

RESEARCH

Open Access



Effect of *Citrus aurantium* L. oil peel against *Tribolium castanum* on wheat (*Triticum aestivum*) under storage previously treated by mycorrhizal and potassium humate under field conditions

George Morris Nasr¹ and Ahmed Fayez Omar^{2*}

Abstract

Arbuscular mycorrhizal fungi and humic substances were used to promote plant growth and boost yields in two wheat cultivars, Misr-1 and Gemmiza-11. After harvest, the grain of the two wheat varieties were treated with *Citrus aurantium* essential oil peel at concentrations of 500, 750, 1250, 2500, and 5000 mg/L. The LC₅₀ for *Tribolium castaneum*, progeny emergence, and adult reduction percentage were determined, along with their impact on carbohydrate and protein content after one year of storage. Data from the present study showed that the application of mycorrhizal infection (250 spores/ seed) and potassium humate (6 kg fad⁻¹) positively correlated with *Citrus aurantium* oil peel concentration. The essential oils were subjected to Gas chromatography–mass spectrometry (GC-MS). The results indicated that the main compound was limonene, 85.47%. The treatment of the two wheat cultivars (Misr-1 and Gemmiza-11) resulted in increased mortality percentage, reduced progeny emergence, and a reduction in adult numbers. Additionally, there was an increase in both carbohydrate and protein content in the wheat grains.

Keywords Citrus aurantium, Mycorrhizal, Potassium humate, Reduction.

Introduction

Wheat is a staple crop in many countries worldwide, yet its cultivation, yield, and storage are often hindered by environmental challenges (Salwan et al. 2019; Kheya et al. 2023; Arif et al. 2025). Wheat is considered one of the strategic crops cultivated in Egypt, where the cultivated area amounts to approximately at 1.35 million hectares, producing 9.7 million tons (Devkota et al. 2026; Rashad et al., 2026). Which is exposed to quantitative and qualitative losses by 10–30% annually during the storage process as a result of infestation by stored-grain pests (Singh and Jayas 2024). To mitigate these constraints,

*Correspondence:

Ahmed Fayez Omar
ahmed.fayez_a011@agr.kfs.edu.eg

¹Stored Product Pests, Department, Plant Protection Research Institute, Agricultural Research Center, Sakha, Kafr El-Shiekh, Egypt

²Pesticides Chemistry and Toxicology Department, Faculty of Agriculture, Kafrelsheikh University, Kafrelsheikh 33516, Egypt

eco-friendly approaches such as applying mycorrhizal fungi and humic substances have gained attention for their role in reducing soil-related stresses, including salinity, which adversely affects crop productivity. Studies by (Periasamy et al. 2025; Simarmata et al. 2025; Ibrahim et al. 2011) found that wheat inoculated with mycorrhizal fungi exhibits greater vigor and stress tolerance than untreated plants. Additionally, humic substances—key elements of organic soil matter—are known to improve wheat development, increasing both yield parameters and total grain production (Kandil et al. 2016; de Moura et al., 2023; Sheteiwy et al., 2025). Mycorrhizal fungi enhance plant growth by improving phosphorus uptake in wheat, with some strains of arbuscular mycorrhizal (AM) fungi leading to yield improvements of up to 60% (Li et al. 2024; Naseer et al., 2024; Prasad et al., 2013).

Effective postharvest storage is critical for maintaining wheat quality. Although harvested grains may appear free of insects, they often contain hidden eggs or larvae from field conditions. Poor storage practices further exacerbate grain deterioration and elevate the risk of pest infestations (Yassen et al. 2019; Ileke and Adeniran 2025; Kadir et al. 2025). Among storage pests, the red flour beetle (*Tribolium castaneum* [Herbst]) is particularly destructive, causing substantial economic losses in wheat supplies, especially in developing regions (Carvalho et al. 2023). Conventional reliance on chemical pesticides raises concerns due to their adverse health and environmental impacts, compounded by the beetle's growing resistance to many insecticides (Kumawat and Naga 2013; Alasmari et al. 2025). As a sustainable alternative, plant-derived essential oils have shown promise for pest control, exhibiting both contact toxicity (Omar et al. 2021; Omar et al., 2024) and fumigant effects (Janaki et al. 2018; da Silva et al., 2021). Notably, citrus species (Rutaceae), abundant in tropical climates, produce bioactive essential oils with potential applications in suppressing wheat storage pests (Chou et al. 2022; Jie et al. 2024).

This study aimed to evaluate the chemical composition, insecticidal efficacy, and generational impact of *Citrus aurantium* essential oil against *Tribolium castaneum* infestations in two wheat varieties. The selected wheat cultivars had undergone pre-treatment with arbuscular mycorrhizal fungi and humic acid during field cultivation.

Materials and methods

A two-year field study was conducted during consecutive wheat growing seasons (2022/2023 and 2023/2024) at the Experimental Farm of Sakha Agricultural Research Station, located in Kafr El-Sheikh Governorate, Egypt. The investigation focused on comparative evaluation of two Egyptian wheat cultivars (Misr-1 and Gemmiza-11) under specified growing conditions.

Experimental materials and design

Plant material and treatment protocol

The study utilized grains of common wheat (*Triticum aestivum* L., syn. *T. vulgare*), specifically cultivars Misr 1 and Gemmiza 11.

Mycorrhizal fungi (250 spores/seed) was obtained from Plant Production Department, Faculty of Agriculture, Saba Basha, Alexandria University. While potassium humate (6 kg ha⁻¹) was purchased from the local market.

