



PLANT BOTANICALS, A PROMISING FUTURE PESTICIDE FOR BOTH FIELD AND STORE INSECT PESTS: A REVIEW

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ABSTRACT

The escalating concerns over synthetic pesticide-associated human health hazards, environmental contamination and accelerating insecticide resistance in pest populations have intensified the global search for safer and more sustainable alternatives. Botanical pesticides derived from plant secondary metabolites including alkaloids, terpenoids, flavonoids and essential oils represent a promising class of biopesticides that are biodegradable, locally accessible and generally compatible with integrated pest management (IPM) frameworks. This review examines the current state of knowledge on the efficacy of plant-derived botanical extracts, powders and essential oils for the management of both field crop and stored grain insect pests. Key botanical sources reviewed include neem (*Azadirachta indica*), pyrethrum (*Chrysanthemum cinerariaefolium*), garlic (*Allium sativum*), Mexican sunflower (*Tithonia diversifolia*), eucalyptus (*Eucalyptus globulus*), tobacco (*Nicotiana tabacum*) and Annona (*Annona squamosa*) among others. Their documented bioactive compounds, mechanisms of pesticidal action and efficacy against major pest species are critically synthesised from recent literature (2020–2025). The review further discusses the comparative advantages and limitations of botanical pesticides relative to synthetic counterparts, challenges to their commercialization, regulatory approval and emerging innovations such as nano-formulations and synergistic multi-plant combinations. It is concluded that botanical pesticides, while not yet a wholesale replacement for synthetic insecticides, constitute an indispensable component of future sustainable pest management systems, particularly for smallholder farming communities in sub-Saharan Africa and other tropical regions. Strategic investment in formulation technology, field validation, and harmonised regulatory frameworks is urgently needed to unlock their full potential.

Keywords: Biopesticides, Botanical, Insecticides, Crop, Pests; Management

INTRODUCTION

Global food security is increasingly imperilled by crop losses attributable to insect pests, both during the growing season and after harvest during storage. Current estimates suggest that insect pests account for approximately 18–26% of pre-harvest crop losses and an additional 10–40% of post-harvest losses during storage, with the burden falling disproportionately on smallholder farmers in tropical and subtropical regions (Hikal *et al.*, 2024). The conventional response to these losses has been the heavy and often indiscriminate use of synthetic chemical insecticides. Synthetic insecticides, particularly organophosphates, pyrethroids, carbamates, and neonicotinoids, have been the mainstay of pest management since the mid-twentieth century. Their rapid action, broad-spectrum activity, and cost-effectiveness have made them attractive to farmers worldwide. However, decades of intensive and often injudicious use have generated an array of serious environmental and public health consequences. These include the development of insecticide resistance in target pest populations, disruption of beneficial insect communities including pollinators and natural enemies, contamination of soil and water bodies, and accumulation of toxic residues in food commodities (Ngegba *et al.*, 2022; Pereira *et al.*, 2024). These challenges have generated sustained scientific, regulatory, and public pressure to identify and develop safer alternatives.

Botanical pesticides—products derived from plant parts including leaves, seeds, bark, roots, and flowers, or from plant-extracted essential oils and isolated bioactive compounds—represent one of the most promising categories of such alternatives. Plants have evolved over millions of years to produce an elaborate arsenal of secondary metabolites as defence mechanisms against herbivores,



pathogens, and competing plants. These compounds, which include alkaloids, terpenoids (including triterpenoids and sesquiterpenes), flavonoids, phenolics, and glucosinolates, exhibit diverse and potent biological activities against insect pests (Isman, 2020; Thomine & Siegwart, 2024). The documented insecticidal history of botanicals is ancient: neem preparations have been used in Indian agriculture for over two millennia, and pyrethrum extracted from *Chrysanthemum* flowers has been employed as an insecticide for over 150 years (Isman, 2020). Despite this long history, the adoption of botanical pesticides in modern agricultural systems has been uneven and often limited. A number of constraints—including variability in active ingredient concentration, rapid environmental degradation, lack of standardised formulations, and complex regulatory pathways—have impeded their commercialisation relative to synthetic products (Saikumar *et al.*, 2025; Marchand, 2024). However, the recent convergence of growing consumer demand for residue-free food, tightening regulatory restrictions on synthetic pesticides in the European Union and other jurisdictions, and renewed scientific interest in plant-derived compounds has created a new momentum for botanical pesticide research and development. The global botanical pesticides market was valued at USD 1.7–3.2 billion in 2024 and is projected to grow at a compound annual growth rate (CAGR) of 7–10% through 2030 (HDIn Research, 2025).

