

Insecticidal Potential of *Datura stramonium* Against Stored-Product Insect Pests: A Review of Efficacy, Mechanisms and Future Prospects

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Abstract

The growing problem of stored-product insect pests, coupled with increasing resistance to synthetic insecticides and environmental concerns, has intensified the search for safer plant-based alternatives. *Datura stramonium* L. (Solanaceae), commonly known as jimsonweed or thorn apple, is a bioactive plant rich in tropane alkaloids, including atropine, hyoscyamine, and scopolamine. This review examines the taxonomic, phytochemical, and insecticidal properties of *D. stramonium*, with emphasis on its potential for managing major stored-product insect pests. Available evidence indicates that its extracts exhibit contact, fumigant, and repellent activities against economically important beetles, weevils, and bruchids. These effects may result from bioactive compounds that interfere with insect behaviour, feeding, and physiological processes. Despite its potential for integration into pest management programs, dosage standardization, formulation, persistence, non-target effects, toxicity, and commodity safety remains a challenge. Further research is needed to establish effective application rates and validate its performance under practical storage conditions.

Keywords: *Datura stramonium*; botanical insecticide; stored-product insect pests; phytochemicals; integrated pest management

1 Introduction

1.1 The global problem of stored-product insect pests

The preservation of agricultural commodities during storage is essential for ensuring food security and minimizing post-harvest losses worldwide (Hagstrum & Phillips, 2017; Hubert et al., 2018). Stored products, including grains, seeds, nuts, dried fruits, flour, and tobacco, are vulnerable to insect and mite infestations that cause quantitative and qualitative losses, threatening food security, income, and livelihoods, particularly among smallholder farmers (Hagstrum & Phillips, 2017; Adler et al., 2022). Stored-product insects can reduce commodity quantity and quality while potentially compromising plant, animal, and human health (Hubert et al., 2018; Devi et al., 2024). Losses associated with major stored-product pests and pathogens may reach 20–40% annually, with severe consequences for smallholder farmers (Hagstrum & Phillips, 2017; Chahande et al., 2024).

Major primary pests include *Callosobruchus maculatus*, *Sitophilus* spp., *Rhyzopertha dominica*, and *Trogoderma granarium*, while secondary pests such as *Tribolium castaneum* also cause substantial economic losses (Attia et al., 2020; Hendrival et al., 2019; Jehajo & Shah, 2023). *C. maculatus* damage varies with temperature and humidity, while *R. dominica* severely affects stored wheat and other

grains (Jehajo & Shah, 2023; Nayak & Daglish, 2017; Hendrival et al., 2019). Infestations may also cause

1.2 Current pest management strategies and their limitations

Conventional stored-product pest management has largely depended on synthetic insecticides and fumigants, with phosphine remaining a major tool for grain protection worldwide (Nayak et al., 2026; Attia et al., 2020). However, increasing resistance in important pests such as *Tribolium castaneum*, *Sitophilus oryzae*, and *Rhyzopertha dominica* threatens the effectiveness and sustainability of these control methods (Nayak et al., 2026; Attia et al., 2020; Khan et al., 2024). Widespread resistance has therefore become a serious challenge to effective post-harvest grain protection globally (Ramzan et al., 2018; Shamjana & Grace, 2021).

Resistance may develop through several mechanisms, including enhanced metabolic detoxification involving cytochrome P450 enzymes, target-site mutations, and reduced insecticide penetration (Chen et al., 2022; Shamjana & Grace, 2021). Specific examples include the super-kdr T929I mutation associated with deltamethrin resistance in *S. oryzae* (Singh et al., 2021), involvement of nicotinic acetylcholine receptor $\alpha 6$ in spinosad resistance in *R. dominica* (Wang et al., 2018), and molecular changes linked to s-methoprene resistance (Sakka et al., 2021). Beyond resistance, synthetic insecticides raise concerns about residues, human health, environmental contamination, and regulatory restrictions (Vryzas et al., 2020; Stejskal et al., 2021). Consequently, safer, sustainable, and effective alternatives are urgently needed (Nayak et al., 2026; Yallappa et al., 2025; Devi et al., 2024).

1.3 Botanical insecticides as promising alternatives

Botanical insecticides derived from plants offer eco-friendly alternatives to synthetic chemicals and have been used traditionally for generations (Devi et al., 2024; Chahande et al., 2024). Plant extracts, particularly essential oils, are increasingly investigated for stored-product pest management because of their multiple insecticidal actions, biodegradability, and relatively low mammalian toxicity (Liu et al., 2022; Campolo et al., 2018; Singh et al., 2021). However, volatility and chemical instability can limit their application (Yallappa et al., 2025). The genus *Datura* (Solanaceae) contains bioactive secondary metabolites, particularly tropane alkaloids, with insecticidal potential (Cinelli & Jones, 2021; Sharma et al., 2021; Lian et al., 2022). Studies have documented insecticidal effects of *Datura* species against agricultural pests (Sharma et al., 2023). This review examines the phytochemistry, insecticidal efficacy, mechanisms, comparative potential, and future prospects of *D. stramonium* against stored-product insect pests (Chahande et al., 2024).

