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Article

Attraction of the Indian Meal Moth *Plodia interpunctella* (Lepidoptera: Pyralidae) to Commercially Available Vegetable Oils: Implications in Integrated Pest Management

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Abstract: The Indian meal moth, *Plodia interpunctella*, poses a significant threat to global agricultural products. Although pheromone-based technologies show promise for *P. interpunctella* management, limitations like single-sex targeting necessitate exploring complementary strategies. Vegetable-based oils represent a potential alternative, but their efficacy, sex-specificity, and interaction with sex pheromones remain unclear. To answer these questions, we first examined attraction of *P. interpunctella* female and male adults to ten different vegetable oils, i.e., camellia, corn, olive, peanut, rapeseed, sesame, soybean, sunflower, walnut, and a blended oil (mixture of sunflower seed, rapeseed, soybean, peanut, and sesame oils), in the semi-field conditions. Sesame, olive, and blended oils demonstrated most attractive, capturing significantly more adults compared to other oils. We then evaluated effectiveness of these three attractive oils and their combinations with *P. interpunctella* sex pheromone in a grain warehouse. Traps baited with these oils captured significantly more females and males compared to control traps without attractants. However, sex pheromone addition did not improve male capture and significantly reduced female capture, suggesting an inhibitory effect. Our findings highlight the potential of blended, olive, or sesame oil trap alone as alternative monitoring and trapping tools for *P. interpunctella*, delivering novel insights into the development of efficient integrated pest management strategies for stored products.

Keywords: attractant; *Plodia interpunctella*; sex pheromone; storage pests; vegetable oil

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1. Introduction

Ensuring global food security is a paramount challenge requiring efficient storage and preservation practices. Stored product pests, particularly insects, cause significant quantitative and qualitative losses on stored grains, diminishing their economic value [1,2]. The Indian meal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), is a major polyphagous pest damaging stored grains and processed agricultural products worldwide [3], with reports of emergence even on the Antarctic Peninsula [4,5]. It has been reported that *P. interpunctella* causes damage to many stored products, including herbs, legumes, dried fruits, nuts, cereals, powdered milk, chocolate, birdseed, and dry pet food [6–8].

Infestations by *P. interpunctella* have substantial economic consequences due to direct product loss, pest control costs, and consumer complaints arising from product contamination. Larval feeding and the resulting production of silk and frass (insect excrement) are the primary causes of damage. This degrades product quality, promotes fungal growth, and ultimately leads to spoilage [9].

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Contaminated products become intermixed with insect remains and waste products, significantly reducing their germination rate, nutritional value, and overall safety. This has translated to substantial economic losses in the United States, China, and many European countries [10,11]. Furthermore, *P. interpunctella* can potentially serve as a vector for various pathogens, including bacteria, viruses, fungi, protozoa, and helminths, and has been linked to human allergies such as asthma and skin diseases [12]. Its generalist feeding habits, diverse diet, and high capacity to damage food products have demonstrated its status as a globally recognised pest of significant concern [3,11].

Management of *P. interpunctella* infestations relies on various tactics, including irradiation [13], application of diatomaceous earth and fungal pathogens [14], insect growth regulators [15], and fogging [16]. Fumigation [17], introduction of parasitoid wasps [18], extreme temperature treatments [19,20], and pheromone-based approaches have also been employed [21]. The major components of sex pheromone of female *P. interpunctella* are (*Z*,*E*)-9,12-tetradecadienyl acetate (*Z*9,*E*12–14:OAc) and (*Z*,*E*)-9,12-tetradecadienol (*Z*9,*E*12–14:OH) [22–24], with the highest trapping efficacy at a 7:3 ratio at a 0.5 mg dose [25]. Pheromone-based technologies like monitoring traps, mass trapping, and mating disruption show promise for *P. interpunctella* management [26–30]. However, due to limitations like single-sex targeting and low catch rates [3,8,26], it is necessary to explore the integration of pheromones with other approaches, such as food-based attractants [31–33] to improve efficacy of pest management.

