

Exploring the Efficacy of Botanical Insecticides for Managing Red Flour Beetle (*Tribolium castaneum*) in Stored Grains: A Sustainable Approach to Food Security

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ABSTRACT

The increasing global population is contributing to a growing food security crisis, with stored agricultural products facing significant threats from insect pests. Among these pests, red flour beetle (*Tribolium castaneum*) is one of the most destructive, infesting a wide range of stored grains and processed food products. This pest causes considerable damage to food quality and quantity, leading to significant economic losses in both developed and developing countries. In developing regions, up to 30% of stored grain can be lost to insect infestations. Afghanistan faces significant pest pressure, especially given the limited use of integrated pest management (IPM) practices. Traditional pest control methods, such as synthetic chemical pesticides, are commonly used but present environmental and health risks, particularly in resource-limited settings. The use of botanicals could help control pest populations without harming the environment, beneficial insects, or human health. Afghanistan has diverse ecosystems with a range of plant species that could serve as the basis for developing botanicals. As a result, there is a growing interest in exploring safer, more affordable alternatives. Recent research has focused on plant-derived products, which have demonstrated insecticidal and repellent properties against *T. castaneum*. Botanicals such as neem, eucalyptus, turmeric, garlic, lemongrass, and citrus have shown potential for controlling this pest. This paper reviews the effectiveness of various plant-based treatments for controlling *T. castaneum*, emphasizing their potential as environmentally friendly alternatives to chemical pesticides. Such natural protectants could significantly improve food security, particularly in subsistence farming communities where access to costly chemical pesticides is limited.

Keywords: Food security, *Tribolium castaneum*, Botanical Insecticides, Sustainable Pest Management

INTRODUCTION

The increasing global population is leading to a food crisis. Under these circumstances, food and agricultural products must be stored and shielded from insect contamination using various materials, like synthetic chemical pesticides (Chaubey, 2007). Pest contamination is a major issue for stored food products, affecting them from the time of harvest through to storage. Ensuring food security largely relies on the proper storage and safeguarding of grain commodities worldwide. These stored grains are continuously vulnerable to pest infestations (Islam, 2017). Pests in stored products cause significant losses in both the quality and quantity of post-harvest food grains. In developed countries, post-harvest losses due to

insects, mites, rodents, and microbes in stored grains are estimated at 10%, while in developing countries, the losses can range from 10% to 30% (Ahmady *et al.*, 2016). It has been estimated that over one-third of food products are lost to various pests during post-harvest storage (Tripathi *et al.*, 2009). Insect infestations during storage represent a particularly serious issue, especially in developing countries. Among the pests that affect stored goods, the Red Flour Beetle, *Tribolium castaneum*, is one of the most widespread and destructive. It feeds on a range of stored grains and products, including peas, beans, cocoa, nuts, dried fruits, and spices, with milled grain products like flour being its most favored food source (Mishra *et al.*, 2012). According to the 2011 survey reports from the Plant Protection and

Quarantine Department (PPQD) of the Ministry of Agriculture, Irrigation and Livestock (MAIL) of Afghanistan, losses caused by storage pests such as *Rhyzopertha dominica*, *Trichoderma granarium*, and *Tribolium castaneum* are estimated to exceed 30% for rice, flour, beans, and oilseeds in storage (NGOLLO, 2011). These pests are particularly drawn to grains with high moisture content, where they promote mold growth and produce an unpleasant, musty odor.

Various insect control methods have been assessed to protect grain and reduce reliance on chemical insecticides. A significant issue with chemical insecticides is the residue they leave on food grains, which can pose health risks to consumers. According to Islam (2017), *Tribolium castaneum* (red flour beetle) ranks 19th among the top 20 insecticide-resistant arthropods, with 132 recorded instances of resistance. This highlights the urgent need to find alternatives that can replace these harmful chemicals. To address these challenges, exploring alternative pest control methods is crucial. Botanical pesticides, which protect stored grains from pests, offer numerous benefits. These include being easily produced by farmers and being more affordable. More than 120 plant species and their products have been identified for controlling stored grain insect pests. Recent studies have reported various plants with insecticidal and repellent properties against the red flour beetle (Padin *et al.*, 2013; Sagheer *et al.*, 2014; Bilal *et al.*, 2015; Nattuduraj *et al.*, 2015). With the growing interest in medicinal plants, this review discusses the potential of eco-friendly and cost-effective methods for managing the red flour beetle, focusing on recent research into phyto-derivatives in the 21st century.