2 Taxonomy, botany, and distribution of *Datura stramonium*

2.1 Taxonomic classification

Datura stramonium L. belongs to the family Solanaceae and is a richly bioactive plant well recognized as a resource for novel natural product discovery (Cinelli & Jones, 2021; Lian et al., 2022). The genus *Datura* L. (Solanaceae) has been systematically reviewed for its botany, traditional uses, phytochemistry, pharmacology, and toxicology, confirming its taxonomic placement within the order Solanales (Lian et al., 2022). The genus *Datura* is also recognized as a rich source of bioactive compounds, particularly tropane alkaloids, which contribute substantially to its pharmacological and pesticidal properties (Cinelli & Jones, 2021). The taxonomic position and classification of *Datura stramonium* L., together with its commonly recognized names, are presented in Table 1.

Table 1. Taxonomic classification of *Datura stramonium* L. (Solanaceae).

Rank	Classification
Kingdom	Plantae
Division	Magnoliophyta
Class	Magnoliopsida
Order	Solanales
Family	Solanaceae
Genus	<i>Datura</i> L.
Species	<i>Datura stramonium</i> L.
Common Names	Jimsonweed, Thorn Apple, Devil's Snare, Jamestown Weed, Stinkweed

Source: Cinelli & Jones, 2021; Lian et al., 2022; Sharma et al., 2021.

2.2 Botanical description and distribution

Datura stramonium is an annual or short-lived perennial herb widely distributed across tropical and temperate regions (Lian et al., 2022; Sharma et al., 2021). It is easily recognized by its large, lobed, strongly scented leaves, trumpet-shaped flowers, and spiny capsules containing numerous dark seeds (Sharma et al., 2021; Aćimović, 2025). The plant commonly grows along roadsides, disturbed areas, waste sites, and agricultural fields (Lian et al., 2022; Aćimović, 2025). Its wide distribution is partly linked to strong phenotypic plasticity and local adaptation in chemical defense against herbivores (De-la-Cruz et al., 2020; Castillo et al., 2025).

2.3 Genomic basis of chemical defense

The chromosome-scale genome of *D. stramonium* has been sequenced, revealing the genetic architecture underlying its resistance machinery against insect herbivores (De-la-Cruz et al., 2023). Genomic signatures of the evolution of defense against natural enemies in *D. stramonium* include expansions of gene families involved in alkaloid biosynthesis, suggesting that chemical defense is a core evolutionary strategy of the plant (De-la-Cruz et al., 2021). These genomic insights are valuable for identifying high-alkaloid strains for potential use in botanical insecticide development (De-la-Cruz et al., 2023; De-la-Cruz et al., 2021).

3 Phytochemical composition of *Datura stramonium*

3.1 Major alkaloids

The insecticidal potential of *Datura stramonium* is largely linked to its rich alkaloid content, particularly tropane alkaloids such as atropine, hyoscyamine, and scopolamine (Cinelli & Jones, 2021; Sharma et al., 2021; Lian et al., 2022). These compounds are produced through well-established biosynthetic pathways in Solanaceae and possess notable neuroactive properties. Scopolamine differs structurally from atropine because of its epoxide bridge, which contributes to its distinct biological effects. Besides tropane alkaloids, *D. stramonium* contains flavonoids, saponins, tannins, glycosides, steroids, phenols, and terpenoids, which may collectively contribute to its diverse biological and pesticidal activities (Sharma et al., 2021; Lian et al., 2022).

3.2 Variation in alkaloid content across plant parts and growth stages

The concentrations of atropine, scopolamine, and hyoscyamine differ significantly among plant parts and across different growth stages (Lian et al., 2022; Sharma et al., 2021). Leaves develop maximum alkaloid concentrations during the vegetative phase, with concentrations declining rapidly during the generative (reproductive) phase (Sharma et al., 2021; Lian et al., 2022). The levels of hyoscyamine, scopolamine, and atropine are highly variable not only among different parts of *D. stramonium* but also across different populations, reflecting local adaptation patterns documented in genomic studies (De-la-Cruz et al., 2020; Sharma et al., 2021). Analytical studies have further indicated that alkaloid accumulation varies with plant development, with substantial concentrations occurring toward the later stages of the reproductive period (Lian et al., 2022; Cinelli & Jones, 2021). The distribution of the major alkaloids across the different organs of *Datura stramonium* L., together with their principal characteristics and relevance, is summarized in **Table 2**.

Table 2. Distribution of major alkaloids across plant organs of *Datura stramonium* L.

Plant Part	Dominant Alkaloid(s)	Notes
Roots	Hyoscyamine, Scopolamine	Primary biosynthesis site; high alkaloid accumulation
Leaves	Hyoscyamine (young), Atropine + Scopolamine (mature)	Highest concentration during vegetative phase
Seeds	Atropine, Scopolamine	Richest organ for pesticidal bioassays
Stems	Hyoscyamine, Bioactive proteins	Lower alkaloid concentrations; protein bioactives also present
Flowers	Scopolamine, Atropine	Present in moderate concentrations
Fruits	Atropine, Scopolamine	Spiny capsules; seeds highly toxic

Source: Sharma et al., 2021; Lian et al., 2022; Cinelli & Jones, 2021.

