

The efficacy, mode of action, and protective ability of neem (*Azadirachta indica* A. Juss.) in controlling grain coleopteran pests: A scoping review

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ABSTRACT

Post-harvest losses in stored grains caused by Coleopteran pests pose a significant threat to global food security. While synthetic insecticides are effective, their extensive use has accelerated resistance development, creating an urgent need for sustainable bio-rational alternatives. Although neem (*Azadirachta indica*) is a widely recognized botanical insecticide, a comprehensive synthesis focusing on its specific modes of action and recent formulation advancements is lacking. This scoping review addresses this gap by systematically evaluating neem's efficacy and protective ability against stored-grain pests. Following Synthesis Without Meta-Analysis (SWiM) guidelines, we searched Google Scholar for literature published between 2000 and 2025. From 981 initial records, a multi-stage screening process selected 66 peer-reviewed studies for synthesis. The review highlights neem's multifaceted activity across six major pest families, operating through direct toxicity, repellency, oviposition deterrence, and progeny inhibition. Crucially, the analysis reveals that efficacy is highly dependent on formulation; while crude extracts vary in stability, advanced nano-encapsulated formulations and oil-based extracts demonstrate superior persistence and bioactivity while preserving grain quality. The findings confirm neem as a potent, sustainable grain protectant, particularly when integrated into broader pest management strategies, though standardized field trials are essential to bridge the gap between laboratory success and commercial scalability.

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INTRODUCTION

Proper storage of agricultural products, particularly grains, is vital in ensuring food security by reducing post-harvest losses. These losses can reach over 50% due to poor storage practices, while good storage methods can keep losses very low (1–2%) (Kumar & Kalita, 2017; Sandeep et al., 2024). These losses are primarily caused by insect pests (Adel et al., 2022). Among these pests, beetles (Coleoptera) cause the most significant damage. Key species include weevils (*Sitophilus* spp.) (Alam et al., 2020; Kathirvelu & Raja, 2015; Mehta & Kumar, 2020; Wahedi, 2012), the red flour beetle (*Tribolium castaneum*) (Adarkwah et al., 2010), the lesser grain borer (*Rhyzopertha dominica*) (Devi & Devi, 2014; M. N. Khan et al., 2020; Mon et al., 2015), and legume bruchids (*Callosobruchus* spp.) (Akuba et al., 2023; Hasan et al., 2021; Nizamani et al., 2020; Regmi et al., 2012). These insects

do not just eat the grain. They also lower its nutritional value and increase moisture levels. This leads to mold growth and makes the food unsafe to eat (Stathas et al., 2023).

For a long time, the primary strategy for controlling these pests was using chemical insecticides. They offer rapid and reliable suppression of a broad spectrum of pests, ensuring long-term protection of stored products (Hamel et al., 2020; Stejskal et al., 2021). However, continuous and improper use of these chemicals has led to resistance in several major pest species, threatening their long-term effectiveness (Baliota et al., 2022). For instance, phosphine is widely used as a fumigant. However, resistance to phosphine has been reported in several stored-grain pests worldwide (Ali et al., 2022; Aulicky et al., 2022; Wakil et al., 2021). Resistance is not limited to phosphine alone. Several stored-grain pests have shown varying tolerance to other insecticide, such as deltamethrin, cypermethrin, and pirimiphos-methyl (Baliota et al., 2022).

Botanical insecticides derived from plants have emerged as a leading alternative due to their biodegradability and lower risk of harmful residues (Bibi et al., 2016). Among these, products derived from the neem (*Azadirachta indica*) contain bioactive compounds that exhibit multiple modes of action. These including repellency, antifeedant effects, growth disruption, and mortality against a wide range of stored-grain pests (Ahmad et al., 2023; Ahmed et al., 2022; Alam et al., 2020; Magsi et al., 2022; Martins et al., 2024; Paranagama et al., 2003; Tariq et al., 2022; Yahaya et al., 2013). The plant is native to the India-Pakistan subcontinent, particularly in the arid and semi-arid regions of South and Southeast Asia (Islas et al., 2020).

Although many studies have shown that neem is effective against different pests, the available evidence is still scattered. The results are published in various journals using diverse methods. Consequently, there is currently no clear summary that focuses specifically on how well neem works against Coleopteran pests, the most common insects found in stored grains. A full review is needed to synthesize these findings and assess neem's effectiveness, mode of action, and potential as a grain protectant. This scoping review aims to evaluate the effectiveness of neem (*A. indica*) in controlling Coleopteran pests in stored grains by collecting and summarizing data from peer-reviewed studies.

