*Azadirachta indica* L.)—has garnered attention for its multifaceted properties. Azadirachtin manifests antifeedant, ovicidal, larvicidal, insect growth regulatory, and repellent activities (Chaudhary et al., 2017). Its mode of action involves disrupting the molting process in insects by interfering with ecdysteroid function, thereby affecting growth and reproductive capabilities (Gonzalez-Coloma et al., 2010).

Azadirachtin exhibits both repellent and toxic effects on various stored-product insects, making it a promising candidate for pest management strategies. Research has demonstrated that azadirachtin is primarily responsible for the behavioral and physiological actions observed in neem extracts against pests such as *Cryptolestes ferrugineus* (Stephens), *Sitophilus oryzae* (L.), and *Tribolium castaneum* (Herbst). Notably, neem extracts containing varying concentrations of azadirachtin have indicated enhanced activity compared to pure azadirachtin, suggesting the presence of additional bioactive compounds within neem which contribute to its insecticidal efficacy (Xie et al., 1995). Also, limonoids isolated from *A. indica* A. Juss such as salannin have

been identified as compounds that inhibit larval growth and feeding in various lepidopteran species, further highlighting the multifaceted nature of neem's insecticidal properties. It lowered growth and consumption rate when fed to larvae without any effect on efficiency of conversion of ingested food (ECI), suggesting antifeedant activity alone alone (Koul et al., 2004). Azadirachtin-based formulations, such as NeemAzal®, manifest varying effectiveness depending on the grain type, with significant mortality rates observed against pests such as *Rhyzopertha dominica* (F.), *S. oryzae* and *Tribolium confusum* Jacquelin du Val. across different grains. The reduction in progeny production in treated grains highlights the potential of azadirachtin as a viable option for managing stored-product insect populations (Athanassiou et al., 2005). Comparative evaluations of different azadirachtin formulations have indicated that NeemAzal®-T/S outperforms Oikos 32 EC against adult populations of *S. oryzae* and *T. confusum* on wheat and maize (Kavallieratos et al., 2007). Further, azadirachtin influences larval development by inducing weight loss, developmental delays, and elevated mortality rates in *P. interpunctella* (Rharrabe et al., 2008). Ingestion of azadirachtin at specific concentrations (1 and 10 ppm) significantly impacts pupation and adult emergence rates (Lynn et al., 2012). Further, topical applications of azadirachtin have been found to disrupt metamorphosis in *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae), leading to malformed adults and other developmental anomalies (Taffar et al., 2021).

Given the pressing need for effective pest management strategies that minimize reliance on synthetic chemicals, this study aims to ascertain the susceptibility of five maize varieties to infestation by *P. interpunctella* while assessing the efficacy of azadirachtin on both mortality rates and nutritional performance of this pest. By examining these dimensions, the research intends to provide practical implications for developing integrated pest management strategies that enhance food security while promoting environmental sustainability. The findings may contribute valuable insights into alternative control measures that align with contemporary agricultural practices aimed at mitigating post-harvest losses in stored cereals.

Materials and Methods

Insect rearing

The adults of *P. interpunctella* were collected from the grain shop (31°72'17.0"N 47°98'69.2"E) infected with this pest in Bostan, Khuzestan province. Five distinct cylindrical containers (1 L) were set up, each filled with kernels (300 g) from a unique variety of maize. Clean, un-infested maize kernels were broken using mortar to provide better access to food for the larvae. Then, 15 pairs of moths (male and female) were transferred to each container and covered with muslin cloth for sufficient ventilation. Therefore, *P. interpunctella* were reared on five different maize kernels for three consecutive generations and the population reared on each variety was then used for the experiments related to that variety. The containers were kept at 28 ºC, 60 ± 5% R.H. and 14:10 (L:D) h (Predojević et al., 2017).

Maize varieties

Five commercial maize varieties were Simon, Valbom, 703, BK, and BC678, obtained from Dezful Maize Cultivation Development Company, Khuzestan, Iran. The moisture content was determined by milling then drying 10 g of maize kernels in an oven (Shimaz Co., Tehran, Iran). The experiment was replicated three times and moisture content was 9.00 ± 0.06, 7.76 ± 0.03, 8.33±0.09, 8.20±0.06, and 8.80±0.06%, respectively.

Azadirachtin

NeemAzal® T/S EC1% (Trifolio-M GmbH, Lahnau, Germany) was used in the experiments.

Effects of azadirachtin on the mortality of *P. interpunctella*

Azadirachtin was tested at 4 ppm (a.i.) as a grain protectant (Rharrabe et al., 2008). A solution of 400 µL per 1 L distilled water. For each replication, 4 g of kernels of different maize varieties were treated with 2 ml of azadirachtin solution in a glass vial (100 mL). Maize kernels treated with distilled water were considered as the control group. The vials were shaken for 30 s. Then, 10 fourth instar larvae were released separately in the vials and covered with muslin cloth. The experiment was carried out with five replications. The mortality was determined daily under a stereomicroscope (NSZ-606 Zoom, Xiamen Phio Scientific Instruments Co., China) until death or pupation. The larvae were considered dead if their body color changed to black or when the larvae were immobile underbrush irritation.

