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Study of some bio-ecological aspects of some stored product pests

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Fatma Zohra

List of acronyms

RH	Relative humidity
ANOVA	Analyse Of Variance
FAO	Food and Agriculture Organisation
FOASTAT	Food and Agriculture Organisation (Organisation des Nations unies pour l’Agriculture et l’Alimentation Statistique).
QX	Quintaux
B1,B2,B3,B4	Boxes
MARD	Ministry of Agriculture and Rural Development
ITGC	Technical Institute of Broad Crops
OAIC	Algerian Interprofessional Bureau for Cereals

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Introduction

Introduction

Cereals continue to serve as the staple food for the majority of the global population, with harvested areas spanning over 736 million hectares worldwide (FAOSTAT, 2025). Global cereal production has demonstrated substantial growth, reaching a record volume of approximately 3.043 billion tonnes (FAOSTAT, 2025). Within this context, cereals maintain a highly strategic role in ensuring food security, particularly across Mediterranean countries, where they constitute the basis of human nutrition and livestock feeding (FAO, 2025).

In Algeria, the total land surface area allocated to cereal cultivation fluctuates between 3.3 and 3.5 million hectares (MADR, 2024). However, the national average yield varies considerably across regions due to differences in climatic conditions and the adoption of modern agricultural technologies. In the traditional rainfed northern plains, recurrent droughts limit average yields to approximately 13–15 quintals per hectare (qx/ha) (ITGC, 2023), whereas irrigated cereal production in the southern Saharan regions, supported by advanced pivot irrigation systems and mechanized farming, can achieve yields ranging from 60 to over 90 qx/ha (OAIC, 2024). These productivity differences highlight the importance of irrigation and technological development in Algeria's strategy to increase domestic cereal production and reduce dependence on imports.

Despite their importance, stored cereals are subjected to numerous forms of deterioration during storage. These alterations may be biological, biotic, or abiotic in nature and are caused by rodents, birds, mites, fungi, and especially insects, which are considered among the most destructive agents of post-harvest losses (Keskin and Ozkaya, 2015). Insect infestations are responsible for substantial quantitative and qualitative losses that may reach 10% worldwide and exceed 50% in developing countries under inadequate storage conditions (Brader *et al.*, 2002; De Carvalho *et al.*, 2013).

Stored-product insects are generally classified into primary and secondary pests according to their feeding behavior. Primary pests are capable of attacking sound and intact grains, whereas secondary pests infest previously damaged or processed products. Among the numerous species associated with stored commodities, three coleopteran insects are of particular economic importance: *Trogoderma granarium* Everts, *Tribolium castaneum* Herbst, and *Callosobruchus maculatus*. These species are characterized by high reproductive potential, remarkable adaptability to storage environments, and the ability to cause severe damage to cereals and legumes during storage (Delobel and Tran, 1993; Rees, 2004).

INTRODUCTION

- The khapra beetle (*Trogoderma granarium*) is considered one of the most destructive pests of stored products worldwide. Its economic importance is related to its high capacity to survive prolonged starvation, tolerate low-moisture conditions, and spread through international trade, making it a pest of major quarantine concern (OEPP/EPPO, 1981; OEPP/CABI, 1997).
- The red flour beetle (*Tribolium castaneum*), is one of the most common secondary pests of stored cereals and processed grain products. It mainly infests flour, semolina, and other milled products, causing significant qualitative and quantitative losses during storage (Sokoloff, 1974; Hagstrum and Subramanyam, 2006).
- *Callosobruchus maculatus* is one of the most important pests of stored legumes, particularly in tropical and subtropical regions. Infestation often begins in the field and continues during storage, leading to considerable reductions in seed quality, viability, and market value (Ketoh *et al.*, 1998; Ngamo *et al.*, 2007).

Although these species have been extensively studied individually, important questions remain regarding the influence of substrate characteristics and species interactions on their biological performance and behavioral responses. In particular, the role of substrate texture in larval development, adult feeding behavior, starvation resistance, locomotor activity, and competitive interactions remains insufficiently documented under local storage conditions.

Therefore, the present study was conducted in the Laboratory of Phoenix at Kasdi Merbah University of Ouargla to investigate selected bio-ecological aspects of *Trogoderma granarium*, *Tribolium castaneum*, and *Callosobruchus maculatus*. Particular attention was given to their biological performance, behavioral responses, food preference, starvation tolerance, locomotor activity, and interspecific interactions under laboratory conditions.

This dissertation presents and discusses the results obtained for the different biological and behavioral parameters investigated and concludes with a general conclusion.

Chapter I

Material and Methods

1. Material and methods

This study was conducted to investigate selected bio-ecological aspects of major stored-product pests, the work focused on monitoring larval development up to the adult stage, assessing growth, evaluating food preferences, and studying reproduction and progeny.

1.1 Material

1.1.1. Animal material

This section focuses on three economically important stored-product insect pests: the khapra beetle (*Trogoderma granarium*), the chickpea bruchid (*Callosobruchus maculatus*), and the red flour beetle (*Tribolium castaneum*). For each of these target species, the subsequent sections provide a detailed overview encompassing their, classification, and specific morphology and biology.

1.1.1.1. Khapra Beetle *Trogoderma granarium*

Trogoderma granarium Everts (Coleoptera: Dermestidae), commonly known as the khapra beetle, is one of the world's most destructive pests of stored products and is classified as an A2 quarantine pest (EPPO) due to its high invasive potential and its capacity to cause severe quantitative and qualitative losses in stored grains and other food commodities (Ahmedani *et al.*, 2007).

1.1.1.1.1. Classification

- **Phylum:** Arthropoda
- **Class:** Insecta
- **Order:** Coleoptera
- **Family:** Dermestidae
- **Genus:** *Trogoderma*
- **Species:** *Trogoderma granarium* Everts, 1898

1.1.1.1.2. Morphology and biology of *Trogoderma granarium*

Adults of the khapra beetle are small, oval-shaped beetles measuring 1,6 to 3 mm in length and 0,9 to 1,7 mm in width (Fig 1). Sexual dimorphism is evident in this species; males are generally brown to black with indistinct reddish-brown markings on the elytra, whereas females are slightly larger and lighter in color. The antennae are composed of 11 segments, and the head is small and usually deflexed. The larval stage is the most destructive stage and is characterized by dense reddish-brown body hairs (Ahmedani *et al.*, 2007). Larvae undergo 5 to 12 molts during development (Banks, 1994) and may reach approximately 6 mm in length (Ahmedani *et*

al., 2007). Development is strongly influenced by temperature, with the life cycle ranging from about 26 days at 35°C to 220 days at 28°C (OEPP/CABI, 1997). Young larvae generally feed on damaged grains, whereas older larvae are capable of attacking whole grains, causing significant quantitative and qualitative losses in stored products (Beal, 1982).



Figure 1. *Trogoderma granarium* adult (GX 40)

1.1.1.2.Chickpea bruchid *Callosobruchus maculatus*

Callosobruchus maculatus (Coleoptera: Chrysomelidae), commonly known as the chickpea bruchid, is a beetle pest that primarily develops inside legume seeds .It is recognized as one of the most destructive insect species causing severe qualitative and quantitative damage to stored chickpea stocks (Lepesme, 1944).

1.1.1.2.1.Classification

- **Phylum:** Arthropoda
- **Class:** Insecta
- **Order:** Coleoptera
- **Family:** Chrysomelidae
- **Genus:** *Callosobruchus*
- **Species :** *Callosobruchus maculatus*. Fabricius,1775

1.1.1.2.2.Morphology and biology of *Callosobruchus maculatus*

The adult chickpea weevil is a dark reddish insect (4 mm) with a quadrangular pronotum and characteristic spots on the wings and pygidium (fig 2). The life cycle begins with bright yellow eggs (0,6 mm) deposited on seeds, followed by a larval stage that penetrates the grain to develop internally (Balachowsky, 1962). This species is strictly monophagous, attacking only chickpeas. Its longevity is highly influenced by temperature, decreasing from 26 days at 15°C to only 2 days at 44°C . Females are prolific, laying up to 400 eggs on mature pods (Lepesme,

1944). Larval development takes 15 to 20 days under optimal conditions, after which the larva cuts a circular exit hole (operculum) for the adult to emerge (Balachowsky, 1962).



Figure 2. *Callosobruchus maculatus* adult (GX 20)

1.1.1.3.Red Flour beetle *Tribolium castaneum*

Tribolium castaneum (Coleoptera: Tenebrionidae), commonly known as the red flour beetle, is a widespread secondary beetle pest that primarily infests milled grain products and broken seeds. It is recognized as one of the most economically significant contaminants of post-harvest food supply chains, causing severe qualitative and quantitative losses in stored flour, processed commodities, and damaged cereal grains (Rees, 2004)

1.1.1.3.1.Classification

- **Phylum:** Arthropoda
- **Class:** Insecta
- **Order:** Coleoptera
- **Family:** Tenebrionidae
- **Genus:** *Tribolium*
- **Species:** *Tribolium castaneum* Herbst,1797

1.1.1.3.2. Morphology and biology of *Tribolium castaneum*

The adult *Tribolium castaneum* is an elongated, reddish-brown beetle (2,3 to 4,4 mm) distinguished by its three-segmented antennal club and its ability to fly short distances (fig 3) (Delobel and Tran, 1993; Sinha and Watters, 1985). The life cycle begins with transparent oblong eggs (0,3 to 0,6 mm), followed by pale yellow cylindrical larvae (7 mm) that feature two pairs of urogomphi (Tripathi *et al.*, 2001). This species is highly prolific, with females laying up to 1,000 eggs and populations multiplying 70 times within 28 days under optimal conditions (Delobel and Tran, 1993). At 32,5°C and 70% humidity, the biological cycle is completed in 24 to 26 days, passing through 5 to 12 larval stages and a pupal stage (3,75 to 4

mm) that undergoes melanization before adult emergence (Delobel *et al.*, 1993; Lepesme, 1944). Adults are notably long-lived, surviving for two to three years in stored products (Delobel and Tran, 1993).



Figure 3. Adults of *Tribolium castaneum* (GX 20)

1.1.2. Materials and laboratory equipment

The practical part of this research was conducted at the Laboratory of Phoenix, affiliated with the Department of Agricultural Sciences at the University of Kasdi Merbah, Ouargla. This laboratory provides a specialized environment equipped with the necessary tools for entomological research and controlled bioassays.

To rear the insects and complete the experiments, we used an **incubator** to keep stable conditions, a **stereomicroscope** to examine the insects, and a **precision balance** for accurate weighing. The insects were kept in **vials**, **Petri dishes**, and **cardboard boxes** and they were separated from the food using **laboratory sieves**. To examine the insects closely, a **mortar and pestle** was used to gently break chickpea and barley grains to extract the larvae from inside them. Also, **ethanol** was used to slow down the movement of active insects for a better microscopic view, while **forceps** were used for careful handling, and **millimeter paper** was used to measure their length (Fig 4 and 5).



Figure 4. Laboratory equipment used in the study

(A) Precision balance, (B) Stereomicroscope, (C) Incubator .

