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Original article

Chemical Composition and Toxicity of *Laurus nobilis* L. Essential Oil against *Tribolium castaneum* (Herbst) Following Topical and Dietary Exposure

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Abstract

Synthetic pesticides have shown important limitations in the control of stored-products pests. The investigation of plant essential oils as an ecofriendly alternative has attracted the attention of many researchers. This study focuses on the chemical composition of Laurus nobilis L essential oil and its insecticidal potential against the larval, pupal, and adult stages of Tribolium castaneum (Herbst) following topical and dietary exposure. GC–FID and GC–MS analyses showed that the essential oil contained 47.18% identified terpenes, including 36.10% oxygenated monoterpenes. The major constituents were 1,8-cineole (13.52%) and α-terpinyl acetate (12.34%). The obtained results following topical application at concentrations of 1%, 10% and 20% highlight a significant ($p < 0.05$) mortality after 7 days of exposure, where the highest concentration (20%) caused 100%, 88%, and 72% mortality in larvae, adults, and pupae, respectively. The toxicity increases with exposure time, as reflected by the decrease of LC_{50} values, where larvae are the most susceptible developmental stage (LC50 = 2.83% after 7 days). However, the ingestion assays showed moderate toxicity at all tested concentrations, the highest mortality was registered for larvae (40%) after 21 days with a gradual reduction in LC_{50} values from 54.16% to 22.54%. Nutritional analyses revealed a significant increase in the relative consumption rate (RCR), with a negative feeding deterrence index (FDI) recorded at all tested concentrations, especially at 1% (−131.85 ± 51.81%), indicating a phagostimulant effect. The obtained results highlighted that L. nobilis essential oil is more toxic against T. castaneum through contact than through ingestion. This study supports the potential of L. nobilis essential oil as a promising botanical insecticide for the management of stored-product pests.

Keywords: Nutritional index, Median lethal concentration, Median lethal time, Larva, Pupa, Adult

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INTRODUCTION

Post-harvest insect infestations continue to pose a serious threat to food security in the world, causing considerable losses in both the quantity and quality of stored agricultural products. Beyond reducing food availability, these pests also impair the nutritional value, commercial quality, and marketability of stored commodities, resulting in significant economic losses throughout the supply chain (Khan et al., 2024; Athanassiou et al., 2025). Among stored-product insects, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), is one of the most destructive secondary pests of cereals and processed grain products worldwide (Stathas et al., 2023). For several decades, the protection of stored commodities has relied predominantly on synthetic contact insecticides and fumigants because of their rapid action, broad-spectrum efficacy, and cost-effectiveness. However, the intensive and repeated use of these chemicals has promoted the development and worldwide spread of insecticide and phosphine resistance in *T. castaneum* and other major stored-product pests, thereby compromising long-term control efficacy (Nayak et al., 2026 ; Karthik et al., 2024;). In addition, increasing concerns regarding pesticide residues in food, environmental contamination, adverse effects on non-target organisms, and increasingly stringent regulatory requirements have accelerated the search for safer and more sustainable alternatives, including botanical insecticides and other eco-friendly pest management approaches (Kariyanna et al., 2024).

Among botanical pesticides, essential oils have attracted considerable attention because of their broad-spectrum biological activities, fast biodegradability, low environmental persistence, and complex chemical composition, which reduces the likelihood of resistance development through their multitarget modes of action (Ayllón-Gutiérrez et al., 2024). Essential oils consist primarily of mono- and sesquiterpenes together with their oxygenated derivatives, whose biological activities often result from synergistic interactions among major and minor compounds rather than from a single dominant compound (Li et al., 2025). Numerous essential oils have demonstrated insecticidal, fumigant, repellent, ovicidal, antifeedant, and growth-inhibitory activities against a wide range of stored-product insects, highlighting their promise as environmentally friendly substitutes for conventional synthetic insecticides (Kavallieratos et al., 2025; Singh et al., 2024).

