DOI: 10.21608/alexja.2025.400193.1152

Insecticidal Potency and Biochemical Activity of *Beauveria bassiana* and *Cymbopogon schoenanthus* Extract on *Sitophilus zeamais* (Coleoptera: Curculionidae)

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ARTICLE INFO
Article History
Received: 02/07/2025
Revised: 13/07/2025
Accepted: 13/07/2025

Key words: *Beauveria bassiana*, *Cymbopogon schoenanthus*, *Sitophilus zeamais*, biocontrol, oxidative stress, sesquiterpenes, stored grain, antioxidant enzymes.

ABSTRACT

Among the important postharvest challenges that pest grain infestation causes worldwide, one of the most destructive primary pests of cereal grains is the *Sitophilus zeamais*. The current study investigates and compares the biocontrol potential of the entomopathogenic fungus *Beauveria bassiana* and the ethyl acetate extract of *Cymbopogon schoenanthus* against *S. zeamais* in terms of evaluating insecticidal efficiency and biochemical effects on oxidative stress biomarkers. *C. schoenanthus* extracts yielded nine major bioactive compounds by GC-MS analysis, the predominant ones being α-eudesmol (43.9%), elemol (15.66%), and cryptomeridiol (13.38%). Bioassays indicated concentration-dependent mortality for both treatments: *B. bassiana* yielded 80.0% mortality at 14 days (LC_{50}: 1.08×10^6 spores/mL), whereas *C. schoenanthus* extract yielded 73.0% (LC_{50}: 29.42 mg/mL). Both treatments reduced F_1 progeny production significantly by 81.5% (*B. bassiana*) and 70.6% (*C. schoenanthus*), where losses in weight of grains were only reduced to 2.4% and 5.2%, respectively, compared to the 30% loss observed in controls. Biochemical evaluation indicated different responses to oxidative stress. *C. schoenanthus* extract caused chronic but manageable oxidative stress with the sustained rise of the antioxidant enzymes (catalase: 1.53-fold, superoxide dismutase: 1.28-fold, glutathione S-transferase: 1.34-fold), and mild lipid peroxidation by 44.1% MDA increase. *B. bassiana* exhibited a biphasic pattern: initial enzyme upregulation followed by the total collapse of the antioxidant system at day five (20-22% below control levels), accompanying severe oxidative damage (71.2% MDA increase), synchronizing with increased mortality. Both fungal and botanical biocontrol agents are promising eco-friendly alternatives to synthetic pesticides for stored grain pest management, as this study's findings show.

INTRODUCTION

Stored grain postharvest loss, food security, and economic stability are indeed global challenges. An estimated 10–40% of stored grains are lost annually worldwide due to pest infestation, with losses increasing to $100 billion in economic terms (Kumar and Kalita 2017; Olakiumide 2021; Tefera et al. 2011). In Egypt, losses are particularly severe, amounting to approximately 15–20% of total grain production annually, aggravated by the fact that these losses hinder the country from adequately feeding its increasing population of over 100 million (Abdelaal and Thilmany 2019; El-Wakeil et al. 2013). For smallholder farmers in Egypt, who constitute approximately 80% of the agricultural sector, postharvest losses are associated with reduced income and food availability; thus, pest control is an important national economic focus (Ali et al. 2021a; Hussien 2022).

Among storage pests, the maize weevil *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) is considered one of the most destructive primary pests of stored cereals in the world, especially in tropical and subtropical regions (Demis and Yenewa 2022; Nwosu 2016; Suleiman et al. 2015). This pest inflicts considerable damage by eating grain kernels directly and creating conditions for infestation by secondary pests and fungal contamination (Suleiman et al. 2015). Adult weevils bore into the kernels for feeding and egg laying, whereas the larvae develop inside by consuming the endosperm and the germ, which results in weight loss, a reduction in nutritional value, a decrease in the germination rate, and, finally, substantial monetary losses (Arrahman et al. 2022; Ojo and Omoloye 2016).

Over the years, insect control for stored grain has depended mainly on chemical insecticides. Many commonly used agents include organophosphates, pyrethroids, and fumigants such as phosphine and methyl bromide (Collins 2006; Daglish et al. 2018; White and Leesch 2018). While they provide short-term results, this chemical control method faces resistance from insects, environmental contamination, human and nontarget organism health hazards, and residues on food commodities (Ali et al. 2021b; Kumar et al. 2019). The more adaptable maize weevil populations have shown resistance to several insecticides, including phosphine, which has been recorded in different areas of the world (Nguyen et al. 2016; Wakil et al. 2021). The increasing restrictions on the use of many conventional pesticides due to health and environmental concerns have created an urgent need for alternative control strategies (Damalas and Eleftherohorinos 2011).

Entomopathogenic fungi (EPFs) represent a promising alternative form of biological control that can be used for the management of pests that infest stored grains. *Beauveria bassiana* (Balsamo) Vuillemin, among other EPFs, has become an effective agent for biocontrol of various storage products, such as *S. zeamais* (Ak 2019; Mbata et al. 2018). The colonization process by this fungus takes place when insects come into contact with spores, and the subsequent release of spores results in penetration of the cuticle via enzymatic tolerance as well as mechanical pressure, causing depletion of nutrients, invasion of tissues, and toxin production, eventually causing death (Barra-Bucarei et al. 2019; Litwin et al. 2020). Some of these advantages of *B. bassiana* over chemical insecticides are target specificity, environmental friendliness, low risk to human health, and compatibility with other pest management strategies (Lacey et al. 2015). The efficacy of *B. bassiana* against stored-product insects in laboratory and storage trials has been reported, with recorded mortality rates ranging from 70–95% depending on the fungal strain, formulation, and application method (Cherry et al. 2005; Sabbour and Abd-El-Aziz 2012).

Concurrently, the use of botanical insecticides from aromatic plants has emerged as a good alternative to synthetic chemicals used for the protection of stored products. These include essential oils and plant extracts, which are complex mixtures of bioactive compounds with insecticidal, repellent, antifeedant, and growth-regulating properties against several stored-product pests (Campolo et al. 2018; Trivedi et al. 2018). *Cymbopogon schoenanthus* (L.) Spreng. (Poaceae), or camelgrass, is also an aromatic grass found in North Africa and the Middle East, with proven insecticidal efficacy (Ketoh et al. 2005; Savadogo et al. 2020). The essential oil and extracts from this plant contain bioactive compounds that include piperitone, δ-2-carene, and elemol, which have been demonstrated to be quite toxic to many stored-product insects(Alitonou et al. 2012; Ketoh et al. 2005; Koba et al. 2009). Previous studies have shown that extracts of *C. schoenanthus* can cause mortality, suppress oviposition, and inhibit the production of F1 progeny in different storage pests, such as *Callosobruchus maculatus* and *Tribolium castaneum* (Ketoh et al. 2005; Nyamador et al. 2017).

Another sustainable means of dealing with stored grain pests is the use of plant insecticides such that biodegradable alternatives with a lower environmental footprint and a low risk of resistance development are made available to customers. *C. schoenanthus* (L.) Spreng., commonly called camelgrass or sweet rush, belongs to the Poaceae family. It has been acknowledged for its potent insecticidal activity due to its bioactive components, such as essential oils, terpenoids, and phenolic compounds (Aous et al. 2019). Research has shown the effectiveness of *C. schoenanthus* extracts and essential oils against different stored-grain pests through multiple action mechanisms, including contact toxicity, repellency, and feeding deterrent (Pérez et al. 2010). Previous investigations have shown that the essential oils from *C. schoenanthus* are effective against, inter alia, coleopteran storage pests such as *Tribolium castaneum* and many others of economic significance (Stefanazzi et al. 2011). They are also biodegradable, remain less persistent in the environment, have lower prospects for resistance development, and are generally regarded as safe for ingestion by humans when well applied(Trivedi et al. 2018).

Oxidative stress mechanisms play a major role in insect physiology, which in turn is a significant target in understanding the actions of several pesticides and biopesticides. The insect has a highly sophisticated antioxidant defense mechanism with both enzymatic and nonenzymatic components to prevent reactive oxygen species (ROS) damage to cellular structures (Bhagat and Ingole 2016). The key antioxidant enzymes include catalase (CAT), which breaks down hydrogen peroxide; superoxide dismutase (SOD), which neutralizes superoxide radicals; and glutathione S-transferase (GST), which conjugates glutathione with electrophilic compounds for detoxification (Jemec et al. 2010). Oxidative stress is induced in target insects by either synthetic or biological pesticides when their antioxidant capacity surpasses the oxidative burden, triggering processes such as lipid peroxidation and protein oxidation and subsequently leading to cell death Ranjith et al., 2023. Biochemical biomarkers, including malondialdehyde (MDA) content and antioxidant enzyme activities, are sensitive indicators of pesticide-induced stress and provide valuable insight into possible mechanisms associated with insect mortality (El-Saad et al. 2017). The knowledge of these biochemical responses would help in formulating practical biopesticide products and fine-tuning their application strategies.