3.3 Non-alkaloid bioactive secondary metabolites

Beyond tropane alkaloids, *D. stramonium* contains several other phytochemical classes, including flavonoids, tannins, steroids, phenolics, saponins, terpenoids, glycosides, and bioactive proteins, which may contribute individually or synergistically to its pesticidal activity (Sharma et al., 2021; Lian et al., 2022). Flavonoids and tannins may deter feeding and interfere with digestive processes, while terpenoids can contribute to repellent and fumigant effects. In addition, certain protein compounds have demonstrated larvicidal activity, further highlighting the diverse chemical basis of the plant's insecticidal potential (Kirar et al., 2022). The major phytochemical classes reported or associated with *Datura stramonium* L., their representative compounds, and their documented potential roles in insect control are summarized in **Table 3**.

Table 3. Major phytochemical classes and their documented or potential insecticidal relevance in *Datura stramonium* L).

Phytochemical Class	Key Compounds	Potential Insecticidal Role
Tropane Alkaloids	Atropine, Hyoscyamine, Scopolamine	Anticholinergic neurotoxicity, AChE inhibition
Flavonoids	Quercetin, Kaempferol, Rutin	Antifeedant, growth inhibitory
Tannins	Hydrolysable and condensed tannins	Protein digestion inhibition

Phytochemical Class	Key Compounds	Potential Insecticidal Role
Steroids	β -Sitosterol, Stigmasterol	Hormonal disruption in insects
Saponins	Steroidal saponins	Membrane disruption, antifeedant
Phenolics	Chlorogenic acid, Ferulic acid	Oxidative stress, enzyme inhibition
Terpenoids	Diterpenoids, sesquiterpenes	Repellent, fumigant activity
Bioactive Proteins	Novel stem proteins	Larvicidal, cytotoxic
Glycosides	Withanolides-related	Secondary bioactivity

Source: Devi et al., 2024.

4 Documented insecticidal activity of *Datura stramonium*

4.1 Activity against stored-grain beetles and bruchids

Laboratory studies have shown that *D. stramonium* extracts can effectively control important stored-product beetles and bruchids (Sharma et al., 2023; Chahande et al., 2024). Contact bioassays have reported dose-dependent mortality in *Callosobruchus maculatus*, *C. chinensis*, and *Tribolium castaneum* (Sharma et al., 2023). Recent reviews further recognize *D. stramonium* and other plant-based materials as promising alternatives or complements to conventional insecticides for protecting stored grains (Chahande et al., 2024; Devi et al., 2024; Yallappa et al., 2025).

4.2 Activity against *Callosobruchus maculatus* (cowpea weevil)

Callosobruchus maculatus (Fab.) (Coleoptera: Bruchidae), commonly known as the cowpea weevil, is a major pest of stored legumes, causing substantial losses in cowpea, mung bean, and chickpea (Jehajo & Shah, 2023; Chahande et al., 2024). Its ability to survive under varying temperature and humidity conditions contributes to its persistence in storage (Jehajo & Shah, 2023). Studies have demonstrated the insecticidal activity of *Datura* species, including *D. stramonium*, against *C. maculatus*, with mortality generally increasing with concentration (Sharma et al., 2023; Devi et al., 2024). Botanical mixtures may further enhance efficacy through synergistic effects (Et-tazy et al., 2025).

4.3 Activity against *Sitophilus* spp. (grain weevils)

Sitophilus oryzae (L.), the rice weevil, is a major primary pest of stored cereals, causing significant economic losses worldwide (Attia et al., 2020; Singh et al., 2021). Studies have reported insecticidal activity of *Datura* species against *Sitophilus* weevils (Sharma et al., 2023). Botanical oils and synergistic combinations also show promise for improving stored-grain protection and could support future *D. stramonium*-based control strategies (Kifle et al., 2024; Hassan et al., 2022).

4.4 Activity against *Tribolium castaneum* (red flour beetle)

Tribolium castaneum (Herbst) is a major secondary pest of stored and processed products, with increasing concern over insecticide resistance (Attia et al., 2020; Shamjana & Grace, 2021). Studies indicate that *Datura* extracts can cause mortality and behavioural changes in this pest, while essential oils and nanoformulations may further enhance control efficacy (Sharma et al., 2023; Chahande et al., 2024).

4.5 Activity against *Rhyzopertha dominica* (lesser grain borer)

Rhyzopertha dominica (F.), commonly called the lesser grain borer, is a serious primary pest of wheat and other stored cereals and can develop strong resistance to phosphine (Nayak & Daglish, 2017; Daglish et al., 2024). This resistance has increased the need for alternative grain protectants. Plant-derived compounds, including essential oils, can influence the pest's behaviour and physiology in dose-dependent ways (Parichanon et al., 2025). Datura alkaloids are therefore promising candidates for managing *R. dominica*, particularly where resistance limits conventional insecticides (Sharma et al., 2023; Nayak et al., 2026).