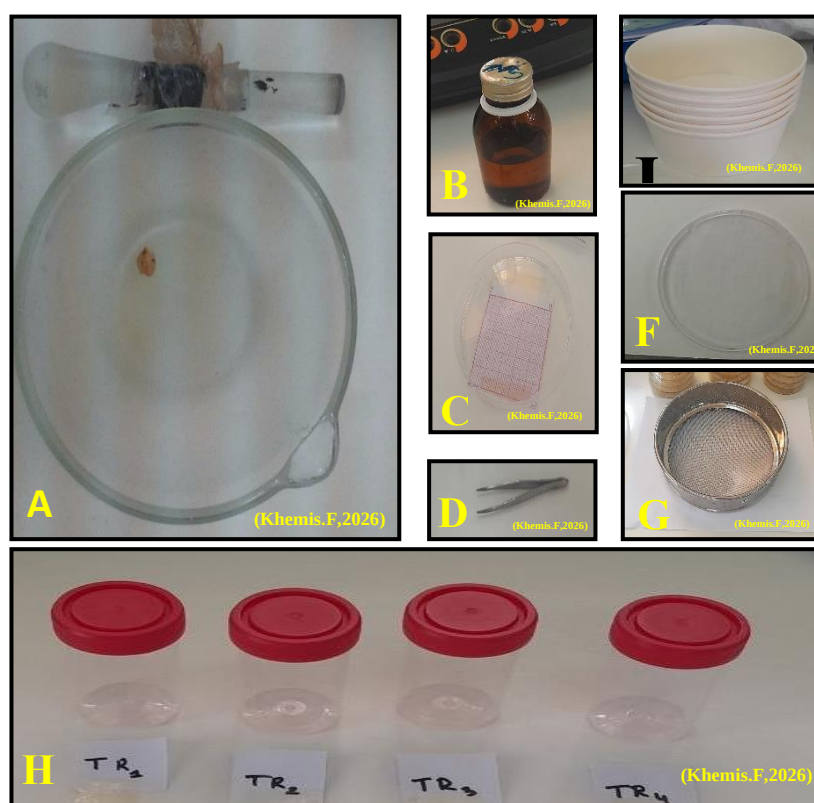


Figure 5. Laboratory equipment and tools used for insect rearing and experimental procedures

(A) Mortar and pestle, (B) Ethanol, (C) Millimeter paper, (D) Forceps, (E) Cardboard boxes, (F) Petri dishes, (G) Laboratory sieve, (H) Vials.

1.2. Experimental methods

1.2.1. Larval development and morphometry

To monitor the growth stages of *T. granarium*, a longitudinal study was designed utilizing five Petri dishes, each containing three replicates, (totaling 15 replicates per experimental group) (Fig 6). Individual larvae were placed in Petri dishes containing either semolina or wheat flour. Three additional replicates served as the control group, where larvae were maintained on their original rearing substrate consisting of broken barley grains and grain dust. All experimental and control groups were maintained at a constant temperature of 28°C and 35% relative humidity. Larval lengths were documented periodically on millimeter paper using a microscope connected to a digital camera. This experiment provides practical information on host suitability under controlled storage conditions by identifying substrates that promote larval growth, thereby contributing to a better understanding of the developmental biology of *T. granarium*.

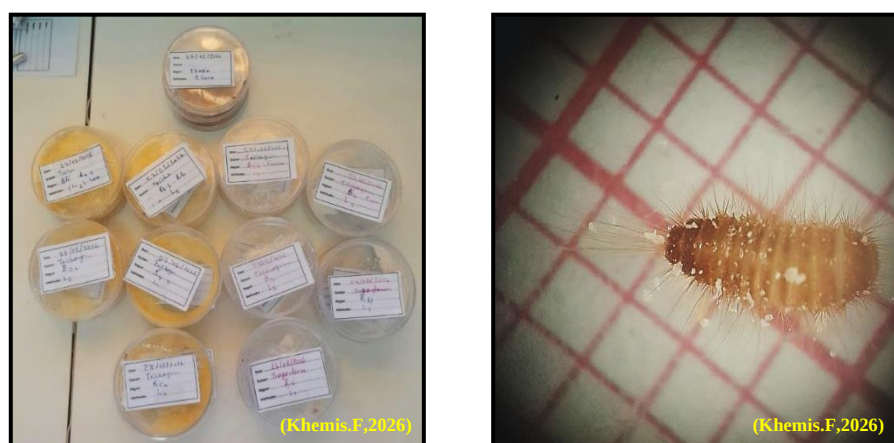


Figure 6. Microscopic observation of *T. granarium* (GX 35).

1.2.2. Breeding and sex-ratio determination

Following adult emergence, mating was conducted across 11 Petri dishes at a controlled temperature of 28°C and 35% RH. Successful reproduction occurred in 8 dishes. To ensure the accuracy of the sex ratio and subsequent statistical tests, only the first generation of emerged adults was recorded to avoid data errors resulting from overlapping generations. Following the enumeration of the emerged adults, sex determination was executed based on morphological dimorphism, where males were identified by their smaller size and darker brown-to-black bodies with faint reddish-brown wing markings, while females were distinguished by their larger size and lighter coloration (Ahmedani *et al.*, 2007). Once identified, the determination of the sex ratio was conducted utilizing the following formula (Dagnelie, 1975).

$$\text{Sex-ratio} = \text{Total number of males} / \text{Total number of females}$$

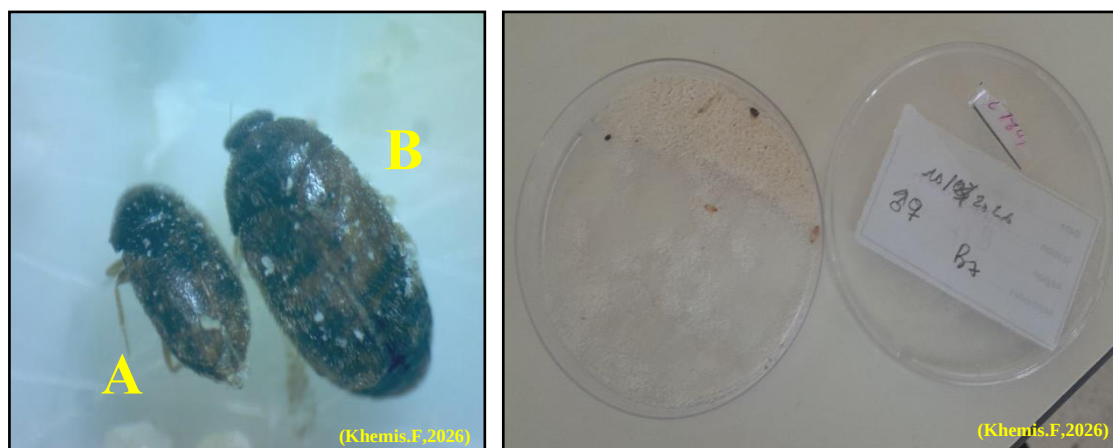


Figure 7.Adult pairs (A) Male, (B) Female and progeny (larvae) of *T. granarium* (GX 30)

1.2.3.Starvation tolerance test

A comparative experiment evaluated the survival capacity of different species under nutritional stress. Adults of *T. castaneum* and *C. maculatus* were monitored alongside the larvae of *T. granarium*. Due to the biological nature of *Trogoderma* adults, which typically expire within 10 days post-emergence regardless of mating, the starvation test focused on the larval stage of *Trogoderma* due to its known physiological resilience . The practical value of this starvation tolerance test lies in comparing the tolerance of different stored-product insect species to food deprivation, thereby contributing to a better understanding of their physiological resilience and adaptation to storage conditions.

1.2.4.Dry matter loss assessment

To evaluate quantitative damage, a weight loss test was performed on semolina utilizing 18 replicates under controlled environmental conditions of 27°C and 35% RH (Fig 8).The experiment directly compared three distinct levels of initial larval density: 5, 20, and 50 larvae of *T. granarium* per 5 g of semolina, with six replicates allocated to each density group. The initial and final dry weights of the substrate were recorded before and after the infestation period to determine the cumulative percentage of dry matter loss induced across the different density levels according to (Adams, 1977). The percentage of dry matter loss was calculated for each replicate using the standard biometric formula adapted from (Adams,1977)

$$\text{Dry Matter Loss (\%)} = \frac{W_i - W_f}{W_i} \times 100$$

W_i : Initial Substrate

Weight (g)

W_f : Final Substrate Weight (g)

Where W_i represents the initial substrate weight (5.00 g) and W_f denotes the final remaining weight recorded at the end of the incubation period.



Figure 8. Comparative samples of semolina showing dry matter loss after infestation with different larval densities.(5, 20, and 50 larvae)

1.2.5.Vertical climbing behavior

To evaluate locomotor activity, a vertical climbing assay based on negative geotaxis was performed using 8 cm high cylindrical plastic containers (Fig. 9). For *T. granarium* and *T. castaneum* larvae, individuals were placed at the base and maintained in an incubator at 28°C and 35% RH, with climbing monitored over 3 days. For *C. maculatus* adults, climbing capacity was recorded at room temperature over a 1-hour period. The number of individuals reaching the 8 cm threshold was documented to determine dispersal potential (Arthur, 2002). The practical value of this locomotor activity test lies in simulating the climbing behavior of stored-product insects under conditions representative of storage environments. By assessing their ability to climb vertical surfaces, the test provides insights into their dispersal potential and movement within storage environments, thereby contributing to a better understanding of their movement and dispersal behavior.

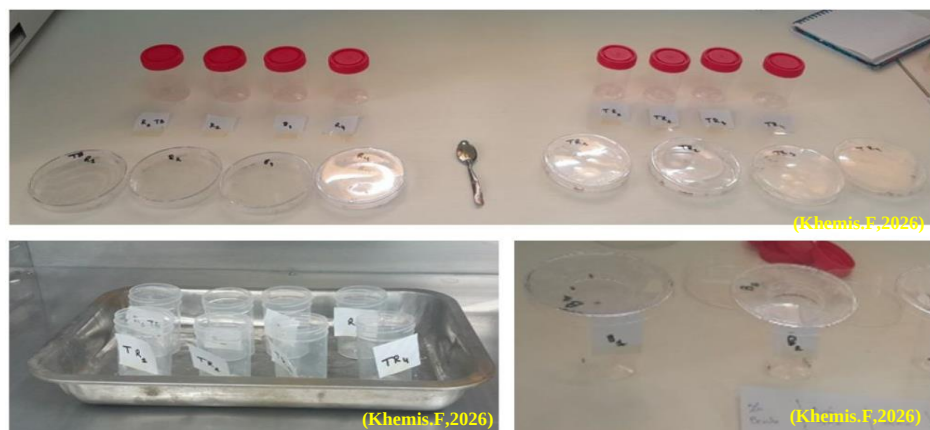


Figure 9.Experimental laboratory setup and data recording for the vertical climbing and locomotor activity assays of various stored-product insect species

1.2.6. Interspecific competition (*Trogoderma* vs. *Tribolium*)

An interspecific study was designed with 20 larvae each of *T. granarium* and *T. castaneum* in shared media, alongside independent control jars for each species, to evaluate competitive dominance over one month at 28°C and 35% RH. Studies indicate that under these conditions, specific humidity levels can significantly influence the population dynamics and competitive outcomes between these species (Fig 10).



Figure 10. Population distribution of *T. granarium* and *T. castaneum* after 30 days of interspecific competition in a shared medium

1.2.7. Food preference and host selection assay

To evaluate the host selection behavior of *T. granarium* and *T. castaneum*, a multi-choice preference test was conducted.

Experimental arena: A circular container was partitioned into six equal sections, each containing 5g of a specific substrate: Maize (Corn), Lentils, Oats, Semolina, Wheat Flour, and Barley (fig 11).