The present review aims to: (i) provide a comprehensive and up-to-date synthesis of the major botanical sources and their bioactive principles relevant to pest management; (ii) critically evaluate the efficacy of botanical pesticides against both field crop and stored product insect pests; (iii) compare the relative merits and limitations of botanical versus synthetic insecticides; (iv) examine challenges to commercialisation and regulatory acceptance; and (v) highlight emerging innovations and research priorities that could advance botanical pest management into mainstream agricultural practice.

MAJOR BOTANICAL PESTICIDE SOURCES AND THEIR BIOACTIVE PRINCIPLES

Neem (*Azadirachta indica* A. Juss.)

Neem is arguably the most extensively studied and commercially important botanical pesticide source globally. The neem tree, native to the Indian subcontinent and naturalised across tropical Africa, produces a complex array of bioactive limonoids, of which azadirachtin—a highly oxygenated tetranortriterpenoid—is the principal insecticidal compound. Azadirachtin acts primarily as an ecdysone antagonist, interfering with the insect moulting hormone (20-hydroxyecdysone) and thereby disrupting larval development, pupation, and adult emergence. Additionally, azadirachtin exerts potent antifeedant effects, suppresses oviposition, and disrupts fecundity in a wide range of insect orders including Lepidoptera, Coleoptera, Hemiptera, and Diptera (Isman, 2020; Harun-Ur-Rashid *et al.*, 2025).

Neem-based formulations include crude leaf extracts, seed kernel extracts (neem seed kernel extract, NSKE), neem oil, and commercial azadirachtin-standardised products (e.g., Neemix, Aza-Direct). A key limitation of neem products is their susceptibility to UV photodegradation: azadirachtin can degrade within three to four days of foliar application under field conditions, necessitating repeated applications (Isman, 2020). Nevertheless, neem's safety profile—minimal mammalian toxicity, non-persistence in the environment, and compatibility with natural enemies—makes it a cornerstone of IPM programmes worldwide.

Pyrethrum (*Chrysanthemum cinerariaefolium* Vis.)

Pyrethrum, derived from the dried flowers of *Chrysanthemum cinerariaefolium*, contains six closely related esters collectively termed pyrethrins. These compounds exert their insecticidal action by interacting with voltage-gated sodium channels in the insect nervous system, causing sustained depolarisation, repetitive nerve firing, paralysis, and death. Pyrethrum is a fast-acting contact poison with a characteristic rapid 'knockdown' effect, distinguishing it from the slower-acting neem products (Pereira *et al.*, 2024). It is also documented to have repellent activity at sub-lethal concentrations.

Pyrethrum has a broad spectrum of activity against aphids, thrips, whitefly, leafhoppers, caterpillars, and numerous stored product beetles and moths. Its key advantages include rapid biodegradation in the environment, low vertebrate toxicity relative to organophosphates, and compatibility with organic production standards. However, pyrethrins can be acutely toxic to aquatic invertebrates and some natural enemies, and their short residual activity means multiple applications



are required for sustained pest control (Dassanayake *et al.*, 2021; Pereira *et al.*, 2024). Pyrethrum is the biological precursor to the synthetic pyrethroids, one of the largest classes of synthetic insecticides, underscoring the profound influence of botanical discovery on agrochemical development.

Rotenone (*Derris elliptica* and Related Species)

Rotenone, a flavonoid-derived isoflavonoid extracted from the roots of *Derris elliptica*, *Lonchocarpus* spp., and related leguminous plants, has been used as a botanical insecticide and fish toxicant for centuries. Its insecticidal mechanism involves specific inhibition of the mitochondrial electron transport chain at complex I (NADH dehydrogenase), leading to ATP depletion and death in target organisms. Rotenone is broadly active against caterpillars, aphids, beetles, and mites (Isman, 2020). However, it is acutely toxic to fish and has documented mammalian neurotoxicity at high doses, raising concerns that have limited its regulatory approval in several jurisdictions (Pereira *et al.*, 2024). Its biodegradability (half-life of 1–3 days in sunlight) remains an advantage in terms of environmental persistence.