Despite the increasing interest in biological and botanical control agents, there is substantial knowledge regarding their comparative effectiveness and biochemical impacts on stored-grain pests. Only a handful of studies have analysed the biochemical mechanisms by which *B. bassiana* and plant extracts affect *S. zeamais*, particularly in relation to oxidative stress biomarkers and antioxidant enzyme systems. Existing studies have largely concentrated on mortality without much assessment of the physiological and biochemical changes within target insects throughout the process of intoxication. Similarly, few comparative studies have investigated the relative efficacy and biochemical effects of fungal and botanical control agents; hence, the potential for their integrated or complementary use is not logically understood. Another critical gap in knowledge that can allow researchers to design increasingly efficient integrated pest management strategies relates to the knowledge of potential synergistic or additive effects among different biopesticide classes. Similarly, the relationships of biochemical stress indicators with insect mortality are still poorly understood, leaving something to be desired in terms of optimizing biopesticide applications and predicting treatment outcomes.

Understanding the mechanisms of biopesticides is essential for developing the effective, eco-friendly alternatives to synthetic pesticides that our world urgently required. The present work aims to bridge the knowledge gap between *B. bassiana* and *C. schoenanthus* extracts in the overall comparative evaluation of their effects on *S. zeamais*, with a primary focus on their biochemical effects on oxidative stress biomarkers. The objectives of this study are as follows: (1) to evaluate the insecticidal effects of both treatments through the assessment of mortality and progeny; and (2) to evaluate the effects of these biopesticides on the levels of major antioxidant enzymes, such as catalase, superoxide dismutase, and glutathione S-transferase.

MATERIALS AND METHODS

1. Plant materials and extraction

Leaves of *Cymbopogon schoenanthus* were collected from a field in El-Beheira Governorate in June 2021 and dried under shade at room temperature, a powder was prepared by grinding the dried leaves with a mortar and pestle. The powdered material was then subjected to extraction via maceration in ethyl acetate at a ratio of 1:10 (w:v) for 48 hours at room temperature in a glass jar and then intermittently hand shaken (four times daily for 3 minutes each session) to improve extraction. After the maceration period, the extract was filtered through Whatman filter paper No. 1 to remove plant debris; the filtrate was evaporated under reduced pressure via a rotary evaporator (Heidolph: ML G3) at 40°C. The extract was subsequently stored in a dark vial in a refrigerator for protection against degradation by light and for stability for analysis and bioassay procedures(Aamer et al. 2024).

2. GC–MS analysis of the extract

The chemical composition of the *C. Schoenanthus* ethyl acetate extract was analysed via a Thermo Scientific Trace GC Ultra ISQ mass spectrometer with a TraceGOLD TG-5MS capillary column (30 m × 0.25 mm × 0.25 μm). The solution was injected (1 μL) at a 1:30 split ratio. The temperature program started at 50°C, increased at 5°C/min to 230°C (2 min hold), and then increased to 290°C (2 min hold). The injector and MS transfer lines were maintained at 250°C and 260°C, respectively. Helium served as the carrier gas. The mass spectrometer was operated in EI mode (70 eV) with a scan range of 40–1000 m/z. The components were identified by comparing their mass spectra and retention times with those of the Wiley and NIST MS library databases(Aamer et al. 2024).

3. Fungal isolation and conidial suspension preparation

Cultures of a previously isolated *Beauveria. bassiana* isolate obtained via an insect bait technique from soil samples in the Alexandria Governorate were grown on Sabouraud dextrose agar (SDA) at pH 6.8 at 25±1°C (Aamer et al. 2015). After 10 days of incubation, the fungal culture was harvested via surface rubbing with 10 mL of a 0.01% (v/v) Tween 80 solution in distilled water. The resulting suspension was vortexed for approximately five minutes and then filtered through sterilized cheesecloth to remove mycelial debris. The conidial concentration was determined via a hemacytometer and adjusted to 1×10^{10} conidia/mL. Serial dilutions were then prepared in a 0.01% (w/v) Tween 80 solution to achieve concentrations of 1×10^5, 1×10^6, 1×10^7, and 1×10^8 spores/mL for bioassay investigations. The conidial suspensions were stored at 4°C for 3–4 days until they were used. Conidial viability was checked via a germination test before experimentation; all the isolates presented viability above 95% (Hsia et al. 2014).

4. Insect culture

A laboratory stock culture of *Sitophilus zeamais* has been maintained continuously since the 2020 establishment of its rearing without exposure to insecticides. The insects were reared in 1 liter plastic jars with sufficient amounts of maize grains serving as the food and ovipositional substrate. Each rearing jar was covered with muslin cloth, tightly secured by rubber bands to ensure adequate aeration for the insects while preventing their escape. The culture was maintained inside a controlled growth chamber at an optimum temperature of 28 ±1°C and 70% relative humidity and maintained in total darkness. For experimental purposes, adult weevils aged 5–8 days postemergence were removed and subsequently subjected to bioassays and other experimental treatments (Kumari et al. 2022).

5. Insecticidal potency of B. bassiana and extracts

The insecticidal activities of *C. schoenanthus* extract and *B. bassiana* against *Sitophilus zeamais* were tested via a grain treatment bioassay. Fifty grams of maize grain were treated with 1 mL of *B. bassiana* conidial suspensions at concentrations of 1×10^5, 1×10^6, 1×10^7, and 1×10^8 spores/mL or *C. schoenanthus* extract at concentrations of 10, 30, 50, and 70 mg/mL in acetone. The treatments were carried out separately in glass jars of 350 mL capacity. Immediately after application, the treated grains were manually shaken for approximately 3 minutes to allow even distribution of fungal spores or plant extracts across the mass of the grains. The treated grains were then allowed to stand for 30 min to allow complete evaporation of the solvent or water carrier in both treatments and control. Twenty adult *S. zeamais* weevils (5–8 days old) were subsequently introduced into each jar. All the experimental units were placed inside an incubator maintained at a temperature of 30°C and 65% RH. Each treatment was replicated five times (n = 5). Weevil mortality was then assessed after 7 and 14 days following treatment. To assess survival, weevils were separated, and the jars were returned to the incubator with grains. F_1 progeny emergence and grain weight loss were recorded from posttreatment day 50 (Danga et al. 2015).

6. *Biochemical impact of B. bassiana and C. schoenanthus extract.*

Fifty grams of maize grain were treated with the LC_{50} concentration of each *B. bassiana* conidial suspension and *C. schoenanthus* extract as separate treatments in addition to the control treatment in 350 mL glass jars. Following application and solvent evaporation, adult *S. zeamais* weevils (5–8 days old) were introduced into each jar. The experimental units were maintained at 30°C and 65% RH, and at 3- and 5-days posttreatment, the surviving weevils were collected for biochemical analysis.

The collected live weevils were homogenized in ice-cold phosphate buffer (0.1 M, pH 7.4) via a glass homogenizer at a ratio of 1:5 (w/v). The homogenate was subsequently centrifuged at 10,000 × g for 15 minutes at 4°C. The resulting supernatant was carefully collected and used as the enzyme source for subsequent biochemical assays (Petrović et al. 2019).

Malondialdehyde (MDA) content determination

The content of malondialdehyde, a biomarker of oxidative stress and lipid peroxidation, was determined via the thiobarbituric acid reactive substances (TBARS) method according to Nair and Turner (1984), with slight modifications. Briefly, 0.5 mL of the homogenate was mixed with 1 mL of 15% trichloroacetic acid (TCA) and 1 mL of 0.67% thiobarbituric acid (TBA). The mixture was heated in a boiling water bath for 10 minutes, cooled rapidly on ice, and then centrifuged at 5,000 × g for 10 minutes. The absorbance of the supernatant was measured spectrophotometrically at 532 nm, and the nonspecific absorption at 600 nm was subtracted. The MDA concentration was calculated via an extinction coefficient of 155 $mM^{-1}cm^{-1}$ and expressed as nmol MDA per mg protein.

Antioxidant enzyme activity assays

Catalase

Catalase activity was determined by measuring the rate of H_2O_2 decomposition according to the method of Aebi (1984). The reaction mixture contained 0.05 mL of enzyme extract, 1.5 mL of 0.1 M phosphate buffer (pH 7.0), and 0.95 mL of 0.059 M H_2O_2 in phosphate buffer. The reaction was initiated by adding the enzyme extract. The decrease in absorbance at 240 nm was recorded for 3 minutes at 30-second intervals via a UV–visible spectrophotometer (Beckman DU640). The enzyme activity was calculated via an extinction coefficient of 39.4 $mM^{-1}cm^{-1}$ and expressed as μmol H_2O_2 decomposed min^{-1} mg^{-1} protein.

Superoxide dismutase (SOD)

SOD activity was measured on the basis of its ability to inhibit the photochemical reduction of nitroblue tetrazolium (NBT) according to the method of Beauchamp and Fridovich (1971). The reaction mixture contained 0.05 mL of enzyme extract, 1.5 mL of 0.1 M phosphate buffer (pH 7.8), 0.3 mL of 130 mM methionine, 0.3 mL of 750 μM NBT, 0.3 mL of 100 μM EDTA, and 0.3 mL of 20 μM riboflavin. The reaction was initiated by irradiating the mixture with fluorescent light (15 W) for 15 minutes, after which the absorbance was measured at 560 nm. One unit of SOD activity was defined as the amount of enzyme required to cause 50% inhibition of NBT reduction and expressed as units mg^{-1} protein.

