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Wood Vinegar: A novel, environmentally friendly insecticide for suppressing storage pests

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Abstract

Global grain security is most threatened by coleopteran pests, such as the khapra beetle, *Trogoderma granarium*, and the southern cowpea beetle, *Callosobruchus maculatus*. Wood vinegar has shown suppression effects similar to synthetic organophosphates, which form the basis of traditional management. The study evaluated the effect of wood vinegar, a novel, environmentally friendly insecticide, on controlling adult *T. granarium* and *C. maculatus*, as well as fourth-instar larvae of the khapra beetle reared on wheat and cowpea seeds. The results showed that breeding adult females of *T. granarium* and *C. maculatus*, and fourth-instar larvae of *T. granarium*, significantly affected the mortality rates of the two insects on wood vinegar-treated wheat and cowpea. We used two wood vinegar concentrations (50% and 100%), and the results showed the highest mortality rates for adult khapra beetle and southern cowpea beetle at 100% (77.44% and 75.68%, respectively). As for the fourth larval stage of the khapra beetle, the highest mortality rate at 100% concentration was 23.98 after 5 days, and wood vinegar reduced the productivity of adult females to the lowest level, as the productivity rate of adult khapra beetle and southern cowpea beetle reached (0.67 and 5.7) eggs/female, respectively, at 100% concentration.

1. Introduction

Grains collected post-harvest and stored for months under suitable conditions are known as stored grains. This term also includes products and foods made from these grains (Mezher, 2022). Cereals play a crucial role in global agriculture. Their significance lies in their link to people's food security. Grains, products, and stored foods supply essential calories and are a primary source of starches in human diets (Shewry, 2007). Insects that infest stored grains are some of the most economically damaging pests. This is because stored grains and their products form the world's largest food source. Warehouse insects pose major threats because they jeopardise grain quality. These insects consume and contaminate grains and related products with their secretions, thereby reducing their economic value (Akrawi and Mahmoud, 2019).

Insects in the order Coleoptera, commonly known as beetles, are among the most important pests affecting stored grains. They account for about 75% of stored-grain pests. The most notable among these are the khapra beetle (*Trogoderma granarium*) from the family Dermestidae and the southern cowpea beetle (*Callosobruchus maculatus*) from the family Chrysomelidae (Abbasi et al., 2021).

The capillary khapra beetle is among the most harmful storage insects and is most resistant to environmental conditions (Mohammed et al., 2019). This pest poses a major risk to cereal storage in Iraq, as its larvae can survive 23 months without food (Al-Mallah and Abdul-Razzaq, 2011). Severe infestations cause total grain loss, leaving only husks and causing health issues from residues (Al-Iraqi, 2002). The southern cowpea beetle is among the most dangerous pests affecting cowpea worldwide (Sedaghat et al., 2014). They first appear in fields in small numbers, then move with the crop to storage.

Even minor field infestations can cause major economic losses in stored beans, as these pests are the main source of spread in post-harvest and legume stores (Khanvilkar and Dalvi, 1984).

Chemical control is the main strategy for managing khapra and southern cowpea beetles because it works quickly. However, these pests have developed resistance to many pesticides (Saljoqi et al., 2006). Pesticide residues also raise health concerns among consumers. To address this, researchers are exploring alternative pest control methods. These include using plant parts or extracts to protect stored grains (Asiry and Zaitoun, 2020). Plants contain unique chemicals that can deter insects or disrupt their growth (Domingue et al., 2022). For example, Rajendran and Sriranjini (2008) tested the insecticidal activity of 75 plant species from various families against stored-grain pests.

Researchers have evaluated 75 plant species from various families for their ability to control stored-grain pests. Wood vinegar (pyroligneous acid) has a deterrent effect similar to that of synthetic organophosphates traditionally used in pest management. Wood vinegar is a valuable by-product produced from the biomass pyrolysis process that takes place during charcoal manufacturing. During the pyrolysis of biomass to generate biochar, the brown liquid collected via condensation is referred to as "wood vinegar. This unrefined wood vinegar comprises tar and other compounds, generally harvested at a temperature of 450°C, while non-condensable gases such CO2, CO, and CH4 are emitted into the environment (Grewal et al., 2018). Othman et al. (2023) reported that wood vinegar repels *Sitophilus oryzae* by 98.3%. Wood vinegar made from Pinus and Cinnamomum species can kill termites (Yatagai et al., 2002) and completely eliminate other storage beetles (Derbali et al., 2023; Oramahi et al., 2023). Wood vinegar's uniqueness stems from its complex chemical composition, which makes pests less likely to develop resistance. Wood vinegar contains over 200 chemicals, mainly guaiacol, phenols, and acetic acid. These chemicals disrupt insects' respiration and metabolism. In addition to its direct toxicity, wood vinegar exhibits strong antifeedant effects (Iacomino et al., 2024). In treated rice, phenolic compounds in wood vinegar discouraged feeding, resulting in only 2% grain weight loss in tests (Othman et al., 2023).