METHOD

Study Design, Eligibility, and Search Strategy

This scoping review follows the reporting guidelines for Synthesis Without Meta-Analysis (SWiM) (Campbell et al., 2020). We also adapted the review steps from the PRISMA guidelines (Stewart et al., 2015). We primarily used Google Scholar for the search. This database was chosen for its broad accessibility and lack of subscription barriers. We performed the searches using the Publish or Perish software on Microsoft Windows (<https://harzing.com/>). We retrieved a maximum of 1,000 results per query. We developed a search string based on the study objectives using the following keywords: “((neem OR *Azadirachta indica*) AND (insect OR Coleoptera) AND (store* pest OR grain pest OR houseware pest OR warehouse pest OR cereal pest OR seed pest))”.

Studies were selected based on the following inclusion criteria: (1) peer-reviewed, full-text articles published in scientific journals between 2000 and 2025; (2) research involving any form of neem-derived products (e.g., powder, crude extracts, essential oils); (3) studies specifically addressing coleopteran pests of stored grains; (4) publications written in English. The exclusion criteria were as

follows: (1) grey literature (e.g., theses, reports, conference proceedings); (2) articles without full-text availability; (3) review articles, books; (4) non-English publications.

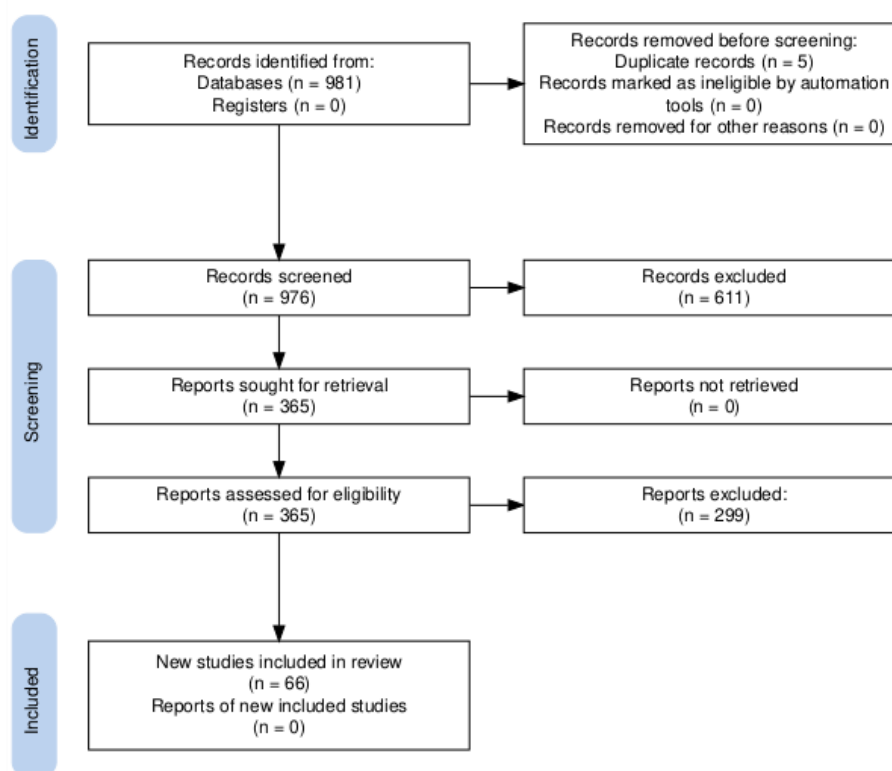


Figure 1. The screening flowchart illustrates the screening process used to assess the eligibility of studies. The review process consisted of five sequential stages: identification, title and abstract screening, full-text screening, data extraction, and analysis.

Selection of Sources and Reliability

We downloaded all collected studies in Research Information Systems (RIS) format and imported them into the online systematic review screening platform, Catchii (<https://catchii.org/>). We conducted screening based on the predefined eligibility criteria. This involved evaluating titles, abstracts, and full texts.

The initial screening focused on titles and abstracts. We identified a total of 981 records from Google Scholar. After removing five duplicate entries, 976 unique records remained. The screening process used a structured design where four independent reviewers assessed the publications. The screening team consisted of senior undergraduate students from the Department of Biology at Andalas University. Before screening, all reviewers received specific training to familiarize them with the platform and the selection criteria. To ensure consistency and reliability, we held weekly meetings. Any disagreements regarding the inclusion of an article were resolved through discussion and consensus among the reviewers. If a consensus could not be reached, a senior researcher made the final decision.

