Toxicology International
DOI: 10.18311/ti/2026/v33i1/52671
INFORMATICS JOURNALS
eISSN: 0976-5131 | Vol 33(1), 2026 | pp. 125-133

Entomocidal Activity of *Cinnamomum tamala* Leaf and Bark Essential Oils Against *Sitotroga cerealella* (Lepidoptera: Gelechiidae) Infesting Stored Products

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Abstract

The lepidopteran pest *Sitotroga cerealella* is one of the most destructive pests of stored cereal grains, particularly maize. Infestations of this pest can cause large quantitative and qualitative losses by lowering grain weight, harming seeds, and lowering germination potential. **Aim:** This study evaluated the efficacy of *Cinnamomum tamala* against *S. cerealella* under laboratory conditions. **Methods and Materials:** The essential oil of *C. tamala* leaf and bark was extracted by hydrodistillation and investigated for its potential as an insecticidal agent against *S. cerealella*. These two essential oils cause lethality in larvae at 49.33 µL/L and 41.69 µL/L and in adults at 55.54 µL/L and 64.38 µL/L in fumigant toxicity assays after 48-h exposure. These two essential oils reduce oviposition potential in insects and interfere with the metamorphic transformation of larva to pupa and pupa to adult, besides inhibiting the hatching of eggs when fumigated by *C. tamala* leaf and bark essential oils. **Results:** Both botanical pesticides in the form of essential oil showed the most rapid and effective control of lepidopteran pests *S. cerealella*; therefore, it is suggested that they be used in pest management techniques during storage of stored products. This research underscores the efficacy of plant extracts as an eco-friendly pest management solution.

Major Findings: *Sitotroga cerealella* is one of the most destructive primary pests of maize and other cereals during storage. The findings provide a strong scientific basis for developing plant-derived essential oils for stored-grain protection. This contribution is particularly important for regions with high maize production and limited access to safe grain-protection technologies.

Keywords: *C. tamala*, Entomocidal Activity, Essential oils, Toxicity, *Sitotroga cerealella*, Stored Products

Article Received on: 15.10.2025 **Revised on:** 15.12.2025 **Accepted on:** 01.01.2026

1. Introduction

India is an agriculture-based country and has achieved magnificent strides in self-dependence in many crops, including maize. Bihar is a major maize producer, but facing a loss of productivity due to several insect pests. Maize (*Zea mays* L.) is well known for its high value as a stable food and its widespread use in building, animal feed, and fuel and is one of the most important and widely grown cereal crops[1,2]. In terms of rural households, maize is also the most significant staple crop. The Majority of the maize crop is consumed as grain or green cobs[3]. Due to its many benefits, it is the most productive of the major cereal crops and ranks second in terms of production area[4].

Although maize is still more productive than other main cereal crops, it is currently below its potential. One of the main causes of the low yields that maize agriculture is currently experiencing is arthropod pests[5].

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Sitotroga cerealella, commonly known as angoumois grain moth, is a destructive primary insect pest damaging a variety of stored products like maize, rice, barley, rye, sorghum and wheat. It is found in China, Egypt, Japan, India, Indonesia, Malaysia, Nigeria and South Africa[6]. The transport and distribution of this moth takes place through the eggs laid either singly or in groups among the grains during the processing, transportation or storage. The infestation of *S. cerealella* starts from the field when females start laying eggs and then reaches to store houses[7]. To manage such losses by insect pests, several chemicals of synthetic origin were developed and used in different forms indiscriminately, but besides achieving success in reducing insect populations and their infestation outputs, these insecticides have caused resistance development in most of the insects due to their high persistence in the environment[8-10]. These synthetic insecticides are responsible for the origin of different chromosomal aberrations and for forming DNA adducts[11-13]. These synthetic pesticides are also responsible for various environmental issues like thinning of the ozone layer, poor consumable quality of soil, air and water, toxic activity in other animals like beneficial insects and cause a variety of health problems like neurotoxicity, carcinogenicity and teratogenicity[14-17].