- **Larval assay (*T. granarium*):** For each of the 6 replicates, 25 larvae were released into the center of the arena, allowing them free access to choose between the six substrates.
- **Adult assay (*T. castaneum*):** Two distinct groups of adults were tested to compare the influence of physiological state on food preference:
 - ❖ **Satiated group:** 25 adults per replicate (5 replicates) were released directly.
 - ❖ **Starved group:** 25 adults per replicate were subjected to a 72 hour (3 day) starvation period prior to the test to stimulate foraging activity and standardize their response to the nutritional triggers.

The entire experiment was maintained at a controlled temperature of 28°C. The distribution of the insects across the different substrates was recorded **after intervals of 48 and 72 hours** to

determine the order of preference. This methodology follows the protocols established by Nawrot *and al.*(1986), for feeding preference and (Sokoloff, 1974) for *Tribolium* behavior.

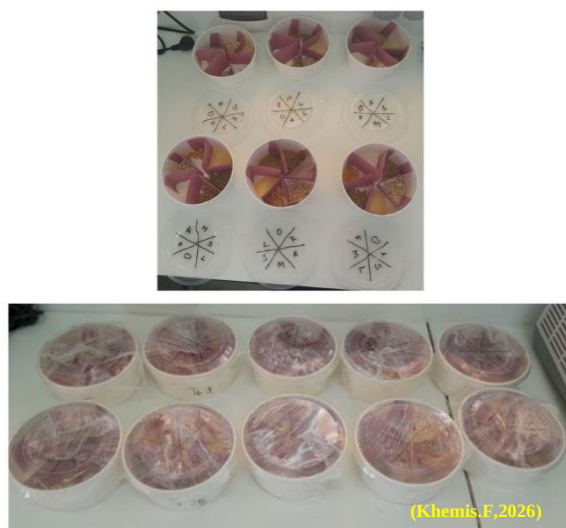


Figure 11.Multi-choice arena for food preference testing, illustrating the distribution of insects among six different substrates

(Maize, Lentils, Oats, Semolina, Flour, and Barley)

1.3.Statistical analysis

The data collected during this study were organized and analyzed using Excel 2019. Arithmetic means and standard deviations (Mean $\pm$ SD) were calculated for all measured parameters, and graphical representations were generated. Statistical analysis was performed using one-way analysis of variance (One-Way ANOVA) to evaluate differences among the studied groups, with a significance level set at $P < 0.005$.

Chapter II

Results and discussion

2. Results and discussion

This section presents the compilation, interpretation, and analysis of the experimental data obtained from the biological, morphological, and behavioral evaluations of *Trogoderma granarium*, *Callosobruchus maculatus*, and *Tribolium castaneum*. The findings are structured into distinct subsections, providing a detailed qualitative and quantitative analysis of the compiled empirical results, observations, and illustrative data.

2.1. Morphological description of the three species

2.1.1. Khapra Beetle *Trogoderma granarium*

2.1.1.1. Larva

The larvae are yellowish-white with a brown head capsule. After the fourth instar, the fully developed larva measures $5 \pm 0,22$ mm in length and $1,5 \pm 0,03$ mm in width and is covered with yellowish-brown setae. Similar larval characteristics were reported by Ahmedani *et al.* (2007), who described the larval stage as the most recognizable stage of development. The larval stage is the most recognizable stage of development. The larvae are covered with dense reddish-brown setae. Their body is yellowish-white with a dark brown head capsule. At the posterior end, the larvae possess characteristic hastisetae (spear-headed hairs), which are considered a distinctive feature of this stage.

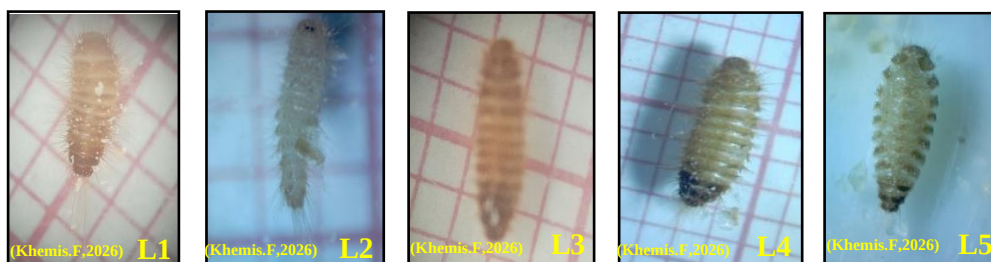


Figure 12. *Trogoderma granarium* larva (GX 35)
Larval instars (L1 ,L2 ,L3, L4 ,L5)

2.1.1.2. The pupal stage

The *T. granarium* pupa is enclosed within its protective final larval skin. The body is clearly visible through a distinct dorsal split, displaying a transitional yellowish-brown to dark brown coloration (Fig. 13). This exarate specimen exhibits free appendages with a noticeable darkening concentrated near the anterior region. The pupal characteristics observed in the present study are consistent with those described by Ahmedani *et al.* (2007) It is the intermediate developmental stage between the larva and the adult, occurring inside the last

larval skin (exuviae) for protection. The pupa is of the exarate type, initially yellowish-white, and characterized by free appendages that gradually darken as adult emergence approaches.



Figure 13. Pupal stage of *Trogoderma granarium* (GX 40)

2.1.1.3. Adult

The emerged adult *T. granarium* reveals a small, elongated-oval beetle characterized by a dark brown body coloration. The dorsal surface exhibits fine, dense pubescence, with subtle, faint reddish-brown bands distributed across the elytra. Structurally, the small head appears partially retracted beneath the pronotum. Morphometric measurements show clear sexual dimorphism in body size; the adult males measure approximately 2 mm in length and 1 mm in width, whereas the larger adult females measure approximately 3 mm in length and 1,2 mm in width (Fig 14). These morphological features closely correspond to those described by Hagstrum (2009). Small (2 to 3 mm) oval-shaped, and dark brown. The head is small and often retracted. They have indistinct reddish-brown markings on the elytra (wing covers) and are covered in fine hairs.



Figure 14. *Trogoderma granarium* adult (A) Female, (B) Male (GX 35)

2.1.1.4. Life cycle of *Trogoderma granarium*

Under controlled experimental conditions maintained at an optimal temperature of 28°C and 35% relative humidity, laboratory monitoring of the *T. granarium* life cycle revealed a highly synchronized developmental pattern, as illustrated in (Fig 15). The cycle begins with an egg incubation period lasting $6 \pm 0,30$ days prior to hatching. Following eclosion, the larval stage extends for $28 \pm 0,75$ days of active feeding. The pupal stage lasts $4,5 \pm 0,35$ days, during which metamorphosis is completed within the larval exuviae. Upon emergence, adults exhibit a lifespan of $8,5 \pm 0,4$ days. Consequently, under these controlled conditions, the total life cycle from oviposition to adult senescence is completed within a mean duration of $47 \pm 1,4$ days, ranging approximately from 45 to 49 days. The developmental pattern observed in the present study is comparable to previous reports, with minor variations in the duration of certain developmental stages. The incubation period of the eggs typically lasts about one week, ranging from 5 to 7 days at temperatures between 32°C and 35°C (Ahmedani *et al.*, 2007). However, environmental factors such as temperature and relative humidity significantly influence the duration of each stage (Hagstrum, 2009). The larval stage is the most variable; it generally lasts between 4 and 6 weeks under optimal conditions but can be prolonged for several years if the larvae enter diapause due to unfavorable conditions (Ahmedani *et al.*, 2007).

Regarding the pupal stage (nymphosis), the duration differs according to temperature and humidity, usually lasting between 3 to 5 days at 35°C (Hagstrum, 2009). The total life cycle from egg to adult emergence takes approximately 25 to 30 days at 35°C, but can extend to over 50 days at 28°C depending on the quality and quantity of food (Ahmedani *et al.*, 2007). In the larval stage, 4 to 7 instars are commonly observed in optimal conditions, but this number can reach up to 15 when conditions are unfavorable (Rees, 2004).

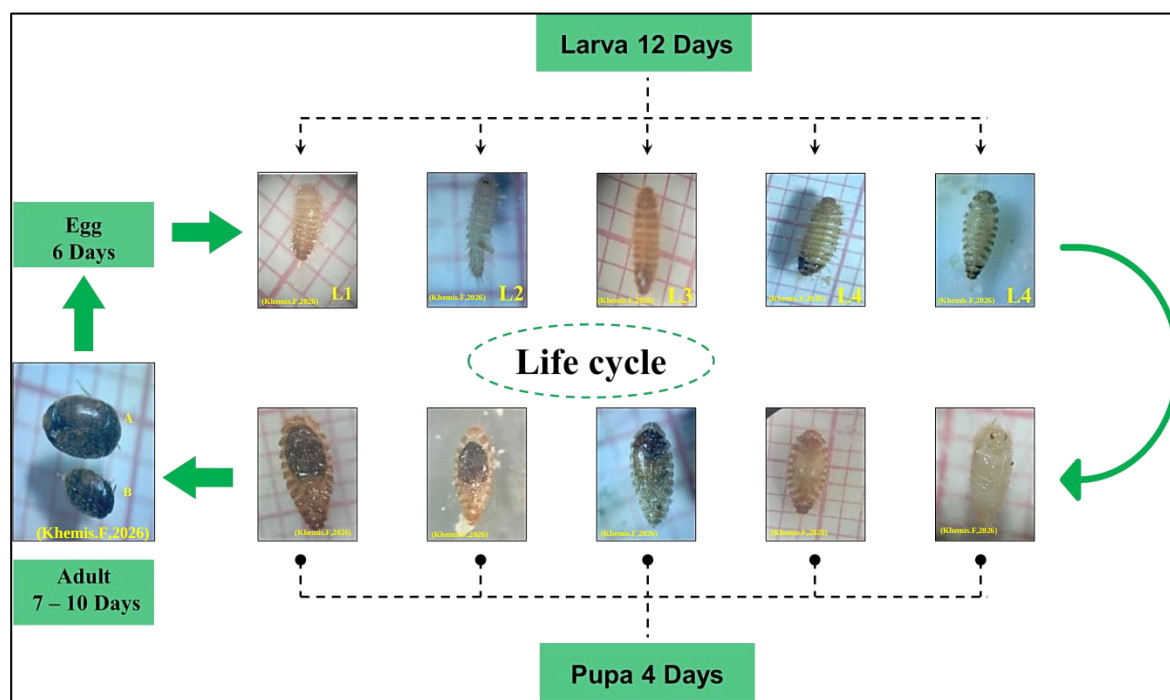


Figure 15. Developmental cycle of *Trogoderma granarium* with mean duration of each stage, Larval instars (L1, L2, L3, L4, L5) and Adults: (A):Female, (B):Male) (GX 35) T: 28°C , RH: 35%

2.1.2 Chickpea bruchid *Callosobruchus maculatus*

2.1.2.1 Egg

The eggs of *Callosobruchus maculatus*, observed under a microscope, were individually deposited on the surface of a Petri dish. They are oval to slightly elliptical in shape, with a smooth, transparent chorion and a glossy appearance. Freshly laid eggs are translucent to milky white, allowing partial observation of internal embryonic development. As development progresses, a darkly pigmented region appears at one pole, corresponding to the cephalic region of the developing larva, while the remainder of the egg remains creamy white due to tissue differentiation (Fig 16 A, B). The eggs show no external ornamentation and maintain a delicate, membranous structure throughout development. A similar description of *C. maculatus* eggs has been reported in previous studies. After mating, the *C. maculatus* female deposits her eggs on the seeds (Alzouma, 1987); these are attached by a gelatinous substance to the surface of the seeds and pods (Delobel and Tran, 1993). The eggs have an ovoid shape, measuring 0,4 to 0,7 mm long and 0,3 to 0,45 mm wide (Albert, 1978). They are translucent yellowish in color, turning milky white if hatching occurs (Giga and Smith, 1987).