DESCRIPTION OF RED FLOUR BEETLE

A significant secondary pest in food storage areas, particularly in warmer regions of the world, is commonly known as the Red Flour Beetle, Rust Red Flour Beetle, or simply Flour Beetle. Its taxonomic classification is as follows: Phylum: Arthropoda; Class: Hexapoda (Insecta); Order: Coleoptera; Family: Tenebrionidae (CABI, 2007).

The eggs are tiny (microscopic), whitish, and cylindrical, with flour remnants sticking to their surface due to a sticky substance that coats the eggshell (Devi and Devi, 2015; Li and Arbogast, 1991). The larvae are small and brownish-white, growing to about 4-5 mm in length when fully mature. These larvae can be distinguished from

other species by their two-pointed, well-defined, segmented ends.

The pupa of *Tribolium castaneum* lacks a cocoon, is inactive, and does not feed, typical of all holometabolous insects. It gradually changes from yellowish-tan to brown (Beeman *et al.*, 2012). The average body length for male pupae is around 3 mm with a width of 1 mm, while female pupae typically measure 4 mm in length and 1.15 mm in width (Devi and Devi, 2015).

Adult beetles range from 2.3 to 4 mm in length (Hill, 2002) and are red-brown in color (Baldwin and Fasulo, 2014). The antennae consist of eleven segments, with the last three segments slightly enlarged compared to the four segments in *T. confusum* (Baldwin and Fasulo, 2014). Males have a setaceous lesion on the ventral surface of the front femur (Haines, 1991). The compound eyes are partially horizontally divided by a backward projection of the head (Anonymous, 1986).

According to CABI (2007), the red flour beetle (*Tribolium castaneum*) can be easily confused with the confused flour beetle (*Tribolium confusum*). Distinguishing between the larvae of these two species is particularly challenging. While the adults of both species are similar in size and color, there are several key differences that set them apart.

BIOLOGY AND LIFE CYCLE

Under optimal conditions, the life cycle of *T. castaneum* is typically very short, taking about 20 days to complete (Haines, 1991). The cycle begins when mature female adults lay eggs on or between stored products. These females have a long lifespan, surviving up to three years, and can lay between 400-500 sticky, white eggs, which hatch within 1-2 weeks (Abdullahi *et al.*, 2019).

The larvae are active feeders and tend to hide in cracks and crevices of stored products, using these areas for shelter when disturbed. The larvae can be identified by their distinctive two-pointed, segmented ends. Under favorable conditions, the beetle can produce 4-5 generations per year (Rees, 1996; Abdullahi *et al.*, 2019).

The duration of the larval stage is primarily influenced by the availability, type, and quality of food, as well as the environmental conditions, particularly temperature and relative humidity (Haines, 1991). Different studies report varying lengths for the larval period, with averages ranging from 12.9 days (Haines, 1991) to 12-13 days (Howe, 1956), and even 70-80 days (Devi and Devi, 2015).

Each larval instar also has distinct characteristics that help differentiate it from the others (Devi and Devi, 2015).

The pupae of *Tribolium castaneum* do not form a cocoon and remain inactive, not feeding, similar to other holometabolous insects. The duration of the pupal stage differs between sexes, with males undergoing pupation for 6-7 days, while females take 7-9 days (Devi and Devi, 2015). Abdullahi *et al.* (2019) reported an average pupal duration of 4 days, which aligns closely with the 4.5 days found by Haines (1991). Arpitha (2021) observed an 8-day pupal period. Thus, the average pupal period is generally considered to be around 6-7 days.