Laurus nobilis L. (Lauraceae), commonly referred to as bay laurel, is an aromatic evergreen tree native to and extensively cultivated across the Mediterranean region (Fantasma et al., 2024). Its essential oil is rich in biologically active monoterpenes, particularly 1,8-cineole, α-pinene, sabinene, linalool, α-terpinyl acetate, and other oxygenated monoterpenes, although its chemical profile may vary according to geographical origin, environmental conditions, harvest season, and extraction method (Khodja et al., 2023). Previous studies have demonstrated antimicrobial, antioxidant, antifungal, and insecticidal activities of *L. nobilis* essential oil against various agricultural and stored-product pests (Guedri et al., 2020 ; Paparella et al., 2022 ; Tahiri et al., 2024 ; Karabörklü & Ayvaz, 2023). The insecticidal properties of bay laurel essential oil have mostly been attributed to the combined action of its volatile

constituents, which affect multiple physiological targets and reduce feeding activity while increasing mortality. Nevertheless, considerable variability in biological efficacy has been reported among insect species and experimental conditions, indicating that toxicity is strongly influenced by essential oil composition, exposure route, insect developmental stage, and duration of exposure (Kavallieratos et al., 2025; Elkiran et al., 2026).

Although the insecticidal efficacy of *L. nobilis* essential oil has been documented against various stored-product insects, information remains scarce regarding its stage-specific toxicity, its effects on feeding performance, and the estimation of lethal concentrations and lethal times in *T. castaneum*.

Therefore, this study aimed to characterize the chemical composition of *L. nobilis* essential oil collected from the Kef region and assess its insecticidal efficacy against larvae, pupal and adult stages of *T. castaneum* through ingestion bioassays. The study further investigated its effects on nutritional indices and estimated lethal concentrations (LC_{50} and LC_{90}) as well as lethal times (LT_{50} and LT_{90}) to provide a comprehensive assessment of its bioactivity.

MATERIALS and METHODS

Plant material

Fresh leaves of *L. nobilis* were collected in March 2025 from Le Kef, northwestern Tunisia (36°09′57″ N, 8°43′35″ E).

Essential Oil Extraction

The essential oil was extracted from 250g of fresh L. nobilis leaves by hydrodistillation using a Clevenger-type apparatus for 4 h. The plant material was mixed with 150 ml of distilled water. Following hydrodistillation, the recovered oil was collected and stored at 4 °C until further chemical analysis and bioassays.

GC-FID and GC-MS Analysis of Laurus nobilis Essential Oil

The chemical profile of the essential oil was determined at the Technological Platform of the Faculty of Pharmacy, University of Monastir (Tunisia), using gas chromatography coupled with flame ionization detection (GC–FID) and gas chromatography–mass spectrometry (GC–MS).

Quantitative analysis was carried out on an HP 5890 Series II gas chromatograph (Hewlett-Packard, USA) equipped with a flame ionization detector (FID) and an HP-5 fused-silica capillary column (30 m × 0.25 mm i.d., 0.25 μm film thickness). The oven temperature was initially maintained at 60 °C for 10 min, then increased at a rate of 5 °C min^{-1} to 220 °C, where it was held for an additional 10 min. Both the injector and detector were maintained at 240 °C. Helium was used as the carrier gas at a constant flow rate of 2.0 mL min^{-1}. Samples were injected in split mode (1:30) using 0.5 μL of a 10% (v/v) solution prepared in n-hexane.

Qualitative characterization was performed using an Agilent 7890A gas chromatograph coupled to an Agilent 5975C mass selective detector (MSD) and fitted with an HP-5 capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). The injector and transfer line temperatures were set at 220 and 240 °C, respectively. The oven temperature program started at 60 °C and was increased to 240 °C at a rate of 3 °C min^{-1}. Helium was employed as the carrier gas, and 0.2 µL of a 10% (v/v) solution in n-hexane was injected in split mode (1:30).