During sowing, seeds were inoculated with arbuscular mycorrhizal fungi at a standardized rate of 250 (spores/seed) by soaking the seeds and mixing them with the fungus, then leaving them to dry. Concurrently, potassium humate was soil-applied at an agronomic rate of (6 kg ha⁻¹).

Laboratory bioassays

For toxicity evaluations, bitter orange essential oil peel (*Citrus aurantium* L.) was obtained from Hashem Brothers Company's as a gift, tested in a series of laboratory bioassays employing five concentrations: 500, 750, 1250, 2500, and 5000 mg L⁻¹.

Chemical characterization of *Citrus aurantium* essential oil

The chemical composition of *Citrus aurantium* essential oil was analyzed using gas chromatography-mass spectrometry (GC-MS) at Hashem Brothers Company's analytical facility. Analyses were performed on an HP 5890 Series II gas chromatograph (Hewlett Packard, USA) interfaced with an HP 5972 mass selective detector.

Chromatographic conditions

Separation was achieved using a DB-Wax fused silica capillary column (60 m × 0.25 mm i.d., 0.25 µm film thickness) with the following parameters:

- Carrier gas: Helium (constant flow mode at 1.5 mL/min).
- Injector: Split/splitless (250 °C) in split mode (0.2 µL injection volume).
- Oven program: 50 °C (2 min hold) to 250 °C at 6 °C/min ramp rate.
- MS interface temperature: 230 °C.

Mass spectrometric parameters

- Ionization mode: Electron impact (EI) at 70 eV.
- Mass range: 50–650 m/z.
- Scan rate: 2.9 scans/sec.

Sample preparation

To prevent degradation of volatile constituents, crude essential oils were analyzed without derivatization or dilution. This approach ensured comprehensive detection

of all volatile organic compounds present in the native oil.

Insect rearing for bioassay

Adult red flour beetles (*Tribolium castaneum*) were maintained under controlled laboratory conditions at the Stored Product Pests Department, Plant Protection Research Institute, Sakha Agricultural Research Station. The insects were kept at a temperature of 30 ± 1 °C and a relative humidity (R.H.) of $70 \pm 5\%$. For the toxicity assessment, newly emerged adults (aged 1–2 weeks) were selected.

Contact toxicity bioassay

The essential oil stock solution was diluted in analytical-grade acetone to prepare five different concentrations of *Citrus aurantium* oil for testing on *T. castaneum*. Each concentration was thoroughly mixed with crushed wheat grains (1 mL per 20 g of wheat) in a sterilized 250 mL glass jar. The mixture was agitated for 18 min and left to dry. Three replicates were prepared for each wheat cultivar at every concentration. Twenty adult *T. castaneum* beetles were introduced into each jar, which was then covered with a cloth secured by rubber bands. A control group treated with acetone alone was included for comparison. Mortality rates were assessed after 48 and 72 h and adjusted using Abbott's formula (1925). The median lethal concentration (LC_{50}) was determined through probit analysis (Finney, 1971) by using statistical Package for Social Sciences (IBM SPSS Statistics software Version 24.0, IBM Corp., Armonk, NY).

Emergence inhibition bioassay

This study employed an emergence bioassay protocol adapted from Haddi et al. (2015). Test insects ($n=20$ per replicate) were exposed to wheat treated with five concentrations (500, 750, 1250, 2500, and 5000 mg/L) of orange essential oil peel. The wheat substrate (50 g crushed grain) had been pre-treated with either mycorrhizal fungi or potassium humate amendments. A parallel control treatment, identical in all aspects except for the absence of essential oil, was included for comparison.

Table 1 Chemical composition of essential oil of bitter orange, *C. aurantium* peel analyzed by gas chromatography-mass spectrometry (GC-MS)

Compounds	Retention time (min)	Percent composition %	Molecular formula
1. α -pinene	5.49	1.01	$C_{10}H_{16}$
2. β -myrcene	7.09	1.67	$C_{10}H_{16}$
3. Limonene	8.89	85.47	$C_{10}H_{16}$
4. α -terpineol	14.55	2.37	$C_{10}H_{18}O$
Monoterpenoids 82			
Non-terpene alcohols 18			

Following a 15-day exposure period, all surviving insects were removed from the treated substrate. Subsequent adult emergence was monitored and quantified daily throughout a 60-day observation period. All treatments, including controls, were conducted in triplicate to ensure experimental reliability.

Biochemical composition analysis

The carbohydrate content was quantitatively determined through spectrophotometric analysis, employing the phenol-sulfuric acid method established by Dubois and colleagues (1956). This involved constructing a standard calibration curve using known carbohydrate concentrations for accurate quantification.

For protein determination, seed samples (0.1 g aliquots) underwent acid digestion using a micro-Kjeldahl apparatus to liberate nitrogen content. The total crude protein content was subsequently derived by applying a conversion factor of 5.75 to the measured nitrogen values, in accordance with the standardized protocols of the Association of Official Analytical Chemists (AOAC, 1990).

Statistical analysis

All experimental data were subjected to statistical evaluation using one-way analysis of variance (ANOVA) to assess treatment effects. Dose-response relationships were characterized by calculating the median lethal concentration (LC_{50}) through logarithmic probit regression analysis. Categorical data comparisons were performed using Pearson's chi-square test of independence. All statistical computations were conducted using IBM SPSS Statistics software (Version 24.0, IBM Corp., Armonk, NY). Treatment means were compared using post-hoc tests, with statistical significance established at $\alpha \leq 0.05$ probability level.