HOST RANGE AND DAMAGE

Tribolium castaneum is one of the most widespread pests of stored products (Fedina and Lewis, 2007; Bachrouh *et al.*, 2010;), known for its polyphagous feeding habits (Bachrouh *et al.*, 2010). It attacks a wide range of stored products and their by-products (Obeng-Ofori and Reichmuth, 1999). This pest is commonly found on wheat and wheat flour, and it often causes significant damage to processed cereal-based foods such as biscuits, nuts, beans, pasta, cornflakes, and even dried fruits (Hussain *et al.*, 1996; Kheradpir, 2014; Devi and Devi, 2015). Wheat flour is considered its preferred food source (Lu *et al.*, 2010; Kheradpir, 2014). Additionally, it has been reported to infest groundnuts/peanuts (Rao *et al.*, 2010), as well as other cereals like maize, rice, and sorghum, along with their flours (Ajayi and Rahman, 2006). Other studies have documented *T. castaneum* in a variety of products including beans, dried flours, pasta, spices, cocoa beans, chocolate, dried pet food, dried museum specimens, yam, cassava (Ajayi and Rahman, 2006; Tettey *et al.*, 2014), pearl millet (Lale and Yusuf, 2000; Ahmed *et al.*, 2010), wheat grain (White and Lambkin, 1988), soybean meal (Cox and Simms, 1978), and other stored grains and grain products (Nadeem *et al.*, 2012) across the globe.

Damage caused by *T. castaneum* typically results in both a reduction in quantity and a decline in quality (Bachrouh *et al.*, 2010). Infestation is often visible through the presence of adults on the grain surface, and extensive damage is seen in grains that are already broken or holed, or those affected by other pests. Both larvae and adults contribute to the damage. Infested products usually contain frass, carcasses, and exuviae, and the grain often turns grey with a strong, unpleasant odor due to the release

of benzoquinones, a defensive chemical from their prothoracic and abdominal glands, making the product unfit for human consumption (Lale, 2002; Devi and Devi, 2015). Both larvae and adults feed on the surface of grains and processed foods, causing severe damage, though larvae primarily affect the germ of wheat grains (White and Lambkin, 1988). These forms of damage lead to significant losses, both in terms of reduced value and the additional costs for pest control measures, such as pesticides and expensive, pest-proof packaging (Obeng-Ofori and Reichmuth, 1999; Lale and Yusuf, 2000). Therefore, there is a pressing need to develop more affordable and safer control methods for this pest that can be applied across its entire host range, which would greatly improve food security, particularly for subsistence families with limited resources who cannot afford the high costs of insecticides and other protective measures.

BOTANICAL INSECTICIDES

Since the beginning of the 21st century, researchers have increasingly turned to plants as a source of safer, more affordable, and locally accessible botanical substances for managing the red flour beetle. Botanical pesticides are natural plant extracts or products used against insects, thereby suppressing their biology and development, which may lead to their death (Negbenebor and Nura, 2024). Recent studies have highlighted the effectiveness of various plant-derived materials in controlling this pest (Padin *et al.*, 2013; Sagheer *et al.*, 2014; Bilal *et al.*, 2015; Nattuduraj *et al.*, 2015; Joel, 2015; Saeed *et al.*, 2016). Using plant materials as traditional protectants for stored products is a longstanding practice that has been used worldwide (Talukder, 2009). Typically, this protection involves mixing grains with plant-based protectants (Tapondjou *et al.*, 2002).

Botanicals are chemical compounds derived from plants that serve as insect repellents, feeding and oviposition deterrents, and disrupt the biochemistry, physiology, and behavior of insect pests. A variety of spice crops, including chili, garlic, turmeric, and ginger, as well as plants like neem, bakaino, century plant, undi, China berry, and lac tree, have been effectively used to control insect pests (Shukla *et al.*, 2007). Srinivasan (2008) notes that many plant-based substances have been thoroughly tested and found to be effective in preventing infestations by various stored-grain insect pests.