Data Charting and Synthesis

Following the title and abstract screening, we selected 365 studies for full-text review. Out of these, 66 articles met all inclusion criteria and were suitable for data extraction (Fig. 1). We extracted data using a standardized form. Key variables included the Coleopteran species studied, types of neem

products used, experimental methods, types of grains, and the mode of action. We also noted any effects on grain quality. We synthesized the findings narratively. We grouped the studies based on the type of neem formulation and the specific pest family to identify patterns in efficacy and protective ability.

Methodological Limitations

This review has some limitations. First, we relied primarily on Google Scholar. While it is comprehensive, it may contain different coverage biases compared to subscription-based databases like Scopus or Web of Science. Second, we restricted our search to articles published in English. This means we may have missed relevant studies published in other languages. Finally, we did not register the study protocol in a public database, as this review focuses on agricultural pests rather than health outcomes.

RESULTS AND DISCUSSION

Coleopteran Species Associated with Stored Grain Infestation

The scoping review identified economically significant pest species from six distinct families: Bostrichidae, Chrysomelidae, Dermestidae, Dryophthoridae, Silvanidae, and Tenebrionidae. These species are categorized based on their feeding habits as either primary or secondary pests. A detailed summary of the species and their target grains is presented in Table 1.

The majority of the reviewed studies focused on primary pests capable of infesting whole, undamaged grains. The family Dryophthoridae, particularly the genus *Sitophilus*, appeared most frequently. *Sitophilus zeamais* (maize weevil) and *Sitophilus oryzae* (rice weevil) are primary targets in research because their larvae develop inside the grain kernel. This internal development poses a challenge for control measures (Alam et al., 2020; Adel et al., 2022). Similarly, the Bostrichidae family, represented by *Rhyzopertha dominica* and *Prostephanus truncatus*, is crucial for stored cereals such as wheat and rice. These pests are significant drivers of quantitative loss in tropical regions (Khan et al., 2020). Notably, several primary pests identified in this review, including *S. zeamais*, *R. dominica*, and *Callosobruchus* spp., are classified as field-to-store pests, meaning infestation often initiates in the field prior to harvest (Ahmad et al., 2015; Mon et al., 2015). This behavior highlights the importance of residual protection during the transition from field to storage.

For legume storage, the Chrysomelidae family is the dominant concern. Species such as *Callosobruchus chinensis* and *Callosobruchus maculatus* have been extensively studied due to their devastating impact on pulses, including cowpea and mung bean (Akuba et al., 2023). Additionally, the Dermestidae family includes *Trogoderma granarium* (khapra beetle). This species is highlighted in several studies not only for its damage potential but also for its status as a regulated quarantine pest that requires strict control measures (Ali et al., 2022).

Secondary pests, which typically feed on broken grain or processed products, were also well-represented. The Tenebrionidae family, specifically *Tribolium castaneum* (the red flour beetle), is the most extensively studied secondary pest. Research on *T. castaneum* emphasizes its impact on grain quality, as it produces quinone secretions that cause foul odors and deter consumption (Ahmad et al., 2023). Finally, the Silvanidae family is represented by *Oryzaephilus surinamensis*. This species

is often studied in the context of mixed infestations alongside primary pests (Adel et al., 2022).

Table 1. Coleopteran species associated with stored grain infestation

Family	Species	Common Name	Pest Type
Bostrichidae	<i>Prostephanus truncatus</i>	Larger grain borer	-
	<i>Rhyzopertha dominica</i>	Lesser Grain Borer	Primary pest; Field-to-store pest
Chrysomelidae	<i>Callosobruchus chinensis</i>	Pulse Beetle	Field-to-store pest
	<i>Callosobruchus maculatus</i>	Cowpea Bruchid	Primary pest; Field-to-store pest
Dermestidae	<i>Trogoderma granarium</i>	Khapra Beetle	Primary pest; Quarantine pest
	<i>Sitophilus granarius</i>	Grain Weevil	Primary pest
Dryophthoridae	<i>Sitophilus oryzae</i> A.	Rice Weevil	Primary pest
	<i>Sitophilus zeamais</i>	Maize Weevil	Primary pest; Field-to-store pest
Silvanidae	<i>Oryzaephilus surinamensis</i>	Saw-toothed Grain Beetle	Secondary pest
Tenebrionidae	<i>Tribolium castaneum</i>	Red Flour Beetle	Secondary pest

Mode of Action of Neem in Suppressing Coleopteran Pests Infesting Stored Grains

Ovicidal, larvicidal, and adulticidal activity of neem-based formulations against coleopteran grain pests

The effectiveness of neem-based formulations consistently follows a dose-dependent pattern, where higher concentrations and extended exposure periods result in greater mortality rates. This fundamental relationship has been documented across various formulations of neem, including whole plant extracts and isolated compounds like Azadirachtin (Ahmad et al., 2015; Alam et al., 2020; Gereziher et al., 2016; Ukatu et al., 2021; Umair et al., 2020). Throughout these studies, neem formulations have shown significant insecticidal activity, achieving mortality rates of 60% to 100% depending on the formulation type and exposure duration.