Linear retention indices (Lr.i.) were calculated using a homologous series of n-alkanes (C_8–C_{40}) according to the method of Van den Dool and Kratz (1963). Compound identification was achieved by comparing the calculated retention indices with published data (Adams, 2017) and by matching the obtained mass spectra with those contained in the NIST 2011 mass spectral library and a validated in-house database. Whenever available, compound identities were further confirmed by comparison with authentic reference standards.

Insect Rearing

Larvae, pupae and adults of T. castaneum were obtained from a laboratory stock colony maintained at 30 ± 1 °C, 70–80% relative humidity and complete darkness. The insects were reared on an artificial diet composed of wheat flour supplemented with brewer's yeast (10:1, w/w), and healthy individuals were used for all bioassays.

Biological Essays

Topical Toxicity Bioassay

The topical toxicity of *L. nobilis* essential oil was assessed according to the method of Pascual-Villalobos and Fernández (1999), with minor modifications. A 1µL droplet of either pure acetone (control) or an essential oil solution prepared in acetone at concentrations of 1, 10, and 20% (v/v) was applied to the ventral thoracic surface of *T. castaneum* adults (10–14 days old), pupae (<24 h old) or larvae.

Immediately after treatment, groups of 10 adults, 10 pupae or 10 larvae were transferred to glass vials covered with muslin cloth to ensure adequate ventilation while preventing insect escape. Each treatment, including the control, was replicated five times. The insects were kept at 30 ± 1 °C, 70–80% relative humidity, and in complete darkness throughout the experimental period.

Adult, pupal and larvae mortality was recorded at 24-h intervals for seven consecutive days. Dead insects were removed after each assessment. The mortality data were subsequently subjected to probit analysis to determine the median and 90% lethal concentrations (LC_{50} and LC_{90}) and the median and 90% lethal times (LT_{50} and LT_{90}).

Antifeedant Activity and Growth Inhibition

The antifeedant activity and growth-inhibitory effects of *L. nobilis* essential oil were evaluated using a no-choice feeding bioassay. Artificial diet discs received individually 5 µL of essential oil diluted in acetone to obtain a final concentration of 1%, 10% and 20% (v/v). Control diet discs received 5 µL of acetone only. After treatment, the discs were kept at room temperature for 10 min to allow complete evaporation of the solvent and were then individually weighed.

Two treated diet discs or two untreated (control) diet discs were placed in separate 5-cm-diameter glass Petri dishes. Ten larvae of *T. castaneum* were individually weighed and introduced into each Petri dish. Five replications were performed for each treatment. After seven days of exposure, the remaining diet discs were collected and reweighed to determine food consumption.

The nutritional performance of the larvae was assessed using the nutritional indices described by Manuwoto and Scriber (1982) and Farrar et al. (1989), with the modifications proposed by Huang et al. (1997). The following indices were calculated:

Relative Growth Rate $RGR = (A - B)/(B \times t)$

Relative Consumption Rate $(RCR) = D / (B \times t)$

Efficiency of Conversion of Ingested Food $(ECI) = (RGR / RCR) \times 100$

where A is the mean body weight (mg) of surviving larvae on day 7, B is the mean initial body weight (mg) of the larvae at the beginning of the experiment, D is the amount of diet consumed (mg) per surviving larva, and t is the duration of the experiment (7 days).

The antifeedant activity of the essential oil was expressed as the Feeding Deterrence Index (FDI) according to Isman et al. (1990), as modified by Huang et al. (2000), using the following equation:

$$FDI\ (\%) = [(C - T) / C] \times 100$$

where C is the mean amount of diet consumed by larvae in the untreated control (no-choice test) and T is the mean amount of diet consumed by larvae exposed to the essential oil treatment. Positive FDI values indicate feeding deterrence, whereas negative FDI values indicate feeding stimulation (phagostimulant activity).

Larval mortality was assessed after 7, 14, and 21 days for each treatment, and the LC_{50}, LC_{90}, LT_{50}, and LT_{90} values were determined.