Impacts of azadirachtin on the nutritional performance of *P. interpunctella*

The experiment was conducted based on the method of Nasirian et al. (2014) with some modifications. To determine the effects of azadirachtin on the nutritional indices of *P. interpunctella*, maize varieties were treated with azadirachtin at 4 ppm (a.i.). Maize kernels treated with distilled water were considered as the control group. For each variety, 40 fourth instar larvae were placed individually in plastic containers (100 mL) containing 2 g of treated or untreated maize kernels. Broken maize kernels were used in the experiments. The larval weight was quantified before and after feeding on different maize varieties until the larvae reached the pupal stage. Also, the frass weight, the weight of the consumed food, and the pupal weight were measured daily. If any larva died before pupation, it was replaced by a new fourth instar larva. All parameters were evaluated based on the dry weight. To estimate the dry weights of the larvae, maize kernels, and feces, 40 additional samples were weighed, then dried at 60 ºC for 48 h. The nutritional indices, including approximate digestibility (AD), efficiency of conversion of ingested food (ECI), efficiency of conversion of digested food (ECD), relative growth rate (RGR), and relative consumption rate (RCR), were calculated using Waldbauer (1968) formulas.

Influences of azadirachtin on the morphological abnormalities of *P. interpunctella*

The emerging pupae from the previous experiment were transferred to four containers (100 mL), each containing 10 pupae. The containers were kept for 10 days in the experimental conditions until the emerged adults were examined morphologically. The adults were classified into four categories, including normal, malformed adult, partial molt, and blocked molt in the control and azadirachtin groups (Taffar et al., 2021).

Effects of azadirachtin on the oviposition performance of *P. interpunctella*

To evaluate the effects of azadirachtin on the oviposition performance of *P. interpunctella*, maize varieties were treated with azadirachtin at 4 ppm (a.i.). For each replicate, one male-female pair moth (1-2 day old virgins) was placed in a plastic container (100 ml) containing 10 g of treated or untreated maize kernels. Ten replicates were conducted for each treatment. After the female adults died, the moths were removed from the containers and the number of eggs laid on the maize kernels was counted using a stereomicroscope. The kernels were then returned to the containers and kept at experimental conditions. The containers were checked 10 days after setting up the experiment and continued daily until no larvae were observed (Predojević et al.,

2017). The larvae were counted and removed from the containers and the egg hatching percentage was calculated. For all the experiments, distilled water-treated maize kernels were used as the control group. All bioassays were conducted at 28 ºC, 60 ± 5% R.H., and 14:10 (L:D) h photoperiod.

Data analysis

The data were checked for normality using the Shapiro-Wilk test. If the data were normal, no transformation was performed (Zar, 1999). Separately for each treatment, data were analyzed using one-way ANOVA, with variety as the main effect. Tukey-Kramer honestly significant difference (HSD) test was used to determine significant differences between varieties. For each variety, an independent sample t-test was performed to compare the control and azadirachtin groups (Sokal & Rohlf, 1995). A dendrogram was designed for the various maize varieties according to the nutritional indices of *P. interpunctella* reared on untreated maize kernels using cluster analysis by Ward's method. All analyses were performed using SPSS software version 16.0 at $P = 0.05$ (IBM Corp., 2007).

Results

Effects of azadirachtin on the mortality of *P. interpunctella*

The mortality percentage of the larvae exposed to maize varieties treated with azadirachtin grew with time. The highest mortality percentage (22.0%) was observed in the BK variety, 7 days post-treatment. At the same time, the lowest mortality percentage was 12% in Simon, Valbom, and BC678 varieties. After 7 days, the surviving larvae developed into the pre-pupae stage (Figure 1).

Impacts of azadirachtin on the nutritional performance of *P. interpunctella*

For the control group, the larval weight was the maximum when reared on 703, while it was the lowest for the larvae reared on Simon and BK ($F_{4,195} = 8.403$; $P < 0.001$). There were significant differences among maize varieties in the weight of larvae exposed to azadirachtin-treated groups ($F_{4,195} = 7.256$; $P < 0.001$). The larval weight ranged from 9.85 to 10.775 mg on different treated-maize varieties. For all tested varieties, the larval weight was lower in the azadirachtin-treated kernels compared to the control group (Figure 2a). Regarding the control group, the highest gained weight was found when the larvae were reared on 703 followed by BC678, while the lowest was witnessed on Simon and BK ($F_{4,195} = 7.505$; $P < 0.001$). In the azadirachtin-treated kernels, no significant differences were observed among maize varieties ($F_{4,195} = 1.618$; $P = 0.171$), and the gained weight did not exceed 3.85 mg. For all tested varieties, the larval gained weight in the control group was significantly greater than that of the azadirachtin group (Figure 2b). There was a significant difference in the amount of frass produced between the different maize varieties in larvae reared on the untreated ($F_{4,195} = 3.840$; $P < 0.001$) and azadirachtin-treated maize kernels ($F_{4,195} = 3.008$; $P < 0.001$). The maximum amount of frass in the control group was produced in the larvae reared on 703, while it occurred on BK in the azadirachtin-treated kernels. A significant difference in the frass weight was observed between the control and azadirachtin for all varieties except for the BK (Figure 2c). The highest food consumed in the control group was observed when the larvae were reared on 703 and BC678 ($F_{4,195} = 11.776$; $P < 0.001$). Nevertheless, there were no significant differences among varieties in the azadirachtin group ($F_{4,195} = 1.644$; $P = 0.165$). For all tested varieties, significantly more food was consumed when the larvae were reared in the control group when compared to the azadirachtin-treated kernels (Figure 2d). The pupal weight in the control group peaked when the larvae were reared on 703, followed by BC678 and Valbom ($F_{4,195}$

