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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Toxicity of Propylene Oxide Alone and Combined with Low Pressure or Carbon Dioxide on the Life Stages of *Plodia interpunctella* Hübner (Pyralidae: Lepidoptera)

Propilen Oksitin Tek Başına ve Düşük Basınç veya Karbondioksit ile Birlikte *Plodia interpunctella* Hübner'in (Pyralidae: Lepidoptera) Yaşam Evreleri Üzerindeki Toksisitesi

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Abstract

The primary objective of this research was to explore the viability of employing propylene oxide (PO) as an alternative fumigant to methyl bromide for effectively and rapidly controlling *Plodia interpunctella* infestations. To this end, laboratory bioassays were carried out to determine the toxicity levels—Lethal Concentration$_{50}$ (LC_{50}) and Lethal Concentration$_{90}$ (LC_{90})—of PO under three conditions: normal pressure (PO alone), low pressure of 100 mm Hg (PO + vacuum), and in the presence of 92% CO_2 (PO + CO_2) against all developmental stages of *P. interpunctella* (eggs, larvae, pupae, and adults) for short exposure time (4 hours). The results of the lethal concentration tests indicated that the most toxic treatment against all biological stages of *P. interpunctella* was the combination of PO and vacuum, followed by the PO + CO_2 combination and PO alone treatment. Compared to the toxicity values with PO alone treated, there was a significant reduction in LC_{90} values ranging from 2.07 to 4.04 times for all biological stages of *P. interpunctella* when PO was treated under vacuum. In the case of the PO+CO_2 combination, there was also a notable decrease in LC_{90} values ranging from 1.24 to 1.95 times. Toxicity data revealed a significantly higher reduction in LC_{90} values with the PO + vacuum compared to PO+CO_2 treatment and suggests a synergistic effect of the combination of PO with 100 mm Hg vacuum and 92% CO_2 on biological stages of *P. interpunctella*. According to the results of lethal concentration tests, it was determined that PO showed different toxicity against the life stages of *P. interpunctella*. As a result of the study, in general, *P. interpunctella* larvae and pupae were the most resistant to PO alone, PO + vacuum, and PO + CO_2 treatments, while *P. interpunctella* adults and eggs were the most sensitive. When exposed to PO alone for 4 hours, the order of tolerance between life stages at LC_{90} was found to be pupa > larva > adult > egg. The results of the study revealed that PO could be a promising alternative fumigant for rapid control of insect contamination. However, further research and testing in real-storage conditions will be essential to validate the practical viability of implementing PO-based fumigation on a larger scale.

Keywords: Propylene oxide, Fumigant, *Plodia interpunctella*, Methyl bromide, Quarantine

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*This study was summarized from the Yeter Bilgili's MSc Thesis.

Öz

Bu çalışmanın temel amacı, metil bromide alternatif olarak propilen oksit (PO)'in *Plodia interpunctella*'nın hızlı ve etkili kontrolü için potansiyel kullanımını araştırmaktır. Bu nedenle, bu çalışma çerçevesinde PO'un üç farklı koşullar altındaki [normal atmosfer basınçta (yalnız PO), 100 mm Hg düşük basınç (PO + vakum) ve %92 CO_2 atmosferinde (PO + CO_2)] *P. interpunctella*'nın tüm biyolojik evreleri (yumurta, larva, pupa ve ergin) üzerindeki toksisite değerlerine [Lethal konsantrasyon$_{50}$ (LC_{50}) ve Lethal konsantrasyon$_{90}$ (LC_{90})] belirlenmesine yönelik laboratuvar çalışmaları yürütülmüştür. Lethal konsantrasyon testleri sonuçlarına göre, *P. interpunctella*'nın tüm biyolojik evrelerine yönelik en yüksek toksisite PO + vakum kombinasyonunda bulunurken, bunu sırasıyla PO + CO_2 kombinasyonu ve yalnızca PO uygulaması izlemiştir. PO + vakum kombinasyonunda; PO'nun tek başına uygulanmasıyla karşılaştırıldığında, *P. interpunctella*'nın tüm yaşam evreleri için LC_{90} değerinde %2.07 ile %4.04 kat arasında değişen bir azalma olurken, PO + CO_2 kombinasyonunda ise %1.24 ile %1.95 kat arasında değişen bir azalma olduğu saptanmıştır. LC_{90} değerindeki azalmanın PO + vakum uygulamasında PO+CO_2 uygulamasına göre daha belirgin olduğu ve düşük basınç (100 mm Hg) ve yüksek karbondioksit içeriğinin (%92 CO_2) PO'nun *P. interpunctella*'ya karşı toksisitesi üzerinde sinerjistik bir etkiye sahip olduğu belirlenmiştir. Lethal konsantrasyon testleri sonuçlarına göre, PO'nun *P. interpunctella*'nın yaşam evrelerine karşı farklı toksisite gösterdiği belirlenmiştir. Yapılan çalışma sonucunda, genel olarak *P. interpunctella* larva ve pupaları tek başına PO, PO + vakum ve PO + CO_2 uygulamalarına karşı en dayanıklı dönemler olurken, en hassas dönemlerin ergin ve yumurtalarının olduğu tespit edilmiştir. Dört saat boyunca tek başına PO'ya maruz bırakıldığında LC_{90}'daki yaşam evreleri arasındaki tolerans sırasının pupa> larva > ergin> yumurta şeklinde olduğu tespit edilmiştir. Çalışmanın sonuçları, PO'nun böcek kontaminasyonunda hızlı kontrol için umut verici bir alternatif fumigant olabileceğini ortaya çıkarmıştır. Ancak, bu uygulamaların pratikte kullanılabilirliğini kesinleştirmek ve ticari ölçekte uygulanabilirliğini belirlemek için daha büyük ölçekli denemelere ihtiyaç duyulmaktadır.