Glutathione s-transferase (GST)

GST activity was determined via the use of 1-chloro-2,4-dinitrobenzene (CDNB) as a substrate according to the methods of Habig et al. (1974). The reaction mixture contained 0.1 mL of enzyme extract, 1.0 mL of 0.1 M phosphate buffer (pH 6.5), 0.1 mL of 30 mM CDNB, and 0.1 mL of 30 mM reduced glutathione (GSH). The reaction was initiated by the addition of GSH. The increase in absorbance at 340 nm was recorded for 3 minutes at 30-second intervals. Enzyme activity was calculated via an extinction coefficient of 9.6 $mM^{-1}cm^{-1}$ and expressed as nmol CDNB conjugated min^{-1} mg^{-1} protein.

Protein determination

The protein concentration in the enzyme extracts was determined via the Lowry method (Lowry et al. 1951) with bovine serum albumin (BSA) as the standard. The procedure involved two steps: (1) the reaction of proteins with copper ions in alkaline medium and (2) the reduction of the Folin–Ciocalteu reagent by the copper-treated protein. Briefly, 0.5 mL of the enzyme extract was mixed with 2.5 mL of Lowry reagent (prepared by mixing 50 mL of 2% Na_2CO_3 in 0.1 N NaOH, 0.5 mL of 1% $CuSO_4·5H_2O$, and 0.5 mL of 2% sodium potassium tartrate) and incubated at room temperature for 10 minutes. Subsequently, 0.25 mL of 1 N Folin-Ciocalteu reagent was added, mixed immediately, and incubated for 30 minutes at room temperature in the dark. The absorbance was measured at 750 nm against a reagent blank. The protein concentration was calculated via a standard curve prepared with known concentrations of BSA (0–100 µg/mL). This allowed for the normalization of enzyme activities per mg of protein.

7. Statistical analysis

The experimental data were subjected to comprehensive statistical analysis to evaluate the efficacy of *B. bassiana* and *C. schoenanthus* extracts against *S. zeamais*. For mortality data, probit analysis (SPSS version 23.0) was used to determine the median lethal concentrations (LC_{50}) with 95% confidence intervals for both treatments. No mortality was recorded in the control treatment, so no correction for natural mortality was needed. For all other experimental parameters, one-way analysis of variance (ANOVA) was employed, followed by Tukey's honestly significant difference (HSD) test at $p \leq 0.05$ to determine significant differences between treatment means. This included analysis of (1) mean mortality rates across different concentrations; (2) F_1 progeny production; (3) grain weight loss; and (4) biochemical parameters, including antioxidant enzyme activities (CAT, SOD, and GST) and lipid peroxidation (MDA content). All the statistical analyses were performed via SPSS software (V. 27 IBM Corp., Armonk, NY, USA) and GraphPad prism (V. 10.4.2 San Diego, CA, USA), and the data are presented as the means ± standard deviations (SDs).

RESULTS AND DISCUSSION

1. Chemical composition of C. schoenanthus extract

GC–MS analysis of the *C. schoenanthus* ethyl acetate extract revealed the presence of nine major bioactive compounds from various classes of chemicals (Table 1, Figure 1). α-Eudesmol (43.9%) was the most abundant in the extract, followed by elemol (15.66%) and cryptomeridiol (13.38%). These oxygenated sesquiterpene alcohols constituted approximately 73% of the total composition of the extract and are therefore likely to contribute significantly to the insecticidal activity observed. The other compounds present were piperitone (1.75%), β-elemene (1.79%), isospathulenol (1.26%), oleyl palmitoleate (2.83%), phytosterol (3.95%), and β-sitosterol (3.16%).

The occurrence of α-eudesmol in our extract is particularly interesting, as this sesquiterpene alcohol has already been associated with acetylcholinesterase inhibition, a mode of action that can lead to neurotoxic effects in insects that possess significant insecticidal activity(Anne 2016; Regnault-Roger et al. 2012). Elemol, the second major compound (15.66%), has insecticidal activity against a wide range of arthropod pests. Ganjewala (2009) reported that elemol shows contact toxicity and neurotoxicity in insects through the disruption of ion channels and nervous system function. The presence of piperitone (1.75%), although at lower concentrations, is interesting because of its established insecticidal properties. Noudogbessi et al. (2012) demonstrated that piperitone has strong insecticidal activity against *Callosobruchus maculatus*, with acetylcholinesterase inhibition and neurotoxicity as the mechanisms of action.

Table 1: Chemical composition of the *C. schoenanthus* ethyl acetate extract derived from GC-MS analysis

No.	Name	RT. [min.]	Area %	Class
1	Piperitone	10.78	1.75	Oxygenated monoterpene ketone
2	β-Elemene	16.62	1.79	Sesquiterpene hydrocarbon
3	Elemol	18.06	15.66	Oxygenated sesquiterpene alcohol
4	α-Eudesmol	20.48	43.9	Oxygenated sesquiterpene alcohol
5	Cryptomeridiol	23.93	13.38	Oxygenated sesquiterpene diol
6	Isospathulenol	25.46	1.26	Oxygenated sesquiterpene alcohol with epoxide
7	oleyl palmitoleate	42.03	2.83	Fatty acid ester
8	Phytosterol	44.68	3.95	Steroid alcohol
9	β-Sitosterol	45.71	3.16	Steroid alcohol

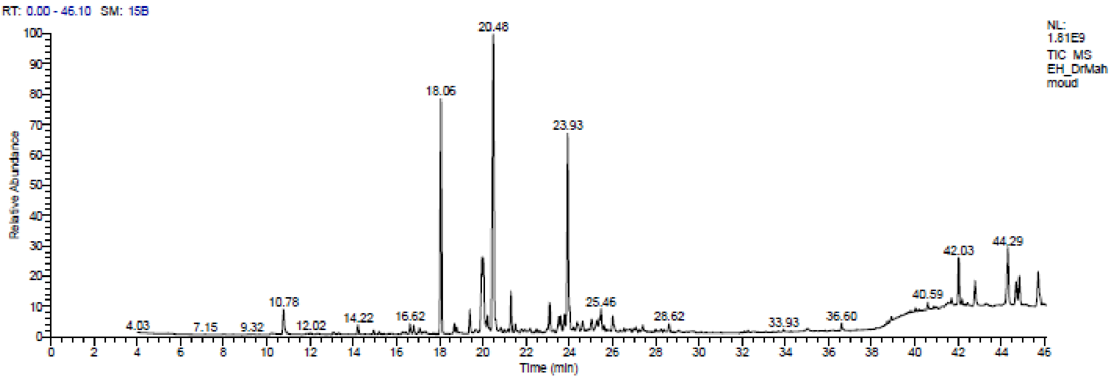

Figure 1: GC-MS chromatogram of the *Cymbopogon schoenanthus* ethyl acetate extract.

The sterol compounds β-sitosterol (3.16%) and phytosterol (3.95%) account for the bioactivity of the extract through different mechanisms. Mishra et al. (2020) reported that β-sitosterol disrupts the physiological process of insects by interfering with cholesterol metabolism because most insects cannot efficiently metabolize β-sitosterol to cholesterol, which leads to abnormalities and death. The complex mixture of these bioactive compounds likely contributes to the observed insecticidal efficacy through synergistic interactions, reducing the likelihood of resistance development compared with single-compound treatments.

2. Insecticidal efficacy against Sitophilus zeamais

Both *C. schoenanthus* extract and *B. bassiana* caused concentration-dependent mortality in *S. zeamais* adults (Figure 2). The mortality of *B. bassiana* ranged from 20.0±2.2% to 59.0±2.9% at 7 days and 32.0±2.5% to 80.0±3.5% at 14 days at concentrations ranging from 1×10^5 to 1×10^8 spores/mL. The *C. schoenanthus* extract induced 15.0±1.6% to 63.0±3.4% mortality on day 7 and 27.0±2.0% to 73.0±3.7% mortality on day 14 at concentrations of 10 to 70 mg/mL. The calculated L_{50} values (Table 2) indicated that the treatment efficacy varied with time. *B. bassiana* presented an LC_{50} value of 1.89×10^7 spores/mL at 7 days, which decreased to 1.08×10^6 spores/mL at 14 days, reflecting the time-dependent nature of fungal pathogenesis. However, *C. schoenanthus* extract had LC_{50} values of 50.27 mg/mL at 7 days and 29.42 mg/mL at 14 days.