Results

Chemical composition and toxicity of *C. aurantium* essential oil

The chemical constituents of *C. aurantium* essential oil (EO) were characterized using gas chromatography-mass spectrometry (GC-MS). By comparing retention times and mass spectra with reference data from the NIST/EPA/NIH Mass Spectral Library, a total of 48 distinct compounds were identified (Table 1). The predominant component was limonene (85.47%), followed by minor constituents such as α -Terpineol (2.37%), β -Myrcene (1.67%) and α -Pinene (1.01%). Terpenoids constituted the major chemical class, with monoterpenes representing 82% of the total composition, while non-terpene alcohols accounted for the remaining 18%.

Insecticidal efficacy of *C. aurantium* essential oil

The bioassay results demonstrated a clear concentration-dependent mortality response in *T. castaneum* when.

exposed to *C. aurantium* essential oil. Analysis of LC_{50} values revealed significant differences between treatments after 24 h exposure as follow:

- The grains of the two wheat cultivars treated with Mycorrhiza showed LC_{50} values ranging from 7975 mg/L (Misr 1) to 5434 mg/L (Gemmiza-11).
- The grains of the two wheat cultivars treated with Potassium humate exhibited lower LC_{50} values, ranging from 6396 mg/L (Misr 1) to 5884 mg/L (Gemmiza-11).

Notably, the lowest LC_{50} value (5434 mg/L) was observed in the grains of wheat cultivar Misr 1 previously treated with potassium humate (6 kg fad⁻¹) indicating its enhanced susceptibility to the essential oil treatment. This concentration-mortality relationship remained consistent at the 48-hour evaluation period, demonstrating similar trends in treatment efficacy (Table 2).

Effect of treatments on progeny production

Both wheat grains of the varieties (Misr-1 and Gemmiza-11) previously treated with mycorrhizal fungi (250 spores/grain) and potassium humate (6 Kg fad⁻¹) demonstrated significant suppression of progeny production with all tested concentrations (500–5000 mg/L.) of *C. aurantium*, as shown in Fig. 1. Quantitative analysis revealed that potassium humate treatment consistently exhibited superior efficacy compared to mycorrhizal fungi treatment. In the Misr-1 variety, the inhibition rates for mycorrhizal fungi treatment ranged from 31.41% (minimum) to 84.43% (maximum), while potassium humate treatment achieved a broader suppression ranged from 31.40 to 88.15%. Similar trends were observed in Gemmiza-11 cultivar, where mycorrhiza fungi (250 spores/

grain) treatment reduced progeny by 23.30–84.01%, compared to 40.45–89.04% for potassium humate (6 Kg fad⁻¹) treatments.

Long-term effects of *C. aurantium* essential oil on wheat grain cultivars composition

Figure 2 presents the impact of LC_{50} concentrations of *C. aurantium* essential oil on the biochemical composition (carbohydrate and protein %) of stored wheat grain over a 12-month period, with analyses conducted at 6-month intervals. Both tested cultivars (Misr-1 and Gemmiza-11) treated with mycorrhizal fungi (250 spores/grain) and potassium humate (6 kg fad⁻¹) showed significant increase in wheat grain composition percentage compared to control treatment.

Discussion

Scientific background on humic substances and mycorrhizal fungi associations

Previous research has extensively documented the significant roles of humic acids and mycorrhizal symbiosis in plant physiology and stress mitigation. Mycorrhizal Fungi help the plant acquire essential nutrients such as phosphorus and nitrogen (Huang et al., 2026), in addition to enhancing water uptake, improving stress tolerance and increasing yield (Sheteiwy et al., 2025). These factors in addition to the use of essential oils are expected to improve crop characteristics and quality and help it resist insect infestations, especially stored-grain pests, particularly the flour beetle (*Tribolium castaneum*), which causes significant losses in this strategic crop (Singh and Choudhary 2026). Key findings from the literature include:

Nutrient management and detoxification

The results in Table 2 indicated that the lowest LC_{50} value was observed in the grains of wheat cultivar Misr 1 previously treated with potassium humate, in this

Table 2 Adulticidal bioactivity of *C. aurantium* essential oil against *T. castaneum* adults in Misr 1 and Gemmiza-11 after 24 and 48 h of exposure

Treatment	Exposure time (hours)	LC_{50} (mg/L)	Confidence limits	Slope value $\pm$ SE	Chi-square (X^2)	P value
Mycorrhizal						
Misr-1		7975	5653–10,904	1.56 $\pm$ 0.21	3.56	0.36
Gemmiza-11		6396	5215–8493	1.79 $\pm$ 0.81	1.38	0.70
Pot. Humate	24 h					
Misr-1		5434	4205–7902	1.69 $\pm$ 0.20	3.35	0.33
Gemmiza-11		5884	4495–8782	1.68 $\pm$ 0.26	2.71	0.43
Mycorrhizal						
Misr-1		3730	2984–5077	1.55 $\pm$ 0.18	5.84	0.11
Gemmiza-11		3312	2391–9110	1.79 $\pm$ 0.18	6.65	0.02
Pot. Humate	48 h					
Misr-1		3324	2811–4098	2.03 $\pm$ 0.19	1.95	0.58
Gemmiza-11		2942	2073–7128	1.73 $\pm$ 0.18	0.64	0.03