Wood vinegar is recognised as an important tool in integrated pest management (IPM). Combining wood vinegar with small amounts of plant extracts or synthetic insecticides, such as deltamethrin, can increase effectiveness to 90% under various storage conditions (Chidege et al., 2024). As sustainable agriculture becomes increasingly important, wood vinegar offers an environmentally acceptable alternative to synthetic pesticides for pests such as the khapra beetle and southern cowpea beetle. The study assessed wood vinegar's bio-insecticide potential by first determining the lethal dose required to kill adults in both species. The study then examined the susceptibility of khapra beetle larvae, focusing on the stage most damaging to stored grains. Finally, the study evaluated whether wood vinegar reduced the pests' reproductive output.

2. Materials and methods

2.1. Insect Rearing

The Insect Laboratory at Kufa University's Faculty of Agriculture provided Khapra and Southern cowpea beetles. The Natural History Museum in Baghdad confirmed species identity. The insects were reared in glass containers (9 × 15 cm) containing 200 g of sterilised wheat (for *T. granarium*) or cowpea (for *C. maculatus*). The openings were covered with fine muslin cloth, a lightweight, loosely woven cotton material that allows airflow but prevents insects from escaping, and secured with rubber bands. The insects were kept in an incubator at 30 ± 1°C and 60 ± 5% relative humidity (Al-Iraqi & Suleiman, 2002). Colonies were kept viable by adding both adult and larval insects to fresh sterile food sources, ensuring a consistent supply of insects for experiments.

2.2. Wood Vinegar Source and Preparation

Generating wood vinegar from indigenous eucalyptus timber relies on the thermal breakdown of wood in an oxygen-free environment, a method known as carbonisation or destructive distillation. The vapours and gases produced in this procedure are gathered and condensed to produce liquid wood vinegar. The technique begins with selecting premium, dry, impurity-free local eucalyptus timber, then chopping it into smaller fragments to optimise pyrolysis. This study used wood vinegar, a byproduct of wood pyrolysis from Palm, sidr, and Eucalyptus, derived from the vapour condensation of thermally treated hardwoods in an anoxic environment (AL-Janabi, 2020), and sourced from local laboratories in Mosul. Bioassays were performed at 50% and 100% concentrations. The Mosul-based Al-Amin Laboratory for Agricultural Material Production extracted wood vinegar. These concentrations were chosen to compare an undiluted and diluted wood vinegar solution. Because this study was not intended to predict LC_{20} values, a more comprehensive concentration series would be needed for precise $LC•_{0}$ determination.

2.3. Effectiveness of Wood Vinegar on Adult Beetles

The effectiveness of wood vinegar was assessed by applying 5 mL of each concentration (50% and 100%) to 500 g of sterile wheat and cowpea seeds (Local variety) purchased from local markets. They mechanically agitated the seeds for uniform coating and air-dried them in an incubator (25 ± 5°C). The experimental setup comprised three replicates of 5 g of treated seeds in plastic vessels, each containing 10 adults (5 males and 5 females), incubated at 30 ± 1°C, with daily mortality monitored over 5 days using distilled water as the sole treatment.

Wood Vinegar on Fourth-Instar larvae of T. granarium

The aforementioned treatment protocol was implemented on sterile wheat, with 10 fourth-instar larvae introduced per replicate (3 replicates per concentration), and mortality was monitored daily over a 5-day incubation period.

2.4. Impact of Wood Vinegar on Fecundity

Five grams of seeds were subjected to 1 mL of wood vinegar at 50% and 100% concentrations to evaluate reproductive effects. Adult pairs of *T. granarium* and *C. maculatus* were incubated with treated wheat and cowpeas, respectively, after which egg counts were recorded after removing the adults.