4.6 Activity against mosquito vectors and other Diptera

Although dipterans are not primarily stored-product pests, studies demonstrate the broad pesticidal potential of *D. stramonium*. Methanol and ethyl acetate extracts showed strong larvicidal activity against *Culex pipiens* and *Aedes aegypti* (Baz et al., 2026). Additionally, a bioactive protein isolated from *D. stramonium* stems exhibited significant larvicidal activity against *Anopheles stephensi*, suggesting that non-alkaloid compounds also contribute to its insecticidal properties (Kirar et al., 2022).

4.7 Activity against sawfly and forest pests

The vegetable extract of *D. stramonium* L. demonstrated notable insecticidal efficacy against sawfly pests in forest settings, highlighting the broad pesticidal potential of its bioactive constituents (Flores-Villegas et al., 2019). Similarly, studies involving different plant parts and extract types have reported insecticidal, larvicidal, repellent, fumigant, and enzyme-inhibitory effects against a range of insect pests (Kirar et al., 2022; Sharma et al., 2023; Chahande et al., 2024). These findings suggest that the insecticidal activity of *D. stramonium* is not restricted to a single pest group or plant organ but may vary according to the target species, plant part, extraction method, and concentration applied. A summary of documented insecticidal activities of *Datura stramonium* extracts and other bioactive preparations against selected insect pests, including the plant parts or extract types evaluated and the reported biological effects, is presented in **Table 4**.

Table 4. Insecticidal activity of *Datura stramonium* extracts against various pest species.

Target Pest	Order: Family	Plant Part/ Extract Type	Activity Observed	Reference
<i>Callosobruchus maculatus</i>	Coleoptera: Bruchidae	Leaf, seed (multiple solvents)	Contact and fumigant toxicity; dose-dependent mortality	Sharma et al., 2023
<i>Callosobruchus chinensis</i>	Coleoptera: Bruchidae	Leaf, seed extracts	Contact toxicity; repellent effects	Sharma et al., 2023
<i>Tribolium castaneum</i>	Coleoptera: Tenebrionidae	Leaf, seed extracts	Adult and larval mortality; AChE inhibition	Sharma et al., 2023; Chahande et al., 2024
<i>Sitophilus oryzae</i>	Coleoptera: Curculionidae	Seed extracts	Significant adult mortality in stored wheat	Sharma et al., 2023
<i>Rhyzopertha dominica</i>	Coleoptera: Bostrichidae	Leaf, stem extracts	Insecticidal activity reported	Sharma et al., 2023; Devi et al., 2024
<i>Culex pipiens</i>	Diptera: Culicidae	MeOH, EtOAc extracts	Larvicidal and adulticidal; potent LC ₅₀ values	Baz et al., 2026

Target Pest	Order: Family	Plant Part/ Extract Type	Activity Observed	Reference
<i>Aedes aegypti</i>	Diptera: Culicidae	MeOH, EtOAc extracts	Larvicidal activity documented	Baz et al., 2026
<i>Anopheles stephensi</i>	Diptera: Culicidae	Stem protein isolate	Significant larvicidal bioactivity	Kirar et al., 2022
Sawfly (Diprionidae)	Hymenoptera: Diprionidae	Vegetable extract	Effective insecticidal control	Flores-Villegas et al., 2019
<i>Spodoptera litura</i>	Lepidoptera: Noctuidae	Leaf/seed extracts	Dose-dependent mortality	Sharma et al., 2023

5 Mechanisms of insecticidal action

5.1 Anticholinergic and neurotoxic mechanisms

The insecticidal activity of *D. stramonium* is largely associated with its tropane alkaloids, particularly atropine, hyoscyamine, and scopolamine, which interfere with cholinergic signalling (Cinelli & Jones, 2021; Lian et al., 2022). These compounds interact with muscarinic acetylcholine receptors, disrupting normal nervous-system function and potentially causing paralysis and mortality in insects (Sharma et al., 2021). Hyoscyamine acts as a competitive muscarinic receptor antagonist, while scopolamine has strong neuroactive properties (Lian et al., 2022). This distinct mode of action may provide opportunities for managing insect populations that have developed resistance to conventional insecticides (Devi et al., 2024; Chahande et al., 2024).

5.2 Acetylcholinesterase (AChE) inhibition

D. stramonium alkaloids may contribute to insect mortality by interfering with acetylcholinesterase (AChE), disrupting acetylcholine breakdown and normal nerve function (Sharma et al., 2021; Sharma et al., 2023). Such inhibition can cause excessive neural stimulation, paralysis, and death. This mechanism may complement receptor-level cholinergic disruption, enhancing overall insecticidal activity (Devi et al., 2024; Chahande et al., 2024).