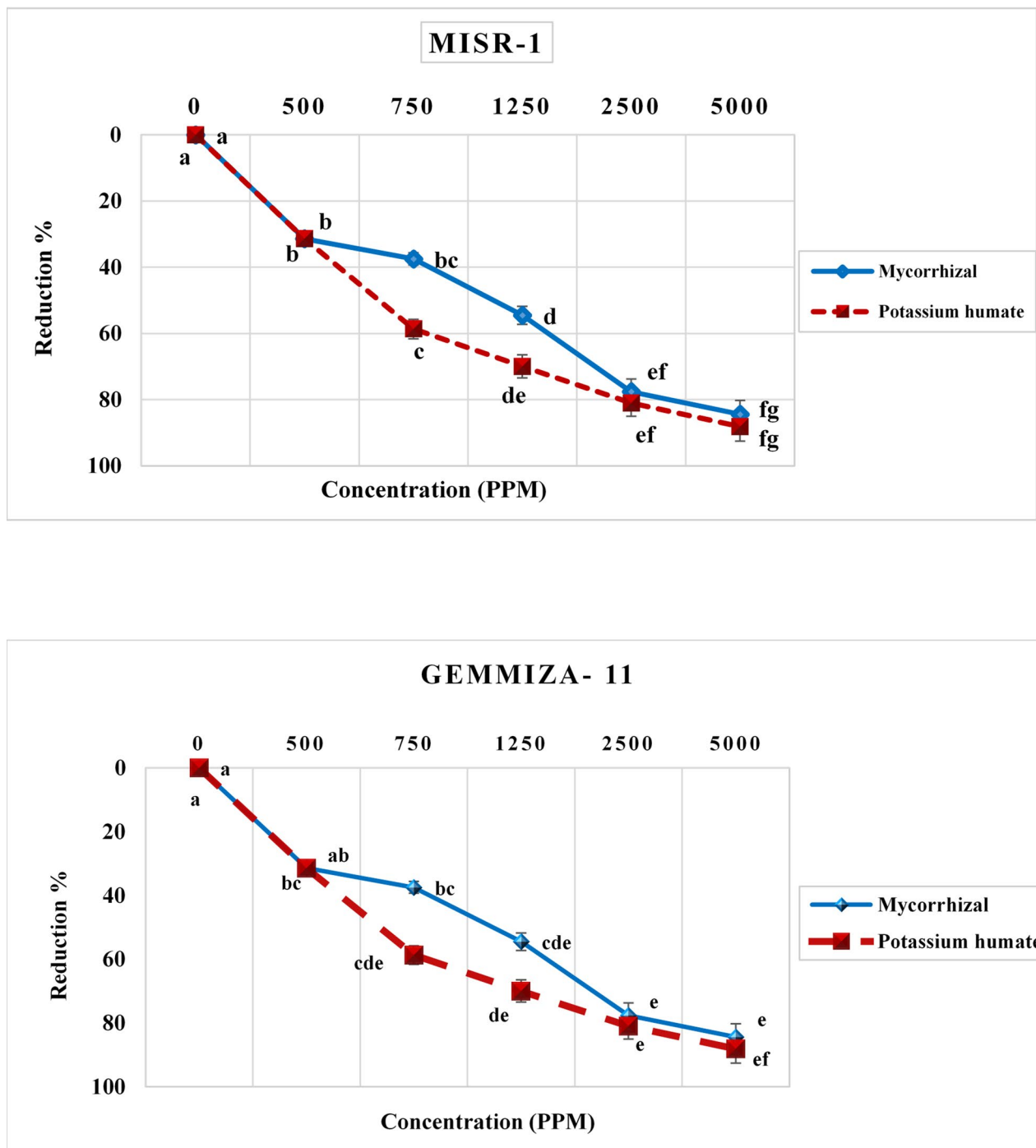


Fig. 1 Effect of *C. aurantium* EO on number of *T. castanum* emerged progeny adults and reduction percentage in Misr-1 and Gemmiza-11 treated by Mycorrhizal and Potassium Humate. [Values followed by the same letters are not significantly different ($P > 0.05$)]

connection, (Islam et al. 2020; Jin et al. 2024) demonstrated that humic substances function as: Chelating agents for toxic elements Enhancers of nutrient bioavailability and uptake efficiency.

Physiological enhancement mechanisms

Both tested cultivars (Misr-1 and Gemmiza-11) treated with mycorrhizal fungi (250 spores/grain) and potassium humate (6 kg fad-1) and stored over a 12-month period treated with LC_{50} concentrations of *C. aurantium* essential oil showed increase in (carbohydrate and protein %) biochemical composition as Othman et al. (2020)