Various plant-derived substances have been reported to exhibit harmful bioactivity against all life stages of *T. castaneum* and have been used with varying success to control this pest on different stored products. For example, Ahmed *et al.* (2010) found that *Annona squamosa* L. powder provided the best protection for stored millet against *T. castaneum* infestation. Additionally, powders from neem (*Azadirachta indica* Juss.) seeds, turmeric (*Curcuma longa* L.) rhizomes, and sweet flag (*Acorus calamus* L.) have shown promising potential for managing *T. castaneum* (Iqbal *et al.*, 2015).

A laboratory study was conducted to evaluate the toxic effects of acetone and water extracts from *Eucalyptus globulus*, *Vitex negundo*, *Datura fastuosa*, and *Aphanamixis polystachya* against the red flour beetle, *Tribolium castaneum*. The results indicated that all four plants were toxic to the insect (Begum and Sarker, 2010). Garlic (*Allium sativum*) has been found to repel *T. castaneum*, with its oil being particularly effective in killing both *T. castaneum* and *Sitophilus zeamais*, and reduce fungal contamination in wheat storage (Ho, 1996; Batta, 2014).

In Southeast Asia, eucalyptus is a locally available plant with a wide range of species known for their medicinal properties. This plant has demonstrated repellent and inhibitory effects against the red flour beetle (*Tribolium castaneum*) (Saeed *et al.*, 2016; Haq *et al.*, 2005; Mishra *et al.*, 2012; Fathi and Shakarami, 2014). Additionally, citrus peel, seeds, seed extracts, and decoctions have been found to contain acidic properties that repel adult red flour beetles when used in higher concentrations (Abdullahi *et al.*, 2011; Iram *et al.*, 2013; Bilal *et al.*, 2015).

An experiment was conducted to assess the effects of plant extracts and insecticides on the mortality of adult *Tribolium castaneum*. Among the botanical treatments, neem leaf powder caused the highest mortality, followed by eucalyptus leaf powder (Krishna and Yadav, 2023). The insecticidal properties of neem against various insect pests have also been studied by Sharma (1999) and Khattak *et al.* (1996). Sahayaraj and Paulraj (2000) found that neem leaf extract was the most effective repellent against *T. castaneum* on groundnut seeds. Additionally, neem (*Azadirachta indica* Juss.) seeds, turmeric (*Curcuma longa* L.) rhizomes, and sweet flag (*Acorus calamus* L.) powders have all shown considerable potential in managing *T.*

castaneum (Iqbal *et al.*, 2015). Peppermint (*Mentha piperita*), Cinnamon (*Cinnamomum verum*), and Citronella (*Cymbopogon nardus*) can be used to repel insects like ants, moths, and weevils in wheat storage, while also protecting against mold and fungal growth there (Jalali and Nikbakht, 2011; Sahu and Sahu, 2014; Liew and Yong, 2017).

Other plant products that have shown strong bioactivity against *T. castaneum* include camphor, *Peganum harmala* L., citrus essential oils, neem (*Azadirachta indica*) seed kernels, and fruit powder extracts of *Citrullus colocynthis* L. (Xie *et al.*, 1995; Obeng-Ofori *et al.*, 1998; Jbilou *et al.*, 2006; Nadeem *et al.*, 2012; Bilal *et al.*, 2015). Neem oil, turmeric powder, and mustard oil, as well as *C. longa* leaf oil, have also been shown to have insecticidal effects (Chander *et al.*, 1992; Khattak *et al.*, 2001; Tripathi *et al.*, 2002).