Plants are complex organisms and have a complex metabolism that produces many chemicals. Botanical insecticides (insecticides derived from plant extracts) have emerged as a promising alternative to chemical insecticides for the control of insect pests of crops. In agronomic science, this application is becoming more accepted as an alternative to chemical integrated plant protection, with plant extracts being concentrated formulations of various possible consistencies derived from dried plant materials, and produced using a solvent-based process. The production process consists of two stages: the extraction of specific compounds from a complex medium and the drug or plant that is being used. The Essential oils extracted from aromatic plants are known to exhibit fumigant toxicity, repellency, oviposition deterrence, ovicidal activity, and growth-regulating effects against a wide range of stored-product insects. However, most previous studies have focused primarily on adult mortality[18-20], with comparatively limited information on their effects across multiple developmental stages and reproductive parameters of *S. cerealella*. Moreover, comprehensive evaluations combining fumigant toxicity with oviposition inhibition, egg hatching suppression, and developmental disruption are scarce, particularly for botanicals of indigenous importance.

Cinnamomum tamala (Family: Lauraceae), commonly called Bay plant, is a native tree of Asian countries. Its leaves possess aromatic properties and, thus, are used as a spice and in the preparation of several medicines. The major chemical constituents present in the leaf oil are eugenol, α-phellandrene and β-phellandrene[21]. *C. tamala* leaf possesses antibacterial effects[22]. The aqueous solution of *C. tamala* bark shows antidiabetic effects[23]. Several bark extracts of this plant show antimicrobial activity against a variety of microbes[24,25]. *C. tamala* bark essential oil includes cinnamaldehyde, δ-cadinine, γ-gurjunine, α-muurolol, γ-cadinine and α-muurolene as major constituents[26]. Bark essential oil shows antimicrobial activity against a variety of bacteria and fungi[27]. Despite its traditional use and known biological activity, systematic studies assessing the comparative fumigant efficacy of *C. tamala* leaf and bark essential oils against different life stages of *S. cerealella* remain limited. In particular, information on their sub-lethal effects on oviposition, egg viability, and post-embryonic development is insufficient, representing a clear research gap in stored-grain pest management.

Therefore, the present study introduces a comparative evaluation of essential oils extracted from the leaf and bark of *C. tamala*, a plant whose insecticidal potential against *S. cerealella* has not been comprehensively studied before. While *C. tamala* is known for its antimicrobial and medicinal properties, its dual-source essential oils (leaf and bark) have not been simultaneously assessed for their toxicity and repellency against a major stored-grain pest.

2. Materials and Methods

2.1 Plant Collection

Leaves and bark of *C. tamala* were collected from the local areas of Madhepura district, Bihar. The collected materials were dried in the absence of sunlight at room temperature (20-25°C) for 5-7 days.

2.2 Essential Oil Extraction

The essential oil was extracted by hydro-distillation methods using a Clevenger-type apparatus for 4 h. The anhydrous sodium sulphate was used for drying and stored at 4-5°C in Eppendorf tubes.

2.3 Insects

Lepidopteran pest, *S. cerealella,* was reared in the laboratory in a glass jar (30 cm height, 20 cm diameter). Insects were fed crushed rice grain mixed with 5% (w/w) and kept at a hearing room temperature of 28±1°C, with RH of 65±5% and a photoperiod of 12 h (L:D). 2-3 days old newly hatched adults were used for the further experimental process.

2.4 Fumigant Toxicity

The essential oils of the leaf and bark of *C. tamala* were used for testing their insecticidal activities in a solution made of acetone. 10 adults and third instar larvae of *S. cerealella* collected from laboratory culture were placed in a glass jar (15 cm height, 10cm diameter) floored by Whatman filter paper No. 1. A paper strip (2 cm diameter) treated with different concentrations was pasted on the inner surface of the glass cover of each glass jar. The treated filter was covered with a wire mesh to avoid contact of the treated filter with the test. Finally, the glass jar was covered with a glass cover and sealed with parafilm. During 24 h of the experiment, the six replicates of each concentration of glass were kept in the dark, and after this, the treated adults were transferred to a fresh glass jar of similar measurement. After 24 h and 48 h of exposure, mortality in adults and larvae was recorded.