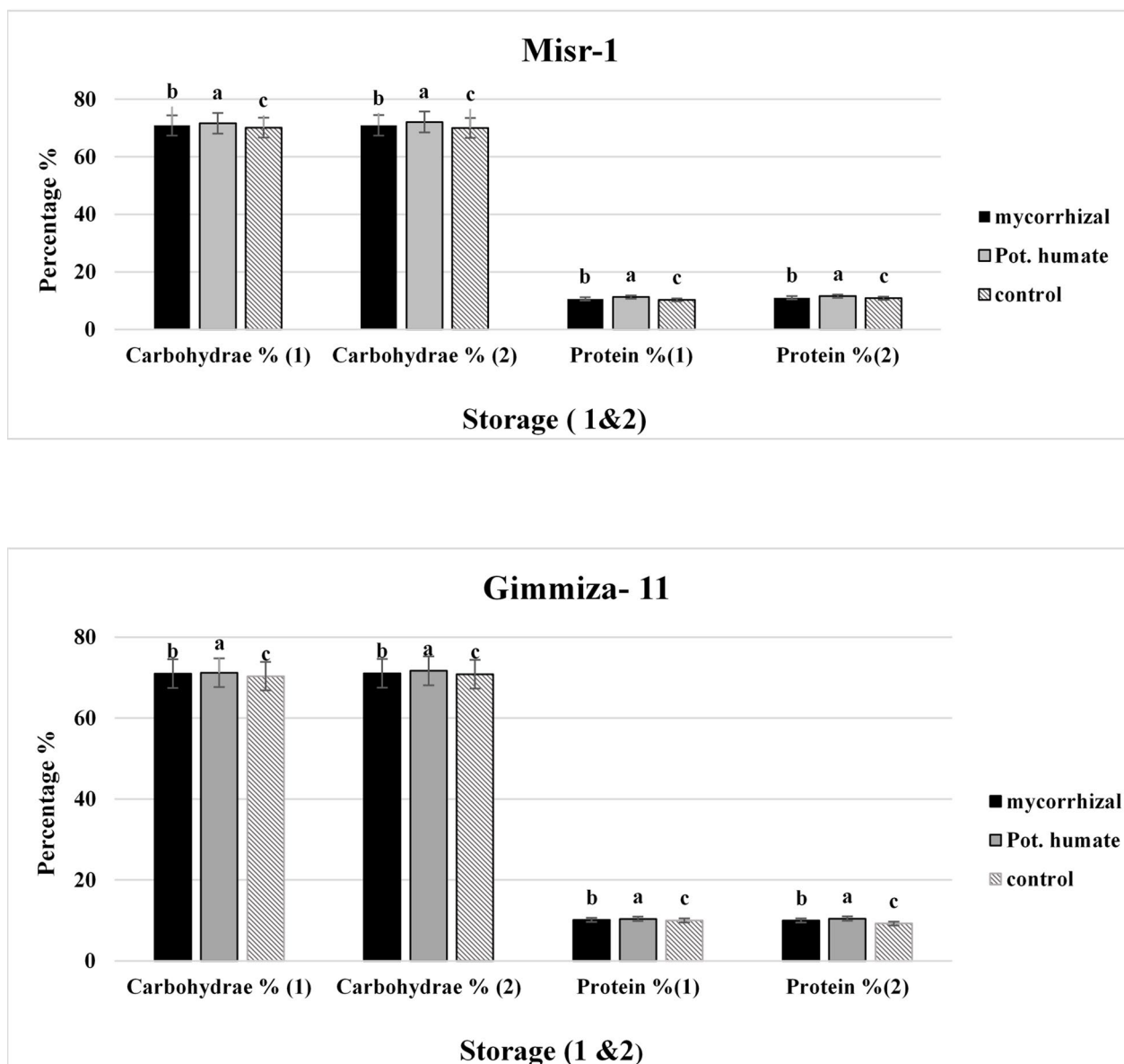


Fig. 2 Effect of *C. aurantium* essential oil LC_{50} value on % carbohydrate and % protein on two cultivar wheat grain Misr1 and Gimmza11 after 1 year (every 6 month) of storage. [Values followed by the same letters are not significantly different ($P > 0.05$)]

elucidated multiple protective mechanisms of humic acids in wheat under saline conditions: Modulation of cell membrane permeability Stimulation of photosynthetic activity and respiratory metabolism Enhancement of phosphorus assimilation Selective ion regulation, particularly in restricting Na^+ accumulation in shoot tissues. These studies collectively highlight the dual benefits of humic substances in both stress alleviation and plant performance optimization, while mycorrhizal associations are known to complement these effects through their extensive hyphal networks and nutrient exchange capabilities.

Reducing the LC_{50} value over time indicates the effectiveness of tested essential oil in controlling the insect as

shown in Table 2. Essential oils (EOs) extracted after harvest show great potential as an alternative for pesticide development, thanks to their distinctive chemical properties and insecticidal effects. Chemical composition of *Citrus aurantium* essential oil peel shown in Table 1 consist of complex mixtures of bioactive compounds with diverse physicochemical properties, enabling multiple modes of action against insect pests (Oviedo-Sarmiento et al. 2021; Omar et al., 2024). A key component of EOs is monoterpenoids (Subaharan et al. 2021), which play a major role in their high acute toxicity against pests (Subaitha et al. 2024). Monoterpenes represent the primary bioactive constituents that drive the insecticidal efficacy of essential oils (Campolo et al. 2014; Yip et al.

2024). Research by Bnina et al. (2019) demonstrated that *Citrus aurantium* essential oils and their dominant component, limonene, showed potent contact toxicity against three key stored-product pests: *Tribolium castaneum*, *Cryptolestes ferrugineus*, and *Liposcelis bostrychophila*. Oyedeji et al. (2020) investigated the insecticidal activity of essential oils (EOs) derived from *Citrus aurantium* (L.) and other citrus species against 1- to 7-day-old *Tribolium castaneum* adults. Their findings revealed that *C. aurantium* and *C. paradisi* oils exhibited particularly strong pesticidal effects.

The study included an exploratory analysis to assess the correlation between chemical composition and toxicity. While previous research had documented the toxicity of some of these oils against *T. castaneum*, the LC_{50} values in this study (Table 2) varied, likely due to differences in chemical profiles (e.g., relative abundance of specific compounds) or bioassay methodology.

The results suggested that elevated monoterpenoid content (82%), especially when combined with nutrient treatments, could significantly improve contact-based lethality. Our investigation further demonstrated that *C. aurantium* essential oils significantly impaired the reproductive fitness of *T. castaneum*, as evidenced by reduced progeny production. Analysis of population growth parameters revealed a notable decline in the intrinsic rate of increase following exposure to the tested nutritional treatments. This reproductive suppression was particularly pronounced when *C. aurantium* oil was combined with wheat grains amended with either potassium humate or mycorrhizal fungi. The observed progeny counts were substantially lower than control values, suggesting that such treatments could effectively limit the pest's reproductive potential and subsequent population spread. This finding holds particular significance given that under field conditions, pest insects typically exhibit brief contact periods with treated surfaces (Bnina et al. 2019). The observed effects align with previous research demonstrating that mycorrhizal fungi applications can enhance wheat grain quality; Radwan et al. 2014; Xue et al., 2024) reported substantial increases in grain protein content following treatments by mycorrhizal fungi. Such quality preservation is critical for maintaining post-harvest grain value and ensuring end-product quality for consumers. Our results corroborate the findings of George et al. (2023), who documented significant improvements in crude protein and ash content in wheat grains inoculated with arbuscular mycorrhizal fungi after six months of storage when protected with *Cyperus rotundus* essential oil.