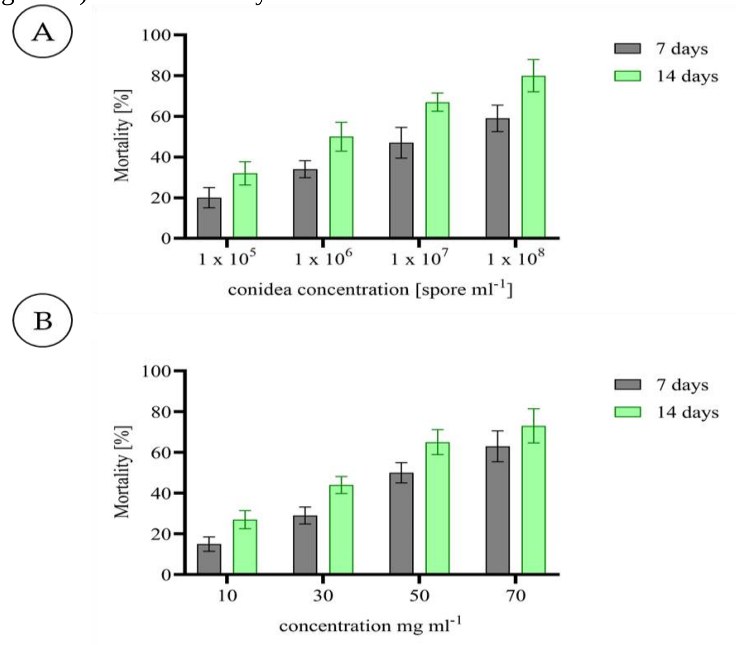

Figure 2: *Sitophilus zeamase* adult mortality percentage after 7 and 14 days of exposure to different concentrations of *B. bassiana* EPF (A) or the ethyl acetate extract of *Cymbopogon schoenanthus* (B) on maize grains.

The trend of progressive but delayed mortality observed with *B. bassiana* is in line with the reported infection process of entomopathogenic fungi described by Litwin et al. (2020). The fungus requires time to conidially germinate, penetrate the cuticle through enzymatic action, colonize internally, and secrete toxins before it can kill the host. This finding was also supported by Barra-Bucarei et al. (2019), who described the progressive *B. bassiana* pathogenesis in stored-product pests.

On the other hand, the almost immediate response corresponds to the development of contact toxicity associated with most botanical insecticides. Such rapid activity could also be associated with the bioactive compounds present in our extract, especially α-eudesmol and elemol, which are thought to have immediate neurotoxic effects by disrupting the function of the insect nervous system, as shown by Stefanazzi et al. (2011), for essential oils against stored-grain pests.

3. Progeny suppression and grain protection.

Compared with the untreated controls, both treatments significantly reduced F_1 progeny production (76.8±2.0 progeny), providing an indication for storing protection against long-term grains (Figure 3). The concentration gradient of *B. bassiana* reduced the number of progeny from 50.0±0.7 to 14.2±0.9, with the percentage reduction in the number of progeny resulting from the treatment ranging from 34.9% to 81.5%. The extract of *C. schoenanthus* resulted in a reduction in the number of progeny of 58.8±1.3 to 22.6±0.8%, with percentage reduction values ranging from 23.4%-70.6%.

The maximum progeny reduction recorded by *B. bassiana* (maximum of 81.5%) against the *C. schoenanthus* extract (maximum of 70.6%) suggests that fungal infection might have more profound effects on the reproductive capacity of the insect. This finding supports the work of Cherry et al. (2005), who reported that *B. bassiana* infection can be caused by adult mortality, which contrasts with the physiological reorganization of reproduction because of the secretion and extensive consumption of resources.

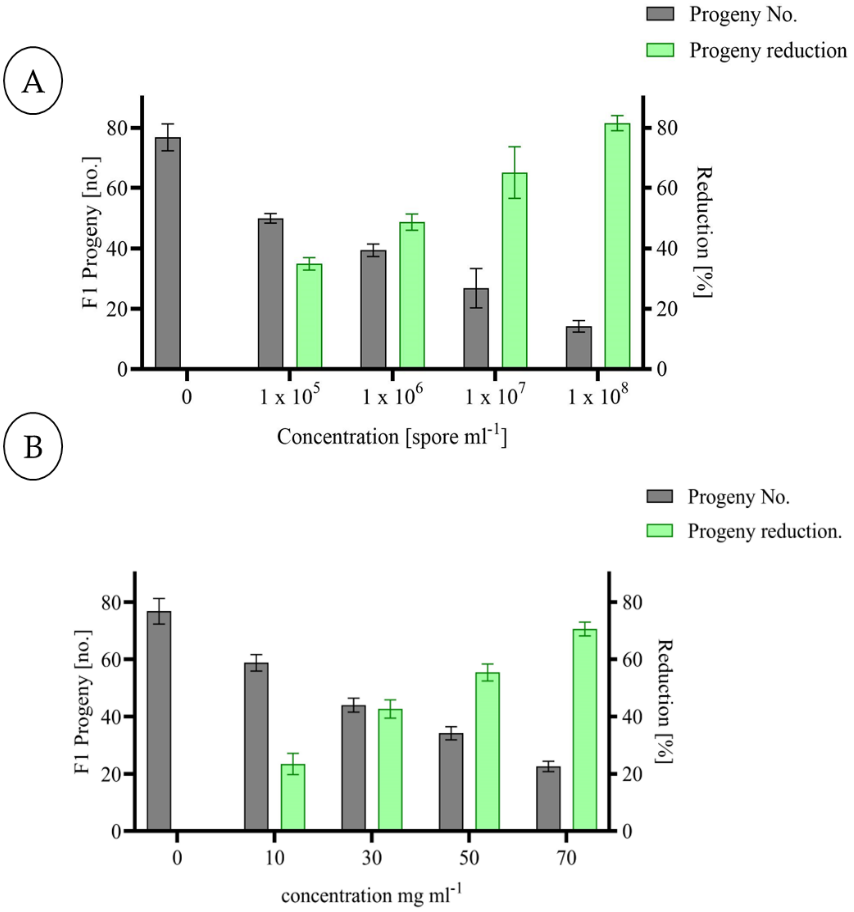

Figure 3: Progeny production F1 (mean no. ± SD) and progeny reduction (% ± SD) of *S. zeamais* on maize grains treated with different concentrations of *B. bassiana* EPF (A) or the ethyl acetate extract of *C. schoenanthus* (B).

Assessment of the weight loss of the grains revealed the benefits of both treatments. The highest concentration of *B. bassiana* resulted in a decrease in weight from 30.0±0.9% (control) to 2.4±0.7%, whereas *C. schoenanthus* extract resulted in a decrease of up to 5.2±0.5% (Table 2). *B. bassiana* is superior because of its systemic effect and long persistence in the storage environment, as reported by Batta and and Kavallieratos (2018).

4. Biochemical impact on oxidative stress biomarkers

The content of malondialdehyde (MDA) is a very useful index for assessing lipid peroxidation and oxidative stress. In our study, the MDA levels in the treated insects were significantly greater than those in the control insects. After 5 days of exposure, the MDA levels were increased by 44.1% and 71.2% in insects treated with *C. schoenanthus* extract and *B. bassiana*, respectively, compared with those in the controls (Figure 4). This pronounced increase in MDA levels in *B. bassiana*-treated insects may indicate a severe state of oxidative stress during fungal invasion, possibly due to the production of reactive oxygen species (ROS) and the release of mycotoxins that disturb cellular homeostasis (Litwin et al. 2020).

Elevated lipid peroxidation indicates compromised integrity of the cell membrane, which can cause cellular dysfunction and ultimately death. This observation corroborates the findings of Chaurasia et al. (2016), who reported similar oxidative damage in the insect *P. americana* treated with entomopathogenic fungi. The sustained increase in MDA from day 3 to day 5 points to the likelihood of progressive cellular damage, which in turn is consistent with the late insect mortality observed in bioassays.

The mechanism underlying lipid peroxidation induced by *C. schoenanthus* extract likely involves direct membrane interactions involving terpenoid compounds. The high concentrations of α-eudesmol (43.9%) and elemol (15.66%) in our extract may disrupt cellular membrane integrity through their lipophilic properties, as demonstrated by Chintalchere et al. (2021) in their study of the effects of essential oils on insect larvae. Oxidative stress represents a fundamental disruption of cellular homeostasis in insects, arising when reactive oxygen species (ROS) production becomes greater than the neutralizing capacity of the antioxidant defense system (Bhagat and Ingole 2016). Insects maintain redox balance under normal physiological conditions with the help of several well-structured enzymatic and nonenzymatic antioxidant systems that protect cellular components from oxidative damage. Exposure to xenobiotics, including biopesticides, can disrupt this protective system, leading to increased lipid peroxidation, protein oxidation, and DNA damage, which ultimately leads to cell death(Sule et al. 2022; Temiz 2020).

The antioxidant enzyme system under study consists of three major enzymes with unique but interrelated functions. Catalase (CAT) is the first defense against the accumulation of hydrogen peroxide, which is rapidly decomposed by CAT to water and oxygen. SOD converts superoxide radicals into hydrogen peroxide, which catalase subsequently removes. Glutathione S-transferase (GST) acts as an antioxidant enzyme and is a major detoxifying enzyme that conjugates reactive electrophiles with reduced glutathione for cellular elimination (Enayati et al. 2005).