2.5 Oviposition Inhibition

Oviposition inhibitory activity of *C. tamala* leaf and bark oil was tested against *S. cerealella* by fumigation. Ten pairs of 1-2 days old adults were placed in a glass jar (15 cm height, 10 cm diameter) floored by Whatman filter paper No. 1. A paper strip (2 cm diameter) treated with different sub-lethal concentrations, viz. 40 and 80% of 24h-LC_{50} were pasted on the inner surface of the glass cover of each glass jar. Finally, the glass jar was covered with a glass cover and sealed. During 24 h of the experiment, the six replicates of each concentration of glass were kept in the dark. The experimental adults were moved to a fresh glass jar of the same size after exposed for 24 hours. The treated adults received treatment for 4 days before being taken out and discarded. Both the control group and the treated's groups' eggs were counted. The following formula was used to determine the % ODI (Oviposition Deterrence Index).

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

where, C = Control group number, T = Experimental group number

2.6 Ovicidal Assay

In the ovicidal assay, twenty-five freshly laid eggs were placed on Whatman filter paper No. 1. The filter paper containing eggs was then placed in the bottom of a glass Petri dish (10 cm in diameterand 1.0 cm in height). These eggs were fumigated with test solutions prepared with acetone by diluting *C. tamala* leaf and bark oils with acetone. The test solution (100 µl) was pasted on a filter paper strip (2.5 cm diameter) and evaporated for 5 minutes. The coated paper strips were pasted to the inner surface of the glass Petri dish and incubated for 72 h in conditions maintained for insect culture. After completion of the fumigation, the number of eggs hatched was recorded. Six replicates of three concentrations of each oil were set for the Per cent Hatching Inhibition Rate. The following formula was used to determine the percentage of HIR.

$$HIR = [(C-T)/C] \times 100.$$

Where, C=Control group Adults, T = Test group Adults

2.7 Developmental Inhibition

Developmental inhibitory activity of *C. tamala* leaf and bark oils was tested against newly emerged 3rd instar larvae of *S. cerealella*. Twenty larvae were treated with two (40 and 80%) sub-lethal concentrations of 48h-LC_{50} of volatile oil in a Petri dish for experimental periods, such as larvicidal assay, and then the treated larvae were transferred to new glass jars and supplied with crushed rice with 5% (w/w) yeast powder. The number of pupae transformed into emerged adults from pupae was recorded. Six replicates of each concentration were set for oil, as well as the control.

2.8 Data Analysis

POLO Programmed was used for the calculation of LC_{50} [28]. To define all dose-response relationships, correlation and linear regression analysis were conducted[29]. For the equality of the regression coefficient, ANOVA was performed[28].

3. Results

3.1 Fumigant Toxicity

In adults, median lethal concentrations were recorded as 97.39 and 55.54 µl/L, and 98.96 and 64.38 µl/L air against *S. cerealella* adults for *C. tamala* leaf and bark oils after 24

h and 48 h (Table 1). The LC_{50} were 73.62 and 49.33 µl/L, and 78.38 and 41.69 µl/L air against *S. cerealella* larvae for *C. tamala* leaf and bark oils after 24h and 48h exposure period, respectively (Table 1).

Since the mean value is less than 0.5, the g-value, the index of significance of potency estimation, shows that it falls inside the bounds of all probability levels (P<0.1, 0.5, and 0.01). Regression is considered significant when the t-ratio is greater than 1.6. Heterogeneity factor values below 1.0 indicate that the model adequately matches the data. Adults and larvae of *S. cerealella* exhibit concentration-dependent mortality, according to regression analysis (Table 1).

3.2 Oviposition Inhibition

The oviposition potential of the *S. cerealella* was decreased significantly when fumigated with the *C. tamala* leaf and bark oils. The oviposition was reduced to 71.66 and 39.45%, and 64.16 and 36.74% when adults of *S. cerealella* were fumigated with 40 and 80% of 24h-LC_{50} of leaf and bark oils, respectively (For *C. tamala* leaf oil, F = 17.04; and for *C. tamala* bark oil, F = 18.85; P<0.01; Table 2). The per cent ODI was significantly increased to 16.24 and 43.42, and 21.83 and 46.26% when adults of *S. cerealella* fumigated with 40 and 80% of 24h-LC_{50} of leaf and bark oil, respectively (Table 2). All treated and control groups differ significantly (P < 0.05) according to Tukey's Honestly Significant Difference (HSD) analysis (Table 3).