5.3 Antifeedant and repellent mechanisms

Beyond killing insects directly, *D. stramonium* extracts may also act as antifeedants and repellents, offering additional protection against stored-product pests (Sharma et al., 2023; Devi et al., 2024). Compounds such as alkaloids, tannins, and flavonoids can discourage feeding and egg-laying, even at sub-lethal concentrations (Sharma et al., 2021). Plant volatiles are also widely recognized for their repellent effects against storage insects (Singh et al., 2021; Vendl et al., 2021). These complementary effects could reduce pest infestation and support the development of *D. stramonium*-based formulations for stored-grain protection.

5.4 Physiological and metabolic disruption

The diverse phytochemicals present in *D. stramonium* may act on multiple physiological and biochemical processes in insects, potentially producing additive or synergistic effects (Sharma et al., 2021; Lian et al., 2022). Tannins and phenolics may interfere with digestive processes, while flavonoids can contribute to oxidative stress and disruption of cellular functions (Sharma et al., 2021; Devi et al., 2024). In addition, bioactive proteins isolated from *D. stramonium* have demonstrated larvicidal

activity, suggesting that protein-based compounds may contribute to its insecticidal effects through mechanisms distinct from those of its secondary metabolites (Kirar et al., 2022). However, the strength of evidence for these mechanisms varies, with some being directly demonstrated in bioassays and others remaining proposed based on the known biological activities of the respective phytochemical classes. The principal mechanisms proposed to explain the insecticidal activity of *Datura stramonium* compounds, the phytochemical classes involved, their potential biological targets in insects, and the current level of supporting evidence are summarized in Table 5.

Table 5. Summary of proposed mechanisms of insecticidal action of *Datura stramonium* compounds.

Mechanism	Chemical Class Involved	Biological Target in Insect	Evidence Level
Muscarinic receptor antagonism	Atropine, Hyoscyamine	Central and peripheral nervous system	Well documented (pharmacological)
Acetylcholinesterase inhibition	Scopolamine, Hyoscyamine, Alkaloid fractions	Cholinergic synapses	Documented in bioassays
Antifeedant / gustatory deterrence	Tannins, Flavonoids, Alkaloids	Gustatory receptors, midgut	Supported by bioassay data
Volatile compound repellency	Volatile alkaloids, Terpenoids	Olfactory/chemosensory receptors	Partially supported
Protein digestion inhibition	Tannins, Protease inhibitors	Digestive enzyme activity	Inferred from phytochemical data
Oxidative stress induction	Phenolics, Flavonoids	Cellular antioxidant systems	Supported by related studies
Direct cytotoxicity (proteins)	Novel bioactive stem proteins	Larval midgut/cells	Demonstrated (Kirar et al., 2022)
Oviposition deterrence	Alkaloid/volatile fractions	Chemosensory oviposition cues	Requires direct investigation

Source: Cinelli & Jones, 2021; Sharma et al., 2021; Lian et al., 2022; Kirar et al., 2022; Devi et al., 2024; Baz et al., 2026.

6 Comparative efficacy with other botanical insecticides

6.1 Comparison with essential oils

Essential oils are among the most widely studied botanical insecticides for stored-product pest management, with fumigant, contact, and repellent effects (Campolo et al., 2018; Singh et al., 2021; Li et al., 2025). Studies against *Sitophilus zeamais* and *Tribolium castaneum* have demonstrated promising activity from several plant oils, supporting their value as comparative models for *D. stramonium* research (Pimentel et al., 2022; Moutassem et al., 2024; Ramachandran et al., 2022). However, essential oils can be volatile and unstable (Yallappa et al., 2025). In contrast, *D. stramonium* relies mainly on alkaloids, offering a distinct mechanism that may complement existing pest-control strategies (Sharma et al., 2021; Devi et al., 2024).

6.2 Comparison with nanoformulated botanicals

Nanoformulation can improve the stability, efficacy, and persistence of botanical insecticides by reducing problems associated with volatility and degradation (Khandehroo et al., 2024; Kannan & Chandrasekaran, 2026). Nanoemulsions and polymeric nanoparticles have enhanced the activity of

plant compounds against stored-product pests. However, their ecological effects require careful assessment (Modafferi et al., 2024).

6.3 Comparison with diatomaceous earth and inert dusts

Diatomaceous earth (DE) controls stored-product insects primarily through physical desiccation rather than conventional chemical toxicity, making it a useful component of integrated grain protection strategies (Zeni et al., 2021). The combination of inert dusts with conventional insecticides may further improve pest suppression through complementary modes of action (Hassan et al., 2023). In addition, emerging materials such as graphene-based powders have demonstrated potential for the management of stored-product insects, reflecting the continuing development of alternative pest-control technologies (Lampiri et al., 2024). To place the insecticidal potential of *Datura stramonium* in the broader context of alternative pest-management options, Table 6 compares major botanical insecticide categories and selected inert or emerging materials according to their active constituents, target pest spectrum, principal advantages, and key limitations.

Table 6. Comparative overview of major botanical insecticide categories against stored-product insects.