Other Important Botanical Sources

Beyond the 'classic' botanical insecticides described above, a large number of plant species have demonstrated significant pesticidal activity in recent scientific literature. Garlic (*Allium sativum*) extracts, rich in allicin and diallyl disulfide, act principally as repellents and acetylcholinesterase (AChE) inhibitors against aphids, thrips, spider mites, and stored grain pests (Dassanayake *et al.*, 2021). Mexican sunflower (*Tithonia diversifolia*), widely distributed across sub-Saharan Africa, contains sesquiterpene lactones (tagitinins) that disrupt mitochondrial function in insect midgut tissues and exert strong antifeedant activity (Macharia *et al.*, 2021; Mkindi *et al.*, 2020). Eucalyptus (*Eucalyptus globulus* and related species) leaf extracts and essential oils, principally composed of 1,8-cineole and alpha-pinene, exhibit potent fumigant and contact toxicant activity against stored product pests including the maize weevil *Sitophilus zeamais* (Kifle *et al.*, 2025). Tobacco (*Nicotiana tabacum*), whose principal alkaloid nicotine acts as a nicotinic acetylcholine receptor agonist, has historically been used against sucking pests and continues to be evaluated as a locally accessible botanical resource in Nigeria and other tobacco-growing regions (Isman, 2020). *Annona squamosa* (custard apple) seed extracts, containing acetogenins and alkaloids, have demonstrated strong insecticidal activity against multiple stored grain insect species (Kifle *et al.*, 2025).

Table 1 provides a summary of the major botanical sources reviewed, their principal bioactive compounds, target pests and documented modes of action.

Table 1. Major Botanical Pesticide Sources, Bioactive Compounds, Target pests and Mechanisms of Action

Botanical Source	Active Compound(s)	Target Pests	Mode of Action	Reference
<i>Neem (Azadirachta indica)</i>	Azadirachtin, nimbin, salanin	Lepidoptera, Coleoptera, Hemiptera	Antifeedant, growth disruptor, oviposition inhibitor	<i>Isman (2020); Harun-Ur-Rashid et al. (2025)</i>
<i>Pyrethrum (Chrysanthemum cinerariaefolium)</i>	Pyrethrins I & II	Aphids, whitefly, stored grain beetles	Nerve membrane Na ⁺ channel disruptor; contact knockdown	<i>Pereira et al. (2024); Dassanayake et al. (2021)</i>
<i>Rotenone (Derris elliptica)</i>	Rotenone	Caterpillars, aphids, mites	Inhibits mitochondrial complex I; respiratory failure	<i>Isman (2020); Ntalli & Menkissoglu-Spiroudi (2022)</i>
<i>Garlic (Allium sativum)</i>	Allicin, diallyl disulfide	Aphids, thrips, spider mites, stored pests	Repellent; AChE inhibition	<i>Dassanayake et al. (2021); Mkindi et al. (2020)</i>
<i>Eucalyptus (Eucalyptus globulus)</i>	1,8-cineole, alpha-pinene	<i>Maize weevil (Sitophilus zeamais), aphids</i>	Fumigant; contact toxicant; repellent	<i>Kifle et al. (2025)</i>
<i>Mexican sunflower (Tithonia diversifolia)</i>	Tagitinins, sesquiterpene lactones	Lepidoptera, aphids, stored grain pests	Mitochondrial disruption; feeding deterrence	<i>Macharia et al. (2021); Mkindi et al. (2020)</i>
<i>Tobacco (Nicotiana tabacum)</i>	Nicotine, normicotine	Aphids, thrips, leafhoppers	Nicotinic acetylcholine receptor agonist	<i>Isman (2020); Pereira et al. (2024)</i>
<i>Annona (Annona squamosa)</i>	Acetogenins, alkaloids	<i>Sitophilus zeamais, Callosobruchus spp.</i>	Mitochondrial complex I & III inhibition; stomach poison	<i>Kifle et al. (2025)</i>

EFFICACY OF BOTANICAL PESTICIDES AGAINST FIELD CROP INSECT PESTS

Lepidopteran Pests

Lepidopteran pests including armyworms, cutworms, stem borers and fruit borers represent the most economically damaging insect guild in field crop production globally. The fall armyworm (*Spodoptera frugiperda*), now established across all maize producing zones of sub-Saharan Africa, has emerged as a particular focus of botanical pesticide research. Neem-based formulations (NSKE at 5% and commercial azadirachtin products) have demonstrated consistent reduction of FAW larval populations by 40–70% in field and greenhouse trials in Ethiopia, Ghana, and Nigeria, acting primarily through antifeedant effects and growth disruption (Belay *et al.*, 2021; Macharia *et al.*, 2021). *Tithonia diversifolia* extracts and pyrethrum-neem combinations have shown synergistic activity against FAW



larvae, with combined formulations often outperforming individual extracts at equivalent concentrations (Macharia *et al.*, 2021).

Against the diamondback moth (*Plutella xylostella*), a key pest of brassica crops, multiple botanical extracts including neem oil, garlic extracts, and essential oils of eucalyptus and mint have shown larvicidal and oviposition-deterrent activity. Similarly, *Bacillus thuringiensis* compatible botanical combinations have been explored as enhanced IPM tools for managing armyworm and bollworm complexes in cotton and cereals (Dassanayake *et al.*, 2021).