3.3 Ovicidal Activity

The percentage of egg hatching was decreased significantly with an increase in concentration of *C. tamala* leaf and bark oils. Egg hatching was reduced to 83.06, 53.68 and 34.53%; and 73.53, 46.31 and 30.13% of the control when eggs were fumigated with 25, 50 and 75 µl/L of *C. tamala* leaf and bark oils, respectively (For *C. tamala* leaf oil F = 204.85; and for *C. tamala* bark oil F = 215.88; P<0.01; Table 4). The per cent hatching inhibition rate (%HIR) was significantly increased to 16.93, 46.31 and 65.46; 26.46, 55.88 and 69.87 when *S. cerealella* eggs were fumigated with 25, 50 and 75 µl/L of *C. tamala* leaf and bark oils, respectively (Table 4). All treated and control groups differ significantly (P < 0.05) according to Tukey's Honestly Significant Difference (HSD) analysis (Table 5).

Table 1. Fumigant toxicity of *C. tamala* leaf and bark essential oils on *S. cerealella*

Oil	Parameter	Exposure Period	LC_{50} (µl/L)	g-value	t-ratio	Heterogeneity	Regression Equation	Correlation Coefficient
C. tamala leaf	Adult mortality	24h 48h	97.39 55.54	0.27 0.31	3.34 3.67	0.35 0.37	Y = -4.39+1.94X Y = -2.36+4.03X	0.99 0.99
	Larval mortality	24h 48h	73.62 49.33	0.28 0.29	3.96 3.78	0.35 0.34	Y = 4.93+2.98X Y = -3.78+4.19X	0.99 0.98
C. tamala bark	Adult mortality	24h 48h	98.96 64.38	0.25 0.27	3.47 3.65	0.36 0.39	Y = -3.97+2.19X Y = 3.07+4.81X	0.98 0.99
	Larval mortality	24h 48h	78.38 41.69	0.29 0.27	4.03 3.39	0.38 0.336	Y = -3.97+3.02X Y = 1.98+3.07X	0.99 0.98

Table 2. Effect of *C. tamala* leaf and bark essential oils on oviposition potential of *S. cerealella*

Oil	Concentration	Number of larvae emerged/adult (Mean±SE)	%ODI*	F-value** (df=2,15)
Control	-	55.33±2.98 (100)	-	-
C. tamala leaf	40% 24h-LC_{50}	39.65±2.39 (71.66)	16.24	17.04
	80% 24h-LC_{50}	21.83±1.67 (39.45)	43.42	
C. tamala bark	40% 24h-LC_{50}	35.50±2.17 (64.16)	21.83	18.85
	80% 24h-LC_{50}	20.33±1.18 (36.74)	46.26	

Values indicate per cent change with respect to the control group taken as 100%
**Significant at P<0.01

Table 3. Significant difference (HSD) analysis of *C. tamala* leaf and bark essential oils on oviposition in *S. cerealella* by post hoc Tukey's honestly

Oil	Oviposition			
C. tamala leaf	Pair Comparison		$HSD_{0.05}$ = 14.9139 $HSD_{0.01}$ = 19.6336	$Q_{0.05}$ = 3.6734 $Q_{0.01}$ = 4.8254
	T_1:T_2	M_1 = 55.33 M_2 = 39.65	15.7	Q = 3.86*
	T_1:T_3	M_1 = 55.33 M_3 = 21.83	33.50	Q = 8.25*
	T_2:T_3	M_2 = 39.65 M_3 = 21.83	17.83	Q = 4.39*
C. tamala bark	Pair Comparison		$HSD_{0.05}$ = 14.9139 $HSD_{0.01}$ = 19.6336	$Q_{0.05}$ = 3.6734 $Q_{0.01}$ = 4.8254
	T_1:T_2	M_1 = 55.33 M_2 = 35.50	19.83	Q = 4.91*
	T_1:T_3	M_1 = 55.33 M_3 = 20.33	35.00	Q = 8.66*
	T_2:T_3	M_2 = 35.50 M_3 = 20.33	15.17	Q = 3.75*