Botanical Category	Key Active Ingredients	Target Pest Spectrum	Key Advantages	Key Limitations
<i>Datura stramonium</i> extracts	Atropine, Hyoscyamine, Scopolamine, Bioactive proteins	Bruchids, weevils, flour beetles	Unique alkaloid mode of action; multiple bioactivity classes	High mammalian toxicity; formulation complexity
Essential oils (various)	Terpenes, Phenylpropanoids	Broad spectrum beetles, moths	Well-studied; multiple modes of action	High volatility; UV instability
Neem (Azadirachta indica)	Azadirachtin, Nimbin	Very broad spectrum	Growth regulatory; extensively validated	Slow onset of action
Piper spp. extracts	Piperine, Piperlongumine	Weevils, bruchids	Fumigant and contact activity	Limited field data
Diatomaceous earth	Silica particles (physical)	Broad spectrum beetles	Durable residual; no chemical resistance	Dust hazard; humidity sensitive
Nanoformulated botanicals	Nano-encapsulated terpenes	Broad spectrum	Enhanced stability; controlled release	Ecological costs; regulatory uncertainty

Source: Campolo et al., 2018; Singh et al., 2021; Li et al., 2025; Sharma et al., 2023; Zeni et al., 2021; Pavela & Benelli, 2016; Devi et al., 2024; Yallappa et al., 2025.

7 Toxicity and safety profile

7.1 Mammalian toxicity

Although *D. stramonium* shows promising insecticidal potential, its toxicity requires careful consideration before commercial use (Aćimović, 2025; Shifa et al., 2024). Its tropane alkaloids, particularly atropine and scopolamine, can cause severe anticholinergic poisoning, including delirium, hallucinations, coma, and death (Lian et al., 2022; Sharma et al., 2021). Therefore, safe handling, appropriate dosage, and child-resistant formulations are essential. Compared with many synthetic

insecticides, botanical products are generally biodegradable and may pose fewer environmental risks (Devi et al., 2024; Yallappa et al., 2025). However, the persistence, environmental fate, and effects of *D. stramonium* alkaloids require further investigation before wider application

7.2 Selectivity and non-target effects

Differences between insect and mammalian cholinergic receptors may offer some selectivity at carefully controlled doses (Cinelli & Jones, 2021; Lian et al., 2022). However, *D. stramonium* alkaloids are toxic to humans and livestock, requiring thorough safety assessment before use (Aćimović, 2025; Sharma et al., 2021). Appropriate testing across formulations is therefore essential (Stejskal et al., 2021)

8 Factors influencing insecticidal efficacy

8.1 Extraction solvent and method

The insecticidal activity of *D. stramonium* extracts depends strongly on the extraction solvent used (Baz et al., 2026; Kirar et al., 2022). Methanol and ethyl acetate extracts often show greater activity, likely because they recover more alkaloids. Different extraction methods may therefore be needed to capture the plant's full pesticidal potential.

8.2 Plant part, growth stage, and population origin

The insecticidal effectiveness of *D. stramonium* can differ according to the plant part and growth stage when collected (Sharma et al., 2021; Lian et al., 2022). Seeds are often rich in tropane alkaloids, while leaves and stems contain varying amounts of bioactive compounds (Cinelli & Jones, 2021). Alkaloid levels may increase as the plant matures, making harvest timing important for consistent activity (Lian et al., 2022). Geographic differences also influence alkaloid composition and concentration, with populations showing distinct chemical profiles (De-la-Cruz et al., 2020; De-la-Cruz et al., 2021; Castillo et al., 2025). Therefore, standardising plant sources is essential for reliable research and product development.

8.3 Pest species, life stage, and resistance status

The susceptibility of stored-product pests to *D. stramonium* extracts varies according to pest species, developmental stage, extract characteristics, and exposure conditions (Sharma et al., 2023; Devi et al., 2024). Insecticidal effects of *Datura* species have been evaluated against both adult and larval stages of different insect pests, with results demonstrating considerable species- and stage-specific differences in susceptibility (Sharma et al., 2023). In addition, resistance to conventional insecticides may or may not influence susceptibility to *D. stramonium* alkaloids, depending on the underlying resistance mechanisms present in a given pest population (Nayak et al., 2026; Ramzan et al., 2018). The inheritance of permethrin resistance in field strains of *S. oryzae*, for example, illustrates the genetic complexity that should be considered when evaluating alternative insecticidal compounds (Khan et al., 2024). The major factors that can influence the insecticidal efficacy of *Datura stramonium* extracts, their expected effects, and their practical implications for bioassay design and pest-management applications are summarized in **Table 7**.

Table 7. Key factors influencing the insecticidal efficacy of *Datura stramonium* extracts against stored-product insects.