Hemipteran Pests (Aphids, Whiteflies, and Related Pests)

Sucking pests of the order Hemiptera including aphids (*Aphis gossypii*, *Myzus persicae*), whiteflies (*Bemisia tabaci*), and leafhoppers constitute a major threat to vegetable, legume and grain crops, both through direct feeding damage and through vectoring of plant viruses. Botanical pesticides have demonstrated moderate to high efficacy against hemipteran pests in numerous studies. Pyrethrum-based formulations have consistently provided rapid knockdown of aphid colonies in field trials across East and West Africa (Mkindi *et al.*, 2020). Neem seed kernel extract (NSKE) at concentrations of 5% w/v has been shown to reduce aphid populations on cowpea and soybean by 55–75% relative to untreated controls, while also reducing whitefly populations on tomato (Ngegba *et al.*, 2022). Garlic extracts and onion-based formulations, locally accessible to smallholder farmers, have demonstrated repellent and contact toxicity to several aphid species.

Notably, Stevenson *et al.* (2020) and Mkindi *et al.* (2020) documented that farmers in Tanzania and other parts of East Africa routinely prepare and use locally sourced botanical pesticides from neem, *T. diversifolia*, and *Tephrosia vogelii* to manage sucking pests on legumes, with reported efficacy comparable to lower-dose synthetic treatments. These findings underscore the value of ethnobotanical knowledge as a source of leads for formal botanical pesticide research.

Coleopteran and other Field Pests

Coleopteran pests including flea beetles (*Phyllotreta spp.*), leaf-mining beetles, and bean stem maggots cause significant yield losses in vegetable and grain legume systems. Several botanical extracts, particularly those from plants in the Meliaceae and Lamiaceae families, have shown promising activity against coleopteran larvae and adults through both direct toxicity and repellence mechanisms (Ntalli & Menkissoglu-Spiroudi, 2022). Essential oils of eucalyptus, peppermint (*Mentha piperita*), and lemon grass (*Cymbopogon citratus*) have demonstrated fumigant and contact toxicity to several coleopteran pests in laboratory bioassays, though field validation under tropical conditions remains limited.

EFFICACY OF BOTANICAL PESTICIDES AGAINST STORED PRODUCT INSECT PESTS

The Challenge of Stored Grain Insect Pests

Post-harvest losses to insect pests of stored cereals and legumes represent a critical but often underappreciated dimension of food insecurity, particularly in tropical developing countries where grain storage infrastructure is frequently inadequate. The maize weevil (*Sitophilus zeamais*), lesser grain borer (*Rhyzopertha dominica*), granary weevil (*Sitophilus granarius*), *Callosobruchus* species (cowpea beetle) and flour beetles (*Tribolium castaneum* and *T. confusum*) are among the most damaging stored product pests worldwide. Losses attributable to these species can reach 20–40% of stored grain weight within months under poor storage conditions (Hikal *et al.*, 2024; Olanrewaju *et al.*, 2023). Conventional management relies heavily on chemical fumigants (phosphine, methyl bromide) and contact organophosphate insecticides (pirimiphos-methyl, chlorpyrifos-methyl), whose prolonged use has generated resistance in stored product pest populations and left unacceptable chemical residues in food commodities.

Botanical Protectants for Stored Grains

Botanical protectants for use in stored grain systems can be classified by their form of application: grain admixtures (powders blended with grain), surface treatments (dusts or sprays applied to storage bag exteriors or bin walls), fumigants (volatile essential oils in sealed storage), and seed treatments. Each application form has distinct efficacy and practical implications.

Neem leaf and seed kernel powders, when admixed with stored maize or sorghum at 1–5% w/w, have consistently reduced *Sitophilus zeamais* adult emergence, feeding activity, and grain weight



loss in numerous studies across Nigeria, Ghana, and East Africa. Ngegba *et al.* (2022) documented that neem leaf extract at 1.5 mg/100 g of stored grain significantly reduced adult survival and oviposition of *Sitophilus spp.* Kifle *et al.* (2025) demonstrated that fractionated leaf extracts of *Eucalyptus globulus*, *Tagetes minuta*, and *Annona squamosa* at doses of 5–15 g/kg of stored maize achieved significant adult *Sitophilus zeamais* mortality, progeny inhibition, and repellent activity, with the hexane fraction of *A. squamosa* showing the highest insecticidal potency.