= 5.318; $P < 0.001$). In the azadirachtin-treated kernels, the highest pupal weight was observed when the larvae were reared on Simon, Valbom, and BK ($F_{4,195} = 9.499$; $P < 0.001$). For all varieties, the pupal weight significantly diminished when the larvae were reared on the azadirachtin-treated kernels compared to the control (Figure 2e).

The AD value differed significantly among the maize varieties in the control ($F_{4,195} = 3.824$; $P < 0.001$), while there were no significant differences among the varieties in the azadirachtin-treated group ($F_{4,195} = 1.969$; $P = 0.101$). Considering the control, the highest AD value of the larvae was on BC678, while the lowest was on Simon, Valbom, and BK. No significant difference was observed between the control and azadirachtin groups except for 703 and BC678 (Figure 3a). For the control group, the ECI value was highest on Simon, whereas the lowest value was recorded on BC678 ($F_{4,195} = 3.468$; $P < 0.001$). For the azadirachtin-treated group, the highest ECI was on BC678, and the lowest was on 703 ($F_{4,195} = 2.480$; $P = 0.045$). For all tested varieties, the ECI index significantly declined when the larvae were reared on the azadirachtin-treated kernels compared to the control (Figure 3b). Significant differences were observed among the maize varieties in the ECD values in the control ($F_{4,195} = 3.501$; $P < 0.001$); and azadirachtin groups ($F_{4,195} = 2.472$; $P = 0.045$). For the control group, the highest ECD value was found on Simon, and the lowest was on BC678, followed by 703. Nevertheless, for the azadirachtin-treated group, the highest ECD value was calculated for the larvae reared on BC678.

For all tested varieties, a significant difference was noted between the control and azadirachtin-treated kernels (Figure 3c). With regards to the RGR value, there were significant differences among the varieties in the control ($F_{4,195} = 5.452$; $P < 0.001$), while RGR did not differ significantly among varieties in the azadirachtin group ($F_{4,195} = 1.896$; $P = 0.113$). Concerning the control group, the highest RGR value was obtained when the larvae were reared on BC678. For all tested varieties, the RGR index significantly dropped when the larvae were reared on the azadirachtin-treated kernels compared to the control (Figure 3d). A significant difference in the RCR value was observed when larvae were reared on different untreated maize varieties ($F_{4,195} = 8.848$; $P < 0.001$). Nevertheless, there were no significant differences among maize varieties in the azadirachtin-treated kernels ($F_{4,195} = 1.207$; $P = 0.309$). No significant difference was observed between the control and azadirachtin groups in the RCR value, except for 703 and BC678 (Figure 3e).

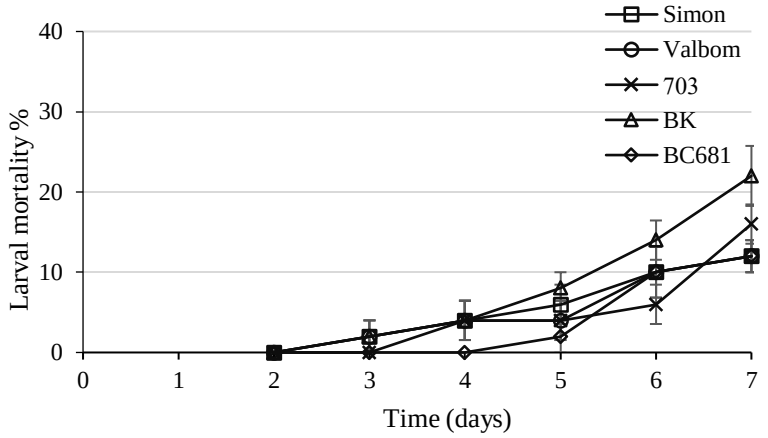


Figure 1. Time-dependent mortality percentage (mean ± SE) of *Plodia interpunctella* fourth instar larvae exposed to azadirachtin-treated kernels of five maize varieties.