Statistical Analysis

All experiments were conducted using five independent replicate vials per treatment, with ten larvae placed in each vial. The vial was considered the experimental unit, and the ten larvae within each vial were not treated as independent statistical replicates. Thus, all statistical analyses were based on five replicate vials per treatment (n = 5). The normality of the data was assessed using the Shapiro–Wilk

test, while the homogeneity of variances was evaluated using Levene's test. Mortality data and nutritional indices associated with the antifeedant assay, as well as mortality following topical application to larvae, pupae, and adults, were analyzed by one-way analysis of variance (ANOVA), and Duncan's multiple range test was applied for post hoc comparisons of treatment means. Median and 90% lethal concentrations (LC_{50} and LC_{90}) and lethal times (LT_{50} and LT_{90}) were estimated by probit analysis. The goodness-of-fit of the probit models was assessed using chi-square (χ^2) statistics and the corresponding degrees of freedom. All statistical analyses were performed using SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA), and differences were considered statistically significant at $p < 0.05$.

RESULTS and DISCUSSION

Chemical composition of *L. nobilis*

Phytochemical analysis of the *L. nobilis* essential oil revealed that terpenes were the predominant constituents, accounting for 47.18% of the total identified compounds. Oxygenated monoterpenes constituted the dominant chemical class (36.10%), with 1,8-cineole (13.52%) and α-terpinyl acetate (12.34%) identified as the major constituents, followed by α-terpineol (4.65%) and linalool (1.27%). Among the monoterpene hydrocarbons, α-pinene (2.96%) was the most abundant constituent, followed by p-cymene (2.05%) (Table 1). The results obtained are comparable to those of the essential oils extracted from L. nobilis collected in Manouba (Tunisia), France, Austria (Mkaddem Guedri et al., 2020), and central-southern Italy (Fantasma et al., 2024). Although the same major compounds were identified. Substantial differences were observed in their relative proportions. Such quantitative differences could be attributed to geographical origin, environmental conditions, and harvesting practices. Elkiran et al. (2026), who showed that geographical location and harvesting conditions mainly influence the relative abundance of individual constituents rather than the fundamental chemical profile of *L. nobilis* essential oil, support this hypothesis.

Table 1. Main Chemical profile of *L. Nobilis* essential oil (EO) identified by GC–FID and GC–MS analysis

N°	Composé	L.r.i.	*L. nobilis*
1	α-pinene	939	2.96
2	Camphene	954	0.7
3	β-Myrcene	991	0.69
4	α-phellandrene	1002	0.18
5	P-Cymene	1024	2.05
6	1.8-cinéole	1033	13.52
7	γ- terpinene	1059	0.45
8	Linalool	1098	1.27
9	Trans-Verbenol	1145	0.15
10	Isoborneol	1158	0.91
11	α-Terpineol	1189	4.65
12	Linalyl acetate	1257	0.74
13	(+)-Borneol acetate	1287	0.87
14	4-Thujen-2-α-yl acetate	1288	0.17
15	δ-terpineol acetate	1345	1.33
16	α-terpenil acetate	1348	12.34
17	Eugenol	1356	1.56
18	Geranyl acetate	1383	0.15
19	Methyl eugenol	1390	8.69
20	Caryophyllene	1418	0.53
21	Germacrene D	1485	0.14
22	Ledol	1565	0.31
23	Isoaromadendrene epoxide	1588	0.43
24	Junenol	1628	0.27
25	14-Hydroxycaryophylene	1630	0.13
26	T-cadinol	1640	0.38
27	α-cadinol	1652	0.87
28	Trans-Longicarvacrol	1708	0.99
Monoterpene hydrocarbons			7.03
Oxygenated monoterpenes			36.1
Sesquiterpene hydrocarbons			0.67
Oxygenated sesquiterpenes			3.38
Total			**47.18**

Insecticidal Effect of Essential Oils

Toxicity by Topical Application

Topical application of L. nobilis essential oil against larvae, pupae, and adults of T. castaneum revealed a significant dose-dependent effect ($p < 0.05$), with the highest concentration (20%) producing the greatest mortality across all developmental stages. Mortality reached 100% in larvae, 88% in adults.