Neem seed and leaf powders exhibited high efficacy, particularly over extended exposure periods. For *Callosobruchus chinensis*, neem seed powder applied at 20 g/kg (2.0%) induced 80% mortality after 24 hours, which increased to 93.67% after four days (Tabu et al., 2012). Similarly, in *Sitophilus zeamais*, seed powder at 50–100 g/kg achieved 100% mortality by 7 days after treatment (DAT), performing statistically comparably to synthetic insecticides like Ethiolathion (Gereziher et al., 2016). Leaf powders also demonstrated potency, with a 5% w/w concentration causing 100% mortality in *S. zeamais* after 14 days (Shiberu & Negeri, 2017). However, solid formulations often exhibit a slow-action trait. For instance, while efficacious, neem powder required up to 7 days to reach mortality levels that synthetic Malathion achieved in 3 days (Kinati et al., 2021).

Liquid formulations generally provided faster knockdown effects. Neem oil at a concentration of 1.5 ml/kg achieved 100% mortality of *S. zeamais* within just 24 hours, outperforming seed powders in speed of action (Wahedi, 2012). For *Tribolium castaneum*, a concentration of 3.0% v/v resulted in 90% mortality after 72 hours (Adarkwah et al., 2010). However, efficacy is highly sensitive to concentration thresholds. Studies indicate that concentrations below 0.5% v/v often fail to achieve significant mortality ranges (Adarkwah et al., 2010; Sintim & Ansah, 2023).

This review highlights a critical distinction between contact and fumigant toxicity. Neem functions predominantly through contact action. In *Callosobruchus maculatus*, contact toxicity assays showed 100% mortality at 3.80 g/L, whereas fumigant activity was negligible or significantly lower (Paranagama et al., 2003). Specifically, neem oil showed 0.0% mortality in fumigant assays against pulse beetles over 72 hours, unlike orange or eucalyptus oils which caused 100% mortality (Swamy & Wesley, 2022). Furthermore, fumigant toxicity of azadirachtin degrades rapidly, dropping from 32% mortality at 6 hours to 0% after 30 hours (Guettal et al., 2021). This confirms that neem requires direct contact or residual surface presence for effective control.

Neem formulations frequently performed on par with synthetic standards. At optimal doses (e.g., 4–5 g/100g), neem leaf powders showed mortality rates statistically similar to Malathion (Alam et al., 2020; Tabu et al., 2012). However, when compared to other botanicals, results vary. While neem outperformed oils like Mahogany and Karanja (Hasan et al., 2021), it was less effective than tobacco leaf powder and black pepper seed powder in some trials, likely due to the faster neurotoxic action of nicotine and piperine (Mon et al., 2015; Khanal et al., 2021). Additionally, one study noted reduced efficacy of neem against *Trogoderma granarium* compared to *Solanum nigrum*, suggesting potential resistance development in populations frequently exposed to neem products (Ali et al., 2022).

Repellent effect of neem-based formulation against coleopteran grain pests

The efficacy of neem formulations varies distinctly by type. Liquid extracts and oils generally demonstrate high immediate repellency, with 5% concentrations often achieving complete deterrence against *Tribolium castaneum* (Ahmad et al., 2023) and significant oviposition deterrence (65.44%) in *Callosobruchus maculatus* (Chudasama et al., 2015). However, this efficacy is nuanced; high mortality rates in liquid treatments can sometimes obscure repellent behavior, leading to false neutral classifications in bioassays (Magsi et al., 2022). In contrast, powdered formulations operate through a dual mechanism of mechanical irritation and chemical deterrence without necessarily causing mortality (Nova et al., 2020). Notably, neem smoke exhibits a unique pattern of progressive efficacy, where repellency significantly increases with prolonged exposure, unlike other botanicals that degrade over time (Tariq et al., 2022).

Stability remains a critical differentiator. While powdered neem and oils have demonstrated the capacity to prevent egg-laying processes for up to eight months (Bashir et al., 2020), surface applications of powders are susceptible to volatilization, resulting in reduced repellency ratings after 96 hours (Parugrug & Roxas, 2008). Similarly, liquid extracts exhibit inconsistent persistence, with repellency potentially decreasing from 100% to 63% over time (Sintim & Ansah, 2023). A critical environmental and biological consideration is the attractant effect observed at sublethal concentrations; insufficient dosages may inadvertently attract pests, such as *Sitophilus zeamais*, rather than repel them (Martins et al., 2024), underscoring the need for precise dosing to avoid counterproductive outcomes.