Insects may show specific behavioural responses to various olfactory cues from their social environments [34–41]. Food-derived volatile compounds can be particularly attractive to stored-product pest insects. For example, Storgard Oil, a blended vegetable-based oil with a proprietary composition [42], has been shown to broadly attract many stored product beetle species [42–44]. Studies also show that *P. interpunctella* can be attracted to traps baited with Storgard Oil [45], and prefers wheat kernels treated with walnut oil for oviposition [46]. These findings highlight the potential of vegetable-based oils as attractant lures for *P. interpunctella*. However, several questions remain unexplored: (1) Can a single, commercially available vegetable-based oil effectively attract both female and male *P. interpunctella* adults? (2) Would using blended oils or combining vegetable oils with sex pheromone enhance the attractancy? (3) Is there a sex-specific response to these vegetable oil attractants?

This study addresses these knowledge gaps by conducting two experiments under different environmental conditions. First, a semi-field experiment examined the attraction of *P. interpunctella* females and males to traps baited with 10 commercially available vegetable oils, i.e., camellia, corn, olive, peanut, rapeseed, sesame, soybean, sunflower, walnut, and a blended oil (mixture of sunflower seed, rapeseed, soybean, peanut, and sesame oils). Second, a field experiment explored the attractancy of traps baited with effective oils selected from the semi-field experiment, both alone and in combination with sex pheromone. Knowledge of this study delivers insights into the development of novel, environment-friendly, and cost-effective monitoring and trapping tools for the management of *P. interpunctella*.

2. Materials and Methods

2.1. Insects and Test Oils

We collected hundreds of *P. interpunctella* adults from the Zhoushan Reserve and Transit Grain Deport in Zhejiang Province, and reared the resultant larvae in transparent plastic boxes (26.0 cm length × 20.0 cm width × 12.5 cm height), with pinholes made in lids of boxes for ventilation. Each box housed 400 larvae on 100 g standard diet consisting of bran middlings, glycerol, and yeast with a 10:1:1 ratio [47]. We maintained the colony at 25 ± 1 °C and 60 ± 10% RH with a photoperiod of 16 h light and 8 h dark.

In this study, 10 commercially available vegetable oils (their corresponding suppliers) were used for experiments: Camellia (Lu Hua), corn (Jin Long Yu), olive (Olivolià), peanut (Lu Hua), rapeseed (Lu Hua), sesame (Chu Bang), soybean (Jin Long Yu), sunflower (Lu Hua), walnut (Dao Zi Shu Le), and a blended oil (Jin Long Yu, mixture of sunflower seed, rapeseed, soybean, peanut, and sesame oils).

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2.2. Semi-Field Experiment

The semi-field experiment was conducted in July 2017 in a controlled environmental room (5.0 m length × 5.0 m width × 3.5 m height) located at the Zhoushan Reserve and Transit Grain Deport. The environmental conditions were the same as that for the laboratory colony. Thirty minutes before the scotophase, we prepared the oil baits by mixing 50 ml of each test oil with 75 ml of analytical grade n-Hexane. The oil baits were then applied to traps (i.e., insect sticky boards, 50.0 cm length × 20.0 cm width). The trap coated with 125 ml of hexane solvent only was used as control.

Eleven traps were numbered and randomly allocated along a loop shape with a radius of approximately 2 m from the moth releasing point (a platform) in the centre of the room (Figure 1). The traps and releasing point were 1.5 m above the floor, and the trap interval was approximately 3 meters between. Ten minutes before the scotophase, 30 female and 30 male adults (1–3 days old) randomly collected from the colony were placed on the releasing point. Moths were released soon after lights off and the room was secured. To eliminate the possible effect of trap location on the attractiveness, we rotated the traps clockwise every 8 hours over the subsequent 6 days, so that each trap occupied every position within the loop at least once. The number of trapped adult moths was recorded at the end of experiment and their sex was identified according to morphological characteristics [3]. We repeated the experiment three times, and the room was fully ventilated between each repetition to eliminate any accumulated odours.