Catalase activity increased relative to controls in both treatments by day 3 (*B. bassiana*: 1.28-fold; *C. schoenanthus*: 1.22-fold). This pattern diverged dramatically by day 5. Insects treated with *C. schoenanthus* extract exhibited a further increase to 1.53-fold the control activity. In contrast, activity in *B. bassiana*-treated insects decreased to 0.80-fold the control level (Figure 4).

Indeed, this biphasic response in insects treated with *B. bassiana* represents the development of fungal infection. The first 1.28-fold increase implies that the insects mount a deterrent reaction by increasing their antioxidant enzyme activity in opposition to fungal oxidative stress.

Table 2: Maize grain weight (%) loss due to infection with *S. zeamaize* and the impact of treatment with *B. bassiana* or the *C. schoenanthus* ethyl acetate extract at different concentrations.

***C. schoenanthus* extract (mg/mL)**	**Weight loss (% ± SD)**	***B. bassiana* (spores/mL)**	**Weight loss (% ± SD)**
Control	30.0±0.9a	Control	30.0±0.9a
10	19.2±1.6b	1 x 10^5	18.0±0.9b
30	15.2±0.8b	1 x 10^6	14.0±0.6c
50	9.6±0.7c	1 x 10^7	8.4±0.7d
70	5.2±0.5d	1 x 10^8	2.4±0.7e
F value	93.33	*F* value	174.82
P	<.0001	*P*	<.0001

Infection becomes more notorious as doses build up in the organism and cause collapse of the antioxidant system, as indicated by a sudden decrease in catalase activity from 36% between day 3 and day 5 and finally below control levels (Jemec et al. 2010).

On the other hand, the continuous 1.53-fold increase evident among *C. schoenanthus*-treated insects indicates chronic but controllable oxidative stress, as it results from exposure to this plant extract. Similar patterns were reported by Ali et al. (2012), who demonstrated that *B. bassiana* produces catalase-inhibiting compounds during infection progression.

The differential CAT responses suggest distinct modes of action between treatments. The sustained increase in CAT activity with *C. schoenanthus* extract indicates that insects attempt to maintain antioxidant defenses against plant-derived oxidants, whereas the collapse of the enzyme system with *B. bassiana* suggests more severe disruption of cellular homeostasis.

The activity of SOD moderately increased in both treatments on the 3rd day, where *C. schoenanthus* extract caused a 1.16-fold increase and *B. bassiana caused* a 1.08-fold increase compared with those of the control. On the 5th day, different behaviors emerged: for *C. schoenanthus* extract, a continuous increase of 1.28-fold was observed, whereas *B. bassiana* treatment caused a decrease of 0.79-fold, which is equivalent to a 21% reduction compared with that of the controls. *C. schoenanthus*-treated insects maintain a continuous 1.28-fold increase in SOD activity, indicating an ongoing but tolerable oxidative challenge, whereby the antioxidant system can respond adequately and even increase its capacity over time (Figure 4). This increase of 28% reflects an insect's attempt to neutralize relatively high amounts of superoxide radicals produced by the plant compounds. In contrast, the decrease in SOD activity to 0.79-fold in *B. bassiana*-treated insects reflects the progressive impairment of antioxidant defenses as the anticancer effects of the fungi proceed. Moreover, compounds from *C. schoenanthus*, particularly sesquiterpenes, may cause oxidative stress by destabilizing membranes and impairing cellular respiration, but to levels that allow for adaptation in the first instance (Bhagat and Ingole 2016). The sustained increase in SOD activity with *C. schoenanthus* extract supports the findings of Farahani and Bandani (2023), who reported that essential oils induce chronic oxidative stress requiring continuous antioxidant enzyme activation. The collapse of SOD activity with *B. bassiana* aligns with Stuart et al. (2022), who demonstrated that fungal metabolites directly inhibit antioxidant enzymes during advanced infection stages.

Cymbopogon schoenanthus extract jolts GST into action, whereas *B. bassiana* tends to be delayed, with downregulation on the fifth day. The first-up regulation by *B. bassiana* on day 3 with GST increased to 1.54-fold, and that of *C. schoenanthus* extract was 1.39-fold greater than that of the control. On day 5, the pattern changed, with insects treated with *B. bassiana* declining dramatically to 0.78-fold and being 22% lower than the control level, while maintenance of elevated levels at 1.34% was ensured by insects treated with *C. schoenanthus*.

The initial enormous decline in GST (1.54-fold for *B. bassiana* and 1.39-fold for *C. schoenanthus*) reflects a transient activation of detoxification responses to both treatments, with the response to fungal treatment being slightly stronger at the onset. GST is a crucial detoxifying enzyme that works by conjugating glutathione with electrophilic compounds, including xenobiotics and oxidatively damaged cellular components. The sustained increase of 1.34-fold in *C. schoenanthus*-treated insects throughout the exposure period clearly indicates ongoing detoxification, although within a tolerable ceiling. The observed decrease in *B. bassiana*-treated insects to 0.78-fold below day 3 demonstrated that system failure was likely caused by one or more of the following: depletion of glutathione, direct inhibition of GST by fungal metabolites, or inability to cope with overwhelming detoxification as the course of infection progressed (Zhang et al. 2023).

The biochemical results revealed extremely different modes of action between *C. schoenanthus* extract and *B. bassiana*. Oxidative stress is induced immediately by the plant extract with chronic elevation of antioxidant enzymes, suggesting that the chemical stress could be compensated to a certain degree by the insects. However, the cumulative increase in MDA levels suggests that compensation fails to counteract the effect, ultimately leading to death through cumulative oxidative damage.

Both *B. bassiana* and the ethyl acetate extract of *C. schoenanthus* can significantly control *S. zeamais*, acting as biological disease control agents, although in different ways with unique advantages complementary to each other. *B. bassiana* provided superior long-term control in terms of mortality rates and progeny suppression, whereas *C. schoenanthus* extract initially achieved a faster control effect. This suggests a mechanism for insect bioactivity in the presence of terpenoid bioactive molecules present in the extract, such as α-eudesmol, elemol, and cryptomeridiol. These sesquiterpene alcohols are known to exhibit neurotoxic properties and disrupt insect physiological processes (Karabörklü and Ayvaz 2023).

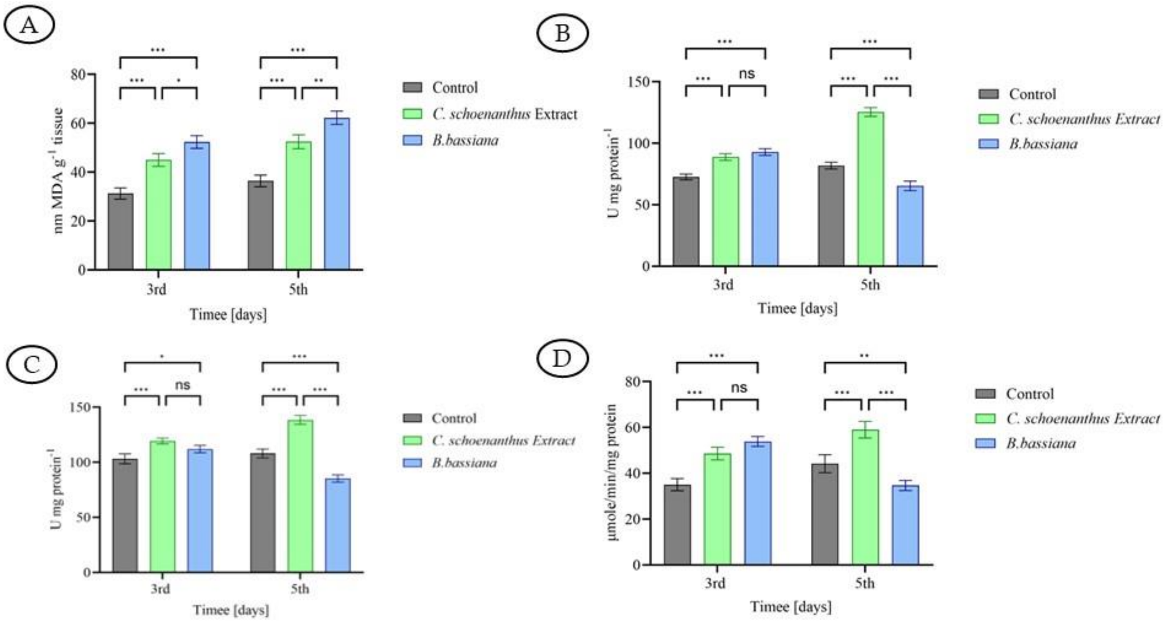

Figure 4: Lipid peroxidation as measured by the MDA content (A) and the activities of the antioxidant enzymes CAT (B), SOD (C) and GST (D) after 3 and 5 days of exposure to maize grains treated with *B. bassiana* or *C. schoenanthus* ethyl acetate extract at the median lethal concentration.