*Significant (P<0.05) difference between control and treated groups

Table 4. Viability effect of leaf and bark essential oils of *C. tamala* on *S. cerealella* eggs

Oil	Concentration (µl/L)	Number of larvae emerged (Mean±SE)	%HIR	F-value*
Control	-	22.67±0.57(100)	-	-
C. tamala leaf	25	18.83±0.43(83.06)	16.93	204.85
	50	12.17±0.41(53.68)	46.31	
	75	7.83±0.47(34.53)	65.46	
C. tamala bark	25	16.67±0.42(73.53)	26.46	215.88
	50	10.50±0.39(46.31)	55.88	
	75	6.83±0.32(30.13)	69.87	

Values indicate per cent change with respect to the control (100%), Hatching inhibition rate
*Significant at P<0.01

3.4 Developmental Inhibition

The larval transformation into the pupa and adult emergence in *S. cerealella* were decreased significantly with an increase in concentration of *C. tamala* leaf and bark oils. Pupal transformation was reduced to 83.48 and 59.60%, and 80.73 and 55.97% of the control when larvae were fumigated with 40 and 80% of 48h-LC_{50} of *C. tamala* leaf and bark oils, respectively (For *C. tamala* leaf oil, F = 59.67; and for *C. tamala* bark oil, F = 68.92; P<0.01; Table 6). Adult emergence from the pupa was reduced to 75.99 and 51.93%, and 66.35 and 44.03% of the control when larvae were fumigated with 40 and 80% of 48h-LC_{50} of

Table 5. Significant difference (HSD) analysis of ovicidal activities of *C. tamala* leaf and bark essential oils in *S. cerealella* by Post Hoc Tukey's Honestly

Oil	Egg hatching			
C. tamala leaf	Pair Comparison		$HSD_{0.05}$ = 1.8366 $HSD_{0.01}$ = 2.3283	$Q_{0.05}$ = 3.9583 $Q_{0.01}$ = 5.0180
	T_1:T_2	M_1 = 22.67 M_2 = 18.83	3.83	Q = 8.26*
	T_1:T_3	M_1 = 22.67 M_3 = 12.17	10.50	Q = 22.63*
	T_1:T_4	M_1 = 22.67 M_4 = 7.83	14.83	Q = 31.97*
	T_2:T_3	M_2 = 18.83 M_3 = 12.17	6.67	Q = 14.37*
	T_2:T_4	M_2 = 18.83 M_4 = 7.83	11.00	Q = 23.71*
	T_3:T_4	M_3 = 12.17 M_4 = 7.83	4.33	Q = 9.34*
C. tamala bark	Pair Comparison		$HSD_{0.05}$ = 1.8776 $HSD_{0.01}$ = 2.3802	$Q_{0.05}$ = 3.9583 $Q_{0.01}$ = 5.0180
	T_1:T_2	M_1 = 22.67 M_2 = 16.67	6.00	Q = 12.65*
	T_1:T_3	M_1 = 22.67 M_3 = 10.50	12.17	Q = 25.65*
	T_1:T_4	M_1 = 22.67 M_4 = 6.83	15.83	Q = 33.38*
	T_2:T_3	M_2 = 16.67 M_3 = 10.53	6.17	Q = 13.00*
	T_2:T_4	M_2 = 16.67 M_4 = 6.83	9.83	Q = 20.73*
	T_3:T_4	M_3 = 10.53 M_4 = 6.83	3.67	Q = 7.73*

*Significant (P<0.05) difference between treated and control groups

Table 6. Developmental inhibitory effect of leaf and bark essential oils of *C. tamala* on *S. cerealella*

Oils	Concentration	Number of pupa transformed (Mean±SE)	F-value*	Number of adult emerged (Mean±SE)	F-value* (df=2,15)
Control	-	18.17±0.38(100)		17.33±0.23(100)	-
C. tamala leaf	40% 48h-LC_{50}	15.17±0.41(83.48)	59.67	13.17±0.21(75.99)	69.52
	80% 48h-LC_{50}	10.83±0.35(59.60)		9.00±0.19(51.93)	
C. tamala bark	40% 48h-LC_{50}	14.67±0.39(80.73)	68.92	11.50±0.28(66.35)	175.25
	80% 48h-LC_{50}	10.17±0.31(55.97)		7.67±0.31(44.03)	