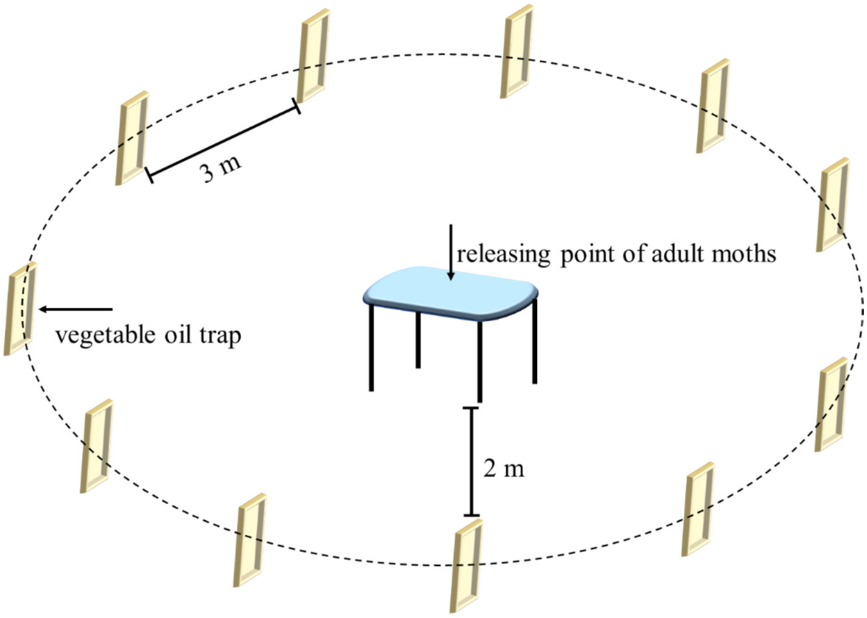

Figure 1. Arrangement of vegetable oil traps in the semi-field experiment.

2.3. Field Experiment

Basing on the high attractiveness of sesame, olive, and blended oils demonstrated in the semi-field experiment (see Figure 3), we conducted a field experiment to investigate potential additive effects of combining these oils with the *P. interpunctella* sex pheromone lure.

We prepared the oil baits as above and applied them to triangular prism sticky traps (20 cm long, side length 8 cm; Pherobio Technology Co., Ltd.; Figure 2). In the combination traps, a female sex pheromone lure containing a 0.5 mg mixture (3:7 ratio) of *Z*9,*E*12–14:OAc and *Z*9,*E*12-14:OH compounds [25] (Shin-Etsu Chemical Co., Ltd., Tokyo, Japan) was placed in the centre button of the trap. This resulted in 8 trap treatments: (1) olive oil only, (2) olive oil with sex pheromone, (3) sesame oil only, (4) sesame oil with sex pheromone, (5) blended oil only, (6) blended oil with sex pheromone, (7) sex pheromone only, and (8) control (no oil or sex pheromone). There were four replicates for each trap treatment with 32 traps in total.

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This experiment was carried out in August 2017 within a *P. interpunctella*-infested warehouse (100.0 m length × 150.0 m width × 12.0 m height) at the Zhoushan Reserve and Transit Grain Deport. The warehouse stored various grain seeds and were ventilated based on the weather conditions. Thirty-two traps were randomly allocated to the arrangement as shown in Figure 2. Traps were 1.5 m above the floor and rotated in order every eight hours over twelve days to ensure each trap occupying each of the 32 positions for at least once. At the end of experiment, the number of trapped moths was recorded and females and males were identified.