Essential oils represent a particularly promising class of stored product botanical pesticides due to their fumigant activity in sealed storage systems. The volatile compounds in essential oils—terpenes such as 1,8-cineole (eucalyptol), thymol, carvacrol, linalool, and limonene—penetrate the insect's cuticle and respiratory system, disrupting neurological and enzymatic functions (Dassanayake *et al.*, 2021; Hikal *et al.*, 2024). Studies reviewed by Hikal *et al.* (2024) confirmed broad insecticidal activity of essential oils from cloves (*Syzygium aromaticum*), peppermint, thyme (*Thymus vulgaris*), and cinnamon (*Cinnamomum zeylanicum*) against key stored product pests including *Tribolium castaneum* and *Callosobruchus maculatus*. Essential oils from *Lippia* species have been documented to be highly effective against *S. zeamais* in sealed grain storage in African field conditions.

Spices and Plant Powders in On-Farm Storage

Beyond essential oils and liquid extracts, dried plant powder admixtures represent one of the most practically accessible and farmer-friendly approaches to botanical pest management in stored grain. Common household spices including black pepper (*Piper nigrum*), cloves, chilli pepper (*Capsicum annum*), and turmeric (*Curcuma longa*) have documented repellent or insecticidal activity against stored product pests (Hikal *et al.*, 2024). These materials are inexpensive, widely available, and require no specialised processing equipment, making them particularly attractive for smallholder farmers in sub-Saharan Africa who lack access to commercial pesticide supply chains. Olanrewaju *et al.* (2023) documented that mixed botanical powder formulations combining neem and chilli substantially reduced *S. zeamais* adult populations in stored maize over a 12-week storage period.

COMPARATIVE ANALYSIS: FIELD VS. STORED PRODUCT PEST MANAGEMENT

The application of botanical pesticides in field versus storage contexts presents distinct challenges and opportunities. Table 2 provides a comparative overview of key parameters distinguishing these two use domains.

Table 2: Comparative Overview of Botanical Pesticide Application for Field Crop and Stored Product Insect Pest Management

Parameter	Field Pest Management	Stored Product Pest Management	Key Challenges	References
Primary botanicals used	Neem, pyrethrum, garlic, <i>T. diversifolia</i>	Neem, eucalyptus, cloves, mint, <i>Annona</i>	Standardisation of active ingredients	<i>Isman (2020)</i>
Application form	Foliar sprays, dusts, seed dressings	Grain admixtures, fumigants, essential oils	Uniform coverage; dosage consistency	<i>Kifle et al. (2025); Hikal et al. (2024)</i>
Efficacy duration	<i>Short (3–7 days); UV degradable</i>	<i>Moderate (2–4 weeks) in sealed storage</i>	Photodegradation; volatility loss	<i>Dassanayake et al. (2021)</i>
Target pest examples	FAW, aphids, thrips, whitefly, caterpillars	<i>S. zeamais</i> , <i>Callosobruchus</i> spp., <i>Tribolium</i> spp.	Broad spectrum needed for mixed infestations	<i>Olanrewaju et al. (2023); Belay et al. (2021)</i>
Environmental safety	High; biodegradable; safe for beneficials	High; no residues in food at low doses	Some botanicals toxic to non-targets at high doses	<i>Pereira et al. (2024)</i>
Farmer accessibility	High for smallholders; locally sourced	High; on-farm preparation possible	Quality control; lack of commercial formulations	<i>Ngegba et al. (2022); Mkindi et al. (2020)</i>

A critical distinction between field and storage applications is the role of UV photodegradation. In open-field conditions, botanicals containing UV-sensitive compounds such as azadirachtin and pyrethrins degrade rapidly—often within 3–7 days necessitating frequent reapplication and precise timing relative to pest infestation peaks (Isman, 2020; Dassanayake *et al.*, 2021). In contrast, within sealed or low-light storage systems, botanical formulations exhibit more persistent activity, particularly when applied as grain admixtures or fumigants in airtight containers. This makes storage systems, in some respects, a more technically suitable environment for certain botanical applications.

In both domains, the locally available and low-cost nature of many botanical sources represents their most strategically important advantage for smallholder farmers in tropical developing countries. Farmers in Nigeria, Ghana, Tanzania, and Ethiopia have been documented to use locally sourced neem, *T. diversifolia*, and *Tephrosia* leaves both as field crop protectants and stored grain treatments with minimal processing, relying on traditional knowledge validated by modern scientific research (Mkindi *et al.*, 2020; Stevenson *et al.*, 2020).

MECHANISMS OF PESTICIDAL ACTION OF BOTANICAL COMPOUNDS

The diversity of bioactive secondary metabolites in botanical pesticides confers a correspondingly diverse array of mechanisms of pesticidal action a feature that is highly advantageous from a resistance management perspective, since insects are less likely to develop resistance to multiple simultaneous modes of action than to a single synthetic compound.