Factor	Direction of Effect	Practical Implication
Extraction solvent	MeOH > EtOAc > n-hexane > aqueous	Select solvent to maximise alkaloid yield
Plant part	Seeds > Leaves > Stems > Roots	Prioritise seeds for highest potency extracts
Growth stage	Vegetative > reproductive (leaves); seeds peak reproductive	Harvest timing critical for maximum bioactivity
Geographic/population origin	High variation due to local adaptation	Standardise source populations for reproducibility
Alkaloid concentration	Positive correlation with mortality	Higher concentrations → higher mortality
Exposure duration	Longer exposure → higher mortality	Time of exposure is a key bioassay parameter
Pest species	Species-specific sensitivity	Species-specific bioassay required
Life stage	Adults vs. larvae differ in susceptibility	Stage-targeted application
Resistance status	May affect sensitivity to alkaloids	Screen against resistant populations
Formulation type	Affects stability, bioavailability, delivery	Formulation optimisation essential

Source: Sharma et al., 2021; Lian et al., 2022; Baz et al., 2026; De-la-Cruz et al., 2020; Sharma et al., 2023; Devi et al., 2024; Kirar et al., 2022.

9 Integration into stored-product pest management systems

9.1 Biorational and integrated pest management frameworks

Biorational management of stored-product insects combines methods such as temperature control, modified atmospheres, irradiation, inert dusts, pheromone traps, botanicals, and biological agents (Phillips & Throne, 2010). Since no single approach provides lasting control, integrated pest management is essential (Hagstrum & Phillips, 2017). Properly formulated *D. stramonium* extracts could complement these tactics (Devi et al., 2024; Yallappa et al., 2025).

9.2 Synergistic combinations with other control tools

Combining *D. stramonium* extracts with inert dusts, diatomaceous earth, botanicals, or reduced-risk insecticides could provide complementary modes of action (Devi et al., 2024; Zeni et al., 2021). Studies showing synergistic effects between botanicals, essential oils, and conventional insecticides support this strategy for improving efficacy and managing resistance (Naseri et al., 2025; Et-tazy et al., 2025).

9.3 Insecticide-treated nets and long-lasting barrier technologies

Long-lasting insecticide-treated nets and interception traps have shown promising results in warehouses by reducing infestation from stored-product beetles (Wilkins et al., 2021). Such nets can also disrupt the movement and dispersal of major stored-product insects, with effects varying across life stages (Wilkins et al., 2020). Their effectiveness has been demonstrated against beetle populations with different levels of phosphine susceptibility, with residual activity maintained over time (Agrafioti & Athanassiou, 2018; Agrafioti et al., 2021). Incorporating *D. stramonium* alkaloids into

coated nets or surface treatments could provide a novel approach for stored-product protection (Yallappa et al., 2025; Nayak et al., 2026).

9.4 Aerosol and space treatment approaches

Aerosol insecticides can provide effective space treatment in storage facilities, but their performance depends on droplet size, formulation, concentration, deposition, and application method (Arthur et al., 2017; 2018; 2019). Studies have also shown that application location can influence residual activity against *Tribolium confusum* larvae (Scheff et al., 2020). These findings suggest that volatile alkaloid fractions from *D. stramonium* could potentially be explored in aerosol or fumigant formulations for stored-product protection (Sharma et al., 2023; Lian et al., 2022). However, formulation stability, exposure risks, and toxicity must be carefully evaluated before practical application.

10 Formulation science and application technology

10.1 Current formulation options and challenges

Stored-product pests can be managed using insecticides formulated as gases, liquids, gels, or solids, with each form offering different benefits and limitations (Stejskal et al., 2021). Gel-based carriers may improve the stability and controlled release of botanical compounds, including alkaloids (Shah et al., 2022). However, the high mammalian toxicity of crude *D. stramonium* extracts requires careful formulation and dosage to ensure safe use (Aćimović, 2025; Shifa et al., 2024). Nanoformulations can further improve the stability, solubility, and persistence of botanical insecticides (Khandehroo et al., 2024; Giunti et al., 2019; Kannan & Chandrasekaran, 2026). Nevertheless, their ecological effects require careful assessment (Modafferi et al., 2024).

10.2 Proposed formulation strategies for *D. stramonium*-based insecticides

Several formulation strategies could support the development of *D. stramonium*-based insecticides, drawing from approaches used with other botanical products (Stejskal et al., 2021; Shah et al., 2022; Khandehroo et al., 2024). These include grain protectant admixtures, using dried plant material or standardised extracts directly on stored grain (Devi et al., 2024; Chahande et al., 2024); solvent extracts, prepared as emulsifiable concentrates or wettable powders for grain and surface treatment (Baz et al., 2026; Sharma et al., 2023); nanoemulsions for improved stability and controlled release (Kannan & Chandrasekaran, 2026); gel matrices for slow release (Shah et al., 2022); and long-lasting treated nets or bags for residual protection (Paudyal et al., 2017; Scheff et al., 2021).

11 Regulatory and commercialisation pathway

Developing *D. stramonium*-based insecticides presents considerable regulatory challenges because its alkaloids are known to be highly toxic to mammals (Aćimović, 2025; Sharma et al., 2021). Regulatory approval would require detailed information on acute and chronic toxicity, environmental fate, effects on non-target organisms, and pesticide residues in treated commodities (Vryzas et al., 2020). The plant's status as a dangerous weed and its association with misuse may also attract closer regulatory attention (Aćimović, 2025). As botanical insecticides face evolving regulatory requirements (Yallappa et al., 2025), successful development of *D. stramonium* products will depend on reliable safety, efficacy, and residue data (Nayak et al., 2026).