2.5. Statistical Analysis

The study used a Completely Randomised Design (CRD), and data were analysed in Genstat version 12.1 (2009), with significance assessed using the Least Significant Difference (LSD) test at $P < 0.05$. Mortality rates were adjusted using the Schneider-Orelli formula (1971) to reflect natural mortality in control groups, and percentage data were angular (arcsine) transformed to improve normality before analysis (Al-Rawi and Khalafallah, 2000).

3. Results and Discussion

3.1. Wood Vinegar Concentrations on the Mortality of Adult Beetles

The empirical findings in Table 1 detail the complex relationship between wood vinegar concentration and exposure duration, with particular focus on its implications for adjusted mortality rates of adult *T. granarium*. Wood vinegar efficacy increased with concentration, reaching a corrected mortality rate of 81.5% at 100% concentration by day five, while 50% concentration yielded 64.4%, highlighting concentration-dependent variability in mortality outcomes. Temporal factors proved pivotal to the success of wood vinegar treatment, underscoring the importance of exposure time: early applications showed low mortality that increased dramatically by day five. Wood vinegar swiftly demonstrated its insect-slaying prowess, underscoring its promise as a powerful pest management tool. On the first day of treatment, substantial corrected mortality rates were observed: 26.6% at the 50% concentration and 63.3% at the 100% concentration, underscoring wood vinegar's efficacy as a highly toxic agent particularly harmful to the Khapra beetle. The accumulation and intensification of lethality with prolonged exposure offer insights beyond mere observation, providing essential knowledge for integrating wood vinegar into advanced pest management strategies to control the Khapra beetle, a significant threat to agricultural products. The complex relationship between wood vinegar concentration and exposure duration warrants further rigorous study, particularly in entomological research and in developing innovative pest control strategies that could enhance pest management efficacy and promote sustainable agriculture and food security.

Table 1
Corrected mortality (%) of adult *T. granarium* exposed to various concentrations (50 and 100%) of wood vinegar over specified time intervals.

Wood Vinegar Concentrations (%)	Day 1	Day 2	Day 3	Day 4	Day 5	Concentration Impact Rate (Mean)
50.0	26.6	46.6	50.6	57.5	64.4	49.14
100	63.3	80.0	77.7	84.7	81.5	77.44
Average per Day	44.95	63.30	64.15	71.10	72.95	—
L.S.D. (0.05) : Concentration: 1.509, Time intervals (Days): 2.385, Interaction (Concentration × Time) : 3.374						

The elevated mortality rates documented in this investigation (84.7% at 100% concentration) are consistent with the observations of Tiilikkala et al. (2010), who reported that wood vinegar acts as a potent biocide, attributable to its composition of more than 200 chemical constituents, predominantly acetic acid and phenolic compounds. The swift "knockdown" effect observed within the first 24 hours at the highest concentration aligns with Theapparat et al. (2015), who showed that low pH, along with organic acids in pyroligneous acid, penetrates the insect cuticle and causes physiological distress and mortality. The notable interplay between concentration and duration suggests a cumulative toxic effect. Konecka and Stepnowski (2021) support this, noting that extended exposure to wood vinegar vapours increases the internal accumulation of toxic phenolic compounds in the insect's respiratory system. While *T. granarium* is recognised for its considerable resistance to conventional insecticides, owing to its robust larval hairs and adult cuticle, the substantial mortality observed in this study suggests that wood vinegar may circumvent these physical barriers more effectively than certain botanical oils. This study echoes Oramahi et al. (2013) by demonstrating that increasing wood vinegar concentration significantly boosts the demise of wood-infesting pests, showcasing its dual role as a contact poison and repellent, making it a promising eco-friendly substitute for synthetic fumigants like phosphine, which are facing pest resistance issues (Konecka et al., 2021).

3.2. Wood Vinegar Concentrations on the Mortality of *C. maculatus*

Table 2 shows the effects of varying wood vinegar concentrations and exposure duration on the modified mortality rates of adult *C. maculatus*. Statistical analyses indicate significant differences among all variables investigated. *C. maculatus* demonstrated remarkable susceptibility to wood vinegar, particularly at the 100% concentration, where the mortality rate surged to an impressive 90.9% by the fifth day. A strikingly positive association emerged between exposure time and mortality, with mortality rising from 46.6% on Day 1 to 77.4% by Day 5; notably, the 100% concentration outperformed the 50% concentration, yielding mean impact rates of 75.68% versus 52.24%. Remarkably, by Day 4, the full concentration achieved a staggering 90.5% mortality rate, demonstrating the effectiveness of swift control.