and 72% in pupae. As shown in Figure 1, the essential oil induced substantial mortality from the first day of exposure particularly in larvae treated with 10% and 20% concentrations, which resulted in mortality rates of 60% and 94%, respectively. Differences in susceptibility among developmental stages could be attributed to variations in cuticle thickness and composition, body size, and the activity of detoxification enzymes, including cytochrome P450 monooxygenases, carboxylesterases and glutathione S-transferases (GSTs), which collectively influence the penetration, metabolism, and detoxification of essential oil constituents. Furthermore, several essential oils have been shown to inhibit these detoxification enzymes, thereby enhancing insect susceptibility and disrupting normal physiological processes (Awad et al., 2024; Kshatriya & Gershenzon, 2024; Gao et al., 2024).

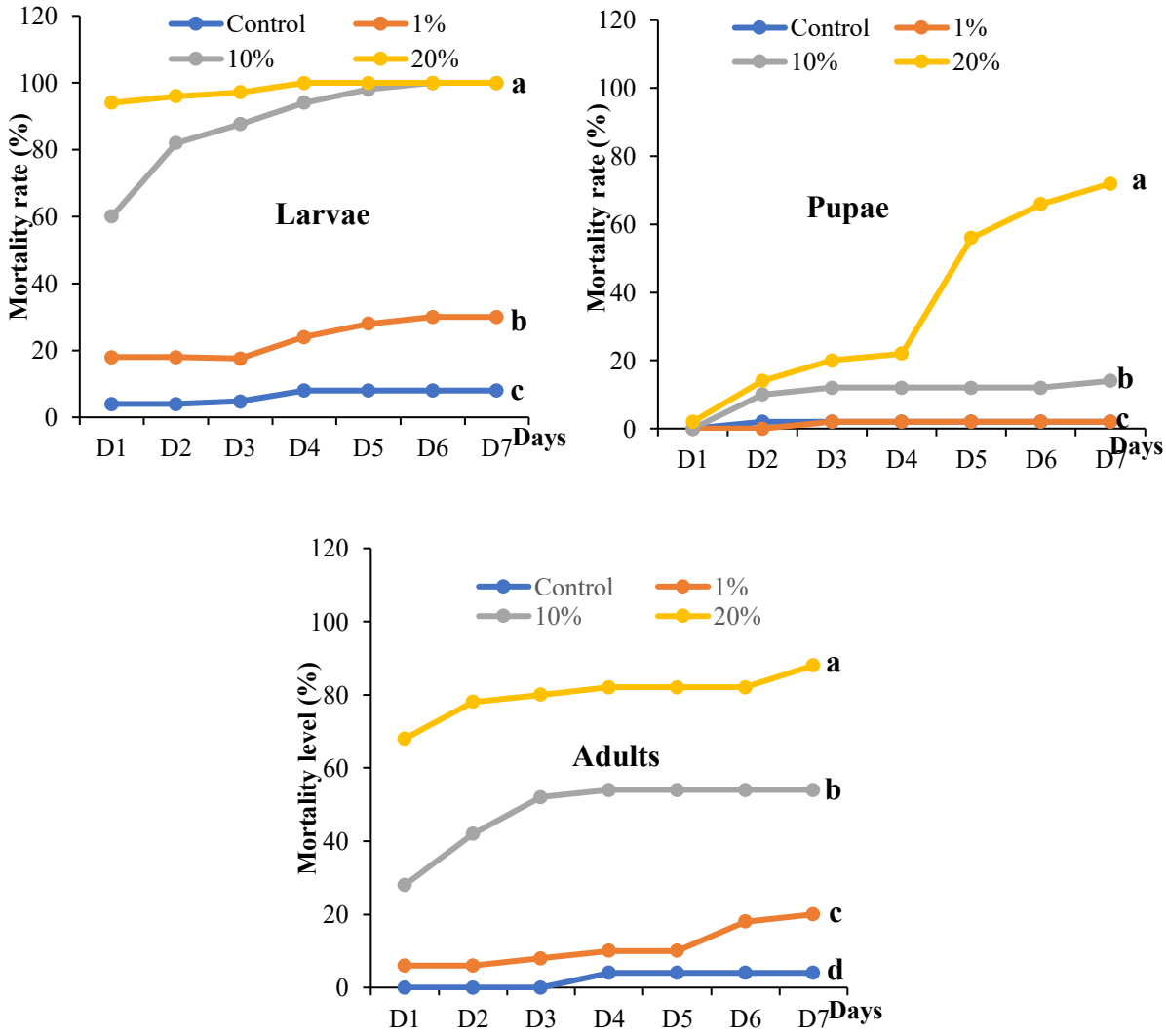

Figure 1. Evaluation of mortality in larvae, pupae, and adults following topical application of *L. nobilis* essential oil at concentrations of 1%, 10%, and 20%. *Curves followed by the same letter on day 7 were not significantly different according to Duncan's multiple range test ($p < 0.01$).

The median lethal concentration (LC_{50}) decreased continually over the 7-day bioassay. The lowest LC_{50} was registered for larvae (2.83%), followed by adults (8.98%) and pupae (16.40%) (Table 2).

Although studies investigating the topical toxicity of *L. nobilis* essential oil against *T. castaneum* remain scarce, the LC_{50} values obtained in the present study are comparable to those reported for several Mediterranean essential oils, including *Artemisia absinthium*, *Artemisia herba-alba*, and *Artemisia brachyloba*, which have demonstrated significant contact toxicity against stored-product beetles (Bachrouch et al., 2015; Liu et al., 2019).