Anahtar Kelimeler: Propilen oksit, Fumigant, *Plodia interpunctella*, Karbondioksit, Düşük basınç

1. Introduction

Propylene oxide (PO) is an important organic chemical raw material known for its clear, colorless, and volatile liquid form (Bilgili, 2015). Compared to methyl bromide, it is recognized that PO has lower environmental risks. In a study conducted by Meylan et al. (1986), the environmental and health impacts of using PO as a fumigant were examined, and it was stated that PO's environmental risks are significantly lower when compared to methyl bromide (MeBr). The research findings indicate that PO does not exhibit ozone-depleting properties, and it undergoes rapid conversion into non-toxic propylene glycol both in the soil and within the human stomach. However, a significant drawback of PO is its flammability in air, ranging from 3% to 37%. Therefore, various measures need to be taken to reduce the risk of ignition for the safe use of PO. One of these methods involves using PO gas in reduced-pressure conditions or within an environment enriched with carbon dioxide (CO_2). This indicates that PO may be an alternative to MeBr for rapid product disinfection (Işikber et al., 2017; Küçüktopçu and Işıkber, 2024a). While previous laboratory studies have demonstrated PO's effectiveness against stored product pests in short-term exposure under low pressure (Küçüktopçu and Işıkber, 2024b), the existing literature provides limited insight into the application of PO in conjunction with CO_2.

Plodia interpunctella (Hübner), commonly known as the Dried Fruit Moth and belonging to the Lepidoptera family Pyralidae, ranks among the prevalent and significant insect pests affecting the long-term storage of valuable commodities, including dried fruits and nuts, worldwide. This moth rapidly multiplies their populations, causing substantial damage to the products and significantly affecting the quality of dry fruits and nuts by feeding on them (Küçüktopcu, 2023). Furthermore, the residue, excrement, and substances secreted by the pest significantly decrease the product's quality and commercial value (Bilgili, 2015; Celik et al., 2008; Ferizli and Emekçi, 2013). Therefore, it has become imperative to develop effective control measures to manage this insect pest and preserve the quality of these high-valued products.

Due to advantages such as rapid effectiveness, extensive applicability, and low cost in combating stored dried fruit and nut pests, MeBr and phosphine have gained widespread recognition as the most commonly used fumigants globally and in Türkiye (Sular et al., 2019). Nevertheless, it is important to note that MeBr has encountered limitations and bans in numerous countries owing to its recognized potential for ozone layer depletion (Schneider et al., 2003; Tütüncü and Emekçi, 2014). The utilization of phosphine comes with specific constraints, including its corrosive nature towards certain metals, potentially leading to irreversible equipment damage, and its flammability at elevated concentrations, posing the risk of accidents during application (Phillips et al., 2012), the development of insect resistance to phosphine (Daglish et al., 2014, Gautam et al., 2016, Sağlam et al., 2015) and its slow action (3 to 10 days for fumigation). Such usage restrictions and environmental concerns have heightened the importance of replacing MeBr and phosphine with alternative methods (Alagöz and Sağlam, 2022). Particularly in the dried fruit and nut industries, the inadequacy of alternatives that allow for the rapid control of insects has resulted in significant adverse impacts on the food industry due to the loss of methyl bromide. Therefore, developing new fumigants that can provide rapid insect mortality in quarantine applications (effective in less than a day) has become an extremely critical necessity.