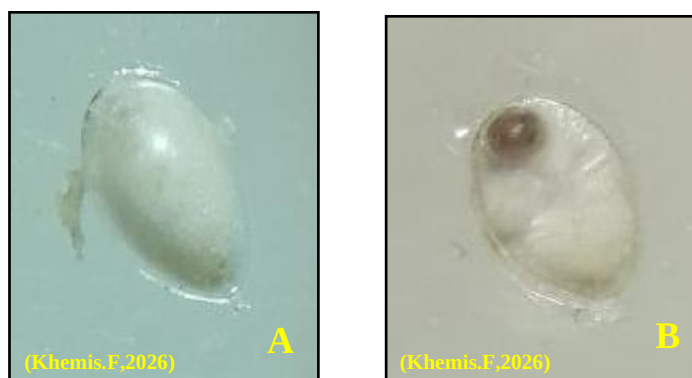


Figure 16. Egg of *Callosobruchus maculatus* observed under a microscope , showing its oval shape, transparent chorion(A), and the visible embryonic development marked by the appearance of a pigmented cephalic region (B) (Gx 40)

2.1.2.2 Larva

Callosobruchus maculatus undergoes four larval instars (Fig 17), all of which develop inside the chickpea seed:

- **(L1):** The newly hatched larva is small, translucent, and mobile. It is of the chrysomelid type and possesses short, well-developed thoracic legs that facilitate movement before penetrating the seed.
- **(L2):** After entering the seed, the larva becomes apodous (legless) and adopts a characteristic curved body shape. The body remains creamy white and soft.
- **(L3):** This stage is characterized by a noticeable increase in body size and width. The larva exhibits a more pronounced segmentation and continues feeding actively on the cotyledon tissues.
- **(L4):** The final larval stage is distinguished by its larger size, fleshy body, and well-developed segmentation. It represents the most voracious feeding stage and is responsible for the majority of seed damage before pupation.

All larval instars develop concealed within the chickpea seed, where they excavate feeding galleries and consume the internal tissues until the onset of pupation. A comparable pattern of larval development has been reported by previous authors. According to Balachowsky (1962), the larval development of *Callosobruchus maculatus* comprises four distinct larval. Larval development takes place entirely within the seed. The larva excavates a gallery along the inner surface of the chorion. During penetration, it pushes seed powder backward, which accumulates beneath the chorion (Kellouche, 2005).

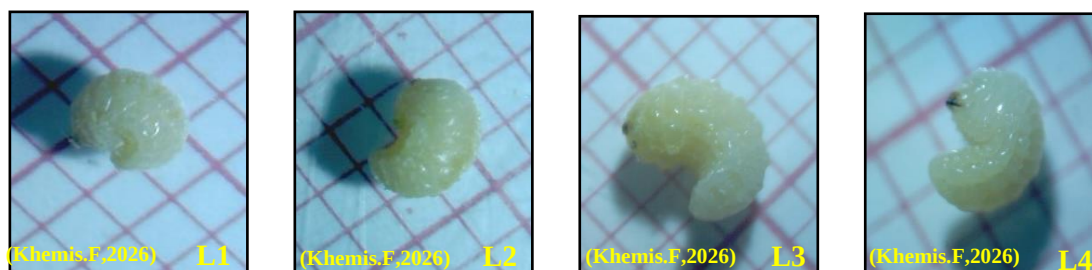


Figure 17. Different larval instars of *Callosobruchus maculatus* (GX 35)

2.1.2.3 Pupal stage (Nymphosis)

The pupal stage of *C. maculatus* was observed inside chickpea seeds after the completion of larval development. The pupa was immobile, creamy white to pale yellow in color, and oval in shape. At this stage, the distinct body parts of the future adult, including the head, legs, antennae, and wing pads, were clearly visible (Fig 18). As development progressed, these structures became more defined, and the eyes gradually darkened. Near adult emergence, the characteristic pigmentation of the adult beetle could be observed through the pupal cuticle. A similar description of the pupal stage has been reported by previous authors. The process of nymphosis typically occurs within the interior of the infested seeds, where the larva develops inside a small chamber constructed just beneath the seed coat. Prior to entering the pupal phase, the larva utilizes its mandibles to perform a precise circular incision on the seed epidermis. This preparation allows the adult insect to eventually lift the resulting operculum to secure its emergence from the grain (Karbache, 2009). Morphologically, the pupa is characterized by a yellowish-white coloration.

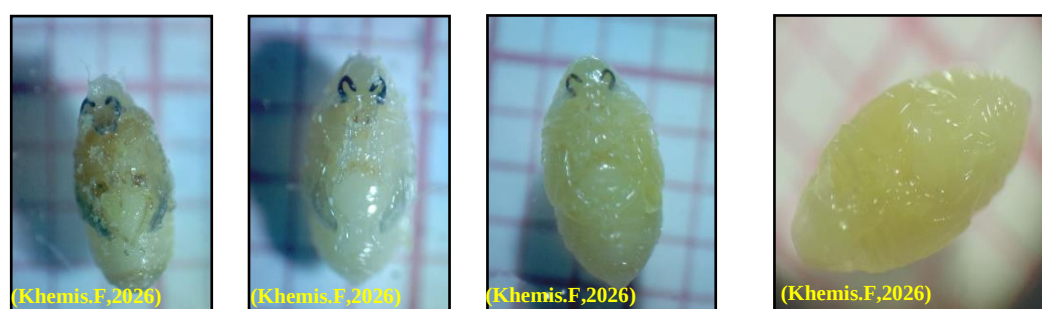


Figure 18. Pupation of *Callosobruchus maculatus* (GX 35)

2.1.2.4. Pre-emergent adult stage

Following the pupal stage, a pre-emergent adult stage was observed inside the chickpea seed. During this phase, the insect had acquired the general morphology of the adult beetle, with fully formed legs, antennae, and wings. Progressive pigmentation was evident, as the body color changed from pale yellow to darker brown shades. The compound eyes became distinctly dark,

and the elytra gradually developed their characteristic coloration and markings (Fig. 19). This stage represents the final phase of metamorphosis before adult emergence from the seed.

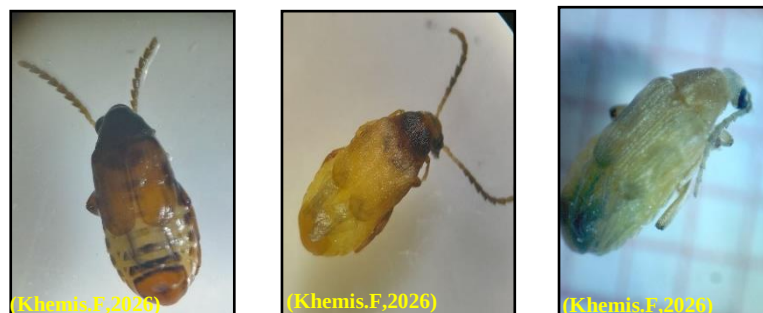


Figure 19. Pre-emergent adult of *Callosobruchus maculatus* inside a chickpea seed showing progressive pigmentation and wing development prior to emergence (GX 35)

2.1.2.5. Adult Stage

The adult of *C. maculatus* is a small beetle with a compact oval body measuring $3,8 \pm 0,1$ mm in length and $2 \pm 0,07$ mm in width. The body is reddish-brown to dark brown in color, with characteristic darker markings on the elytra. The head bears a pair of segmented antennae and well-developed compound eyes. The thorax supports three pairs of articulated legs adapted for locomotion. The forewings are modified into hardened elytra that partially cover the abdomen, while the membranous hindwings are folded beneath them. After emergence from the chickpea seed, the adult becomes fully sclerotized and acquires its definitive coloration. This stage represents the reproductive phase of the insect and is responsible for mating and oviposition. Comparable observations on the adult stage have been reported in previous studies. The adult of *C. maculatus* has a body length between 2,8 and 3,5 mm and is colored black and red. According to (Delobel and Tran, 1993), the head is black, and the wing covers (elytra) are black with red areas, covered by fine white and golden hairs. A very important fact about these adults is that they do not eat. Instead, they live using the energy they stored earlier when they were larvae (Balachowsky, 1962).



Figure 20. *Callosobruchus maculatus* adult. (GX 30)

2.1.2.6 .Mating

Mating in *C. maculatus* was observed shortly after adult emergence. During copulation, the male mounts the female and remains attached to her for a variable period. The two individuals maintain close contact while mating, with limited movement observed during this phase. This behavior marks the beginning of the reproductive period and is followed by oviposition on the host substrate.

Mating is a biological phenomenon in *C. maculatus* that can occur during the day or at night. This process usually happens within the first few hours after the adult emerges, or at the latest, within the 24 hours following its emergence (Aoudjit et Sahouane, 2015).



Figure 21. Copulation of *Callosobruchus maculatus* adults (GX 35)

2.1.2.7. Life cycle of *Callosobruchus maculatus*

Under controlled laboratory conditions maintained at 28 °C and 35% RH, the life cycle of *Callosobruchus maculatus* comprised five distinct developmental stages: egg, larva, pupa, pre-emergent adult, and adult. The egg incubation period lasted $6 \pm 0,35$ days prior to hatching. Larval development occurred entirely within the chickpea seed, extending for $12 \pm 0,65$ days

of active feeding. The pupal stage lasted $3 \pm 0,25$ days, followed by a pre-emergent adult stage of $1,5 \pm 0,2$ days during which adult morphology, pigmentation, and wing development were completed within the seed. Consequently, adult emergence occurred after a total developmental period of $22,5 \pm 0,78$ days (Fig 22). Under the same environmental conditions, adult lifespan showed a mean duration of $9,5 \pm 1,25$ days. The life cycle observed in the present study closely corresponds to previous descriptions under similar laboratory conditions. The ontogenetic development of *Callosobruchus maculatus* is strongly modulated by ambient microclimatic conditions and host grain characteristics. Under controlled laboratory regimes of 28 °C and 35 RH, the holometabolous life cycle spans approximately 22 to 23 days, which aligns with the established thermal optimum for bruchid biological performance (Howe & Currie, 1964; Rees, 2004). Embryonic incubation within this thermal band reliably concludes within 6 days post-oviposition, transitioning into an intensive 12 day internal feeding phase wherein the four larval instars selectively consume the cotyledonary reserves of the chickpea host (Raina, 1970; Beck et Blumer, 2014). Following a brief 3 day pupation and a 1 to 2 day quiescent pre-emergent adult phase required for cuticle sclerotization, adults chew an operculum to emerge. As typical aphagous imagoes, their post-emergence longevity is strictly limited to 7 to 12 days, dedicating their limited metabolic reserves exclusively to immediate copulation and oviposition pathways (Appleby et Credland, 2004; Sanon *et al.*, 2011)