From a practical standpoint, dry dust formulations offer distinct advantages for grain storage in humid regions. Unlike liquid extracts that may facilitate microbial growth and degrade grain food value, neem dust maintains grain dryness and quality. Although neem dust may sometimes be outperformed by other botanicals, such as *Jarul* in raw repellency numbers (Nova et al., 2020) or

Ocimum gratissimum (Adeleke et al., 2022), its non-lethal, safety-focused profile makes it a viable grain protectant for smallholder farmers prioritizing grain viability over pest eradication.

Tabel 2. Comparative analysis of neem-based formulations for the repellency of coleopteran grain pests

Formulation Type	Key Advantages	Limitations	References
Powders/Dusts	1. Combines mechanical irritation with chemical deterrence, no lethal impact found (purely repellent). 2. Avoids moisture introduction, preventing microbial growth in grains. Longevity: Can prevent egg-laying processes for up to eight months.	1. Repellency ratings may decrease over time due to volatilization. 2. Sometimes less effective than other botanicals like Jarul or <i>Ocimum gratissimum</i>.	Bashir et al. (2020); Nova et al. (2020); Parugrug & Roxas (2008); Adeleke et al. (2022)
Oils & Liquid Extracts	1. Can achieve up to 100% repellency at high concentrations (e.g., 5% leaf extract). 2. Significant reduction in egg laying and adult emergence. 3. Clear correlation between concentration and repellency.	1. Repellence can drop significantly over time. 2. High mortality rates can mask repellent behaviour 3. Sublethal doses may trigger an attractive rather than repellent response.	Ahmad et al. (2023); Sintim & Ansah (2023); Magsi et al. (2022); Martins et al. (2024); Chudasama et al. (2015)
Fumigants/Smoke	1. Unique characteristic where repellency increases with exposure time. 2. Consistently demonstrated better repellency than other indigenous plant smokes.	1. Requires controlled environments to maintain smoke concentration. 2. Maximum efficacy is not immediate but achieved after prolonged exposure.	Tariq et al. (2022); Panaragama et al. (2003)

Oviposition inhibition by neem-based formulation on coleopteran grain pests

Accumulated evidence establishes neem as a potent oviposition deterrent against major storage pests, particularly *Callosobruchus* species. This deterrent activity is multifaceted, interfering with reproductive behaviors and physiological processes to create a comprehensive barrier to pest proliferation.

Research consistently demonstrates that neem’s effectiveness follows a clear dose-dependent pattern. For instance, Tabu et al. (2012) reported that neem seed powder significantly reduced *Callosobruchus chinensis* egg counts to between 5 and 30 eggs per 100 seeds, a marked reduction compared to 57 eggs in untreated checks. Visual data further confirmed that higher concentrations directly correlated with fewer eggs. Similarly, Khan et al. (2016) found that neem at 1000 ppm effectively suppressed oviposition, with a mean of 77.50 eggs, whereas lower concentrations (250–500 ppm) allowed significantly higher egg laying (>92 eggs). However, the efficacy drops sharply at sublethal doses; Swamy & Wesley (2022) observed that while a 1 ml dose of neem oil reduced egg counts to 4.33, a 0.5 ml dose failed to provide significant protection (12.67 eggs), performing similarly to the untreated control.

While neem consistently ranks as a top-tier deterrent, its relative performance varies by context. In comparative studies, Hasan et al. (2021) demonstrated that neem oil outperformed Mahogany and Karanja oils, yielding the lowest number of eggs (12.89 per female) at the highest tested dose. Conversely, other investigations indicate that specific essential oils may offer superior absolute inhibition. Swamy & Wesley (2022) noted that while neem oil significantly reduced oviposition, oils from clove, sweet flag, and eucalyptus achieved zero egg laying under identical

conditions. Similarly, [Vanmathi et al. \(2010\)](#) observed that while *Azadirachta indica* showed significant deterrence against *Callosobruchus maculatus*, it was surpassed by *Cynodon dactylon* and *Ocimum tenuiflorum*. This emphasizes that while neem is highly effective, its optimal use may depend on specific pest targets and acceptable tolerance thresholds.