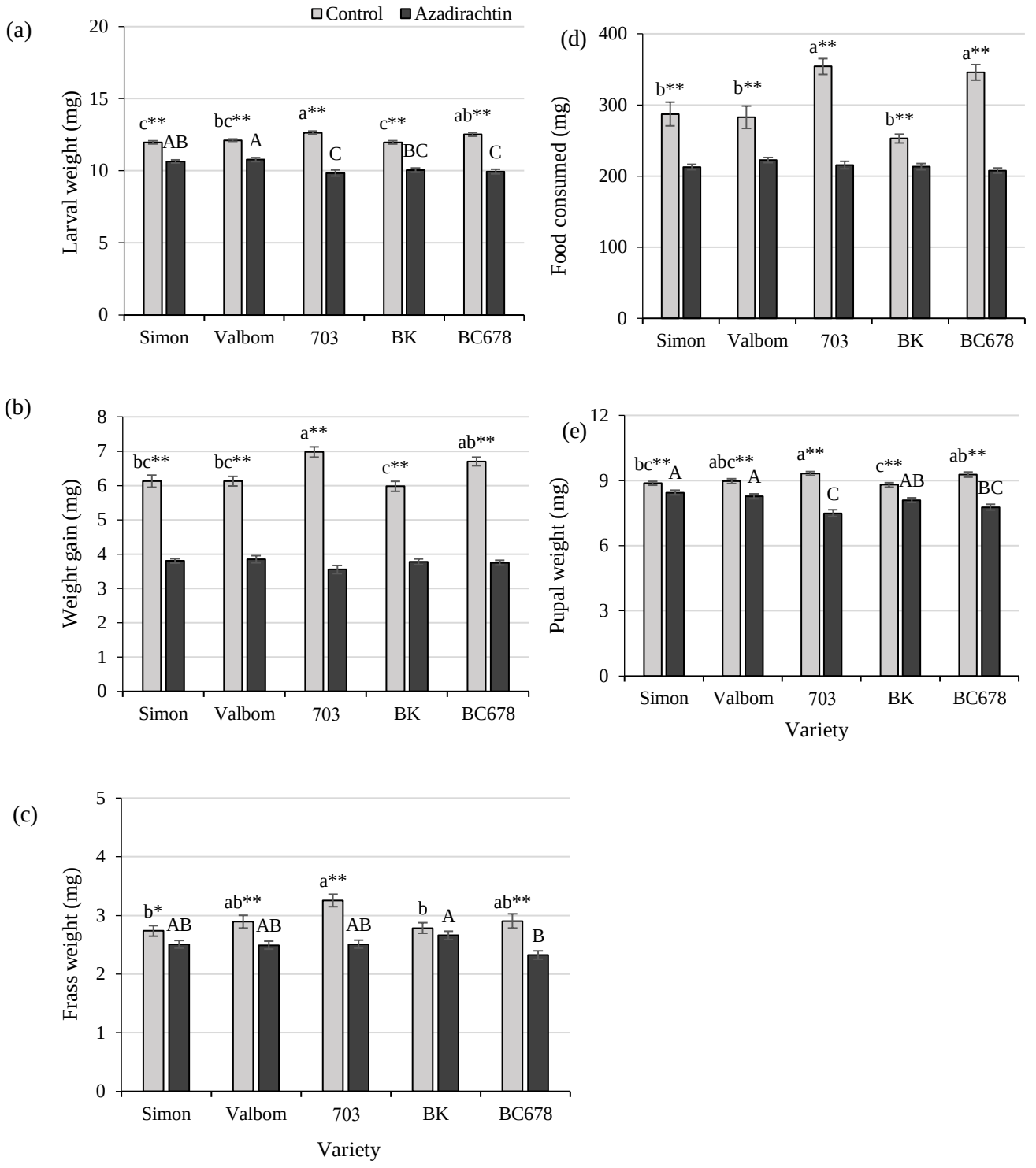


Figure 2. Larval weight (a), larval gain weight (b), frass produced (c), food consumed by fourth instar larvae (d), and pupal weight (e) (mean ±SE) of *Plodia interpunctella* exposed to azadirachtin-treated kernels of five maize varieties. For each variety, differences between control and azadirachtin are denoted with an asterisk (*P* < 0.05, t-test). Different lowercase and uppercase letters indicate significant differences among varieties in the control and azadirachtin treatments, respectively (*P* < 0.05, Tukey–Kramer HSD-test). Where no letters exist, no significant differences were noted.