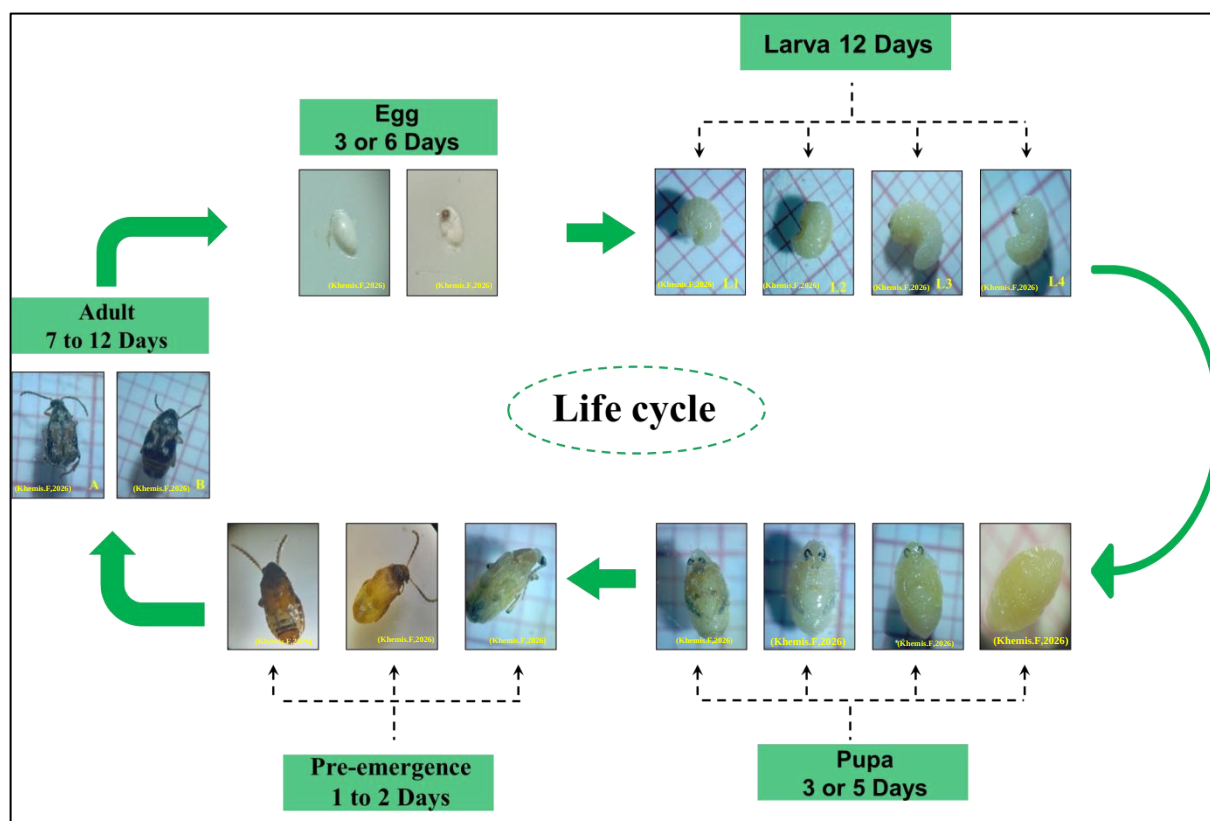


Figure 22.Developmental cycle of *Callosobruchus maculatus* with mean duration of each stage. Larval instars (L1, L2 , L3, L4), (A): Male,(B): Female. T: 28°C , RH: 35%

2.1.3. Red Flour Beetle *Tribolium castaneum*

2.1.3.1 Larva

The early instars exhibit a slender, semi-translucent body with a mean length of $2 \pm 0,15$ mm. As development progresses, the larvae become covered with short yellow setae, develop functional legs, and increase progressively in size, displaying a cream-yellow coloration with a mean length of $4,25 \pm 0,38$ mm .The final larval instar is characterized by a fully developed elongated cylindrical body and a pair of prominent dark, pointed urogomphi located on the terminal abdominal segment. At this stage, larvae reach their maximum size, with a mean length of $6 \pm 0,45$ mm (Fig 23).

A key identifying feature is the last segment of the abdomen, which ends in two small, dark, upward-curving structures called urogomphi (Delobel and Tran, 1993).

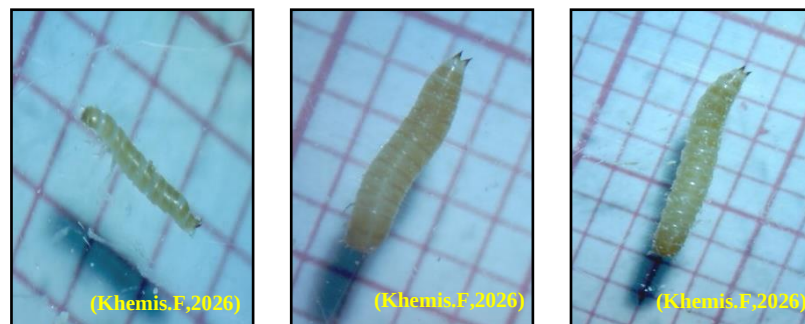


Figure 23. *Tribolium castaneum* larva. (GX 30)

2.1.3.2 Pupa stage

The pupal stage of *Tribolium castaneum* exhibits the typical exarate form, with appendages and wing pads remaining free from the body. Newly formed pupae are pale white in color and translucent, whereas older pupae gradually darken as development progresses. The compound eyes are initially unpigmented and later acquire a darker coloration. The pupa is elongated and oval in shape, with the head, antennae, legs, and wing pads clearly distinguishable. Morphometric measurements indicate a mean length of $3,95 \pm 0,08$ mm.

As described by Christine (2001), the pupa is cylindrical. It starts as a whitish color and gradually turns yellowish as it matures before becoming an adult.

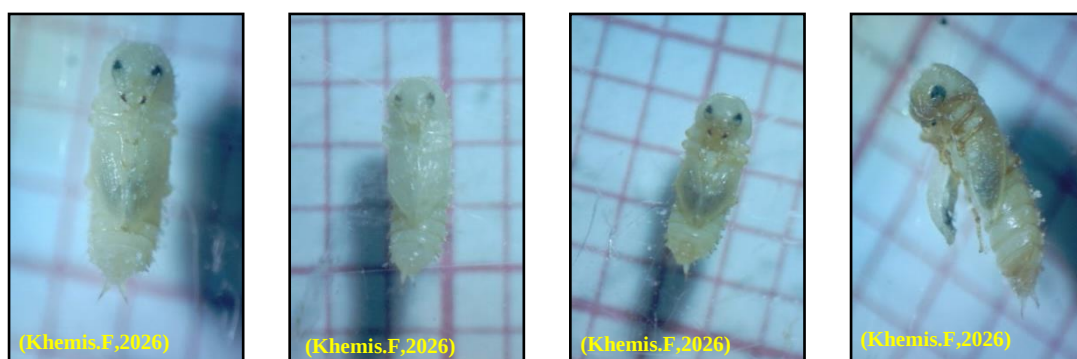


Figure 24. Pupation of *Tribolium castaneum*. (GX 40)

2.1.3.3 Adult stage

The adult *Tribolium castaneum* is a small beetle with an elongated, dorsoventrally flattened body, measuring a mean length of $3,75 \pm 0,38$ mm and a mean width of $1,1 \pm 0,06$ mm. The body is covered by a hardened exoskeleton with a characteristic shiny reddish-brown coloration. The head bears a pair of dark compound eyes and segmented antennae terminating in a distinct three-segmented club, which is a key diagnostic feature of the species. The prothorax is densely punctured, while the hardened forewings (elytra) exhibit parallel

longitudinal striae. The adult stage represents the reproductive phase of the insect, responsible for mating, dispersal, and oviposition. These morphological characteristics are consistent with previous descriptions of the adult stage. The adult is a reddish-brown beetle, measuring 2,3 to 4,4 mm in length. Its body is clearly divided into three parts: the head, a wide thorax, and striated elytra (wing covers). For precise identification, the antennae consist of eleven segments ending in a three-segmented "club" shape. Additionally, sexual dimorphism is observed; males possess a small hairy tubercle on the base of the first femur, which is absent in females (Delobel and Tran, 1993).

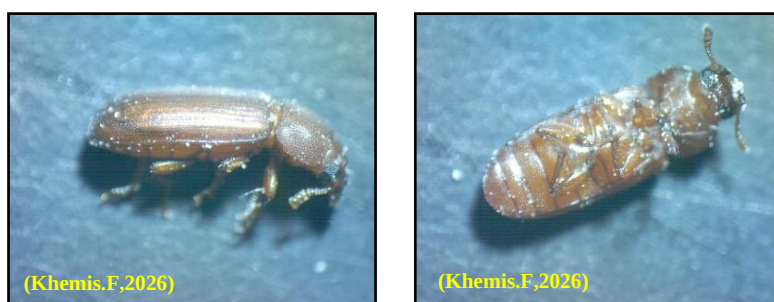


Figure 25.Adults of *Tribolium castaneum*. (GX 40)

2.1.3.4 Life cycle of *Tribolium castaneum*

The red flour beetle, *Tribolium castaneum*, undergoes complete metamorphosis consisting of four developmental stages: egg, larva, pupa, and adult. Under favorable laboratory conditions, the egg incubation period lasts $6 \pm 0,5$ days before hatching. The subsequent larval stage consists of 6–12 instars and extends for a mean duration of 22 ± 2 days, depending on temperature and food quality. Following the final larval instar, the insect enters an exarate pupal stage that lasts $5 \pm 0,5$ days. After adult emergence, the beetles rapidly reach reproductive maturity, with a total pre-imaginal developmental duration of approximately $33 \pm 2,1$ days from oviposition to adult emergence (Fig. 26). Adults are relatively long-lived and typically survive for several months, with longevity varying according to environmental conditions and food availability. A comparable developmental pattern has been reported under similar experimental conditions. The egg stage of *Tribolium castaneum* lasts up to one week under favorable conditions ,but may be reduced to 2–3 days at temperatures of 30–34°C. The larval stage generally lasts 12–13 days; however, under unfavorable conditions, it may be prolonged to 70–80 days.. In contrast, Howe (1956) reported a shorter average pupal duration of approximately 4,5 days(Abdullahi *et al.*, 2019).Temperature has a pronounced effect on the duration of the life cycle. At 35% relative humidity, the complete developmental cycle lasts approximately 37 days at 25°C, 26 days at 28°C, 23 days at 35°C, and 21 days at 38°C. Food substrate also significantly

influences development. At 35°C, the life cycle requires approximately 2–3 months when larvae feed on wheat grains, whereas it may extend to more than one year when flour is used as the food source (Delobel et Tran, 1993).