Beyond behavioral deterrence, neem compounds compromise the viability of the next generation. [Hasan et al. \(2021\)](#) highlighted that, in addition to reducing egg numbers, neem oil treatment resulted in the lowest hatchability percentage (12.89%) among all tested botanical oils. Furthermore, volatile delivery systems show exceptional promise for total control. [Paranagama et al. \(2003\)](#) established that neem leaf volatiles completely inhibited both egg laying and F1 generation emergence in *C. maculatus* at concentrations exceeding 3.80 g/l, suggesting that volatile compounds can interact with pest sensory systems to disrupt reproduction more comprehensively than contact alone.

Environmental factors also modulate the efficacy of deterrent strategies. [Akuba et al. \(2023\)](#) found that combining botanical treatments with increased solar radiation duration further reduced egg laying in *C. maculatus*. This synergistic effect likely stems from the insects seeking shelter from heat, thereby reducing oviposition opportunities. This indicates that successful implementation requires holistic management protocols that consider storage environmental conditions alongside formulation potency.

Inhibition of progeny emergence by neem-based formulation on coleopteran grain pests

The capacity of neem to suppress progeny emergence constitutes a critical component of integrated pest management (IPM), extending beyond simple oviposition deterrence to encompass direct toxicity against immature developmental stages. This multi-stage toxicity creates a comprehensive barrier to population growth, involving mechanisms such as direct contact toxicity and respiratory interference ([Hossain et al., 2014](#)). Mechanistically, this suppression is mediated by bioactive compounds, such as azadirachtin, which function as antifeedants, ecdysis inhibitors, and growth regulators ([Ahmad et al., 2015](#)). By targeting embryonic development and larval molting, neem prevents successful maturation rather than merely deterring egg-laying behavior ([Vanmathi et al., 2010](#)).

The magnitude of suppression is heavily dependent on the developmental stage at the time of exposure. Studies indicate that eggs and early larval stages are significantly more susceptible than mature forms. [Adarkwah et al. \(2010\)](#) demonstrated that while neem oil significantly reduced *Tribolium castaneum* emergence when applied at egg or larval stages, pupal stages were only affected at higher concentrations (2.0–3.0%), likely due to the protective properties of the pupal cuticle. Similarly, [Hossain et al. \(2014\)](#) found that neem oil at 8.0 ml/kg achieved complete inhibition of adult emergence from egg-bearing seeds but only partial inhibition (84.14%) from larva-bearing seeds, reinforcing the need for early intervention.

Neem exhibits a clear dose-response relationship, where higher concentrations result in progressively greater reductions in offspring emergence. Optimal application rates have been documented to achieve the ultimate goal of botanical control: complete elimination of progeny. For instance, [Wahedi et al. \(2012\)](#) reported zero F1 emergence of *Sitophilus zeamais* when using neem seed oil at concentrations of 1.0 mL and 1.5 mL. Likewise, [Adeleke et al. \(2022\)](#) recorded 100% insect

survival reduction (zero emergence) in *Callosobruchus maculatus* treated with *A. indica*. However, efficacy varies by solvent; [Khan et al. \(2016\)](#) noted that while *A. indica* in ethanol allowed significant egg hatching (74.88%); other solvent extracts provided more potent inhibition, highlighting the role of extraction methods.

Formulation technology plays a pivotal role in bioactivity. While traditional powders sometimes fail to penetrate substrates, as seen in [Parugrug & Roxas \(2008\)](#), where neem powder failed to inhibit *Sitophilus zeamais* development inside corn grains, advanced delivery systems show superior promise. [Adel et al. \(2022\)](#) demonstrated that solid lipid nanoparticles (SLNs) loaded with neem oil at just 4.5% achieved 100% inhibition of *Sitophilus oryzae* and *Tribolium castaneum* emergence after 6 weeks, a result that required much higher concentrations (15–45%) when using bulk oil. This suggests that nanocarriers significantly enhance the stability and penetration of active ingredients.

Despite its potency, neem is not always the most effective botanical. [Swamy & Wesley \(2022\)](#) observed that while neem oil reduced *C. maculatus* populations, it still allowed substantial adult emergence (1774 individuals) after 120 days, performing significantly worse than clove or eucalyptus oils, which maintained zero population growth. Similarly, [Regmi et al. \(2012\)](#) found that *A. indica* allowed for high adult emergence (3,510 adults) after 75 days, comparable to Malathion, but far less effective than *Acorus calamus* or *Cinnamomum camphora*. These findings underscore that while neem is effective, it may require higher dosages or synergistic combinations to match the total suppression offered by some essential oils.

Beyond direct mortality, neem interferes with population structure by skewing sex ratios. [Nizamani et al. \(2020\)](#) found that neem treatment resulted in a male-biased population ratio (3:4), effectively limiting future reproductive potential since females drive population expansion. Furthermore, the fertility of survivors is compromised; eggs laid on neem-treated substrates showed significantly reduced hatching rates (50%) compared to controls (86.67%), contributing to long-term population suppression through trans-generational sterility ([Nizamani et al., 2020](#)).