Conclusions

The current investigation demonstrates that both mycorrhizal fungi and potassium humate application (6 kg feddan⁻¹) effectively mitigated saline soil stress in two wheat cultivars (Misr 1 and Gemmiza-11), as evidenced by enhanced total chlorophyll and protein content alongside reduced proline accumulation. The cultivar Misr 1 was specifically selected for its superior agronomic performance and physiological traits, which correlated with optimal yield characteristics. GC-MS analysis identified limonene as the predominant phytochemical constituent of *C. aurantium* essential oil, confirming its potential as a biopesticide for stored-product pest management. Our results substantiate the dual efficacy of *Citrus aurantium* essential oil, demonstrating both acute toxicity and progeny suppression against *Tribolium castaneum*, with particularly pronounced effects observed in potassium humate-treated Misr 1 wheat.

Abbreviations

LC_{50}	Lethal concentration of 50%
GC-MS	Gas chromatography-mass spectrometry
EOs	Essential oils
R.H.	Relative humidity
kg fad ⁻¹	Kilogram per faddan
Pot. Humate	Potassium humate

Acknowledgements

We would like to thank Hashim brother Company for Essential Oils.

Author contributions

George Morris Nasr, Ahmed Fayeze Omar conceived and designed research. George M. Nasr designed and applied the field experiment. George Morris Nasr, Ahmed Fayeze Omar conducted experiments (contact toxicity, Emergence and reduction bioassay and Determination of carbohydrate and protein) and analyzed data and wrote the draft manuscript.

Funding

The authors did not receive support from any organization for the submitted work.

Data availability

Data and material are available from the corresponding author upon request.

Declarations

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 7 August 2025 / Accepted: 8 February 2026

Published online: 27 February 2026

References

- Abbott WS (1925) A method of the effectiveness of insecticides. *J Econ Entomol* 18:265–267
- Alasmari SM, Albogami BZ, Nenaah GE (2025) Potential of using *Clerodendrum inerme* extracts, essential oil, and biosynthesized silver nanoparticles as ecofriendly natural pesticides for controlling the rust floor beetle, *Tribolium castaneum* infesting grain products in stores. *J Stored Prod Res* 114:102715. <https://doi.org/10.1016/j.jspr.2025.102715>