Table 2. Determination of the LC50 and LC90 values of *L. nobilis* essential oil against larvae, pupae, and adults of *T. castaneum* following topical application over different exposure periods.

Insect stage	Days	LC_{50} (%)	LC_{90} (%)	χ^2	P
Larvae	1	8.04	17.90	0.00	0.99
	2	5.91	14.16	4.62	0.03
	3	5.39	13.24	9.95	0.00
	4	4.31	8.91	0.00	0.97
	5	2.98	7.36	0.00	0.99
	6	2.83	7.30	0.00	0.99
	7	2.83	7.30	0.00	0.99
Pupae	1	30.71	36.39	0.00	0.97
	2	36.88	58.90	2.65	0.10
	3	34.24	57.47	0.87	0.34
	4	32.17	53.71	0.69	0.40
	5	18.95	29.40	0.26	0.60
	6	17.37	26.40	0.84	0.35
	7	16.40	24.92	0.79	0.37
Adults	1	15.56	27.63	0.00	0.95
	2	12.81	23.66	1.00	0.31
	3	11.42	22.67	2.59	0.17
	4	10.78	22.12	2.03	0.15
	5	10.78	22.12	2.03	0.15
	6	9.87	23.20	0.41	0.51
	7	8.98	21.06	0.00	0.95

* χ^2: chi-square goodness-of-fit statistic; $p > 0.05$ indicates an acceptable fit of the probit model.

The probit analysis showed a dose-dependent decrease in TL50 and TL90 values across all developmental stages. Larvae were the most susceptible stage, whereas pupae exhibited the longest lethal times particularly at the 1% dose (24.53days). The negative TL50 values observed at 20% in larvae (−3.37 days) and adults (−5.49 days) indicate that 50% mortality had already been reached before the first observation time (table 3). This response could be associated with the ability of lipophilic constituents to penetrate through the insect cuticle and their diffusion efficiency into the haemolymph to reach their site of action (Isman, 2006; Moreira et al., 2022). The compounds 1,8-cineole and α-pinene are particularly effective in this regard because of their high lipophilicity and their accumulation in lipid-

rich tissues (Regnault-Roger et al., 2012; Usseglio et al., 2023). These compounds disrupt several key neurophysiological pathways by inhibiting acetylcholinesterase and interacting with octopamine receptors, GABA-gated chloride channels, and voltage-gated ion channels, leading to paralysis and death (Enan, 2001; Isman, 2020; Usseglio et al., 2023).