In addition, this differential performance aligns with recent findings by Rehman et al. (2020), who demonstrated that, compared with individual treatments, combined applications of *B. bassiana* with botanical extracts resulted in increased mortality rates (up to 71.32%) against *Tribolium castaneum*, suggesting synergistic interactions between fungal and botanical biocontrol agents.

Biochemical analysis revealed dissimilar oxidative stress signatures between the two treatments, leading to fresh insights into their mechanisms of action. *C. schoenanthus* extract appeared to induce oxidative stress in a chronic but compensatory manner, as evidenced by the sustained induction of antioxidant enzymes (CAT, SOD and GST). These findings indicate that although the plant extract imposes an uninterrupted cellular stressor, the antioxidant defence system of the insect exerts compensatory mechanisms toward homeostasis but ultimately fails with time. This mechanism has been reaffirmed through recent studies related to oxidative stress responses in insects exposed to botanical compounds (Ali et al. 2017).

B. bassiana, however, induced a biphasic response consisting of initial upregulation of antioxidant enzymes and, thereafter, their total failure by day 5. This pattern conforms to the understanding of the pathogenesis process of entomopathogenic fungi, wherein the initiation of infection is bound to trigger host immune system responses, but eventually, the metabolites of fungi as well as physical invasion overwhelm the host's defense mechanism (Inayat et al. 2022; Kaur et al. 2021). A striking increase in malondialdehyde concentrations (71.2%) in *B. bassiana*-treated insects was evident, indicating severe lipid peroxidation and damage to cellular membranes, a feature of mycosis at an advanced stage. These findings align with those of Zhang et al. (2020), who demonstrated that entomopathogenic fungi produce secondary metabolites that disrupt cellular antioxidant defences in stored-grain pests.

CONCLUSION

This study revealed that both *B. bassiana* and the ethyl acetate extract of *C. schoenanthus* are very good, eco-superior, and useful alternatives to synthetic pesticides for managing Sitophilus zeamais in stored grain systems. In terms of novel insights into their different biochemical mechanisms of action, *C. schoenanthus* extract was reported to induce chronic oxidative stress by maintaining an increase in several antioxidant enzymes, whereas *B. bassiana* rapidly caused systemic failure through biphasic disruption of the antioxidant system. Both modalities inflict higher adult mortality, encourage F_1 progeny production, and damage grains, with *B. bassiana* promisingly showing greater long-term efficacy (80% mortality, 81.5% progeny reduction) than *C. schoenanthus* extract (73% mortality, 70.6% progeny reduction). This makes most of the complementary nature of their mechanisms—fast short-term action by plant extracts upon an entomopathogenic fungus that is effective for longer-term control—there are enormous opportunities for integrated pest management strategies, which put additional security around food in the world while minimizing the environmental and health characteristic risks associated with chemical pesticide use. Identifying sesquiterpene alcohols (α-eudesmol, elemol and cryptomeridiol) in addition to piperitone as key bioactive compounds forms a basis for establishing standardized botanical formulations. However, further studies on environmental stability, formulation optimization, and economics are vital for the successful realization of practical grain storage systems by approaching these promising biocontrol agents within the scope of field application.

REFERENCES

Aamer H, Kassem F, Ahmed SM, Abdallah E (**2015**) Insecticidal potency of native entomopathogenic fungi isolates against the *Galleria mellonella* (lepidoptera: Pyralidae) and *spodoptera littoralis* (lepidoptera: Noctuidae) larvae. Journal of Plant Protection and Pathology **6**: 727-738. https://doi.org/10.21608/jppp.2015.74498

Aamer HA, Elalem SF, Al-Askar AA, Sharaf OA, Gaber MA, Kowalczewski P, Behiry S, Abdelkhalek A (**2024**) Antioxidant and antimicrobial activities of Salsola imbricata methanolic extract and its phytochemical characterization. Open Life Sciences **19**: https://doi.org/doi:10.1515/biol-2022-1011

Abdelaal HSA, Thilmany D (**2019**) Grains Production Prospects and Long Run Food Security in Egypt. Sustainability **11**: 4457. https://doi.org/10.3390/su11164457

Aebi H (1984) Catalase in vitro. In: *Methods in enzymology*, Elsevier, pp 121-126

Ak K (2019) Efficacy of entomopathogenic fungi against the stored-grain pests, *Sitophilus granarius* L. and S. oryzae L. (Coleoptera: Curculionidae). Egyptian Journal of Biological Pest Control **29**: 12. https://doi.org/10.1186/s41938-019-0115-y

Ali A, Xia C, Ismaiel M, Ouattara NB, Mahmood I, Anshiso D (**2021a**) Analysis of determinants to mitigate food losses and waste in the developing countries: empirical evidence from Egypt. Mitigation and Adaptation Strategies for Global Change **26**: 23. https://doi.org/10.1007/s11027-021-09959-0

Ali K, Sagheer M, Rashid A (**2017**) Impact of extracts of *Azadirachta indica* and *Datura inoxia* on the esterases and phosphatases of three stored grains insect pests of economic importance. Pakistan Journal of Agricultural Sciences **54**: https://doi.org/10.21162/PAKJAS/17.5169

Ali S, Xia J, Ren S, Huang Z (**2012**) Catalase production influences germination, stress tolerance and virulence of *Beauveria bassiana* conidia. Pakistan Journal of Zoology **44**:

Ali S, Ullah MI, Sajjad A, Shakeel Q, Hussain A (**2021b**) Environmental and Health Effects of Pesticide Residues. In: Inamuddin, Ahamed MI, Lichtfouse E (eds) Sustainable Agriculture Reviews 48: Pesticide Occurrence, Analysis and Remediation Vol **2** Analysis, Springer International Publishing, Cham, pp 311-336

Alitonou GA, Avlessi F, Tchobo F, Noudogbessi J-P, Tonouhewa A, Yehouenou B, Menut C, Sohounhloue DK (**2012**) Chemical composition and biological activities of essential oils from the leaves of *Cymbopogon giganteus* Chiov. and *Cymbopogon schoenanthus* (L.) Spreng (Poaceae) from Benin. International Journal of Biological and Chemical Sciences **6**:1819-1827. https://doi.org/10.4314/ijbcs.v6i4.37

Anne NW (**2016**) Anti-acetylcholinesterase activities of leaf extracts of *carphalea glaucescens* and *gnidia glauca* from Mbeere North Subcounty, Kenya on *chilo partellus* larvae. Kenyatta University

Aous W, Otmane B, Tydia O, Mohamed H, Fazia M, Amine Y, and Baaliouamer A (**2019**) Essential oils of *Cymbopogon schoenanthus* (L.) Spreng. from Algerian Sahara: chemical variability, antioxidant, antimicrobial and insecticidal properties. Journal of Essential Oil Research **31**: 562-572. https://doi.org/10.1080/10412905.2019.1612790

Arrahman A, Mirsam H, Djaenuddin N, Suriani, Pakki S, Saenong MS, Sebayang A (**2022**) An in-depth study on *Sitophilus zeamais* Motsch (Coleoptera: Curculionidae) pests on corn plants. IOP Conference Series: Earth and Environmental Science **1107**: 012060. https://doi.org/10.1088/1755-1315/1107/1/012060

Barra-Bucarei L, France Iglesias A, Pino Torres C (**2019**) Entomopathogenic Fungi. In: Souza B, Vázquez LL, Marucci RC (eds) Natural Enemies of Insect Pests in Neotropical Agroecosystems: Biological Control and Functional Biodiversity, Springer International Publishing, Cham, pp 123-136

Batta YA, and Kavallieratos NG (**2018**) The use of entomopathogenic fungi for the control of stored-grain insects. International Journal of Pest Management **64:** 77-87. https://doi.org/10.1080/09670874.2017.1329565

Beauchamp C, Fridovich I (**1971**) Superoxide dismutase: improved assays and an assay applicable to acrylamide gels. Analytical biochemistry **44**: 276-287. https://doi.org/10.1016/0003-2697(71)90370-8

Bhagat J, Ingole B (**2016**) Glutathione S-transferase, catalase, superoxide dismutase, glutathione peroxidase, and lipid peroxidation as a biomarkers of oxidative stress in snails: A review. Invertebrate Survival Journal **13 (1):** 336-349. https://doi.org/10.25431/1824-307X/isj.v13i1.336-349

Campolo O, Giunti G, Russo A, Palmeri V, Zappalà L (**2018**) Essential Oils in Stored Product Insect Pest Control. Journal of Food Quality **2018**: 6906105. https://doi.org/10.1155/2018/6906105

Chaurasia A, Lone Y, Wani O, Gupta US (**2016**) Effect of certain entomopathogenic fungi on oxidative stress and mortality of *Periplaneta americana*. Pesticide Biochemistry and Physiology **127**: 28-37. https://doi.org/10.1016/j.pestbp.2015.09.002

Cherry AJ, Abalo P, Hell K (**2005**) A laboratory assessment of the potential of different strains of the entomopathogenic fungi *Beauveria bassiana* (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metschnikoff) to control *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae) in stored cowpea. Journal of Stored Products Research **41**: 295-309. https://doi.org/10.1016/j.jspr.2004.04.002