- AOAC (1990) Official Methods of Analysis of the Association of Official Analytical Chemists, Vol. II, 15th ed. Section 985.29. The Association: Arlington, VA
- Arif M, Ilyas M, Adnan M, Kalsoom R, Ren M, Xu R, Li L (2025) Molecular mechanisms and breeding strategies for enhancing wheat resilience to environmental stresses: The role of heat shock proteins and implications for food security. *Int J Biol Macromol* 308:142468. <https://doi.org/10.1016/j.jbiomac.2025.142468>
- Bnina EB, Hajlaoui H, Chaieb I, Said MB, Jannet HB, Daami-Remadi M (2019) Chemical composition, antimicrobial and insecticidal activities of the tunisian Citrus aurantium essential oils. *Czech J Food Sci* 37(2):81–92. <https://doi.org/10.17221/202/2017-CJFS>
- Campolo O, Zappalà Malacrinò A, Laudani L, Chiera F, Serra E, Russo D, Palmeri M (2014) V. Fumigant bioactivity of five Citrus essential oils against *Tribolium confusum*. *Phytoparasitica* 2014; 42(2):223–233. <https://doi.org/10.1007/s12600-013-0355-4>
- Carvalho MO, Geirinhas H, Duarte S, Graça C, de Sousa I (2023) Impact of red flour beetle infestations in wheat flour and their effects on dough and bread physical, chemical, and color properties. *J Stored Prod Res* 102:102095. <https://doi.org/10.1016/j.jspr.2023.102095>
- Chou C, Hadi BA, Chiba S, Sato I, Choi IR, Tanaka T (2022) An entomopathogenic fungus and a natural extract benefit rice (*Oryza sativa*) by suppressing populations of insect pests while keeping high populations of their natural enemies. *Biol Control* 165:104793. <https://doi.org/10.1016/j.biocontrol.2021.104793>
- da Silva, A. S., de Lira Pimentel, C. S., dos Santos, F. H. G., de Araújo, H. D. A., Paiva, P. M. G., da Silva, N. H., Navarro, D. M. D. A. F. (2021). Insecticidal activity of the ether extract from the lichen *Ramalina complanata* and an isolated metabolite (divaricatic acid) against *Sitophilus zeamais* (Coleoptera:Curculionidae). *Biocatalysis and Agricultural Biotechnology*, 35, 102049. <https://doi.org/10.1016/j.bcab.2021.102049>
- de Moura, O. V. T., Berbara, R. L. L., de Oliveira Torchia, D. F., Da Silva, H. F. O., de Castro, T. A. V. T., Tavares, O. C. H., Garcia, A. C. (2023). Humic foliar application as sustainable technology for improving the growth, yield, and abiotic stress protection of agricultural crops. A review. *Journal of the Saudi Society of Agricultural Sciences*, 22(8), 493–513. <https://doi.org/10.1016/j.jssas.2023.05.001>
- Devkota M, Devkota KP, Omar MED, Attaher S, Govind A, Nangia V (2026) Context-specific agronomic solutions for achieving agronomic gains with reduced environmental footprints in irrigated drylands of Egypt. *Agric Syst* 232:104566. <https://doi.org/10.1016/j.agry.2025.104566>
- DuBois M, Gilles KA, Hamilton JK, Rebers PA, Smith F (1956) Colorimetric method for determination of sugars and related substances. *Anal Chem* 28(3):350–356
- Finney DJ (1971) Profit Analysis Cambridge university press. Cambridge, 333
- George MN, Nevein LE, Tamer I (2023) Effect of *Cyperus rotundus* essential oil against two stored pests and grain quality of some wheat cultivars during storage period
- Haddi K, Oliveira EE, Faroni LR, Guedes DC, Miranda NN (2015) Sublethal exposure to clove and cinnamon essential oils induces hormetic-like responses and disturbs behavioral and respiratory responses in *Sitophilus zeamais* (Coleoptera: Curculionidae). *J Econ Entomol* 108(6):2815–2822. <https://doi.org/10.1093/ee/tov255>
- Huang, B., Wu, Y., Kan, Z. R., Berckx, F., Fransson, P., Zhang, Q., ... Yang, H. (2026). Contrasting impacts of wheat rhizosphere and hyphosphere on methane and nitrous oxide emissions under straw incorporation. *Soil and Tillage Research*, 255, 106793. <https://doi.org/10.1016/j.still.2025.106793>
- Ibrahim AH, Abdel-Fattah GM, Eman FM, El-Aziz A, M. H., Shohr AE (2011) Arbuscular mycorrhizal fungi and spermine alleviate the adverse effects of salinity stress on electrolyte leakage and productivity of wheat plants. *Phyton* 51(2):261–276
- Ileke KD, Adeniran CO (2025) Chemical composition and insecticidal efficacy of two animals' horn and hoof crude extracts against lesser grains borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae). *Heliyon* 11(2). <https://doi.org/10.1016/j.heliyon.2025.e41778>
- Islam MA, Morton DW, Johnson BB, Angove MJ (2020) Adsorption of humic and fulvic acids onto a range of adsorbents in aqueous systems, and their effect on the adsorption of other species: A review. *Sep Purif Technol* 247:116949. <https://doi.org/10.1016/j.seppur.2020.116949>
- Janaki S, Zandi-Sohani N, Ramezani L, Szumny A (2018) Chemical composition and insecticidal efficacy of *Cyperus rotundus* essential oil against three stored product pests. *Int Biodeterior Biodegrad* 133:93–98. <https://doi.org/10.1016/j.biod.2018.06.008>
- Jie Y, Shi T, Yang D, Zhang Z (2024) Essential oil of Citrus limon Osbeck: An insecticidal natural product against *Cryptolestes pusillus* Schönherr. *J Asia Pac Entomol* 27(1):102203. <https://doi.org/10.1016/j.aspen.2024.102203>
- Jin Y, Yuan Y, Liu Z, Gai S, Cheng K, Yang F (2024) Effect of humic substances on nitrogen cycling in soil-plant ecosystems: Advances, issues, and future perspectives. *J Environ Manage* 351:119738. <https://doi.org/10.1016/j.jenvm.2023.119738>
- Kadir ML, Dageri A, Aslan TN (2025) Nanopesticides for managing primary and secondary stored product pests: current status and future directions. *Heliyon* 11(4). <https://doi.org/10.1016/j.heliyon.2025.e42341>
- Kandil AA, Sharief AEM, Seadh SE, Altai DSK (2016) Role of humic acid and amino acids in limiting loss of nitrogen fertilizer and increasing productivity of some wheat cultivars grown under newly reclaimed sandy soil. *Int J Adv Res Biol Sci* 3(4):123–136
- Kheya, S. A., Talukder, S. K., Datta, P., Yeasmin, S., Rashid, M. H., Hasan, A. K., ... Islam, A. M. (2023). Millets: The future crops for the tropics-Status, challenges and future prospects. *Heliyon*, 9(11). <https://doi.org/10.1016/j.heliyon.2023.e22123>
- Kumawat KC, Naga BL (2013) Effect of plant oils on the infestation of *Rhyzopertha dominica* (Fab.) in wheat, *Triticum aestivum* Linn. *J Plant Prot Res.* <https://doi.org/10.2478/jppr-2013-0045>
- Li Y, Zhou Y, Han X, Tang M, Zhang H (2024) Overexpression of IbPT7 promotes phosphorus uptake by plants and affects phosphorus uptake by arbuscular mycorrhizas under high phosphorus condition. *Russian J Genet* 60(5):588–594. <https://doi.org/10.1134/S1022795424700108>
- Naseer, M., Yang, Y. M., Zhu, Y., Zhao, L., Cao, J., Wang, S., ... Xiong, Y. C. (2024). Nano-iron and AM fungi inoculation in dryland wheat field: A sustainable alternative to plastic film mulching. *Field Crops Research*, 306, 109208. <https://doi.org/10.1016/j.fcr.2023.109208>
- Omar AF, El-Elbiary ME, Nasr GM, Hassan HM (2021) Toxicity and biochemical effects of Cumin and Basil essential oils on *Tribolium Castaneum*. *Sci Agric Bohem* 52(3):39–48. <https://doi.org/10.2478/sab-2021-0005>
- Omar, AF, Khalil, FMA, Alomran, MM, Ismail, T, El-Tokhy, AI, Abdelaal, K, ... Abouelatta, AM. (2024). Toxicity and enzymatic activity changes in rice weevil (*Sitophilus oryzae*) induced by basil (*Ocimum basilicum*) and cumin (*Cuminum cyminum*) essential oils. *Sci Rep* <https://doi.org/10.1038/s41598-024-80329-x>
- Othman MM, Rashwan E, El-Emshaty AM (2020) Influence of foliar application of potassium humate and proline on wheat growth and productivity grown in saline soil. *J Soil Sci Agricultural Eng* 11(11):685–692. <https://doi.org/10.2160/8/JSSAE.2020.164638>
- Oviedo-Sarmiento JS, Cortes JJB, Ávila WAD, Suárez LEC, Daza EH, Patiño-Ladino OJ, Prieto-Rodríguez JA (2021) Fumigant toxicity and biochemical effects of selected essential oils toward the red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae). *Pestic Biochem Physiol* 179:104941. <https://doi.org/10.1016/j.pestbp.2021.104941>
- Oyediji AO, Okunowo WO, Osuntoki AA, Olabode TB, Ayo-Folorunso F (2020) Insecticidal and biochemical activity of essential oil from Citrus sinensis peel and constituents on *Callosobruchus maculatus* and *Sitophilus zeamais*. *Pestic Biochem Physiol* 168:104643. <https://doi.org/10.1016/j.pestbp.2020.104643>
- Periasamy K, Selvaraj PS, Veeraswamy D, Ettiyagounder P, Tamilselvan I, Kathirvel S, Karchiyappan T (2025) Alleviating soil salinity stress in castor (*Ricinus communis* L.): Synergistic effects of organic amendments and arbuscular mycorrhizal fungi on growth, yield, and antioxidant improvement under effluent contaminated ecosystem. *Desalination Water Treat* 323:101295. <https://doi.org/10.1016/j.dwt.2025.101295>
- Prasad KRK, Singh M, Kumar A (2013) Mycorrhiza biofertilizer for sustainable agriculture. *Agriways* 1(1):65–66
- Radwan FI, Gomaa MA, Naser MAA, Mussa IF (2014) Response of some wheat varieties to humic acid, mineral and biofertilization on productivity and quality. *Middle East J Agric Res* 3(3):631–637
- Rashad YM, Elkelish A, Ibrahim OM, El-Sharkawy HH, Hassanein SE, Deng JX (2026) Uncovering differential expressed long non-coding RNAs of wheat in response to the endophyte *Epicoccum italicum* HE20 and yellow rust infection. *Physiol Mol Plant Pathol* <https://doi.org/10.1016/j.pmp.2025.103014>
- Salwan R, Sharma A, Sharma V (2019) Microbes mediated plant stress tolerance in saline agricultural ecosystem. *Plant Soil* 442:1–22. <https://doi.org/10.1007/s1104-019-04202-x>
- Sheteiwy, M. S., Ahmed, M., Alyafei, M., Sulieman, S., Ali, B., Joško, I., ... Abdel-Fattah, G. G. (2025). Sugar metabolism and metabolite profiling of maize grains are largely improved by the combination of arbuscular mycorrhizal