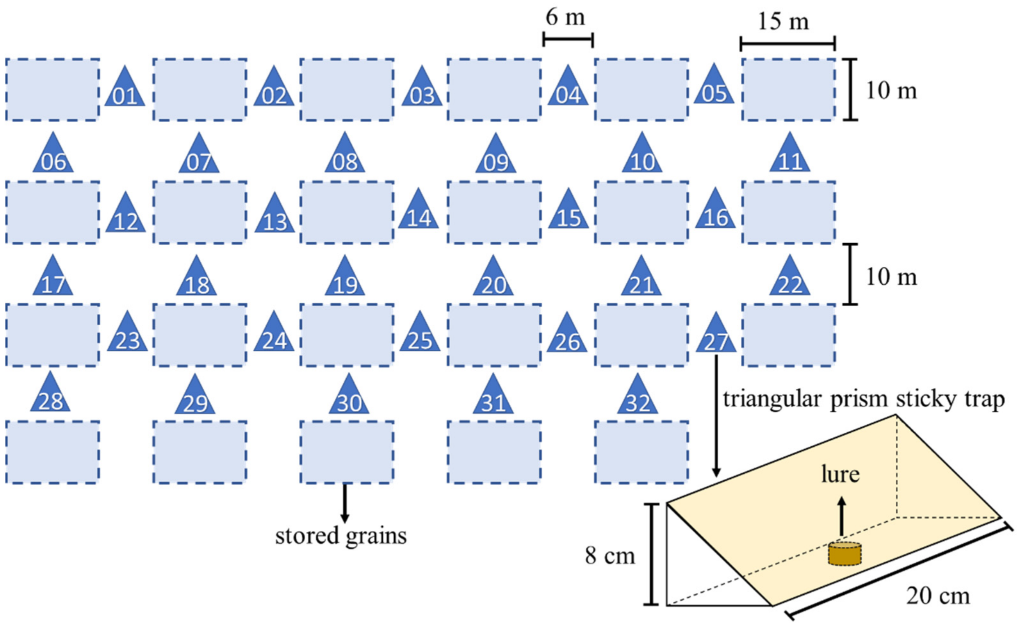

Figure 2. Arrangement of vegetable oil and pheromone traps in the field experiment.

2.4. Statistical Analysis

All data were analysed using SAS v.9.13 software (SAS Institute, Cary, NC, USA) with $\alpha = 0.05$. The raw data from the semi-field experiment and natural-logarithm data [ln(x)] from the field experiment were normally distributed (Shapiro-Wilk test, UNIVARIATE procedure). An analysis of variance (ANOVA) (GLM procedure) was thus applied to compare the difference in number of moths captured between the different baits with a least significant difference (LSD) for multiple comparisons. A paired-t test (TTEST procedure) was used to compare the difference in number of moths captured between sexes for a given trap type in both semi-field and field experiments.

3. Results

3.1. Vegetable Oils Attractiveness to P. interpunctella in Semi-Field Conditions

In the semi-field conditions, sesame oil trap captured significantly more female moths than did olive and blended oil traps, with significantly fewer females captured by the other oil and control traps ($F_{10,22} = 9.86$, $p < 0.0001$) (Figure 3a). The sesame, olive, and blended oil traps captured significant more male moths compared to peanut oil trap ($F_{10,22} = 2.38$, $p = 0.0429$) (Figure 3b). Overall, sesame oil trap had significantly higher efficacy in attracting adult moths than did olive and blended oil traps, and olive and blended oil traps captured significantly more adult moths than the sunflower and walnut oil traps, with significantly fewer adult moths captured by the peanut and soyabean oil traps ($F_{10,22} = 31.32$, $p < 0.0001$, Figure 3c). There was no significant difference in number of moths captured between sexes for all trap treatments ($t_3 = 0$–1.73, $p > 0.05$ for all comparisons).

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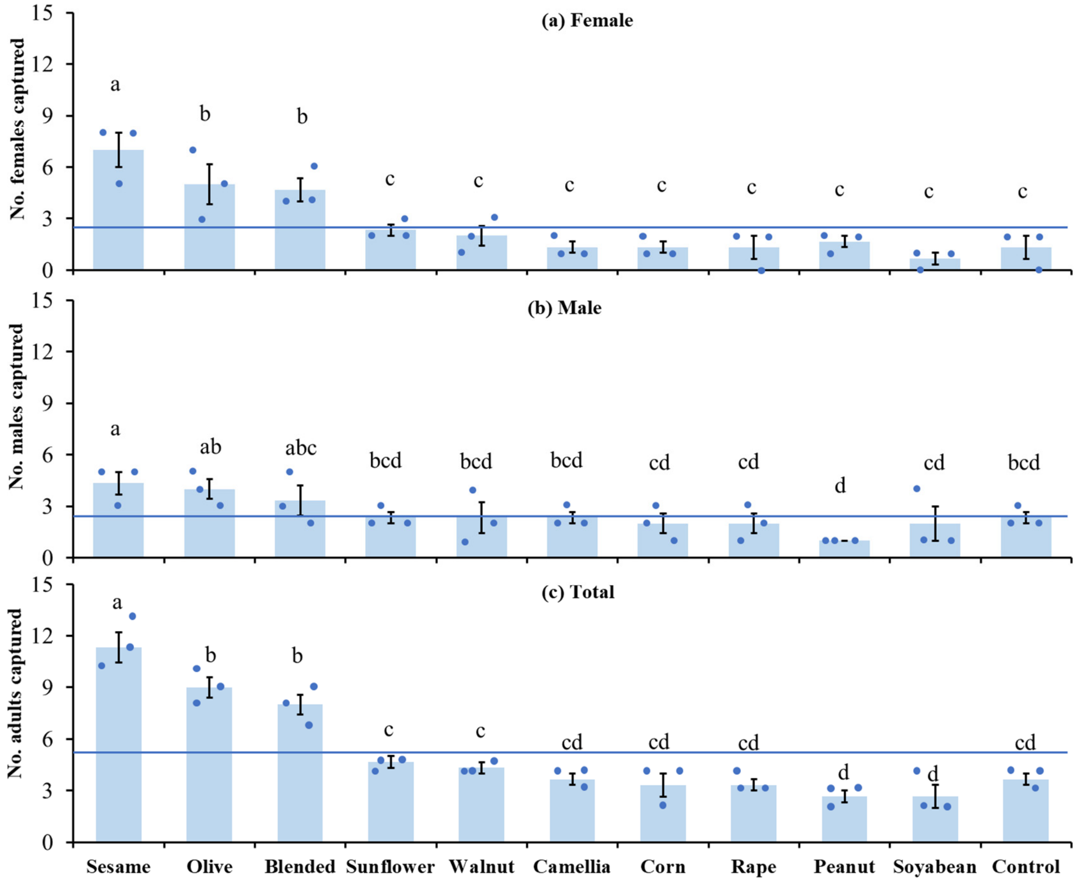