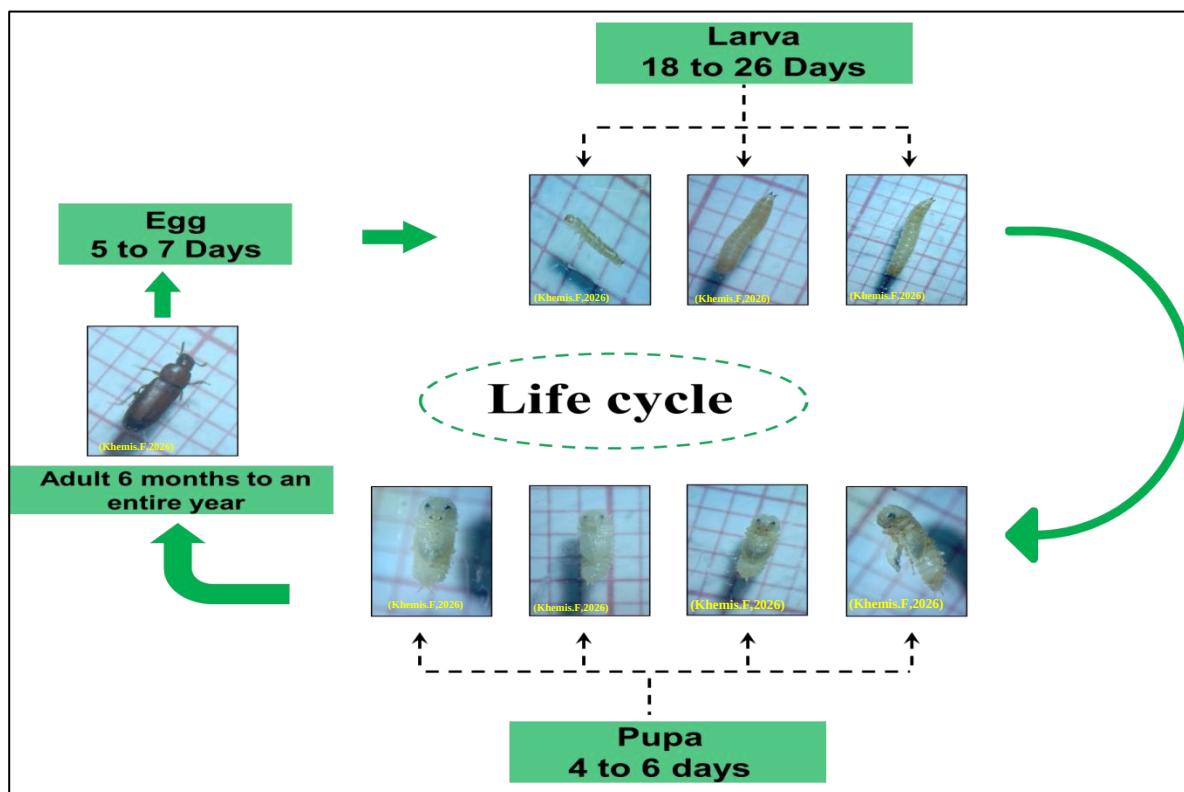


Figure 26. Developmental cycle of *Tribolium castaneum* with mean duration of each stage

T: 28°C , RH: 35%

2.2. Effect of alimentation on the larval morphometric variations and the duration of the stages of *Trogoderma granarium*

Longitudinal monitoring using digital microscopy revealed noticeable differences in the growth patterns of *Trogoderma granarium* larvae according to the physical characteristics of the feeding substrate (Table 1, Fig. 27).

Table 1. Synthesis of biological and morphometric parameters of *Trogoderma granarium* reared on different dietary treatments.

Diet / Treatment	Number of replicates (N)	Initial larval length (mm)	Maximum larval length reached (mm)	Larval duration (Days)	Pupation and adult emergence (%)	Adult sex-ratio (Male/Female)
Semolina	15	0,35 ± 0,02	0,5 ± 0,01	14,2 ± 0,4	100%	8 M / 7 F
Wheat flour	15	0,33 ± 0,02	0,4 ± 0,02	18,5 ± 0,6	100%	6 M / 9 F
Control	3	0,20 ± 0	0,3 ± 0,03	26,0 ± 1,2	66,7%	0 M / 2 F (1 Dead)

Values are presented as mean ± standard deviation (Mean ± SD)

Larvae reared on semolina exhibited greater body growth, with body length increasing from an initial value of 0,35 ± 0,02 mm to a maximum of 0,50 ± 0,01 mm.

This enhanced growth may be associated with the coarse granular texture of semolina, which provides more favorable feeding conditions and may facilitate food consumption and utilization by the larvae (Burgess, 2008).

In contrast, larvae reared on wheat flour showed a comparatively lower increase in body length (Fig. 27), growing from 0,33 ± 0,02 mm to a maximum of 0,48 ± 0,02 mm. Although wheat flour and semolina originate from the same cereal source, the finer texture of flour may reduce feeding efficiency, leading to slower growth and a longer larval developmental period. Indeed, larvae reared on wheat flour required 18,5 ± 0,6 days to reach their maximum length, compared with 14,2 ± 0,4 days for larvae reared on semolina (Hagstrum and Subramanyam, 2006).

These results suggest that, in addition to nutritional composition, the physical characteristics of the food substrate can influence larval growth and development in *T. granarium*.

The shorter developmental period and slightly greater body length observed in larvae reared on semolina indicate that substrate texture may play an important role in larval performance and developmental rate.

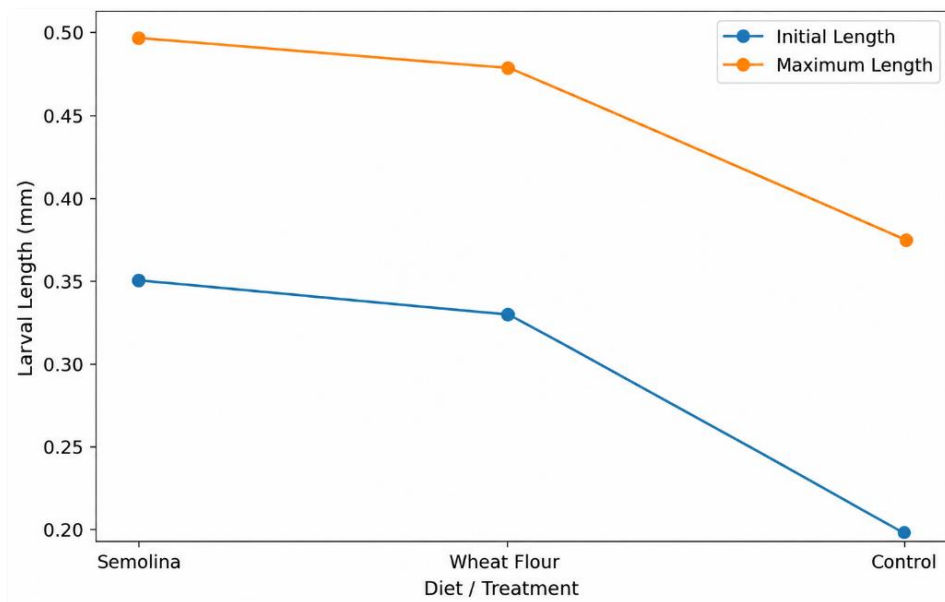


Figure 27. Effect of Diet Type on Larval Length Development

A one-way analysis of variance (ANOVA) was performed to evaluate the effect of diet type on the maximum larval length reached by *Trogoderma granarium*. The results revealed statistically significant differences among the studied groups ($F = 69,23$; $p < 0,001$). These findings indicate that the observed variation in larval length between treatments is strongly associated with the nutritional and physical characteristics of the dietary substrates (semolina, wheat flour, and control).

2.3. Growth trajectory compared to the baseline control

The three individual replicates maintained as the control group (in their original colony substrate) followed a steady baseline growth trajectory, but with a significantly lower elongation rate compared to the semolina group. This statistical contrast confirms that while the original medium is sufficient for structural maintenance, the morphometric potential and elongation rate of *T. granarium* larvae are significantly maximized when transitioning to a granular substrate like semolina (Bell, 1994). Consequently, the morphometric data confirms that semolina represents the most favorable texturized medium for accelerating the larval physical growth and development of this pest.

The physical characteristics of semolina, particularly its coarse particle size compared to flour, are well documented in cereal processing literature (Kent et Evers, 1994), and such substrate properties are known to influence insect feeding behavior and development in stored-product insects (Hagstrum et Subramanyam, 2006).

2.4. Statistical sex-ratio

2.4.1. Sex-ratio of *Trogoderma granarium*

The experimental data documented in Table 2 demonstrate a higher proportion of male adults emerging in the first generation (F1).

Table 2. Sex distribution and overall sex-ratio of the first-generation emerged adults of *Trogoderma granarium*

	Number of males	Number of females	Sex-ratio (M/F)
Mean	6,25	2,75	2,27

A total of 50 males were recorded ($6,25 \pm 1,34$ per dish), compared to 22 females ($2,75 \pm 0,62$ per dish). This resulted in an overall sex-ratio of 2,27 (M/F) (table 2)., suggesting a deviation from the expected 1=1 equilibrium under the controlled experimental temperature of 28°C. This pattern is consistent across most successful replicates

Such demographic variation is consistent with the findings of (Kavallieratos *et al*, 2012), who reported that population parameters of *T. granarium* are strongly influenced by environmental temperature and rearing conditions. Temperatures around 28°C may influence developmental rates and emergence dynamics, potentially contributing to differences in timing and proportions of adult emergence between sexes.

A complete developmental failure was observed in the wheat flour treatment, where larvae did not successfully transition from the pupal stage to the adult stage. This outcome may be associated with the physical characteristics of finely milled flour, which can alter micro-environmental conditions and potentially interfere with normal developmental processes during metamorphosis.

In contrast, semolina-supported development resulted in successful adult emergence, suggesting that differences in substrate structure may influence developmental completion

and survival. Such effects have been previously associated with the physical properties of feeding media, which can affect gas exchange and developmental conditions in stored-product insects (Hagstrum et Subramanyam, 2006; Bell, 1994).

2.4.2. Sex-ratio of *Callosobruchus maculatus*

The demographic analysis of *Callosobruchus maculatus* adults revealed a marked female-biased distribution across the successful replicates, with 11 males and 20 females recorded, resulting in an overall sex ratio of 0,55 (M/F) (Table 3).

Table 3. Sex distribution and overall sex-ratio of the adults of *Callosobruchus maculatus*

	Number of males	Number of females	Sex-ratio (M/F)
Mean	5,5	10	0,55

From a biological perspective, this female-skewed population may contribute to increased post-harvest grain damage, as females are responsible for oviposition and seed penetration activities. Such demographic patterns are consistent with previous studies by (Appleby et Credland, 2003), which reported that population dynamics in *C. maculatus* tend to favor female emergence as an adaptive strategy to enhance reproductive output and facilitate rapid colonization of host seeds across successive generations.

2.5. Starvation tolerance and retrogressive development

Comparative results revealed clear differences in starvation tolerance among the tested species (Figure 28).

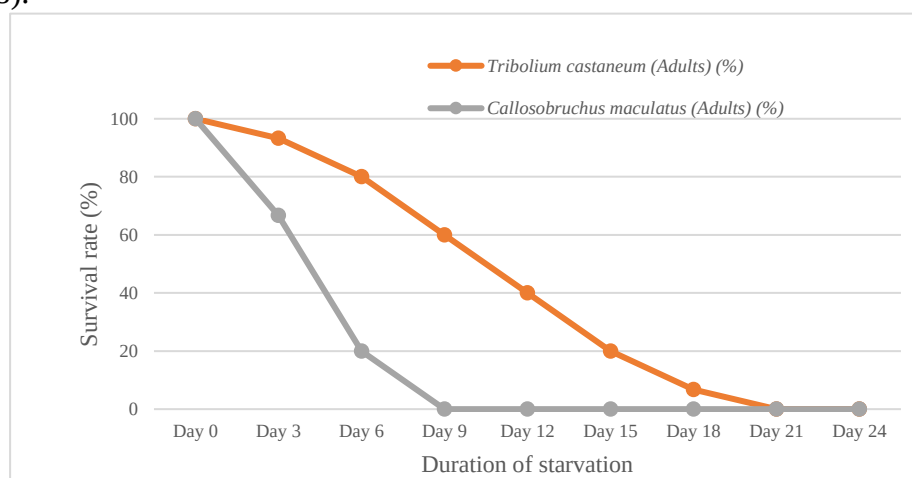


Figure 28. Survival rate (%) of *Tribolium castaneum* adults, and *Callosobruchus maculatus* adults under prolonged nutritional starvation stress.