This study aims to evaluate the effectiveness of three treatment methods: PO alone under normal pressure, PO combined with vacuum at 100 mm Hg low pressure, and PO in conjunction with 92% CO_2 against all developmental stages of *P. interpunctella*, including eggs, larvae, pupae, and adults. This evaluation will entail the determination of toxicity values, specifically Lethal Concentration$_{50}$ (LC_{50}) and Lethal Concentration$_{90}$ (LC_{90}), through a sequence of laboratory bioassays.

2. Material and Methods

2.1. Test insects

In the bioassays, all developmental stages of *P. interpunctella* —adults, larvae, pupae, and eggs—were utilized. The primary insect culture of *P. interpunctella* used in this study was originated from the Laboratory of the Department of Plant Protection, Faculty of Agriculture, Ankara University. The rearing diet consisted of, per 2 kg of wheat bran, 350 g of cornmeal, 350–400 mL of glycerin, 450–500 mL of glucose syrup, and 1 teaspoon of inactive yeast. To minimize the risk of infestation, wheat bran and cornmeal were stored at −20 °C for 3–4 days before use. All ingredients were manually weighed, combined in the specified proportions, and homogenized in a laboratory mixer. To obtain eggs, adults were transferred from culture jars to 3-L glass jars using vacuum assistance, and the jar openings were sealed with mesh covers. After one day in a climate chamber, eggs collected on paper were introduced into 3-L jars containing 350–400 g of diet at a density of 400–500 eggs per jar. The jar openings were covered with gauze of sufficient width to allow air passage. The culture jars were maintained in complete darkness in an incubator at 30 ± 1 °C and 65 ± 5 % relative humidity. These procedures were continued throughout the study to maintain a continuous supply of culture material.

2.2. Fumigation circle and fumigant

The fumigation chamber consisted of 3-L glass jars fitted with metal lids. Each lid contained two metal fittings—one inlet and one outlet—to allow gas entry and exit. To direct the gas flow, two silicone hoses (5 cm in length and 0.62 cm in diameter) were attached to the fittings and secured with metal clamps to prevent leakage. After the lids were closed, silicone sealant was applied around their edges to create an airtight environment and eliminate potential gas leaks. These modifications ensured that vacuum and PPO applications within the fumigation chamber were performed smoothly.

Liquid PO of >99.9 % purity (CAS No. 75569; Catalog No. 33715) was used as the fumigant. The compound was supplied by SERVA Electrophoresis GmbH (Heidelberg, Germany) in a laboratory-grade glass container with a polypropylene cap. For experimental use, PO was transferred into a container sealed with a rubber septum using a gas-tight syringe (Hamilton Company, Bonaduz, Switzerland). A gas-tight micro-syringe with a capacity of 10 or 50 µL was employed to withdraw PO from the glass container.

2.3. Carbon dioxide (CO_2) gas

The CO_2 used in the biological tests, with a purity level of >99.9%, was supplied in a stainless-steel cylinder by Linde Gas (Ankara, Türkiye) company.

2.4. Lethal concentration tests

Lethal concentration bioassays were conducted to determine the LC_{50} and LC_{90} values of PO in combination with low pressure (vacuum) and 92% CO_2, as well as PO alone treatments. Tests were performed on all developmental stages of *P. interpunctella* (egg, larva, pupa, and adult). For each PO treatment, 20 individuals of 1–2-day-old adults, pupae, and late-stage larvae (28–32 days old) were used, whereas 50 individuals of 1–2-day-old eggs were tested. Individuals of each stage were placed in separate 50-mL vials; for larvae, 10 g of fresh food was added to each vial. The vial openings were covered with muslin mesh to prevent insect escape while allowing PO gas to enter. All vials were then placed inside a 3-L gas-tight fumigation chamber fitted with a metal lid.