Neem formulations disrupt detoxification enzymes and affect the behavior of coleopteran grain pests.

Neem treatment triggers a robust activation of detoxification systems in storage pests, serving as a primary defense mechanism against exposure to azadirachtin. Biomarker assays in *Sitophilus granarius* adults revealed a significant upregulation of catalase (CAT) activity at 72 hours for both LC25 and LC50 concentrations. Similarly, glutathione S-transferase (GST) activity significantly increased at 48 and 72 hours post-treatment. This enzymatic surge indicates the establishment of a metabolic defense process. However, this response compromises the non-enzymatic antioxidant system, as glutathione (GSH) levels significantly decrease at 72 hours, likely due to its intensified consumption by GSTs during the detoxification process ([Guettal et al., 2021](#)).

The activation of these defense mechanisms exacts a severe metabolic toll. Azadirachtin treatment resulted in a significant decrease in total protein content and total energy reserves across all tested periods (24, 48, and 72 hours) compared to controls. Furthermore, the Nutrition Depletion Index (NDI) was found to be concentration-dependent, with maximum depletion occurring at LC50. This metabolic disruption suggests that azadirachtin interferes with essential physiological processes

necessary for growth and survival. While effective, the relatively short residual activity of fumigation (lasting only 30 hours) presents a trade-off: it is beneficial for reducing long-term residues in stored products. However, it necessitates repeated applications for continuous protection (Guettal et al., 2021).

Neem extract induces complex, often paradoxical behavioral modifications that differ from conventional repellency. Martins et al. (2024) demonstrated that *Sitophilus zeamais* exposed to neem extract exhibited increased walking activity, characterized by a meandering path and a shortened latency period, meaning the insects approached the treated grain mass faster than the controls. This suggests an initial attractive effect. However, this attraction is deceptive; despite increased contact frequency, no feeding activity was observed, and insects did not remain in the grain mass after initial contact. This manipulation creates a behavioral trap in which insects expend energy moving toward a stimulus that offers no nutritional reward, effectively exhausting their energy reserves while discouraging sustained feeding.

Behavioral interference extends to intraspecific communication and reproductive success. Nizamani et al. (2020) reported that neem treatment significantly reduced the mating percentage of *Callosobruchus chinensis* when virgin pairs were released on neem-treated seeds; mating success decreased to 66.67%, which is significantly lower than in the controls. This reproductive failure is attributed to chemical interference that disrupts the signaling pathways and communication required for successful mating, contributing to population suppression beyond direct mortality.

Efficacy of Neem Formulations in Protecting Stored Grains from Coleopteran Pests

Neem-based treatments demonstrate a robust capacity to preserve grain integrity, with efficacy heavily dependent on concentration and formulation. Tabu et al. (2012) reported that 2.0% neem seed powder reduced seed damage to 1.33% and weight loss to 1.45% in *Callosobruchus chinensis*-infested grains, representing a significant improvement over the 17.5% damage and 6% loss in untreated checks. Similarly, Sintim & Ansah (2023) identified 2% neem extract as the most effective protectant against *Sitophilus zeamais*, reducing grain damage to 8% compared to 31% in the control group.

This protective effect is inversely proportional to dosage. Rafi et al. (2014) established that protection efficiency follows the rank order 3% > 2% > 1%, with 3% neem achieving the lowest total seed weight loss (1.08%) among all tested botanicals. However, efficacy varies by extraction type; Swamy & Wesley (2022) found that while neem oil at a 1 ml dose reduced damage to 31.67%, it was significantly less effective than essential oils like clove, which maintained 0% damage. This highlights that while neem is superior to untreated controls (reducing loss from ~47% to ~13%, as per Bibi et al., 2016), it may not always provide the same level of absolute protection as more volatile essential oils.

A critical advantage of neem is its compatibility with seed preservation for planting. Unlike some chemical treatments, neem generally exerts no phytotoxic effects. Tabu et al. (2012) observed germination rates of 99.66–100% in chickpea seeds treated with *A. indica* powder even after 90 days. Likewise, Iyough et al. (2024) and Mon et al. (2015) confirmed that neem leaf powder maintained high germination rates (>96%) in cowpea and rice, comparable to those of the untreated controls.