- fungi and humic acid. *Industrial Crops and Products*, 234, 121546. <https://doi.org/10.1016/j.indcrop.2025.121546>
- Simarmata T, Hibatullah FH, Khumairah FH, Ambarita DD, Nurbaita A, Herdiyantoro D, Kamaluddin NN (2025) Advancing Climate-Resilient Rhizomicrobiome Engineering for Enhancing Productivity and Sustainability of Strategic Crop Farming in Indonesia's Problematic Soils. *Environ Sustain Indic* <https://doi.org/10.1016/j.indic.2025.100821>
- Singh CB, Jayas DS (2024) Grain storage and management. In *Unit Operations in Food Grain Processing* (pp. 161–174). Academic Press. <https://doi.org/10.1016/B978-0-443-18965-4.00006-6>
- Singh S, Choudhary H (2026) Essential oil composition and synergistic bioefficacy of medicinal plant essential oils against *Tribolium castaneum* (Herbst, 1797) (Coleoptera: Tenebrionidae). *J Stored Prod Res* 115:102842. <https://doi.org/10.1016/j.jspr.2025.102842>
- Subaharan K, Rajendran S, SManjunath S, Geetha G, Thimmegowda V, Shanmugam P, Nandagopal B, Muthu G, Sengottayan SN, Karamankodu JD (2021) Toxicity, behavioural and biochemical effect of Piper beetle L. essential oil and its constituents against housefly, *Musca domestica* L *Sci direct* <https://doi.org/10.1016/j.pestbp.2021.104804>
- Subaitha ZA, Santhoshkumar P, Moses JA, Loganathan M (2024) Nonchemical strategies for stored product pest management: Exploring the potential of spices, herbs, and their formulations. *Food Control* 158:110212. <https://doi.org/10.1016/j.foodcont.2023.110212>
- Xue J, Mei L, Wang X, Zhong Y, Huang M, Wang X, Jiang D (2024) Arbuscular mycorrhizal fungi affected soft wheat quality properties and nutritional index by regulating the composition and secondary structure of protein. *J Cereal Sci*. <https://doi.org/10.1016/j.jcs.2024.104032>
- Yassen M, Kausar T, Praween B, Shah SJ, Jan Y, Shekhawat S, Malik M, Azad ZR (2019) Insect pest infestation during storage of cereal grains, pulses and oil seeds. *Health Saf Aspects Food Process Technol* 11:201–234. https://doi.org/10.1007/978-3-030-24903-8_8
- Yip SC, Ho LY, Wu TY, Sit NW (2024) Chemical composition and bioactivities of Eucalyptus essential oils from selected pure and hybrid species: A review. *Ind Crops Prod* 222:120118. <https://doi.org/10.1016/j.indcrop.2024.120118>

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.