For PO treatments under low pressure (vacuum), after placing the insects inside the fumigation chamber, air was evacuated from the 3-L chamber using a KNF vacuum pump to reduce the pressure to 100 mmHg. The low-pressure level was monitored with a Celesco SE-2000 vacuum gauge. Liquid PO was then introduced into the chamber through a 10- or 50-µL Hamilton micro-syringe.

For PO treatments under high CO_2 concentration, a low pressure of 60.8 mmHg was first established inside the chamber. CO_2 gas was then circulated until atmospheric pressure was reached, and the concentration of CO_2 was monitored using a CO_2/O_2 measurement device (CheckPoint, PBI-Dansensor, Denmark). Once the desired 92 % CO_2 level was achieved, PO at varying concentrations (seven to eight concentrations) was injected into the chamber via a 10- or 50-µL micro-syringe.

For PO-alone treatments under normal atmospheric pressure, all stages of *P. interpunctella* were placed in the fumigation chamber, and the required concentration of PO was directly injected. In PO + vacuum treatments, six to seven concentrations ranging from 1.5 to 15 µL L^{-1} were applied; in PO + CO_2 treatments, seven to eight concentrations ranging from 1 to 20 µL L^{-1} were tested; and in PO-alone treatments, eight to nine concentrations ranging from 2.5 to 30 µL L^{-1} were used. All life stages of *P. interpunctella* were exposed to PO-alone, PO + vacuum, and PO + CO_2 treatments for 4 h.

To maintain relative humidity at 60 ± 5 % during all PO treatments, a salt solution was prepared by mixing 10 mL of distilled water with 100 g of magnesium nitrate ($MgNO_3$). Half of a 5 × 2 cm drying paper was moistened with this solution and placed inside the fumigation chamber. Throughout the fumigation process, temperature and relative humidity were monitored using external data loggers (Hobo® model U12-012, USA). Following each PO treatment, larvae, pupae, and adults were transferred into 200-mL vials containing their respective food sources and maintained at 26 ± 1 °C and 65 ± 5 % relative humidity until mortality counts were made. Each PO treatment was replicated four times, and control groups for each life stage were also established and replicated four times.

2.5. Evaluation and analysis of data

After 4 h of PO exposure, the lids of the fumigation chambers were quickly closed, and the insect-containing vials were placed in a fume hood for 4 h to allow ventilation. Thereafter, eggs were removed from the vials and placed in plexiglass cells with small perforations, while larvae, pupae, and adults were transferred to new vials containing an ample food supply. All developmental stages were subsequently maintained in a climate chamber at 26 ± 1 °C and 65 ± 5 % relative humidity until live and dead individuals were assessed. Egg hatching was examined one week after PO treatment. Mortality of larvae was defined as the number of individuals failing to reach the pupal stage, and mortality during the pupal stage was defined as pupae failing to reach the adult stage within nine days after PO exposure. For adults, live and dead individuals were counted one day after PO exposure.

To determine the lethal concentration (LC_{50} and LC_{90}) values of PO applied alone, under 100 mmHg low pressure (vacuum), and in combination with 92% CO_2 for all developmental stages of *P. interpunctella*, concentration–mortality data for each stage were analyzed by probit analysis using the POLO-PC program (Leora Software, 1987).

3. Results

3.1. Results of lethal concentration tests

The LC_{50} and LC_{90} values for all developmental stages of *P. interpunctella* exposed to PO alone, PO + CO_2, and PO + vacuum for 4 h are presented in Table 1. Application of PO alone exhibited toxicity to all stages, although susceptibility varied considerably among life stages. Dose–response relationships were evaluated by comparing the slopes and intercepts of the probit regressions and examining differences in LC_{90} values. The slopes of the probit regressions ranged from 2.35 to 16.85.

Under PO alone, the egg stage was the most susceptible, with an LC_{90} of 17.28 µL L^{-1}, followed by the adult (17.83 µL L^{-1}), larval (18.34 µL L^{-1}), and pupal stages (22.66 µL L^{-1}). In the PO + vacuum treatment, the adult stage was most susceptible (LC_{90} = 4.32 µL L^{-1}), followed by the pupal (7.26 µL L^{-1}), egg (8.31 µL L^{-1}), and larval stages (11.86 µL L^{-1}). In the PO + CO_2 treatment, the adult stage was also most susceptible (LC_{90} = 9.13 µL L^{-1}), followed by the egg (12.65 µL L^{-1}), larval (14.71 µL L^{-1}), and pupal stages (16.43 µL L^{-1}).