Figure 3. The mean (± SE) number of *Plodia interpunctella* females (**a**), males (**b**), and adults (**c**) captured on sticky traps baited with 10 commercially available vegetable oils in semi-field conditions. Blended refers to the mixture of sunflower, rapeseed, soybean, peanut, and sesame oils. The horizontal line represents the mean number of trapped insects in all treatments. Each dot represents the capture number for a single replicate. Bars with different letters indicate statistically significant differences between oil treatments (LSD test: $p < 0.05$).

3.2. Combined Effects of Vegetable Oil and Sex Pheromone on Plodia interpunctella Captures in Field Conditions

In the field, blended, olive, and sesame oil traps captured significantly more female moths than all other traps ($F_{7,24} = 55.59$, $p < 0.0001$); however, pheromone alone or its combination with blended, olive, or sesame oil did not significantly increase the attraction to the females compared to the control ($p > 0.05$ for all comparisons) (Figure 4a). Blended, olive, sesame oil, and pheromone alone captured significantly more males than the control ($F_{7,24} = 19.19$, $p < 0.0001$); however, the combination of blended, olive, and sesame oil with pheromone did not significantly increase male captures compared to the blend, olive, sesame, or pheromone alone ($p > 0.05$ for all comparisons) (Figure 4b).

Regardless of the sex of moths, the total number of moths captured was significantly higher in blended, olive, and sesame oil traps; and although pheromone alone or its combination with blended, olive, or sesame oil did not significantly increase the number of moths captured, they captured significantly more moths than the control ($F_{7,24} = 50.89$, $p < 0.0001$) (Figure 4c). The blended, olive, or sesame oil traps trapped similar number of male and female moths ($t_3 = 1.29–2.70$, $p > 0.05$ for all comparisons), while pheromone alone or its combination with blended, olive, or sesame oil traps captured significantly more males than females ($t_3 = 6.59–13.66$, $p < 0.05$ for all comparisons) (Figure 4a,b).