Interestingly, some studies suggest a beneficial effect on seedling vigor. [Kiran et al. \(2024\)](#) recorded 97.55% germination in neem-treated wheat compared to 82.01% in controls, attributing this enhancement to the prevention of pest-related degradation rather than direct stimulation. However, [Regmi et al. \(2012\)](#) noted that neem leaf dust resulted in significantly lower germination (33.33%) compared to *Acorus calamus* treated seeds in jute bags, possibly due to increased moisture retention, which promotes fungal growth ([Gereziher et al., 2016](#)). Thus, while neem is generally safe, powder formulations require careful management of moisture during storage to prevent spoilage.

When benchmarked against other botanicals, neem occupies a high-performance tier but is not always the apex protectant. [Mehta & Kumar \(2020\)](#) ranked *Azadirachta indica* as less effective in preventing weight loss than *Melia azedarach* and *Ageratum conyzoides*, but superior to *Eucalyptus citriodora*. In contrast, [Iyough et al. \(2024\)](#) found that while Diatomaceous Earth was most effective in reducing mortality, neem leaf powder was the *most effective* in preventing weight loss, likely due to its strong antifeedant properties.

The temporal dynamics of protection also vary. [Khan et al. \(2020\)](#) observed that the antixenotic (deterrent) effect of neem declined from 35.17% at 15 days to 15.43% at 60 days, indicating a need for re-application or controlled-release formulations for long-term storage. Nevertheless, for resource-limited farmers, the dual benefits of pest suppression and seed viability preservation position neem as an efficient and sustainable solution ([Hossain et al., 2014](#); [Islam et al., 2017](#)).

Future Research Directions and Challenges

While the efficacy of neem-based formulations is well-documented, translating these findings into globally standardized practices requires addressing several critical research gaps. First, the lack of standardization in testing protocols hinders comparative analysis. Future studies should adopt uniform extraction methods and bioassay procedures to facilitate meta-analyses and the development of consistent, commercial-quality standards.

Second, while nanoformulations, such as solid-lipid nanoparticles, show immense promise for enhancing stability and reducing toxicity ([Adel et al., 2022](#)), research must shift from synthesis to scalability. Future efforts should focus on optimizing the cost-effectiveness of production and conducting rigorous biosafety assessments to ensure these nanomaterials are safe for food commodities and non-target organisms.

Third, a significant disconnect remains between laboratory results and real-world application. There is an urgent need for field validation in commercial storage facilities and smallholder silos. Efficacy data derived from controlled laboratory environments often fail to account for the complex biotic and abiotic variables found in large-scale storage, such as fluctuating humidity and grain bulk density.

Fourth, addressing long-term storage stability is paramount. Given the evidence of diminishing efficacy over time ([Mehta & Kumar, 2020](#)), developing controlled-release technologies that can maintain lethal concentrations for 6–12 months is essential. Concurrent with this is the need for monitoring pest resistance. As neem activates detoxification enzymes like GST and CAT ([Guettal](#)

et al., 2021), continuous surveillance of baseline susceptibility in pest populations is necessary to prevent the onset of resistance.

Finally, the future of neem lies in its integration into IPM systems. Rather than viewing neem as a standalone solution, future research should explore synergistic combinations with biological control agents (such as parasitoids), inert dusts (such as diatomaceous earth), and physical control methods. Such holistic approaches will be key to maximizing the utility of neem as a sustainable cornerstone of stored grain protection.

CONCLUSION

This scoping review confirms that neem serves as a versatile botanical insecticide against Coleopteran storage pests, operating through a multifaceted mechanism that combines acute toxicity, behavioral manipulation, and reproductive inhibition. A critical insight distinguishing neem from other treatments is its ability to provide robust protection without compromising seed germination, establishing it as a uniquely dual-purpose solution for both food grain and planting seed preservation. While effective across diverse pest families, efficacy is strongly dose-dependent and heavily influenced by the delivery method, with advanced formulations showing superior bioactivity compared to crude extracts.

Despite these strengths, significant challenges remain regarding formulation stability and performance consistency. The review highlights that neem's repellent and toxic effects often diminish over extended storage periods due to the rapid degradation of active compounds, such as azadirachtin. Furthermore, comparative analyses reveal that while neem is safer than synthetics, its lethal potency can sometimes be outperformed by highly volatile essential oils, suggesting that current bulk formulations may be insufficient for standalone, long-term control in industrial settings without optimization.

To bridge the gap between laboratory potential and commercial viability, future research must prioritize the development of stable, controlled-release nanoformulations to extend residual activity. Efforts should shift from repetitive screening to standardized field validation and the monitoring of pest resistance mechanisms. Ultimately, neem is best utilized as a foundational component of Integrated Pest Management (IPM) systems, where its physiological and behavioral disruption effects are leveraged alongside physical and biological controls to ensure sustainable, resilient grain protection.

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