*Significant at P<0.01

Table 7. Significant Difference (HSD) analysis of the effect of *C. tamala* leaf and bark essential oils on larval transformation in *S. cerealella* by Post Hoc Tukey's Honestly Significant Difference

Oil	Larva transformed into pupa			
C. tamala leaf	Pair Comparison		$HSD_{0.05}$ = 1.7532 $HSD_{0.01}$ = 2.3080	$Q_{0.05}$ = 3.6734 $Q_{0.01}$ = 4.8359
	T_1:T_2	M_1 = 18.17 M_2 = 15.17	3.00	Q = 6.29*
	T_1:T_3	M_1 = 18.17 M_3 = 10.83	7.33	Q = 15.37*
	T_2:T_3	M_2 = 15.17 M_3 = 10.83	4.33	Q = 9.08*
C. tamala bark	Pair Comparison		$HSD_{0.05}$ = 1.7744 $HSD_{0.01}$ = 2.3360	$Q_{0.05}$ = 3.6734 $Q_{0.01}$ = 4.8359
	T_1:T_2	M_1 = 18.17 M_2 = 14.67	3.50	Q = 7.25*
	T_1:T_3	M_1 = 18.17 M_3 = 10.17	16.56	Q = 16.56*
	T_2:T_3	M_2 = 14.67 M_3 = 10.17	9.32	Q = 9.32*

*Significant at (P<0.05)

Table 8. Significant Difference (HSD) analysis of the effect of *C. tamala* leaf and bark essential oils on adult emergence in *S. cerealella* by Post Hoc Tukey's Honestly Significant Difference

Oil	Adult Emergence			
C. tamala leaf	Pair Comparison		$HSD_{0.05}$ = 1.9807 $HSD_{0.01}$ = 2.6075	$Q_{0.05}$ = 3.6734 $Q_{0.01}$ = 4.8352
	T_1:T_2	M_1 = 17.33 M_2 = 14.17	3.17	Q = 5.87*
	T_1:T_3	M_1 = 17.33 M_3 = 9.00	8.33	Q = 13.60*
	T_2:T_3	M_2 = 14.17 M_3 = 9.00	5.17	Q = 7.73*
C. tamala bark	Pair Comparison		$HSD_{0.05}$ = 1.3506 $HSD_{0.01}$ = 1.9780	$Q_{0.05}$ = 3.6734 $Q_{0.01}$ = 4.8352
	T_1:T_2	M_1 = 17.33 M_2 = 11.50	5.83	Q = 15.87*
	T_1:T_3	M_1 = 17.33 M_3 = 7.67	9.67	Q = 26.29*
	T_2:T_3	M_2 = 11.50 M_3 = 7.67	3.83	Q = 10.43*

*Significant at (P<0.05)

C. tamala leaf and bark oils respectively (For *C. tamala* leaf oil, F = 69.52; and for *C. tamala* bark oil, F = 175.25; P<0.01; Table 6). All treated and control groups differ significantly (P<0.05) according to Tukey's Honestly Significant Difference (HSD) analysis (Tables 7 and 8).

4. Discussion

Several volatile products of botanical origin have been reported for their insecticidal nature against a variety of insect pests of stored grains and products. The present investigation clearly demonstrates the strong fumigant toxicity and multifaceted bio-efficacy of *C. tamala* leaf and bark oils caused acute toxicity in adults as well as larvae of *S. cerealella*. The LC_{50} values obtained for adult and larval stages decreased markedly with increased exposure duration indicated concentration and time-dependent mortality in both adults and larvae confirms the high potential of these essential oils as effective fumigants for stored-grain insect pest management.

Such time-dependent efficacy is characteristic of essential oils, fumigant which indicate their limited environmental permanence and act primarily through inhalation and gradually disrupt vital physiological processes, including respiration and nervous system function[30-33]. The comparatively lower LC_{50} values

recorded for bark oil possess higher insecticidal potency than leaf oil, which may be attributed to qualitative and quantitative variations in bioactive constituents, such as those known to interfere with insect neurotransmission that damage insects' neurological systems by interfering with neuromodulator octopamine or GABA-gated chloride channels[34-36].