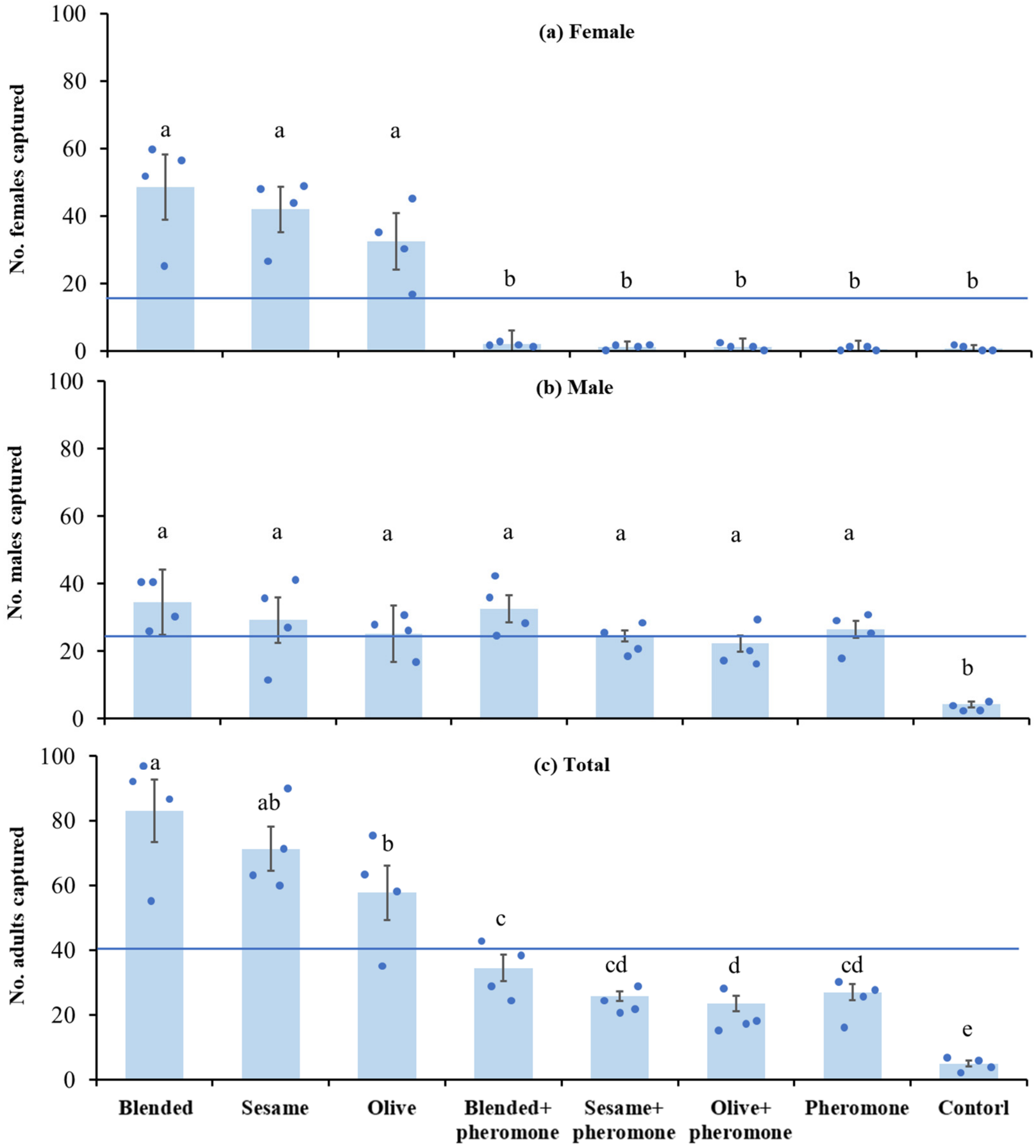

Figure 4. The effect of vegetable oil and pheromone and their combination baits on the mean (± SE) number of *Plodia interpunctella* females (**a**), males (**b**), and all adults (**c**) captured on sticky traps in field conditions. Blended refers to mixture of sunflower, rapeseed, soybean, peanut, and sesame oils. The horizontal line represents the mean number of captured insects in all treatments. Each dot represents the capture number for a single replicate. Bars with different letters indicate statistically significant difference between traps (LSD test: $p < 0.05$).

4. Discussion

This study investigated the olfactory attraction of *P. interpunctella* adults to various commercially available vegetable oils under the semi-field and field conditions. Our results demonstrate that readily available olive, sesame, and blended oils (mixture of sunflower seed, rapeseed, soybean, peanut, and sesame oils) were attractive to both female and male *P. interpunctella* adults (Figures 3 and 4). This is the first evidence on sex-specific attraction of *P. interpunctella* to vegetable oils, as previous work by Morrison et al. [45] only implied attraction of *P. interpunctella* to traps baited with Storgard Oil, a blended vegetable-based oil of undisclosed composition. The volatile compounds in vegetable oils, particularly certain fatty acids, may function as olfactory cues signaling potential food sources to stored product pests [46,48], thus showing attraction to *P. interpunctella* (in this study) and various stored-product pest beetles [42–44]. Such behavioural responses may enhance females' likelihood of finding suitable oviposition sites for oviposition, and offspring feeding and

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development, ultimately improving reproductive fitness [46,49,50], as well as, increase the chance of males encountering females, thereby maximising mating opportunities and reproductive success [51,52]. Exploiting these innate responses of insect pests to food source cues, therefore, provides a foundation for the development of food-based attractant technology for stored product pest monitoring and control [53–55].