Table 3. Lethal time (LT_{50} and LT_{90}) values evaluated for the three concentrations of *L. nobilis* essential oil on *T. castaneum* stage treated with topical application

Insect stage	Concentration	TL_{50} (Days)	TL_{90} (Days)	χ^2	P
Larvae	1%	12.86	28.54	0.56	0.98
	10%	0.33	3.12	1.19	0.94
	20%	-3.37	0.50	2.20	0.82
Pupae	1%	24.53	36.27	1.59	0.90
	10%	17.25	30.43	5.20	0.39
	20%	5.19	8.37	6.32	0.27
Adults	1%	13.55	23.27	0.71	0.98
	10%	4.46	18.05	4.39	0.49
	20%	-5.49	8.73	1.28	0.93

Toxicity by Ingestion

The toxicity of L. nobilis essential oil against T. castaneum larvae was evaluated by ingestion over a 21-day exposure period (Figure 2). In the ingestion assay, L. nobilis essential oil exhibited relatively low toxicity, with mortality not exceeding 40% in larvae exposed to the highest concentration (20%) after 21 days. Moreover, no significant differences were observed among the three concentrations of L. nobilis essential oil. The LC50 value was relatively high after 7 days of exposure (54.16%) but decreased to 22.54% after 21 days, indicating a progressive increase in toxicity with prolonged exposure.

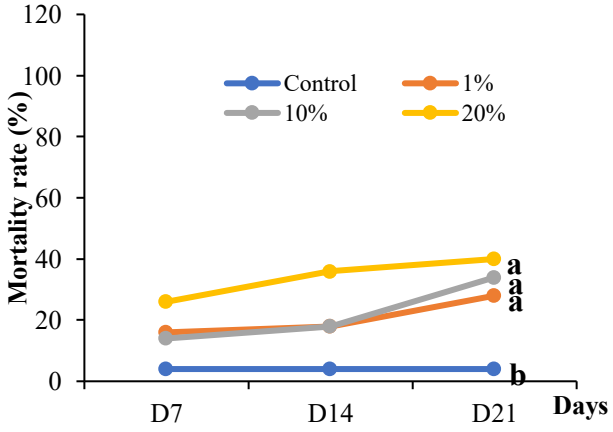

Figure 2. Effect of *L. nobilis* essential oil on *T. castaneum* larvae following ingestion at concentrations of 1%, 10%, and 20%. *Curves followed by the same letter on day 7 were not significantly different according to Duncan's multiple range test ($p < 0.01$).

A clear time-dependent increase in toxicity was observed, as indicated by the progressive reduction in both LC50 and LC90 values. The LC50 decreased from 54.16% after 7 days to 31.74%

after 14 days and 22.54% after 21 days. A similar decline in LC90 values was observed, from 126.22% after 7 days to 76.15% after 14 days and 46.32% after 21 days (Table 4). This decrease in both LC50 and LC90 indicates that prolonged ingestion enhanced the toxic activity of L. nobilis essential oil. Nevertheless, topical application was markedly more effective than oral exposure. This difference could be attributed to the mode of penetration. Orally administered compounds are absorbed across the gut epithelium and may undergo metabolic detoxification before reaching their sites of action, thereby reducing their bioavailability and overall insecticidal effectiveness (Moreira et al., 2022; Usseglio et al., 2023; Assadpour et al., 2024; Jyotsna et al., 2024; Căprar et al., 2024).