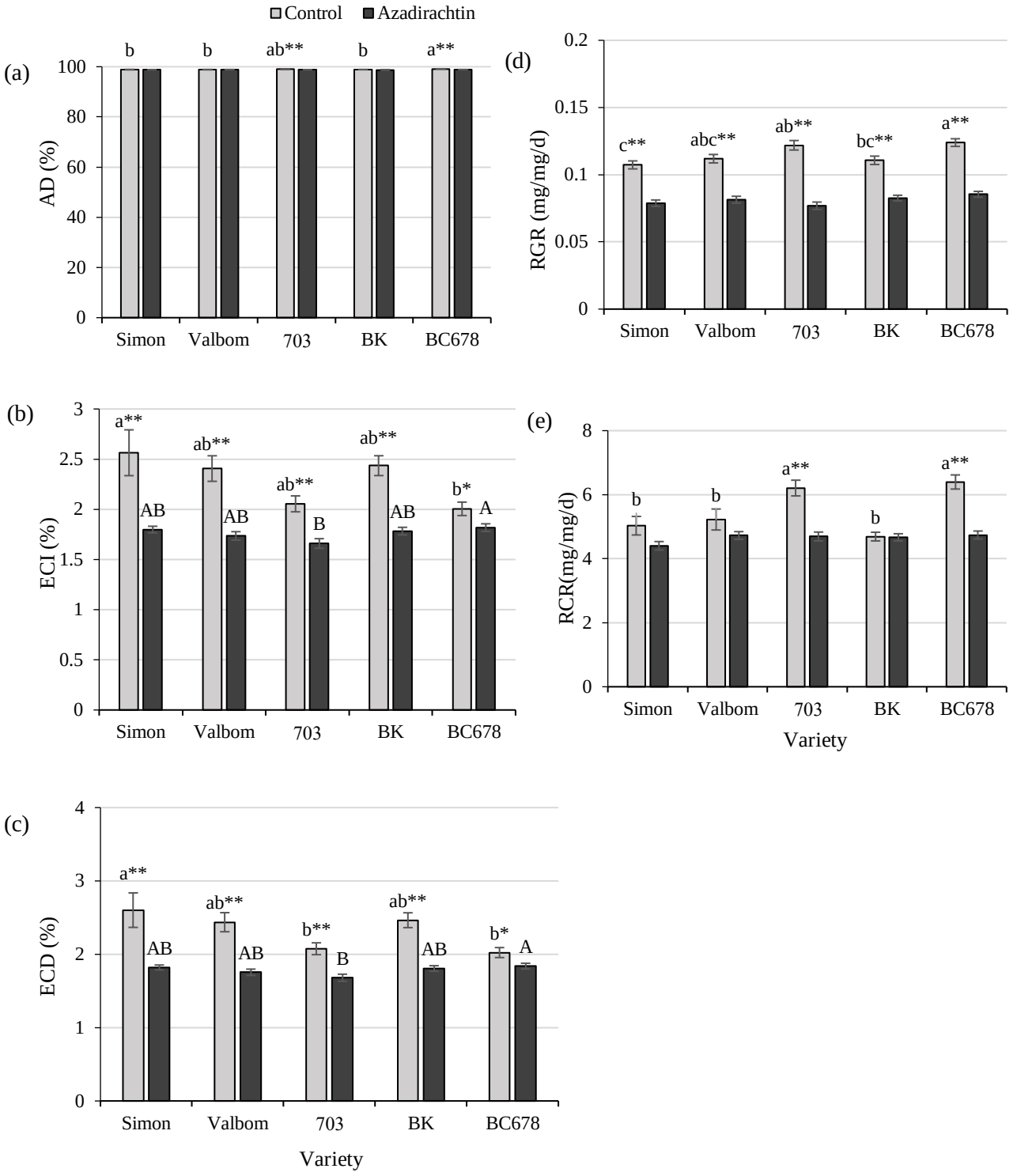


Figure 3. Nutritional indices including AD (a), ECI (b), ECD (c), RGR (d), and RCR (e) (mean ± SE) of *Plodia interpunctella* exposed to azadirachtin-treated kernels of five maize varieties. For each variety, differences between control and azadirachtin are denoted with an asterisk (*P* < 0.05, t-test, SPSS). Different lowercase and uppercase letters indicate significant differences among varieties in the control and azadirachtin treatments, respectively (*P* < 0.05, Tukey–Kramer (HSD)-test, SPSS). Where no letters exist, no significant differences were noted.

Cluster analysis of various maize varieties

Different varieties were grouped within clusters based on the nutritional indices of *P. interpunctella*. Cluster A included sub-clusters A1 (Simon and Valbom) as unsuitable varieties and A2 (BK) as the least suitable variety for rearing *P. interpunctella.* However, cluster B consisted of two sub-clusters, including B1 (703) as a suitable variety, and B2 (BC678) as the most suitable host plant for *P. interpunctella* (Figure 4).