Adults of *Callosobruchus maculatus* exhibited the lowest survival capacity, with survival declining to 0% by Day 9. *Tribolium castaneum* adults showed intermediate tolerance to food deprivation, with survival gradually decreasing throughout the experimental period until complete mortality was reached on Day 21. These results indicate species-specific differences in adult starvation tolerance, reflecting differences in physiological adaptation and energy reserve utilization. From a practical perspective, knowledge of starvation tolerance is important for improving stored-product pest management, as it provides useful information on the persistence of insects under food-limited conditions and may contribute to optimizing sanitation and storage practices aimed at reducing infestation persistence.

It should be noted that *Trogoderma granarium* larvae were not included in the direct comparison because a different developmental stage was evaluated. Nevertheless, the larvae demonstrated remarkable resistance to starvation, remaining alive for a prolonged period in the absence of food. During starvation, they exhibited a progressive reduction in body size and length accompanied by successive molts, a phenomenon known as retrogressive molting (negative growth). According to Burges (1962) and Bell (1994), this adaptive response is associated with a marked reduction in metabolic activity and the utilization of stored energy reserves, enabling larvae to survive extended periods of food deprivation. These characteristics contribute to the exceptional persistence of *T. granarium* under unfavorable environmental conditions.

2.6.Substrate dry matter loss analysis

Quantitative evaluation of semolina degradation revealed differences in dry matter loss among the tested larval densities (Figure 29).

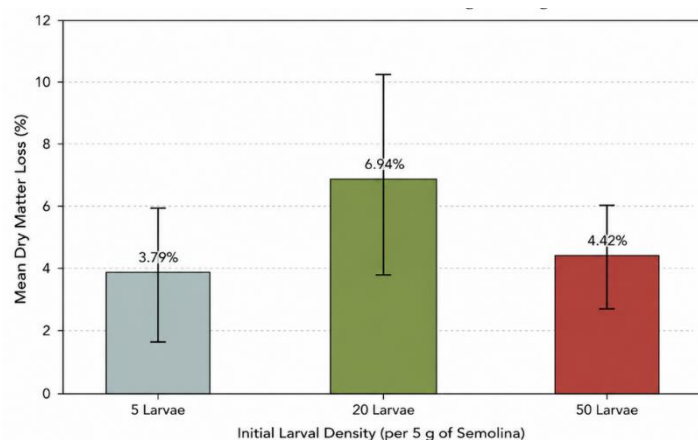


Figure 29. Cumulative dry matter loss percentage (%) in semolina substrate induced by varying initial larval densities of *Trogoderma granarium*

Substrate weight loss resulted from larval feeding activity and metabolic processes, with the highest mean dry matter loss recorded at the intermediate density of 20 larvae ($6,94 \pm 3,12\%$).

In comparison, the treatments containing 5 and 50 larvae exhibited lower losses of $3,79 \pm 2,11\%$ and $4,42 \pm 1,54\%$, respectively.

Interestingly, the highest density treatment (50 larvae) did not result in the greatest percentage of dry matter loss. This pattern may be related to increased inter-larval interactions at high densities, such as competition for food or mutual disturbance, which could reduce feeding efficiency and consequently affect the actual consumption of the substrate.

According to Adams (1977), dry matter loss in stored products is a useful indicator of post-harvest damage caused by insect pests. The feeding activity observed in the present study is consistent with previous reports describing *Trogoderma granarium* larvae as highly destructive feeders capable of causing considerable deterioration of stored commodities. The losses recorded across all treatments confirm the susceptibility of semolina to infestation by this pest, even at relatively low larval densities.

2.7.Locomotor activity and dispersal analysis

The behavioral bioassay revealed distinct locomotive strategies among the tested species under storage conditions. Adult beetles of *Trogoderma granarium* and *Tribolium castaneum* exhibited a total inability to perform vertical climbing (Fig 30).

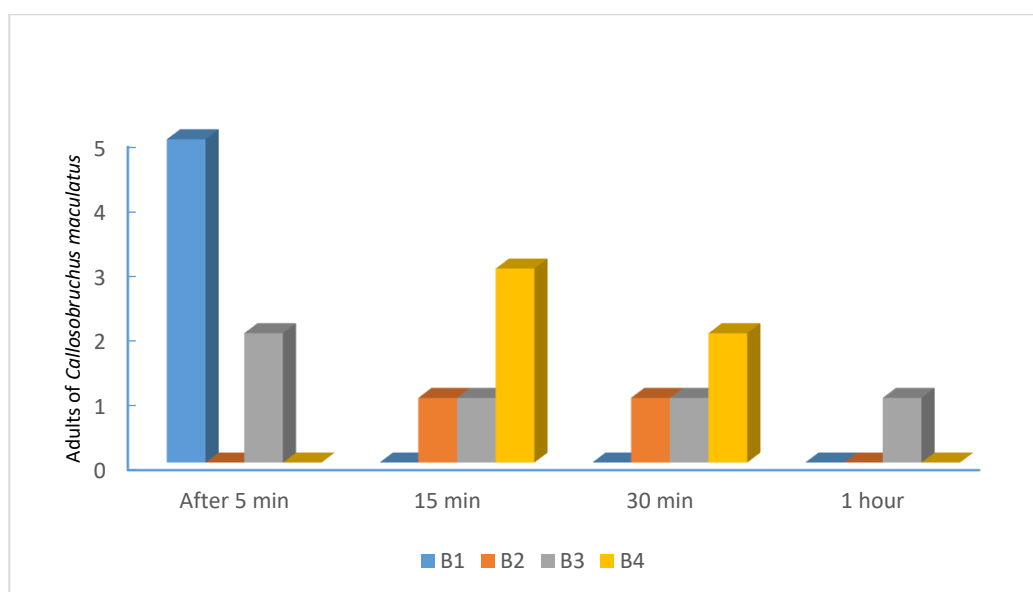


Figure 30. Vertical distribution dynamics of adult *Callosobruchus maculatus*

For *T. granarium*, this limitation is driven by its heavy body mass distribution and robust oval shape, whereas the failure of *T. castaneum* is due to its smooth exoskeleton and lack of specialized ambulatory micro-structures required to generate tactile friction (Aitken, 1975). In contrast, adult *Callosobruchus maculatus* circumvented vertical barriers entirely through active flight, as evidenced by their rapid and high mobilization rate within the 1-hour exposure window. This flight capability enables aggressive macro-dispersal and cross-infestation within silos (Hagstrum and Subramanyam, 2006). Regarding the immature stages, *T. granarium* larvae showed partial vertical mobility, temporarily ascending before falling due to muscle fatigue and gravitational detachment, while *T. castaneum* larvae failed entirely to climb due to their smooth, cylindrical, and unanchored cuticle (Bell, 1994).

2.8. Interspecific competition dynamics (*T. granarium* vs. *T. castaneum*)

The one-month competition bioassay at 28°C resulted in the complete ecological exclusion of *Trogoderma granarium* by the dominant *Tribolium castaneum*. While *T. castaneum* achieved a rapid population explosion, *T. granarium* experienced total developmental stagnation, remaining trapped in the larval phase with continuous molting and adult aggregations over its pupae.

This severe suppression is primarily driven by the chemical modification of the shared substrate; adult *T. castaneum* actively secrete volatile benzoquinones that chemically contaminate the flour (Park, 1934). This toxic accumulation induces severe physiological stress and endocrine disruption in *T. granarium*, forcing repeated larval exuviae shedding while successfully blocking pupal metamorphosis (Prus, 1961). Additionally, the stationary and soft-bodied pupae serve as an opportunistic nutrient and moisture source for the crowded *Tribolium* population (Sokoloff, 1974), reinforcing the competitive superiority of *T. castaneum* through chemical defense and targeted intraguild predation (Prendeville and Stevens, 2002).

2.9. Food preference and host selection behavior

2.9.1. Interpretation of larval selection

The multi-choice preference assay revealed a clear selective feeding pattern of *Trogoderma granarium* larvae across the tested substrates (Fig 31).

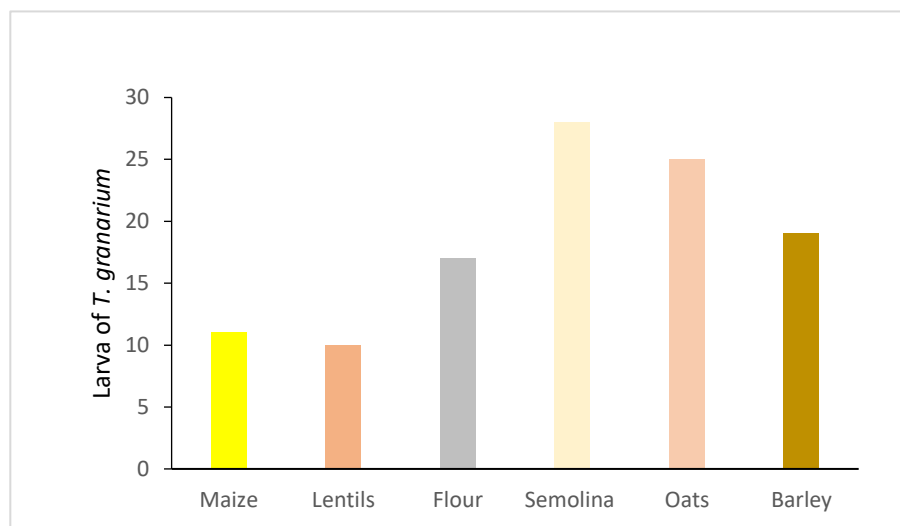


Figure 31. Food preference and substrate selection of *Trogoderma granarium* larvae after 72 hours

Semolina (32 larvae) and oats (18 larvae) recorded the highest larval aggregation, followed by barley (19 larvae) and flour (14 larvae). In contrast, whole-grain substrates such as maize (13 larvae) and lentils (14 larvae) showed comparatively lower attraction levels.

Biologically, this distribution pattern indicates that larval foraging behavior is strongly influenced by the physical structure and accessibility of the substrate. Despite being a major stored-product pest, *T. granarium* larvae tend to concentrate in substrates that minimize mechanical resistance and facilitate feeding. Semolina and oats, being processed or structurally fragmented, offer a greater accessible surface area compared to intact grains such as maize and lentils, which are protected by a hard, lignified pericarp.

According to Nawrot *et al.* (1986), grain processing significantly increases exposed surface area and enhances the release of volatile chemical cues, including free fatty acids and carbohydrate-derived compounds. These volatiles act as olfactory stimuli that promote positive chemotactic responses, guiding larvae toward more suitable feeding substrates (Bell, 1994).

2.9.2. Adult nutritional foraging of *Tribolium castaneum*: satiated vs. starved dynamics

The behavioral monitoring of adult *Tribolium castaneum* under different physiological conditions showed a strong, parallel preference trend across both treatments, with the overall counts being structurally amplified in the satiated population (Fig 32).