Table 4. Determination of the lethal concentration (LC_{50} and LC_{90}) and lethal time (LT_{50} and LT_{90}) values for *T. castaneum* larvae exposed to *L. nobilis* essential oil by ingestion at three concentrations

Days	LC_{50} (%)	LC_{90} (%)	χ^2	P	Concentration	TL_{50} (Days)	TL_{90} (Days)	χ^2	P
7	54.16	126.22	0.25	0.61	1%	41.54	84.06	0.25	0.61
14	31.74	76.15	0.08	0.76	10%	40.93	101.79	0.01	0.91
21	22.54	46.32	3.45	0.06	20%	29.14	75.60	0.16	0.68

Effects of Essential Oil on Nutritional Indices

The feeding indices showed that L. nobilis essential oil significantly affected the relative consumption rate (RCR), whereas no significant differences were observed in the relative growth rate (RGR) or efficiency of conversion of ingested food (ECI) among treatments ($p > 0.05$). The RCR was numerically higher at 10% (0.55 ± 0.19) than at 1% (0.44 ± 0.15) and 20% (0.38 ± 0.12); however, no statistically significant differences were observed among treatments ($p > 0.05$). The FDI values were negative at all concentrations, indicating a phagostimulant activity, with a significant effect observed at 1% (−131.85 ± 51.81%) (Table 5). The obtained result may be associated with the chemical profile of L. nobilis essential oil. Earlier studies by Hafez and Parra (1973) showed that several monoterpenes, including α-pinene and α-terpineol, could stimulate feeding in phytophagous insects. Rather, it is more likely the result of synergistic interactions among the major and minor components of the essential oil, which collectively modulate insect feeding behavior (Popescu et al., 2024).

Table 5. Effect of *L. nobilis* essential oil on nutritional index of *T. castaneum* larvae at concentration of 1%; 10% and 20%

Concentration	RCR (mg/mg/j)	RGR (mg/mg/j)	ECI (%)	FDI (%)
Control	0.25±0.09b	0.70±0.27c	40.18±11.4a	-
1%	0.44±0.15ab	1.46±0.45abc	31.08±9.53a	-131.85±51.81c
10%	0.55±0.19a	1.42±0.66abc	41.32±10.35a	-66.29±22.54a
20%	0.38±0.12ab	1.38±0.36abc	30.81±14.48a	-80.2±12.66ab

*Means followed by the same letter within the same column are not significantly different ($p < 0.05$), according to Duncan's multiple range test. ** RCR: Relative Consumption Rate; RGR: Relative Growth Rate; ECI: Efficiency of Conversion of Ingested Nutrients; and FDI: Feeding Deterrence Index.

Conclusion

The present study on the chemical characterization of *L. nobilis* and its insecticidal activity revealed an essential oil rich in oxygenated monoterpenes, with a predominance of 1,8-cineole and α-terpinyl acetate. A comparison between the two modes of administration (topical application and ingestion) revealed that topical application caused the highest toxicity at a concentration of 20% in larvae (100%), followed by adults (88%) and pupae (72%), resulting in lower lethal concentrations and shorter lethal times than ingestion. The lower toxicity caused by the ingestion of the essential oil did not affect all nutritional index. However, a negative feeding deterrence index further indicates that *L. nobilis* essential oil acted as a phagostimulant.

These findings complement previous results and support the potential of *L. nobilis* essential oil as an environmentally friendly biopesticide against stored product pests. Future research should focus on developing formulations that improve the stability, persistence, and practical applicability of the essential oil, while further investigating its molecular mode of action, validating its efficacy under commercial storage conditions, and assessing its safety for non-target organisms.

Additional Declaration

Author Contributions

Conceptualization: DH, KH. Methodology: DH, KH. Investigation: DH, RN. Plant material selection: DH, RM. Plant material collection: MHM. Essential oil analysis: MAS. Formal analysis: DH. Data interpretation: RN, DH, RM, KT, MHM, MAS. Writing – original draft: DH. Writing – review & editing: RN, RM, KT, MHM, MAS, KH. All authors have read and approved the final manuscript and agree to be accountable for the integrity of the work.

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Responsible Artificial Intelligence Statement

The authors used artificial intelligence (AI) tools solely to improve the clarity and readability of the manuscript. All scientific content, including the study design, data analysis, interpretation of the results, and conclusions, was developed and verified by the authors, who assume full responsibility for the accuracy and integrity of the work.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Ethics Approval

This study did not involve human participants or vertebrate animals requiring ethical approval.

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