The significant regression values, acceptable g-values, and heterogeneity factors below unity further validate the robustness and reliability of the probit model used, confirming a good fit between observed and expected mortality data.

C. tamala leaf and bark oils inhibit oviposition and egg hatching in *S. cerealella* by fumigation action. The marked reduction in oviposition and the corresponding increase in oviposition deterrence index (ODI) at sub-lethal concentrations highlight the strong behavioural and physiological impacts of these oils on adult moths. Such oviposition inhibition may result from disruption of chemoreception, repellency of volatile compounds, or interference with endocrine regulation of reproduction[37,38]. The stronger oviposition deterrent effect of bark oil again supports its higher bioactivity. Importantly, oviposition suppression at doses well below lethal concentrations suggests that *C. tamala* oils could reduce population buildup even when complete adult mortality is not achieved. Several essential oils like *Trachyspermum ammi*, *Piper betle*, *Eucalyptus citriodora*, *Cymbopogan nardus*, *Pelargonium graveolens*, *Rosmarinus officinalis* and *Ocimum basilicum* essential oils produce similar effects on the viability of eggs[39]. Different combinations of *Cedrus deodara*, *Cinnamomum camphora*, *Eucalyptus globulus*, *Cymbopogon flexuosus*, *Mentha piperita* and *Citrus aurantium* essential oils have been reported for ovicidal and developmental inhibitory effects via contact application[40]. Although the exact mechanism of action of these essential oils is unknown, it appears that suffocation or disruption of insect biosynthesis processes causes a decrease in oviposition and development[41]. This speculation has been supported by some essential oils, which have been known to reduce protein, glycogen and lipid contents. These oils not only lowered the consumption index, relative consumption rate, and relative growth rate, but they also decreased the activity of the enzymes amylase and protease[32].

The significant reduction in egg hatching and the concomitant increase in hatching inhibition rate (%HIR) with increasing concentrations indicate that these oils adversely affect embryonic development. Essential oil vapours are known to penetrate the chorion, leading to desiccation, disruption of embryonic respiration, or inhibition of enzyme systems essential for successful hatching. In addition to effects on eggs and adults, the oils exerted pronounced developmental inhibition in immature stages. The significant decline in pupal transformation and adult emergence following larval fumigation indicates that *C. tamala* oils interfere with metamorphosis and growth regulation. Such effects may arise from disruption of hormonal balance, particularly ecdysteroids and juvenile hormone, or from chronic metabolic stress induced by prolonged exposure to sublethal concentrations[38]. The reduction in adult emergence is particularly important from a pest management perspective, as it directly limits the establishment of subsequent generations in stored grain ecosystems.

The results suggested that *C. tamala* leaf and bark oils act not only as acute toxicants but also as potent growth regulators and reproductive inhibitors. This multi-target mode of action is highly desirable in stored-product pest management, as it reduces the likelihood of resistance development and provides sustained population suppression. Moreover, the significant effects observed at relatively low and sub-lethal concentrations underscore the potential of these oils as eco-friendly alternatives to synthetic fumigants, which are often associated with resistance, residue concerns, and environmental hazards.

5. Conclusion

The findings of this study clearly demonstrate that *C. tamala* leaf and bark essential oils possess strong fumigant toxicity and significant growth-regulating effects against multiple life stages of *S. cerealella*. The study highlights the potential of *C. tamala* essential oils as effective, eco-friendly alternatives to synthetic fumigants for managing *S. cerealella* in stored grains. Their broad-spectrum activity, ranging from direct toxicity to profound effects on reproduction and development, supports their suitability for incorporation into sustainable, plant-based pest management strategies. Further field-level evaluations, formulation development, and safety assessments will help advance these oils toward practical application in stored-product protection.

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Author Contributions

BBM: Was involved in formulating the concept and overall design of the study. **PK:** The responsibility of material preparation, data collection and analysis and prepares the first draft or version of the manuscript. **AK:** Thoroughly reviewed ensures with the study's objective and further gave final approval to the submitted version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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