Chintalchere JM, Dar MA, Shaha C, Pandit RS (**2021**) Impact of essential oils on *Musca domestica* larvae: oxidative stress and antioxidant responses. International Journal of Tropical Insect Science **41**: 821-830. https://doi.org/10.1007/s42690-020-00272-y

Collins P (**2006**) Resistance to chemical treatments in insect pests of stored grain and its management. 9th International Working Conference on Stored Product Protection, pp 277-282

Daglish GJ, Nayak MK, Arthur FH, Athanassiou CG (**2018**) Insect Pest Management in Stored Grain. In: Athanassiou CG, Arthur FH (eds) Recent Advances in Stored Product Protection, Springer Berlin Heidelberg, Berlin, Heidelberg, pp 45-63

Damalas CA, Eleftherohorinos IG (**2011**) Pesticide Exposure, Safety Issues, and Risk Assessment Indicators. International Journal of Environmental Research and Public Health **8**:1402-1419. https://doi.org/10.3390/ijerph8051402

Danga SPY, Nukenine EN, Fotso GT, Adler C (2015) Use of NeemPro®, a neem product to control maize weevil *Sitophilus zeamais* (Motsch.) (Coleoptera: Curculionidae) on three maize varieties in Cameroon. Agriculture & Food Security **4**: 18. https://doi.org/10.1186/s40066-015-0039-z

Demis E, Yenewa W (**2022**) Review on major storage insect pests of cereals and pulses. Asian Journal of Advances in Research **12**: 41-56.

El-Saad AMA, Kheirallah DA, El-Samad LM (**2017**) Biochemical and histological biomarkers in the midgut of *Apis mellifera* from polluted environment at Beheira Governorate, Egypt. Environmental Science and Pollution Research **24**: 3181-3193. https://doi.org/10.1007/s11356-016-8059-1

El-Wakeil N, Sallam AA, Gaafar N, Volkmar C (**2013**) Side Effects of Insecticides on Natural Enemies and Possibility of Their Integration in Plant Protection Strategies. In: Trdan S (ed) Insecticides - Development of Safer and More Effective Technologies, IntechOpen, Rijeka

Enayati AA, Ranson H, Hemingway J (**2005**) Insect glutathione transferases and insecticide resistance. Insect Molecular Biology **14**: 3-8. https://doi.org/10.1111/j.1365-2583.2004.00529.x

Farahani S, Bandani AR (**2023**) Plant essential oils induce expression of heat shock proteins and antioxidant enzyme activity in carob moth, *Ectomyelois ceratoniae* (Lepidoptera: Pyralidae). European Journal of Entomology **120**:161-169. https://doi.org/10.14411/eje.2023.021

Ganjewala D (**2009**) Cymbopogon essential oils: Chemical compositions and bioactivities. International journal of essential oil therapeutics **3**: 56-65.

Habig WH, Pabst MJ, Jakoby WB (**1974**) Glutathione S-transferases: the first enzymatic step in mercapturic acid formation. Journal of biological Chemistry **249**: 7130-7139. https://doi.org/10.1016/S0021-9258(19)42083-8

Hsia ICC, Islam MT, Yusof I, How TY, Omar D (**2014**) Evaluation of conidial viability of entomopathogenic fungi as influenced by temperature and additive. International journal of Agriculture and Biology **16**:

Hussien IAA (**2022**) An economic study of the most important problems of Egyptian agriculture. International Journal of Modern Agriculture and Environment **2**: 73-95. https://doi.org/10.21608/ijmae.2023.215948.1010

Inayat R, Khurshid A, Boamah S, Zhang S, Xu B (**2022**) Mortality, enzymatic antioxidant activity and gene expression of cabbage aphid (*Brevicoryne brassicae* L.) in response to *Trichoderma longibrachiatum* T6. Frontiers in Physiology **13:** 901115. https://doi.org/10.3389/fphys.2022.901115

Jemec A, Drobne D, Tišler T, Sepčić K (**2010**) Biochemical biomarkers in environmental studies—lessons learnt from enzymes catalase, glutathione S-transferase and cholinesterase in two crustacean species. Environmental Science and Pollution Research **17**: 571-581. https://doi.org/10.1007/s11356-009-0112-x

Karabörklü S, Ayyaz A (**2023**) A comprehensive review of effective essential oil components in stored-product pest management. Journal of Plant Diseases and Protection **130**: 449-481. https://doi.org/10.1007/s41348-023-00712-0

Kaur M, Chadha P, Kaur S, Kaur A (**2021**) *Aspergillus flavus* induced oxidative stress and immunosuppressive activity in *Spodoptera litura* as well as safety for mammals. BMC microbiology **21:** 180. https://doi.org/10.1186/s12866-021-02249-4

Ketoh GK, Koumaglo HK, Glitho IA (**2005**) Inhibition of *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae) development with essential oil extracted from *Cymbopogon schoenanthus* L. Spreng. (Poaceae), and the wasp *Dinarmus basalis* (Rondani) (Hymenoptera: Pteromalidae). Journal of Stored Products Research **41**: 363-371. https://doi.org/10.1016/j.jspr.2004.02.002

Koba K, Sanda K, Guyon C, Raynaud C, Chaumont J-P, Nicod L (**2009**) In vitro cytotoxic activity of *Cymbopogon citratus* L. and *Cymbopogon nardus* L. essential oils from Togo. Bangladesh Journal of Pharmacology **4**: 29-34. https://doi.org/10.3329/bjp.v4i1.1040

Kumar A, Thakur A, Sharma V, Koundal S (**2019**) Pesticide residues in animal feed: status, safety and scope. J Anim Feed Sci Technol **7**: 73-80. https://doi.org/10.21088/jafst.2321.1628.7219.3

Kumar D, Kalita P (**2017**) Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries. Foods **6**: 8. https://doi.org/10.3390/foods6010008

Kumari N, Kumar V, Kumar A, Kumar A, Sati K, Prakash O, Kapoor N (**2022**) Biology of *Sitophilus zeamais* Motsch. On maize grains under laboratory condition. The Pharma Innovation Journal **11(9)**:1388-1391

Lacey LA, Grzywacz D, Shapiro-Ilan DI, Frutos R, Brownbridge M, Goettel MS (**2015**) Insect pathogens as biological control agents: Back to the future. Journal of Invertebrate Pathology **132:** 1-41. https://doi.org/10.1016/j.jip.2015.07.009

Litwin A, Nowak M, Różalska S (2020) Entomopathogenic fungi: unconventional applications. Reviews in Environmental Science and Bio/Technology **19:** 23-42. https://doi.org/10.1007/s11157-020-09525-1

Lowry OH, Rosebrough NJ, Farr AL, Randall RJ (**1951**) Protein measurement with the Folin phenol reagent. https://doi.org/10.1016/S0021-9258(19)52451-6

Mbata GN, Ivey C, Shapiro-Ilan D (**2018**) The potential for using entomopathogenic nematodes and fungi in the management of the maize weevil, *Sitophilus zeamais* (Motschulsky) (Coleoptera: Curculionidae). Biological Control **125**:39-43. https://doi.org/10.1016/j.biocontrol.2018.06.008

Mishra M, Sharma A, Dagar VS, Kumar S (**2020**) Effects of β-sitosterol on growth, development and midgut enzymes of *Helicoverpa armigera* Hübner. Archives of Biological Sciences **72**: 271-278. https://doi.org/10.2298/ABS200308021M

Nair V, Turner GA (1984) The thiobarbituric acid test for lipid peroxidation: structure of the adduct with malondialdehyde. Lipids 19:804-805.

Nguyen TT, Collins PJ, Duong TM, Schlipalius DI, Ebert PR (2016) Genetic Conservation of Phosphine Resistance in the Rice Weevil *Sitophilus oryzae* (L.). Journal of Heredity **107**: 228-237. https://doi.org/10.1093/jhered/esw001

Noudogbessi J, Sessou P, Wotto V, Figueredo G, Chalard P, Chalchat J, Dansou K, Sohounhloué D (**2012**) Chemical compositions and preventive activity of essential oils extracted from the leaves of two varieties of Tephrosia (*Leguminosae-papilionoideae*) collected in Benin on *Callosobruchus maculatus* (Fabricius). Asian Journal of Research in Chemistry **5**: 1431-1436.

Nwosu LC (**2016**) Chemical bases for maize grain resistance to infestation and damage by the maize weevil, *Sitophilus zeamais* Motschulsky. Journal of Stored Products Research **69**: 41-50. https://doi.org/10.1016/j.jspr.2016.06.001

Nyamador SW, MondÃ AD, Kasseney BD, Ketoh GK, Glitho IA (**2017**) Insecticidal activity of four essential oils on the survival and oviposition of two sympatric bruchid species: *Callosobruchus maculatus* F. and *Callosobruchus subinnotatus* PIC.(Coleoptera: Chrysomelidea: Bruchinae). Journal of Stored Products and Postharvest Research **8**: 103-112. https://doi.org/10.5897/JSPPR2017.0240

Ojo JA, Omoloye AA (**2016**) Development and Life History of *Sitophilus zeamais* (Coleoptera: Curculionidae) on Cereal Crops. Advances in Agriculture **2016**: 7836379. https://doi.org/10.1155/2016/7836379

Olakiumide O (**2021**) Post-harvest loss reduction: Enhancing food security and economic sustainability. Journal Siplieria Sciences 2:7-17.