Influences of azadirachtin on the morphological abnormalities in *P. interpunctella*

The mean percentage of normal adults differed significantly among the maize varieties in the control ($F_{4,15}$ = 10.393; P < 0.001), while there were no significant differences in the azadirachtin-treated group ($F_{4,15}$ = 2.029; P = 0.142). For all tested varieties, the percentage of normal adults significantly diminished when the larvae were reared on the azadirachtin-treated kernels compared to the control (Figure 5a). For the malformed adults, no significant differences were witnessed among maize varieties in the control ($F_{4,15}$ = 2.250; P = 0.112), and azadirachtin-treated groups ($F_{4,15}$ = 2.500; P = 0.087). The mean percentage of malformed adults significantly rose when larvae were reared on azadirachtin-treated kernels (Figure 5b). The mean percentage of partial molt adults did not differ significantly among the tested maize varieties in the control ($F_{4,15}$ = 1.050; P = 0.415), and azadirachtin-treated groups ($F_{4,15}$ = 0.357; P = 0.835). No significant difference was observed between the control and azadirachtin groups except for Simon (Figure 5c). The mean percentage of blocked molt pupae did not differ significantly among the varieties in the control ($F_{4,15}$ = 2.250; P = 0.112), and azadirachtin-treated groups ($F_{4,15}$ = 0.750; P = 0.573). The mean percentage of blocked molt pupae was significantly elevated when the larvae were reared on azadirachtin-treated kernels (Figure 5d).

Effects of azadirachtin on the oviposition performance of *P. interpunctella*

Regarding the control group, there were significant differences among maize varieties in the number of eggs and hatch rate. The highest number of eggs was laid on 703, followed by BC678. The lowest percentage of eggs hatched in BK, while no significant difference was observed among other varieties. For all tested varieties, the number of eggs and hatch rate significantly diminished when exposed to the azadirachtin compared to the control (Table 1).

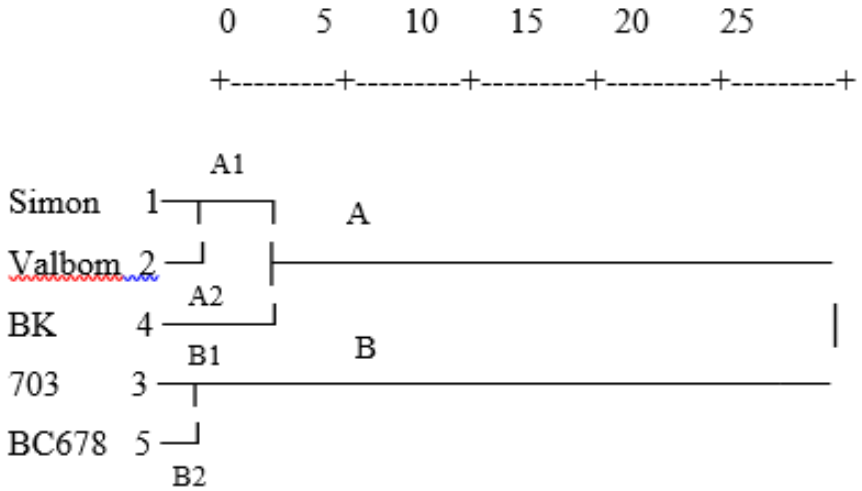


Figure 4. Dendrogram of maize varieties according to nutritional indices of *Plodia interpunctella* reared on different maize varieties (Ward's method).