Other plant oils such as those from coconut, sunflower, sesame, and mustard have demonstrated similar properties (Obeng-Ofori and Reichmut, 1999). Additionally, garlic oil (*Allium sativum* L.), essential oils from *Evodia rutaecarpa*, *Lippia rugosa* L. (Lamiaceae), *Hyptis spicigera* Lam. (Verbenaceae), and essential oils from the rhizomes of *Zingiber zerumbet*, *Alpinia conchigera*, and *Curcuma zedoaria*, along with their major components like camphor, camphene, 1,8-cineole, α -humulene, isoborneol, α -pinene, β -pinene, and terpinen-4-ol, as well as *Nicotiana tabacum* and *Salsola banyosma*, have all been reported to exhibit insecticidal effects on *T. castaneum* (Ho *et al.*, 1996; Liu and Ho, 1999; Kouninki *et al.*, 2007; Suthisut *et al.*, 2011; Sagheer *et al.*, 2013).

MODE OF ACTION OF BOTANICAL INSECTICIDES

The mode of action of a botanical insecticide refers to the specific biochemical processes through which it affects insect pests, typically by interfering with particular enzymes, proteins, or biological systems (Bloomquist *et al.*, 2008). Essentially, it describes how the insecticide causes physiological disruptions at its target site. The action of a botanical insecticide depends on its ability to act as both a contact and systemic poison. Some botanicals function as neurotoxins, inhibiting the acetylcholinesterase enzyme, which in turn disrupts the action of the neuromodulator octopamine (Priestley *et al.*, 2003; Houghton *et al.*, 2006). Botanicals can also serve as repellents, disrupt mating and sexual communication, act as sterilants, retard growth,

deter oviposition, serve as antifeedants, or act as lethal toxins, ultimately causing insect mortality (Odeyemi *et al.*, 2008; Negbenebor and Nura, 2024). These insecticides can be applied as powders or plant extracts to control various insect species in grain storage (Makanjuola, 1989). Different plant parts are utilized as protectants for stored grains (Lale, 1992). The toxicity of botanical extracts varies based on factors such as the chemical composition of the extract, its source (e.g., stem, root, or oil), the season and ecological conditions, extraction methods, solvents used, and extraction time (Lee *et al.*, 2001).

Exposure of insect larvae to botanical pesticides can prevent moulting, causing many insects to die before they reach the pupal stage, which effectively stops their development into adults (Charleston *et al.*, 2005). In summary, the mode of action of a botanical pesticide can include one or more of the following mechanisms:

1. Blocking respiratory passages
2. Acting through contact toxins or impairing digestion
3. Preventing reproduction by reducing hemocyte count, damaging organelles, and destroying plasma membranes
4. Deterring feeding by blocking receptors for feeding stimulants or stimulating deterrent receptor cells, or both
5. Repelling insects or altering their behavior
6. Inhibiting growth by blocking a morphogenetic peptide hormone, affecting ecdysteroid and juvenile hormone levels.

CONCLUSION

In conclusion, the global population growth and increasing demand for food have exacerbated the challenge of food security, particularly due to the significant losses caused by stored product pests such as the red flour beetle (*Tribolium castaneum*). These pests, responsible for considerable damage to stored grains and food products, not only lead to the loss of food quality and quantity but also create economic burdens, especially in developing countries. While chemical insecticides have been the traditional means of pest control, their associated health risks and environmental concerns underscore the urgent need for safer, more sustainable alternatives.

Botanical insecticides present a promising solution, offering eco-friendly, cost-effective, and locally

available options for managing red flour beetle infestations. Various plant-derived substances, such as those from neem, turmeric, garlic, and eucalyptus, have demonstrated notable efficacy in controlling *T. castaneum* at various life stages. These botanicals provide a valuable tool for integrated pest management, particularly in regions where access to chemical pesticides is limited or where their use is not viable.

Given the promising results from recent studies, the potential of medicinal plants and their derivatives for stored grain protection should be further explored and developed. By embracing these natural alternatives, we can reduce reliance on harmful chemicals, mitigate post-harvest losses, and ultimately enhance food security in an environmentally sustainable manner. Future research should focus on optimizing the application of these botanicals, understanding their mechanisms of action, and developing strategies to integrate them effectively into pest management systems, thus improving both the quality and availability of food across the globe. With the support of international partners, local research initiatives, and farmer education programs, botanicals could play an important role in promoting sustainable agriculture in Afghanistan.

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