For *P. interpunctella* adults and eggs in the PO-alone treatment, the lower and upper confidence intervals of the LC_{50} and LC_{90} values for PO alone, PO + vacuum, and PO + CO_2 did not overlap. Based on these values, both PO + vacuum and PO + CO_2 were more toxic to adults than PO alone, with PO + vacuum being the most toxic treatment, followed by PO + CO_2 and then PO alone.

For larvae, comparison of the LC_{50} values showed no overlap in the confidence intervals between PO alone and PO + CO_2, whereas the intervals for PO alone and PO + vacuum overlapped. For the LC_{90} values, the confidence intervals of PO alone and PO + vacuum did not overlap, while those of PO alone and PO + CO_2 did. These results indicate no significant difference in toxicity between PO alone and PO + CO_2 for larvae. However, the PO + vacuum treatment was significantly more toxic to *P. interpunctella* larvae than both PO alone and PO + CO_2.

For *P. interpunctella* pupae, the PO-alone treatment required 10.78 µL L^{-1} and 22.66 µL L^{-1} PO to achieve 50 % and 90 % mortality, respectively. In contrast, PO + vacuum and PO + CO_2 treatments required 5.30–7.26 µL L^{-1} and 4.68–16.43 µL L^{-1} PO, respectively, to reach the same mortality levels. For the LC_{50} values, the confidence intervals of the PO + vacuum treatment did not overlap with those of the PO-alone treatment but did overlap with the confidence intervals of the PO + CO_2 treatment, indicating no significant difference in toxicity between PO + vacuum and PO + CO_2 for pupae. Based on both LC_{50} and LC_{90} values, however, PO + vacuum and PO + CO_2 were more toxic to pupae than PO alone.

Table 1. Toxicity (LC_{50} and LC_{90}) values for all stages of Plodia interpunctella exposed to propylene oxide alone and in conjunction with 92% CO_2 and 100 mm Hg vacuum for 4 hours

Life stages	PO applications	n[a]	Slope±SH	LC_{50} (µL L^{-1}) (Lower-upper confident limit)[a]	LC_{90} (µL L^{-1}) (Lower-upper confident limit)[b]	χ^{2c}	H[d]
Adult	PO	640	5.71±0.97	10.64 (8.92-11.74)	17.83 (16.44-20.37)	17.91	0.69
	PO + vacuum	140	4.23±0.81	1.78 (1.27-2.43)	4.32 (3.95-6.56)	10.39	0.86
	PO + CO_2	480	3.24±0.34	3.68 (3.09-4.20)	9.13 (7.96-10.94)	14.86	0.83
Larvae	PO	640	4.92±0.54	10.07 (9.12-10.92)	18.34 (16.54-21.19)	7.90	0.30
	PO + vacuum	140	16.85±3.07	9.96 (9.37—10.36)	11.86 (11.35-12.79)	8.14	0.63
	PO + CO_2	640	2.42±0.29	4.34 (3.25-5.32)	14.71 (12.31-18.68)	16.42	0.63
Egg	PO	1800	5.96±0.49	10.53 (9.37-11.10)	17.28 (16.37-18.50)	20.33	0.68
	PO + vacuum	350	4.20±0.35	4.12 (3.69-4.51)	8.31 (7.61-9.25)	13.82	0.86
	PO + CO_2	1200	3.60±0.37	5.58 (4.43-6.51)	12.65 (10.85-15.98)	33.76	1.87
Pupae	PO	700	3.97±0.40	10.78 (9.61-11.86)	22.66 (20.07-26.73)	4.99	0.17
	PO + vacuum	140	11.05±2.21	5.30 (4.96-6.52)	7.26 (6.19-8.91)	9.65	0.70
	PO + CO_2	560	2.35±0.33	4.68 (3.42-5.77)	16.43 (13.29-22.71)	7.53	0.34

[a]: Number of individuals tested, excluding controls, [b]: Numbers in parentheses give 95% confidence intervals, [c]: Chi-square ($\chi 2$) value, [d]: Heterogeneity value (H)

4. Discussion

Following the ban on MeBr due to its ozone-depleting effects, alternative chemical fumigants have been sought for the control of stored-product pests (UNEP, 1995). Among these alternatives, PO has shown promising results in short-term applications (Işikber et al., 2006; Navarro et al., 2004). However, environmental conditions during treatment, the type of commodity being fumigated, and equipment performance can all influence the effectiveness of commercial fumigation. It is therefore important to assess the insecticidal efficacy of PO under different environmental conditions to evaluate its potential as a commercial fumigant in the food industry.