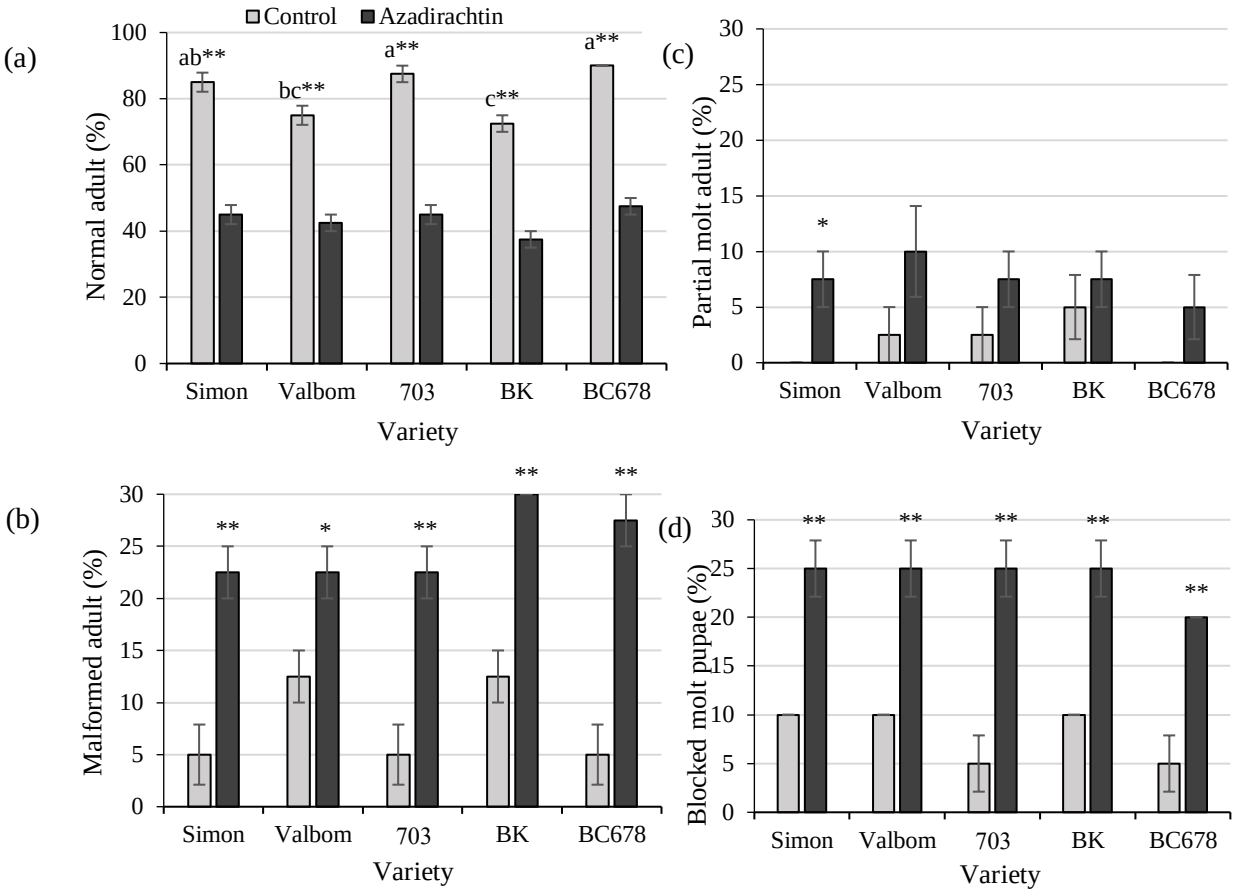


Figure 5. Percentage of normal (a), malformed (b), partial molt adult (c), and blocked molt pupae (d) (mean ±SE) of *Plodia interpunctella* exposed to azadirachtin-treated kernels of five maize varieties. For each variety, differences between control and azadirachtin are denoted with an asterisk ($P < 0.05$, t-test). Different lowercase and uppercase letters indicate significant differences among varieties in the control and azadirachtin treatments, respectively ($P < 0.05$, Tukey–Kramer HSD-test). Where no letters exist, no significant differences were noted.

Table 1. Ovipositional responses (mean ± SE) of *Plodia interpunctella* females exposed to azadirachtin-treated kernels of five maize varieties.

Variety	No. eggs/female		t_{18},	Hatch (%)		t_{18}, P
	Control	Azadirachtin	P	Control	Azadirachtin	
Simon	111.30 ± 4.84b	29.90 ± 0.64bc	16.658, <0.001	88.21 ± 1.16a	42.03 ± 1.52ab	24.068, <0.001
Valbom	114.80 ± 2.49b	32.10 ± 0.46ab	26.118, <0.001	89.64 ± 0.90a	45.56 ± 0.80a	36.455, <0.001
703	140.70 ± 6.07a	35.40 ± 0.86a	17.176, <0.001	87.47 ± 0.91a	40.74 ± 0.62b	42.332, <0.001
BK	110.90 ± 5.45b	27.70 ± 1.07c	14.967, <0.001	79.66 ± 0.61b	42.23 ± 0.71ab	40.024, <0.001
BC678	124.00 ± 8.78ab	29.80 ± 1.34bc	10.599, <0.001	90.35 ± 0.26a	36.27 ± 1.04c	50.369, <0.001
$F_{4,45}$	4.536	9.892		26.809	11.392	
P	<0.001	<0.001		<0.001	<0.001	

For each column, different lowercase letters indicate significantly differences among varieties ($P < 0.05$, Tukey–Kramer HSD-test). In each variety, differences between control and azadirachtin was tested using an independent sample t-test ($P < 0.05$).

Discussion

In the present study, the larval and pupal weights in the control groups were impacted by the type of maize variety. The findings highlight the significant influence of maize variety on the biological characteristics of *P. interpunctella*, including larval and pupal weight, food consumption, and overall pest development. Specifically, the results revealed that larvae reared on maize varieties 703 and BC678 exhibited higher food consumption, leading to augmented larval and pupal weights compared to other varieties. This aligns with previous research by Borzoui et al. (2017), noting the importance of diet in shaping the biological traits of *Sitotroga cerealella* Olivier (Lepidoptera: Gelechiidae) on different grains, including barley, maize, rye, sorghum, triticale, and wheat. The study's cluster analysis further emphasizes that 703 and BC678 are particularly suitable host plants for the growth of *P. interpunctella*, suggesting that these varieties may provide an optimal environment for larval development. This finding is crucial for developing targeted pest management strategies, as it allows for the identification of maize varieties that may be more susceptible to infestation.