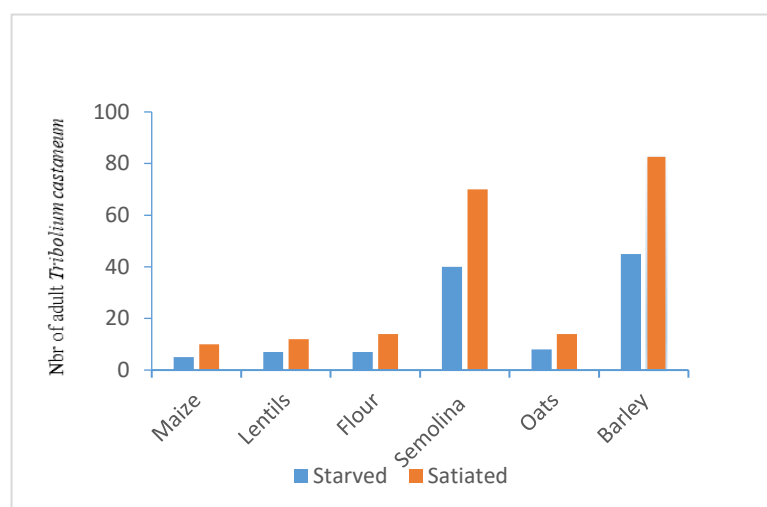


Figure 32. Comparative behavioral distribution of adult *Tribolium castaneum* between starved and satiated states

The satiated group (normal condition) displayed a strong preference for textured substrates, with the highest aggregation observed in barley (83 individuals) and semolina (70 individuals), followed by lower occurrences in flour (14), lentils (12), oats (14), and maize (10).

In contrast, the starved group maintained the same ranking of substrate preference, but with reduced absolute numbers, reflecting starvation-induced changes in activity and overall reduced mobility. Individuals were mainly concentrated in barley (45 individuals) and semolina (40 individuals), with limited distribution toward maize (5), lentils (7), flour (7), and oats (8).

Physiologically, the consistent dominance of barley and semolina over fine wheat flour suggests that *T. castaneum* adults preferentially select substrates based on micro-environmental structure and tactile properties within multi-choice arenas. As a secondary pest, this species is not adapted to penetrate intact grains, but it readily exploits broken kernels and coarse particles such as barley fragments and semolina, which facilitate locomotion and feeding (Sokoloff, 1974).

The coarser texture of these substrates provides improved mechanical support for movement and creates interstitial spaces that favor aggregation, thereby reducing desiccation risk and trans-cuticular moisture loss (Hagstrum et Subramanyam, 2006). Moreover, a 72-hour starvation period acts as a physiological stressor that reduces overall locomotor activity while reinforcing aggregation in nutritionally and structurally favorable zones. Rather than inducing random dispersal, starvation appears to concentrate individuals within optimal microhabitats (barley and semolina), likely as a survival strategy to conserve energy and maximize resource utilization (Bell, 1994).

Conclusion

Conclusion

This comprehensive experimental investigation provides integrated bio-ecological, morphometric, and behavioral insights into three major stored-product insect pests (*Trogoderma granarium*, *Callosobruchus maculatus*, and *Tribolium castaneum*) under controlled laboratory conditions (28 °C and 35 % RH). The results clearly demonstrate that both environmental conditions and the physical structure of dietary substrates play a central role in regulating insect development, survival, and population performance.

Life cycle analysis revealed marked interspecific variation in total developmental duration. *Trogoderma granarium* completed its full life cycle in $47 \pm 1,4$ days, *Callosobruchus maculatus* in $22,8 \pm 0,78$ days, and *Tribolium castaneum* exhibited a longer and more variable developmental pattern with a total duration of approximately 33 ± 2 days. These differences highlight species-specific developmental strategies under identical environmental conditions.

Morphometric observations demonstrated that substrate texture plays a crucial role in regulating larval growth in *Trogoderma granarium*. Larvae reared on coarser substrates such as semolina exhibited enhanced growth and faster development compared to those reared on finer substrates like wheat flour. These findings indicate that coarse-grained food media improve feeding efficiency and accelerate developmental processes, whereas fine particulate substrates tend to reduce feeding efficiency and prolong larval development.

Dry matter loss bioassays further demonstrated that substrate degradation was influenced by larval density, with the intermediate density (20 larvae) resulting in the highest mean dry matter loss ($6,94 \pm 3,12\%$) compared to both low (5 larvae; $3,79 \pm 2,11\%$) and high densities (50 larvae; $4,42 \pm 1,54\%$). This pattern suggests that the relationship between larval density and substrate consumption is not strictly linear and may be influenced by density-dependent interactions among larvae. At higher densities, increased competition for food resources and mutual disturbance may reduce feeding efficiency, thereby limiting overall substrate degradation.

Behavioral and physiological assays highlighted clear species-specific adaptations under starvation conditions. *C. maculatus* showed rapid mortality due to its aphagous adult stage, whereas *T. castaneum* exhibited intermediate tolerance. In contrast, *T. granarium* larvae demonstrated high resistance to starvation, maintaining survival for extended periods through metabolic depression and successive moulting.

CONCLUSION

Substrate preference experiments indicated that insect distribution was strongly influenced by the physical structure of the medium. *Trogoderma granarium* larvae preferentially selected fragmented and coarse substrates, with the highest aggregation recorded in semolina (32 larvae), followed by barley (19 larvae) and oats (18 larvae), whereas lower attraction was observed in maize (13 larvae) and lentils (14 larvae). Similarly, *Tribolium castaneum* adults showed a marked preference for coarse materials, with the highest aggregation observed in barley (83 individuals in the satiated group and 45 individuals in the starved group) and semolina (70 and 40 individuals, respectively). These findings indicate that coarse and structurally fragmented substrates provide more favorable conditions for movement, feeding, and aggregation than intact grains.

Finally, interspecific interactions revealed pronounced competitive differences between species under shared laboratory conditions, with *T. castaneum* showing greater adaptability and ultimately excluding *T. granarium* from the shared environment.

Overall, the findings of this study demonstrate that insect development in stored-product ecosystems is not solely dependent on nutritional composition, but is strongly influenced by substrate physical properties, environmental stability, and species-specific biological traits. These results provide valuable quantitative and ecological insights that can contribute to improving integrated pest management (IPM) strategies in grain storage systems.

Research Perspectives

- ❖ Encourage further investigations in stored-product entomology.
- ❖ Promote sustainable and integrated pest management strategies.
- ❖ Enhance grain storage and post-harvest protection systems.

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Annexe

Annexe

Table One-way ANOVA analysis of the effect of dietary substrate type (semolina, wheat flour, and control) on maximum larval length of *Trogoderma granarium*

SUMMARY				
Groups	Count	Sum	Average	Variance
Column 1	15	7.5	0.5	5.71E-05
Column 2	15	7.2	0.48	0.000371
Column 3	3	1.14	0.38	0.0009

ANOVA					
Source of Variation	SS	df	MS	F	P-value
Between Groups	0.036	2	0.018	69.23077	5.75E-12
Within Groups	0.0078	30	0.00026		
Total	0.0438	32			

Larval density (5g)	Initial substrate weight (g)	Mean final weight (g)	Mean substrate weight loss (g)
N = 5 Larvae	5	4.81	0.19
N = 20 Larvae	5	4.653	0.347
N = 50 Larvae	5	4.779	0.221

Table: Effect of *Trogoderma granarium* larval density on semolina weight loss and dry matter loss (%) after incubation

Abstract

Abstract

Study of some bio-ecological aspects of some stored product pests

This study investigated three major stored-product pests: *Trogoderma granarium*, *Callosobruchus maculatus* and *Tribolium castaneum* under laboratory conditions (28°C and 35% RH). Their life cycles, morphological characteristics and ecological behaviors were examined. The results revealed significant differences among species in developmental duration, starvation tolerance, food preference and interspecific competition. *Trogoderma granarium* completed its life cycle in 47 ± 1.4 days and showed the highest resistance to starvation, while *Tribolium castaneum* required 33 ± 2 days and was the dominant competitor. *Callosobruchus maculatus* completed development in 22.8 ± 0.78 days. Food preference assays indicated a strong attraction to coarse-textured substrates, particularly semolina, with 32 larvae recorded in *T. granarium* and higher aggregation in *T. castaneum* on barley (83 and 45 individuals) and semolina (70 and 40 individuals under satiated and starved conditions, respectively).

Keywords: *Trogoderma granarium*, *Callosobruchus maculatus*, *Tribolium castaneum*, life cycle, behavior, stored products.

دراسة بعض الجوانب البيولوجية لبعض آفات المواد المخزنة.

تناولت هذه الدراسة ثلاثة من أهم آفات المواد المخزنة وهي: خنفساء الخابرا (*Trogoderma granarium*) وسوسة الحمص (*Callosobruchus maculatus*) وخنفساء الدقيق الحمراء (*Tribolium castaneum*) تحت ظروف مخبرية (28°C و 35% رطوبة نسبية). تمت دراسة دورة حياتها وخصائصها المورفولوجية وسلوكياتها البيئية. أظهرت النتائج فروقاً واضحة بين الأنواع من حيث مدة التطور ومقاومة الجوع والتفضيل الغذائي والمنافسة بين الأنواع. أكملت خنفساء الخابرا دورة حياتها في 47 ± 1.4 يوماً وأظهرت أعلى مقاومة للجوع، بينما احتاجت خنفساء الدقيق الحمراء إلى 33 ± 2 يوماً وكانت النوع المهيمن تنافسياً، في حين أكملت سوسة الحمص تطورها في 22.8 ± 0.78 يوماً. أظهرت اختبارات التفضيل الغذائي انجذاباً واضحاً نحو الركائز الخشنة خاصة السميد، مع تسجيل 32 يرقة لدى *T. granarium* وتجمع مرتفع لدى *T. castaneum* في الشعير (83 و 45 فرداً) والسميد (70 و 40 فرداً في حالتي الشبع والجوع على التوالي).

الكلمات المفتاحية: خنفساء الخابرا، سوسة الحمص، خنفساء الدقيق الحمراء، دورة الحياة، السلوك، المواد المخزنة.

Etude de quelques aspects bio-écologiques de quelques ravageurs des denrées stockées.

Résumé

Cette étude a porté sur trois importants ravageurs des denrées stockées : *Trogoderma granarium*, *Callosobruchus maculatus* et *Tribolium castaneum* élevés à 28°C et 35 % d'humidité relative. Les cycles biologiques, les caractéristiques morphologiques et certains comportements écologiques ont été étudiés. Les résultats ont montré des différences significatives entre les espèces concernant la durée du développement, la résistance au jeûne, les préférences alimentaires et la compétition interspécifique. *Trogoderma granarium* a présenté un cycle biologique de $47 \pm 1,4$ jours avec la plus forte résistance au jeûne, tandis que *Tribolium castaneum* a nécessité 33 ± 2 jours et s'est révélé le compétiteur dominant. *Callosobruchus maculatus* a complété son développement en $22,8 \pm 0,78$ jours. Les essais de préférence alimentaire ont montré une attraction marquée pour les substrats à texture grossière, notamment la semoule, avec 32 larves observées chez *T. granarium* et une forte aggrégation chez *T. castaneum* sur l'orge (83 et 45 individus) et la semoule (70 et 40 individus selon les conditions de satiété et de jeûne).

Mots-clés : *Trogoderma granarium*, *Callosobruchus maculatus*, *Tribolium castaneum*, cycle biologique, comportement, denrées stockées.