Table 2
Corrected mortality (%) of adult *C. maculatus* treated with wood vinegar at 50 and 100%.

Wood Vinegar Concentrations (%)	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Conc. Impact Rate (mean)**
50	36.6	46.8	53.5	60.4	63.9	52.24
100	56.6	66.9	73.5	90.5	90.9	75.68
Average per Day	46.60	56.85	63.50	75.45	77.40	—
L.S.D. (0.05): Concentration: 1.078, Time intervals (Days): 1.704, Interaction (Concentration × Time): 2.410						

Table 3
Adjusted Mortality Rates (%) of fourth instar *T. granarium* treated with Wood Vinegar at 50 and 100%.

Wood Vinegar Concentration	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Mean mortality (%)**
50%	6.6	13.3	16.6	26.6	26.6	17.94
100%	13.3	23.3	23.3	30	30.7	23.98
Mean of Days	9.95	18.3	19.9	28.3	28.3	—
L.S.D. (0.05), Concentrations : 0.496, **Time intervals (Days)**: 0.785, **Interaction (Concentration × Time)**:1.11						

The elevated mortality rates observed in *C. maculatus*, compared with those in *T. granarium* (which reached a maximum of 84.7%), may be attributable to distinct physiological characteristics of each species. As Theapparat et al. (2015) highlight, wood vinegar contains organic acids and phenolic compounds that act as contact toxins. The comparatively thinner cuticle of the Southern cowpea beetle presumably facilitates faster absorption of these toxic agents compared with the thicker, hair-covered cuticle of the Khapra beetle (Konecka & Stepnowski, 2021). This interaction underscores that wood vinegar is most effective when applied at elevated concentrations for at least 4 days. These results support using wood vinegar as an effective biofumigant to protect pulse crops against *C. maculatus* infestations, offering a more environmentally friendly alternative to synthetic pesticides (Wititsiri, 2011). A comparative analysis of the two tables indicates that wood vinegar is effective against both pest species, with Southern cowpea beetles showing higher susceptibility and mortality rates exceeding 90%, while Khapra beetles exhibit greater resistance, with mortality rates around 85%.

3.3. Efficacy of Wood Vinegar Against *T. granarium* larvae

The study revealed a significant relationship between wood vinegar concentration and exposure duration in the fourth larval instar of *T. granarium*, with a maximum mortality of 30.0% at 100% concentration after 120 hours. Although initial toxicity was evident, the low peak mortality suggests the need for higher concentrations or extended exposure to determine a definitive LC50, given the larvae's physiological

tolerance. The 100% concentration exhibited a higher mean effect (23.98) than 50% (17.94). The difference of 6.04 exceeds the LSD threshold (0.496), indicating statistical significance.

3.4. T. granirum fecundity

Wood vinegar dramatically reduced *T. granarium* fecundity, dropping to 1 and 0.67 eggs/female at 50% and 100% concentrations, respectively, compared with 13.67 eggs/female in the control group. The control treatment produced the highest egg production (13.67 eggs per female). Both 50% and 100% concentrations significantly reduced egg production. The differences were: Control vs. 50% = 12.67, Control vs. 100% = 13.00, both surpassing LSD (4.84), indicating highly significant differences. The difference between 50% and 100% was 0.33, which is below LSD (4.84), thus not statistically significant. The lack of a notable difference between 50% and 100% concentrations indicates a threshold effect, suggesting that diluted wood vinegar can nearly optimise reproductive suppression. Recent studies on wood vinegar have revealed similar non-linear dose responses, with lower concentrations yielding comparable or optimal biological effects based on the target pest and exposure conditions (Kim et al., 2021; Zhang et al., 2022).

3.5. C. maculatus fecundity

Wood vinegar dramatically reduced female southern cowpea beetle *C. maculatus* egg production to 50% (12%) and 100% (5.7%) of the control, compared with 68.3 eggs/female in the control group (LSD = 23.80). The control treatment yielded the highest egg production (68.3 eggs per female). Both 50% (12.0) and 100% (5.7) concentrations markedly diminished egg production. The differences observed: Control vs 50% = 56.3; Control vs 100% = 62.6, both exceeding LSD (23.80). These differences are highly significant. The difference between 50% and 100% is 6.3, falling below LSD (23.80). Hence, it is not statistically significant. Wood vinegar negatively affects egg production in a dose-dependent manner compared to the control, with no significant difference between the two concentrations.