In this study, the insecticidal activity of PO applied alone and in combination with vacuum or CO_2 was tested against all life stages of *P. interpunctella*. After a 4-h exposure period, LC_{50} and LC_{90} values ranged from 1.78 to 22.66 µL L^{-1}. Compared to PO applied alone, the combination with low pressure (100 mmHg vacuum) produced the greatest reduction in LC_{90} values across all life stages, followed by the combination with 92% CO_2. Specifically, LC_{90} values decreased 2.07–4.04 fold under PO + vacuum and 1.24–1.95 fold under PO + CO_2 relative to PO alone. These results indicate that both low pressure and CO_2 exerted a synergistic effect on the toxicity of PO.

Our findings align with earlier studies. Zettler et al. (2002) reported that a mixture of PPO and CO_2 (8:92 % w/w) effectively controlled several post-harvest insect pests, including *P. interpunctella*, *T. castaneum*, *T. confusum*, *T. variabile*, *L. serricorne*, *R. dominica*, and *O. surinamensis*, during a 48-h fumigation period. Navarro et al. (2004) observed significant reductions in LC_{50} and LC_{90} values for most developmental stages of *P. interpunctella* when PPO was combined with 100 mmHg vacuum or 92% CO_2, particularly for larvae and adults (6.3–6.6-fold decreases) compared to PPO alone. Işikber et al. (2012) similarly reported that fumigations with PPO in combination with CO_2 or low pressure reduced LD_{99} values for all life stages of *P. interpunctella* and *Ephestia cautella* compared to PPO alone. Küçüktopçu and Işıkber (2024b) demonstrated that PPO + vacuum achieved 100 % mortality in all life stages of *E. cautella* except pupae, whereas PPO alone or PPO + CO_2 did not achieve complete mortality.

The present study also revealed differences in susceptibility among life stages of *P. interpunctella*. Generally, larvae and pupae were the most tolerant stages to all PO treatments, whereas adults and eggs were the most susceptible. Under PO alone, the ascending order of tolerance in terms of LC_{90} values was pupa > larva > adult > egg, which parallels the results of Işikber et al. (2002) for PPO. The observed reductions in LC_{90} and LD_{99} values (up to 6.2–7.1-fold for larvae, pupae, and adults) when PO was combined with vacuum or CO_2 highlight the synergistic enhancement of PO toxicity under these conditions. Similar trends have been documented in other stored-product pests, with eggs often showing the highest sensitivity and pupae the greatest tolerance (Navarro et al., 2004; Işikber et al., 2017; Küçüktopçu and Işıkber, 2024c).

These findings underscore the notable effectiveness of PO, particularly against *P. interpunctella* eggs, even under brief exposure times. This is important because eggs of stored-product insects are notoriously difficult to control with conventional fumigants and contact insecticides, often requiring longer exposure periods. Given the scarcity of fumigants with strong ovicidal properties, further research into PO's ovicidal potential is warranted.

5. Conclusion

This study demonstrates that combining PO with 100 mmHg low pressure or 92% CO_2 substantially increases its insecticidal efficacy against all life stages of *P. interpunctella*, compared to PO alone. Adults and eggs were the most susceptible stages under all treatments, while larvae and pupae were more tolerant. The most pronounced toxicity was achieved with the PO + vacuum combination, followed by PO + CO_2 and then PO alone. These results indicate that PO, particularly when combined with low pressure or CO_2, could serve as a viable alternative fumigant for rapid control of insect infestations in stored products, helping to fill the gap left by the ban on methyl bromide.

To advance PO as a practical fumigant, large-scale commercial trials are needed to validate its efficacy under operational conditions. The outcomes of such trials will be crucial for assessing PO's commercial viability and potential integration into pest management strategies in the food industry.

Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Işıkber, A. A.; Design: Işıkber, A. A. and Küçüktopçu, Y.; Data Collection or Processing: Küçüktopçu, Y. and Işıkber, A. A.; Statistical Analyses Küçüktopçu, Y.; Literature Search: Küçüktopçu, Y.; Writing, Küçüktopçu, Y.; Review and Editing: Işıkber, A. A.

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