Neurological Disruption

Several classes of botanical compounds exert their insecticidal effects primarily through disruption of insect neurological function. Pyrethrins bind to and persistently activate voltage-gated sodium channels in nerve cell membranes, causing repetitive and uncontrolled nerve firing, paralysis, and death. Nicotine and related tobacco alkaloids are agonists at nicotinic acetylcholine receptors (nAChR), mimicking the action of the neurotransmitter acetylcholine without being hydrolysed by



acetylcholinesterase, leading to sustained stimulation and eventual paralytic toxicity. Organosulfur compounds in garlic (allicin, diallyl disulfide) inhibit acetylcholinesterase (AChE) activity, preventing normal neurotransmitter recycling at synapses (Dassanayake *et al.*, 2021). Essential oil monoterpenes such as 1,8-cineole interfere with octopamine receptors and GABA-gated chloride channels in the insect nervous system, disrupting normal neural transmission (Hikal *et al.*, 2024).

Disruption of Endocrine and Developmental Processes

Azadirachtin from neem is the premier example of a botanical compound that targets insect endocrine regulation rather than (or in addition to) direct neurological toxicity. By structurally mimicking and competitively antagonising 20-hydroxyecdysone the steroid hormone that triggers moulting in insects azadirachtin disrupts ecdysis, preventing larvae from completing moulting cycles and thereby blocking development to the pupal and adult stages. Sub-lethal doses affect fecundity, larval behaviour, and adult sexual maturation, amplifying its impact on pest population dynamics beyond direct acute toxicity (Isman, 2020; Harun-Ur-Rashid *et al.*, 2025).

Mitochondrial and Metabolic Disruption

Rotenone and related isoflavonoids from Derris species inhibit complex I of the mitochondrial electron transport chain, blocking NADH oxidation and thereby disrupting cellular energy (ATP) production. Sesquiterpene lactones from *T. diversifolia* (tagitinins) and acetogenins from *Annona squamosa* similarly interfere with mitochondrial energy metabolism but at complexes I and III, causing oxidative stress and metabolic failure in insect midgut and muscle tissues (Macharia *et al.*, 2021; Kifle *et al.*, 2025). These mitochondrial-targeting compounds are particularly effective as contact and ingestion poisons.

Antifeedant and Repellent Activity

Beyond direct toxicity, many botanical compounds reduce pest damage through sub-lethal antifeedant and repellent mechanisms. Azadirachtin and other neem limonoids are among the most potent known antifeedants for lepidopteran larvae. Phenolic compounds and tannins in many plant extracts make foliage unpalatable or cause digestive disturbance upon ingestion. Essential oil terpenoids—particularly those in eucalyptus, peppermint, and lemongrass—act as spatial repellents, deterring pest insects from colonising treated crops or stored grain (Dassanayake *et al.*, 2021; Hikal *et al.*, 2024). These sub-lethal modes of action are particularly valuable in IPM systems because they reduce pest damage without the same selection pressure for resistance development as acute toxicants.

CHALLENGES AND LIMITATIONS OF BOTANICAL PESTICIDES

Variability in Active Ingredient Content

One of the most significant technical challenges confronting botanical pesticide development is the natural variability in bioactive compound concentration across different plant populations, ecotypes, harvest times, and growing conditions. The concentration of azadirachtin in neem seeds, for example, can vary by a factor of five or more depending on geographic origin, soil type, rainfall, and plant age. Similarly, essential oil yields and chemical composition in plants such as eucalyptus and lemongrass are highly influenced by seasonal and environmental factors (Saikumar *et al.*, 2025). This variability poses a major challenge to product standardisation—a prerequisite for regulatory approval and consistent field efficacy.

Environmental Degradation and Short Residual Activity

The same rapid biodegradability that makes botanical pesticides environmentally attractive also limits their practical residual activity under field conditions. Photodegradation by UV radiation, hydrolysis by rain, and microbial breakdown in the soil can reduce the effective half-life of key botanical compounds to just a few days in the open field, necessitating more frequent reapplication than synthetic alternatives (Dassanayake *et al.*, 2021; Ngegba *et al.*, 2022). For smallholder farmers with limited labour and resources, frequent application schedules can be a barrier to adoption. Development of UV-protected, microencapsulated, or slow-release formulations is an active research area aimed at overcoming this limitation (Kumar *et al.*, 2025).