This comprehensive study aligns closely with Akkus et al. (2022), who confidently assert that oak wood vinegar significantly protects Scottish pine trees from the detrimental effects of the beetle Hylotrupes bajulus, a member of the Cerambycidae family within the Coleoptera order. This assertion gains additional validation and support from the scholarly investigations conducted by Adfa et al. (2020), who revealed that wood vinegar, which is derived from the distillation or extraction of the wood of the cinnamon tree, scientifically referred to as Cinnamomum parthenoxylon, led to a notable escalation in the mortality rates of termite populations, a finding that is in alignment with the conclusions drawn by Lee et al. (2010) in their thorough investigative analysis. Furthermore, the observations articulated by Wititsiri (2011) suggest that the organic acids contained within wood vinegar, which include acetic acid at a concentration of 42.91%, 3-butenoic acid at 6.89%, and butanoic acid in its 2-propenyl ester form at 2.26%, in conjunction with a variety of ketones such as 1-hydroxy-2-propanone at 5.14% and 3-methylcyclopentane-1,2-dione at 2.34%, play a crucial and instrumental role in the biochemical processes that ultimately lead to the eradication of termite populations, thereby highlighting the intricate chemical complexity that is inherently associated with wood vinegar as a biocontrol agent.

The study showed that wood vinegar significantly reduces the reproductive capability of adult female *Trogoderma granarium*, as indicated by a notable decrease in oviposition at both tested concentrations. This inhibitory effect supports previous research on the insecticidal and reproductive-suppression properties of wood vinegar and pyroligneous acid in pest management (Othman et al., 2023; Akkuş M et al., 2022). The effectiveness of wood vinegar largely stems from its chemical constituents, including organic acids like acetic acid, phenolic compounds, and ketones, which induce physiological stress, disrupt enzymatic activity, and alter hormonal regulation in insects. Recent studies confirm that these components demonstrate dose-dependent toxic, repellent, and growth-inhibitory effects on insect populations (Isman, 2006; Othman et al., 2023; Anggrayni et al., 2025).

These findings enhance the rising global interest in wood vinegar as a sustainable pest management approach. Recent reviews emphasise that wood vinegar is increasingly recognised as a biopesticide within integrated pest management (IPM) frameworks due to its broad-spectrum efficacy, low environmental persistence, and compatibility with sustainable agricultural practices (Mohan et al., 2023; Oramahi and Yoshimura, 2022). Therefore, the significant oviposition-suppressive effect observed in this study highlights its potential to manage stored-product pests effectively and reduce Trogoderma granarium population growth in storage settings. The current results showed that wood vinegar had insecticidal and reproductive-suppressive properties against *Trogoderma granarium* and *Callosobruchus maculatus* in a lab setting. However, more research using a wider range of concentrations, longer observation periods, and real commercial storage settings is needed to validate its usefulness and assess its viability as part of pest control for stored products.

4. Conclusions

Wood vinegar has been shown to be highly effective in managing and controlling the hopper beetle, a notable and damaging pest that poses a serious threat to stored grains and other agricultural products. Furthermore, research indicates that this natural substance may reduce the reproductive capacity of both the granary beetle and the southern cowpea beetle under rigorous laboratory conditions simulating various environments. However, additional comprehensive studies are needed to verify and assess precise LC_{50} values and to confirm seed survivability, emergence, seed quality, and germination. Furthermore, to confirm its efficacy as a sustainable pest management strategy, real-world commercial storage studies are required, where variables may differ significantly from those in laboratory settings. Research in this area is essential to validate wood vinegar's effectiveness as a sustainable pest management solution in agriculture, thereby enhancing food security amid pest challenges.

Declarations

CRediT authorship contribution statement

Ruqaya Ali Kadhim: Writing – review & editing. Abdullah N. Ali: Writing – review & editing, Supervision, Resources, Funding acquisition. Battol Qasem Kteo: Writing – original draft, Investigation, Formal

analysis, Conceptualisation. Sahar Mohammed Jawd: Writing – review & editing, Formal analysis. Sahayaraj Kitherian: Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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