12 Knowledge gaps and future research priorities

12.1 Identified research gaps

Despite encouraging laboratory results, important gaps remain before *D. stramonium* can become a practical stored-product pest management tool (Sharma et al., 2023; Yallappa et al., 2025; Devi et al., 2024; Nayak et al., 2026). Most studies are laboratory-based, with limited field validation under varying storage conditions. Differences in plant source, growth stage, and extraction methods also hinder standardisation and reproducibility (De-la-Cruz et al., 2020; Lian et al., 2022). Further studies should clarify its mechanisms, sub-lethal effects, mammalian safety, formulation stability, resistance risks, and synergistic combinations with other control methods (Cinelli & Jones, 2021; Aćimović, 2025; Khandehroo et al., 2024; Naseri et al., 2025).

12.2 Recommended future research directions

Future research on *D. stramonium* as a stored-product insecticide should move beyond laboratory bioassays toward a more systematic evaluation of its efficacy, safety, consistency, and practical applicability. Priority areas include the identification of high-alkaloid populations through genomic and metabolomic approaches, validation of insecticidal performance under semi-field and farm-storage conditions, development of improved formulations such as nano-encapsulated preparations, and investigation of synergistic combinations with other grain protectants (Yallappa et al., 2025; Kannan & Chandrasekaran, 2026). Further research is also needed to clarify mammalian safety, resistance development, environmental fate, behavioural responses, and sub-lethal and transgenerational effects. Addressing these gaps will be essential for determining whether *D. stramonium* can be developed into a safe, consistent, and practically useful stored-product insecticide. The major knowledge gaps, their priority levels, recommended research approaches, and relevant supporting references for advancing the development of *Datura stramonium* as a stored-product insecticide are summarized in Table 8.

Table 8. Summary of knowledge gaps and recommended future research priorities for *Datura stramonium* as a stored-product insecticide.

Knowledge Gap	Priority Level	Recommended Approach	Key Reference
Field-level validation	Critical	On-farm semi-field trials in diverse storage systems	Yallappa et al., 2025
Extract standardisation	High	Metabolomic profiling; standardised extraction protocols	Sharma et al., 2021; Lian et al., 2022
Mechanism elucidation in stored pests	High	AChE assays, transcriptomics, receptor binding in <i>T. castaneum</i> , <i>S. oryzae</i>	Cinelli & Jones, 2021
Sub-lethal and transgenerational effects	High	Life table studies; fecundity and developmental assays	Farhadi et al., 2025
Mammalian safety data	Critical	Acute and chronic toxicity; residue analysis	Aćimović, 2025; Shifa et al., 2024
Formulation optimisation	High	Nano-encapsulation; gel and solid formulation trials	Kannan & Chandrasekaran, 2026
Resistance risk assessment	High	Selection experiments; genomic resistance characterisation	Nayak et al., 2026; Chen et al., 2022

Knowledge Gap	Priority Level	Recommended Approach	Key Reference
Synergistic combinations	Moderate	Binary and ternary combination bioassays	Et-tazy et al., 2025; Naseri et al., 2025
Environmental fate	High	Degradation studies under storage conditions	Vryzas et al., 2020
High-alkaloid population identification	Moderate	Genomic and metabolomic screening of geographic populations	De-la-Cruz et al., 2023; De-la-Cruz et al., 2020

13 Conclusion

Datura stramonium L. represents a botanically and chemically fascinating candidate for the development of novel stored-product insecticides, supported by a diverse phytochemical profile dominated by potent tropane alkaloids, including atropine, hyoscyamine, and scopolamine. Laboratory bioassays have demonstrated insecticidal activity against major stored-product pests, including *Callosobruchus maculatus*, *Sitophilus oryzae*, and *Tribolium castaneum*, as well as mosquito vectors, suggesting broad pesticidal potential. Its primary mechanisms of action may involve muscarinic receptor antagonism and acetylcholinesterase inhibition, together with antifeedant, repellent, and physiological effects associated with other phytochemicals present in the plant. The need for effective botanical alternatives to conventional insecticides is strengthened by the growing problem of insecticide resistance among stored-product pests, increasing environmental and health concerns linked to synthetic fumigants, and the continuing threat posed by stored-product insects to global food security. Botanical insecticides offer promising opportunities for sustainable integrated pest management, and *D. stramonium* deserves systematic investigation within this framework.

However, the plant's considerable mammalian toxicity, together with formulation challenges and limited field-level efficacy data, means that future research must prioritise rigorous safety evaluation, precise formulation, and appropriate regulatory assessment before practical application. Recently available genomic resources for *D. stramonium* also provide opportunities to improve understanding of alkaloid production and the biological processes underlying its pesticidal properties. With sustained research and appropriate scientific investment, *D. stramonium* could contribute to the development of next-generation botanical insecticides for sustainable stored-product pest management.

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