Regulatory and Commercialisation Barriers

The regulatory pathway to commercialisation of botanical pesticides is often as demanding as for synthetic products, despite the generally superior safety profile of botanicals. In the European Union,



approval dossiers under Regulation (EC) 1107/2009 can take 5–7 years to process, with substantial associated costs that are prohibitive for most botanical product developers (Marchand, 2024). In Nigeria and other African countries, while national pesticide registration authorities exist under institutions such as NAFDAC, the absence of harmonised guidelines specifically tailored to botanical and biopesticide products creates uncertainty and delays (Frontiers, 2025). The difficulty in defining a single 'active ingredient' in complex multi-compound botanical mixtures—in contrast to single-molecule synthetic insecticides—further complicates regulatory evaluation.

Inconsistent Efficacy Under Field Conditions

Laboratory bioassay results for botanical pesticides frequently demonstrate efficacy that is not consistently replicated under field conditions, where environmental variability, non-uniform pest pressure, and plant growth dynamics interact in complex ways. Some botanical products that demonstrate near-complete pest control in controlled experiments show highly variable results across field sites, seasons, and crop varieties, undermining farmer confidence in these alternatives (Springer Nature, 2024). Bridging the gap between laboratory demonstration and reliable field performance requires systematic multi-location, multi-season field validation studies, which remain insufficient for many botanical candidates in sub-Saharan Africa.

EMERGING INNOVATIONS IN BOTANICAL PESTICIDE TECHNOLOGY

Nanoformulations

Nanotechnology offers one of the most promising avenues for overcoming the formulation and stability limitations of botanical pesticides. Nano-encapsulation of botanical active compounds within polymeric or lipid nanoparticles, nanoemulsions, or solid lipid nanoparticles can protect photolabile compounds such as azadirachtin from UV degradation, prolong their environmental persistence, improve their foliar adhesion, and enhance their penetration through the insect cuticle (Kumar *et al.*, 2025; Harun-Ur-Rashid *et al.*, 2025). Nanoemulsions of eucalyptus and patchouli essential oils have demonstrated enhanced efficacy against mosquito larvae compared to conventional formulations, with potential applications for stored product pest management (Hikal *et al.*, 2024). While regulatory pathways for nano-formulated biopesticides are still evolving, this technological frontier holds considerable promise for extending the practical utility of botanical insecticides.

Synergistic Multi-Plant Formulations

The combination of botanical extracts from two or more plant sources with complementary or synergistic modes of action represents a strategically sound approach to enhancing pesticidal efficacy while reducing required application concentrations. Several recent studies have documented synergistic or additive interactions between neem and pyrethrum combinations against aphids and caterpillars in field crops, and between neem and *T. diversifolia* extracts against FAW larvae (Macharia *et al.*, 2021; Dassanayake *et al.*, 2021). By targeting multiple biochemical pathways simultaneously—for example, combining azadirachtin's growth disruption with pyrethrin's rapid neurological knockdown—multi-plant formulations can achieve efficacy approaching synthetic insecticide standards while exerting reduced resistance selection pressure. This approach is particularly relevant for IPM systems in sub-Saharan Africa, where multiple locally available plant species can be combined by farmers with minimal additional infrastructure.

Integration with Biological Control Agents

The compatibility of botanical pesticides with entomopathogenic fungi (EPF) such as *Beauveria bassiana* and *Metarhizium anisopliae*, and with parasitoid wasps such as *Cotesia* spp., offers a pathway to highly integrated, multi-trophic pest management systems. Unlike broad-spectrum synthetic insecticides, many botanical preparations have demonstrated selective toxicity that spares important natural enemies of pests. Pyrethrum-*B. bassiana* combinations have been shown to exploit the rapid knockdown of pyrethrins to increase fungal spore contact with target insects, while the persistent pathogenicity of the fungus provides extended post-application mortality (Frontiers, 2025). Such integrated biopesticide packages are considered a frontier of next-generation IPM design.



FUTURE RESEARCH PERSPECTIVES

Based on the literature reviewed, the following priority areas for future research and policy action are identified:

1. Systematic multi-location, multi-season field trials of the most promising botanical candidates (particularly neem, *T. diversifolia*, eucalyptus, and pyrethrum combinations) across diverse agro-ecological zones in sub-Saharan Africa are urgently needed to generate robust efficacy and safety datasets for regulatory submission.
2. Investment in standardised extraction and formulation protocols, including phytochemical fingerprinting and bioassay-guided fractionation, is necessary to address the active ingredient variability that currently limits product reliability.
3. Research into nano-encapsulation and UV-protective formulation technologies specifically tailored to tropical conditions could substantially extend the residual activity and field efficacy of degradation-prone botanical compounds.
4. Harmonised regulatory frameworks for botanical biopesticides at the regional level—particularly within ECOWAS in West Africa—would reduce registration costs, accelerate market entry of approved products, and stimulate private sector investment in botanical pesticide commercialisation.
5. Farmer participatory research approaches that integrate traditional ethnobotanical knowledge with formal scientific validation offer a cost-effective and culturally appropriate pathway to identifying new botanical leads and validating preparation methods accessible to smallholder farmers.
6. The ecology of botanical pesticide use—including their effects on non-target arthropods, soil microbiota, and pollinators under realistic field application scenarios—requires substantially more research to complete the safety profile needed for broad policy endorsement.