Pérez S, Ramos-López M, Zavala-Sánchez M, Cárdenas-Ortega N (**2010**) Activity of essential oils as a biorational alternative to control coleopteran insects in stored grains. Journal of Medicinal Plants Research **4**: 2827-2835.

Petrović M, Popović A, Kojić D, Šućur J, Bursić V, Aćimović M, Malenčić Đ, Stojanović T, Vuković G (**2019**) Assessment of toxicity and biochemical response of Tenebrio molitor and Tribolium confusum exposed to Carum carvi essential oil. Entomol Gen **38**: 333-348. https://doi.org/ 10.1127/entomologia/2019/0697

Regnault-Roger C, Vincent C, Arnason JT (**2012**) Essential oils in insect control: low-risk products in a high-stakes world. Annual review of entomology **57**: 405-424. https://doi.org/10.1146/annurev-ento-120710-100554

Rehman H-u, Rasul A, Farooqi MA, Aslam HMU, Majeed B, Sagheer M, Ali Q (**2020**) Compatibility of some botanicals and the entomopathogenic fungus, *Beauveria bassiana* (Bals.), against the red flour beetle, *Tribolium castaneum* (Herbst)(Coleoptera: Tenebrionidae). Egyptian Journal of Biological Pest Control **30**: 1-7. https://doi.org/10.1186/s41938-020-00329-7

Sabbour M, Abd-El-Aziz S (**2012**) Efficacy of three entomopathogenic fungi alone or in combination with diatomaceous earth modifications for the control of three pyralid moths in stored grains. Journal of Plant Protection Research https://doi.org/10.2478/v10045-012-0059-7

Savadogo S, Lykke AM, Traore L, Sereme A, Thiombiano A (**2020**) Bio-insecticide potential of three aromatic plants of Burkina Faso (*Ocimum americanum* L., *Cymbopogon schoenanthus* L. and *Hyptis suaveolens* Poit.) and their importance in cowpea seed conservation. International Journal of Biological and Chemical Sciences **14**: 1167-1176. https://doi.org/10.4314/ijbcs.v14i4.1

Stefanazzi N, Stadler T, Ferrero A (**2011**) Composition and toxic, repellent and feeding deterrent activity of essential oils against the stored-grain pests *Tribolium castaneum* (Coleoptera: Tenebrionidae) and *Sitophilus oryzae* (Coleoptera: Curculionidae). Pest Management Science **67**: 639-646. https://doi.org/10.1002/ps.2102

Stuart AKdC, Furuie JL, Cataldi TR, Stuart RM, Zawadneak MAC, Labate CA, Pimentel IC (**2022**) Fungal consortium of two *Beauveria bassiana* strains increases their virulence, growth, and resistance to stress: A metabolomic approach. PLOS ONE **17**: e0271460. https://doi.org/10.1371/journal.pone.0271460

Sule RO, Condon L, Gomes AV (**2022**) A common feature of pesticides: oxidative stress—the role of oxidative stress in pesticide-induced toxicity. Oxidative medicine and cellular longevity **2022**: 5563759. https://doi.org/10.1155/2022/5563759

Suleiman R, Rosentrater KA, Bern CJ (**2015**) Evaluation of maize weevils *Sitophilus zeamais* Motschulsky infestation on seven varieties of maize. Journal of Stored Products Research **64**: 97-102. https://doi.org/10.1016/j.jspr.2015.09.005

Tefera T, Kanampiu F, De Groote H, Hellin J, Mugo S, Kimenju S, Beyene Y, Boddupalli PM, Shiferaw B, Banziger M (**2011**) The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. Crop Protection **30**: 240-245. https://doi.org/10.1016/j.cropro.2010.11.015

Temiz Ö (**2020**) Biopesticide emamectin benzoate in the liver of male mice: evaluation of oxidative toxicity with stress protein, DNA oxidation, and apoptosis biomarkers. Environmental Science and Pollution Research **27**: 23199-23205. https://doi.org/10.1007/s11356-020-08923-w

Trivedi A, Nayak N, Kumar J (**2018**) Recent advances and review on use of botanicals from medicinal and aromatic plants in stored grain pest management. Journal of Entomology and Zoology Studies **6**:295-300.

Wakil W, Kavallieratos NG, Usman M, Gulzar S, El-Shafie HAF (**2021**) Detection of Phosphine Resistance in Field Populations of Four Key Stored-Grain Insect Pests in Pakistan. Insects **12**: 288. https://doi.org/10.3390/insects12040288

White ND, Leesch JG (**2018**) Chemical control. In: Integrated management of insects in stored products, CRC Press, pp 287-330

Zhang C, Teng B, Liu H, Wu C, Wang L, Jin S (**2023**) Impact of *Beauveria bassiana* on antioxidant enzyme activities and metabolomic profiles of *Spodoptera frugiperda*. Journal of Invertebrate Pathology **198**: 107929. https://doi.org/10.1016/j.jip.2023.107929

Zhang L, Fasoyin OE, Molnár I, Xu Y (**2020**) Secondary metabolites from hypocrealean entomopathogenic fungi: novel bioactive compounds. Natural Product Reports **37**: 1181-1206. https://doi.org/10.1039/c9np00065h

الملخص العربي

الفعالية كمبيد حشري والنشاط البيوكيميائي للفطر *Beauveria bassiana* ومستخلص نبات *Cymbopogon schoenanthus* ضد حشرة سوسة الحبوب التابعة لرتبة غمدية الأجنحة: فصيلة السوسيات

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من بين التحديات المهمة التي تواجه الحبوب فما بعد الحصاد الإصابة بالآفات على مستوى العالم، تُعدّ حشرة *Sitophilus zeamais* من أكثر الآفات الأولية تدميراً للحبوب cereal grains. تهدف هذه الدراسة إلى استقصاء ومقارنة الفعالية الحيوية لكل من الفطر الممرض للحشرات *Beauveria bassiana* ومستخلص الإيثيل اسيتات لنبات الحلفا بر *Cymbopogon schoenanthus* ضد *S. zeamais*، من خلال تقييم الكفاءة ضد الحشرات والتأثيرات البيوكيميائية على مؤشرات الإجهاد التأكسدي. أظهرت تحاليل كروماتوغرافيا الغاز المقترن بمطياف الكتلة (GC-MS) أن مستخلصات *C. schoenanthus* تحتوي على تسعة مركبات نشطة حيوياً رئيسية، من أبرزها α-eudesmol (بنسبة ٤٣.٩٪)، و elemol (15.66%)، و cryptomeridiol (13.38%). ظهرت الاختبارات الحيوية أن كلا المعاملتين سببتا معدلات نفوق تعتمد على التركيز؛ حيث بلغت نسبة الموت باستخدام *B. bassiana* نحو ٨٠.٠٪ بعد ١٤ يوماً، في حين بلغ الموت باستخدام مستخلص *C. schoenanthus* نحو ٧٣.٠ %. كما قللت كلا المعاملتين من إنتاج الجيل الأول (F_1) بشكل ملحوظ بنسبة ٨١.٥% (*B. bassiana*) و٧٠.٦% (*C. schoenanthus*) ، في حين انخفض الفقد في وزن الحبوب إلى ٢.٤٪ و٥.٢٪ على التوالي، مقارنةً بخسارة قدرها ٣٠٪ في مجموعة الكنترول. وأظهرت التقييمات البيوكيميائية استجابات مختلفة للإجهاد التأكسدي؛. تسبب مستخلص نبات C. schoenanthus في إجهاد تأكسدي مزمن ولكن يمكن السيطرة عليه مع ارتفاع مستدام في إنزيمات مضادات الأكسدة (الكاتلاز: زيادة بمعدل ١.٥٣ ضعفاً، سوبر أكسيد ديسموتاز: زيادة بمعدل ١.٢٨ ضعفاً، الغلوتاثيون-S ترانسفيراز: زيادة بمعدل ١.٣٤ ضعفاً)، مع زيادة بنسبة ٤٤.١٪ في المالونديالديهيد (MDA). أما فطر B. bassiana فقد أظهر نمطاً ثنائي الطور: زيادة أولية في الإنزيمات تليها انهيار كامل لنظام مضادات الأكسدة في اليوم الخامس (انخفاض بنسبة ٢٠–٢٢٪ عن المستويات الطبيعية)، مصحوباً بضرر تأكسدي شديد (زيادة بنسبة ٧١.٢٪ في المالونديالديهيد). تشير نتائج هذه الدراسة إلى أن كلًا من العاملين الحيويين، الفطري والنباتي، يمثلان بدائل صديقة للبيئة وواعدة كبدائل للمبيدات الكيميائية في إدارة آفات الحبوب المخزونة.