Combining pheromones with food cues (e.g., vegetable oils) is a common strategy to enhance the efficacy of pheromone-based insect pest monitoring and trapping [31–33]. This approach will enable the simultaneous attraction of both sexes. However, our results show that the addition of sex pheromones to the effective oil traps did not improve trapping efficacy for *P. interpunctella* (Figure 4c), but rather it significantly reduced the capture rate compared to that of the oil trap alone (Figure 4a). This unexpected outcome was probably attributed to the inhibitory effect of sex pheromone on female attraction. The observed repellent effect on females strongly suggests that *P. interpunctella* females were capable of detecting their sex pheromone, a phenomenon known as autodetection [56–58]. This autodetection behaviour may serve various functions, such as promoting resource conservation [59], increasing mating success [60] and progeny survival [61], and reducing resource competition among offspring [62] and possibility of predation [58,63]. The lack of enhanced male capture rate in traps baited with both vegetable oil and sex pheromone (Figure 4b) remains unclear and warrants further investigation. Based on these findings, we recommend that the blended, olive, or sesame oil trap alone rather than combining them with sex pheromone will be applied to manage *P. interpunctella* in storages for both practical and economic reasons.

Our findings regarding the attraction of sesame and blended oils to *P. interpunctella* differed between semi-field and field conditions. In the semi-field experiment, sesame oil traps captured significantly more adults than the blended oil ones (Figure 3c). However, in the field experiment, the blended oil traps captured a similar number of adults compared to sesame oil ones (Figure 4c), suggesting an increased efficacy of blended oil in field environments. Field environments are inherently more complex compared to controlled semi-field conditions. This complexity could modify the effects of specific volatile components in the attractant lures. The representation of these volatiles can also be altered by factors such as differences in experimental exposure time [38] and concentration [39]. Studies have shown that the mixture of odours present in an environment can significantly impact insects' ability to detect a specific odour, because the background odour may alter the representation of individual odours [39,64,65]. Riffell et al. [66] demonstrate that in the tobacco hornworm *Manduca sexta*, background odours can influence the neuronal representation in the moth's central olfactory system, leading to either excitation or inhibition of its ability to track the scent of the *Datura wrightii* flower bouquet.

Although *P. interpunctella* can infest a wide variety of stored goods, including the raw materials of the tested blended oil [6–8], olives and olive oil are not typically reported as susceptible commodities. Staff at the experimental site confirmed that the storage facilities were primarily used to store dry forms (seeds) of the blended oil components and their by-products, with minimal storage of olives or olive products. The attraction of *P. interpunctella* to olive oil could be due to its structural similarity to the oxygenated compounds found in other attractive oils (i.e., sesame and blended oils) or it represents a previously unknown attractant encountered in certain environments. Furthermore, our field experiment did not directly address the long-range orientation of *P. interpunctella* towards the test traps. Upon initiation of the experiment, moths were likely already present within or around the warehouse [10]. However, the significantly higher capture rate in traps baited with blended, sesame or olive oil alone compared to pheromone or control traps (Figure 4c) suggest that the volatile oil cues were perceivable at a long distance from the traps (Figure 2). Identifying the specific attractant compounds within these effective vegetable oils would be crucial for developing bisexual long-distance attractants for monitoring or trapping *P. interpunctella* in storages.

5. Conclusions

Our study highlights the potential of commercially available vegetable oils as attractants for both female and male adults of *P. interpunctella*. Identifying the specific attractant compounds within these

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oils will help improve food-based monitoring and trapping tools for this important stored-product pest. In addition, investigating the unexpected repellent effect of sex pheromones on females could develop novel management strategies that exploit autodetection behaviour for *P. interpunctella* control. Further research is needed to address the long-distance orientation of *P. interpunctella* towards vegetable-based attractants and the underlying mechanisms influencing the observed sex-specific responses. Overall, this study contributes valuable insights into the olfactory cues influencing *P. interpunctella* behaviour, providing novel knowledge for the development of safer and efficient integrated pest management strategies for pests of stored products.

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