Further, the application of azadirachtin at a concentration of 4 ppm (a.i.) indicated its potential as an effective grain protectant against *P. interpunctella*. While high mortality rates were not observed, azadirachtin significantly lowered larval growth and food consumption. These results are in line with previous studies, such as those by Rharrabe et al. (2008) and Lynn et al. (2012), which reported similar findings regarding the effectiveness of azadirachtin at low concentrations against *P. interpunctella* on date fruits and pollen grains (*Actinidia arguta* Planch), respectively. The reduction in larval growth and food intake suggests that azadirachtin may act primarily as an antifeedant rather than a direct toxic agent, thereby affecting the pest's overall development and reproductive capabilities. The results are in accordance with those reported by Rharrabe et al. (2008), who ascertained azadirachtin at the rates of 2 and 4 ppm (a.i.) on date fruits. They found that the toxicity was observed with a decline in *P. interpunctella* larval weight and growth. Many authors have reported that azadirachtin can lower the larval and pupal weight (Koul et al., 2004; Rharrabe et al., 2008; Taffar et al., 2021). The observed reduction in the relative growth rate (RGR) and relative consumption rate (RCR) in the larvae exposed to azadirachtin-treated maize kernels further supports this notion. The adverse effects on growth and survival highlight the potential of azadirachtin as a viable alternative to conventional insecticides, particularly in light of growing concerns regarding chemical residues and resistance development in pest populations. The findings resonate with research conducted by Ferdenache et al. (2019), who indicated that treating grains with azadirachtin not only deters feeding but also negatively affects insect growth and reproduction. Interestingly, the study also indicated that the efficacy of azadirachtin varied depending on the maize variety used. Elsewhere, Xie et al. (1995) stated that the mortality of three stored-product insects (*C. ferrugineus*, *S. oryzae*, and *T. castaneum*, exposed to wheat treated with azadirachtin was a consequence of insect starvation owing to the antifeedant effects of this compound, rather than toxic action. The Salannin type of limonoids isolated from *A. indica* acts as feeding deterrence lowering RGR and RCR values of *Helicoverpa armigera* (Hübner) and *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) (Koul et al., 2004). This observation aligns with findings from Athanassiou et al. (2005), who noted that the effectiveness of azadirachtin (NeemAzal®

formulation) against *R. dominica* is affected by the type of commodity being treated. Such variability underscores the necessity for further research to examine how different physical and chemical characteristics of maize varieties might impact the performance of botanical insecticides like azadirachtin.

The findings of our study revealed that azadirachtin significantly impacts growth of *P. interpunctella*, as evidenced by the high percentage of malformed adults (over 20%) observed across all treated groups. These concords with previous research by Chaudhary et al. (2017), who suggested that azadirachtin disrupts the molting process, causing abnormal molts and subsequent morphological deformities. Similarly, Boulahbel et al. (2015) reported that azadirachtin exposure resulted in various malformations in *Drosophila melanogaster* (Meigen), including partial ecdysis and blocked molts, underscoring the compound's role as a potent growth regulator. Our results further indicate that azadirachtin not only affects adult morphology but also significantly hinders pupal development, with 25% of pupae failing to emerge as adults in all treated varieties except BC678. Given growth regulatory effects, azadirachtin can block the developmental stages of different insects (Koul et al., 2004). This finding supports the assertion by Tofel et al. (2016) that azadirachtin is more effective at inhibiting growth and progeny production than at inducing direct adult mortality on *Callosobruchus maculatus* F. and *Sitophilus zeamais* (Motschulsky). The moth emergence of *Cadra cautella* Walker and *Corcyra cephalonica* (Stainton) (Lepidoptera: Pyralidae) significantly diminished when larvae were exposed to rice and wheat treated with Calneem® oil derived from the neem tree (Adarkwah et al., 2011). Azadirachtin disrupted metamorphosis of *E. kuehniella* leading to different morphologic abnormalities including malformed adults, partial molt, and blocked molt (Taffar et al., 2021). Further, our study revealed a reduction in egg-laying and hatching percentages in *P. interpunctella* exposed to azadirachtin-treated maize kernels, indicating a detrimental effect on reproductive potential. This is in line with findings from Olufemi-Salami et al. (2019), who noted that plant extracts of *Uvaria afzelli* (Scott) could inhibit egg hatching and developmental progression in *Galleria mellonella* L. (Lepidoptera: Pyralidae). The interference of azadirachtin with vitellogenesis and oocyte maturation, as described by Boulahbel et al. (2015), emphasizes its potential to lower fertility in target insect populations.

Conclusion

This study highlighted the complex relationship between maize variety, *P. interpunctella* infestation, and the application of azadirachtin as a grain protectant. Simon and Valbom were unsuitable varieties for *P. interpunctella* growth and development. The findings suggest that selecting less susceptible maize varieties could be a key strategy in managing the Indian meal moth infestations while employing botanical insecticides such as azadirachtin. Azadirachtin disrupts the nutritional performance of *P. interpunctella*, and can be an effective compound to be used as a stored grain protectant to suppress the Indian meal moth population. Nevertheless, future research should focus on elucidating the mechanisms underlying these interactions and exploring additional botanical options to further boost pest management strategies in stored grain systems. This approach not only aims to mitigate post-harvest losses but also aligns with sustainable agricultural practices essential for food security in an increasingly challenging global environment.

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Conflict of interest

The authors have no competing interests to declare.

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