CONCLUSION AND RECOMMENDATION

This review demonstrated that plant botanical pesticides represent a scientifically credible, environmentally sound and increasingly important component of contemporary and future pest management systems for both field crops and stored grain commodities. The diversity of bioactive secondary metabolites across plant taxa—from the triterpenoids of neem to the pyrethrins of *Chrysanthemum*, the sesquiterpene lactones of *Tithonia*, and the essential oil terpenoids of eucalyptus and garlic—offers a rich pharmacopoeia of pesticidal compounds with varied and complementary mechanisms of action. Recent literature (2020–2025) has confirmed and extended the documented efficacy of these materials against economically important field crop pests including fall armyworm, aphids, and whitefly, as well as critical stored product pests including *Sitophilus zeamais*, *Tribolium spp.*, and *Callosobruchus spp.*

While significant challenges includes variability in active ingredient content, short residual activity, complex regulatory pathways and inconsistent field performance emerging innovations in nanoformulation technology, synergistic multi-plant combinations and integration with biological control agents are actively addressing these limitations. The global botanical pesticide market's projected growth at 7–10% CAGR through 2030 reflects growing commercial and institutional confidence in these alternatives.

For Nigeria and sub-Saharan Africa more broadly, where toxic synthetic pesticides remain widely misused with inadequate regulatory oversight, where locally occurring botanical pesticide plants are abundant and economically accessible to smallholder farmers, and where the burden of food insecurity demands both higher crop yields and safer food commodities, the strategic promotion of botanical pesticides within IPM frameworks represents both a scientific and a public health imperative. It is anticipated that, with appropriate investment in research, formulation technology, and regulatory harmonisation, plant botanicals will fulfil their promise as major pesticides of the future for both field and storage pest management.



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REFERENCES

- Belay, D.K., Waktole, H., Azerefegn, D., Tesfaye, K., & Sori, W. (2021). Toxicological evaluation of selected synthetic insecticides on fall armyworm (*Spodoptera frugiperda* J.E. Smith) larvae in Ethiopia. *Pest Management Science*, **77**(6): 2809–2817.
- Dassanayake, M.K., Chong, C.H., Khoo, T.J., Figiel, A., Szumny, A., & Choo, C.M. (2021). Synergistic field crop pest management properties of plant-derived essential oils in combination with synthetic pesticides and bioactive molecules: A review. *Foods*, **10**(9): 2016-?.
- Harun-Ur-Rashid, M. (2025). Biomimetic and synthetic advances in natural pesticides: Balancing efficiency and environmental safety. *Journal of Chemistry*, 2025, 1510186.
- Hikal, W.M., Baz, M.M., Alshehri, M.A., Bahattab, O., Baeshen, R.S., & Selim, A.M. (2024). Plant-based bioactive compounds for grain storage: A comprehensive review. *Cogent Food & Agriculture*, **10**(1): 2316152.
- Isman, M.B. (2020). Botanical insecticides in the twenty-first century: Fits and starts, successes and failures. *Annual Review of Entomology*, **65**: 433–453.
- Kifle, F., Girma, M., Gebresilassie, A., Woldehawariat, Y., & Ele, E. (2025). Chemical composition and insecticidal potential of botanical fractionation extracts for the management of *Sitophilus zeamais* (Coleoptera: Curculionidae) in stored maize. *Heliyon*, **11**: 42131.
- Kumar, R., Kaur, R., Ranout, A.S., & Nadda, G. (2025). A review on novel formulations and delivery systems of botanical insecticides for enhanced efficacy. *Neotropical Entomology*, **54**(1): 234–240.
- Macharia, M., Kamau, A.W., Nderitu, J.H., Kasina, M., & Amudavi, D.M. (2021). Pesticidal potential of *Tithonia diversifolia* leaf extracts against *Spodoptera exigua*. *Industrial Crops and Products*, **111**: 113540.
- Marchand, P.A. (2024). Biopesticide regulation in the EU: Current challenges and future opportunities. *Current Opinion in Environmental Science and Health*, **38**: 100541.
- Mkindi, A., Mpumi, N., Temba, Y., Stevenson, P.C., Ndakidemi, P.A., Mtei, K., & Belmain, S.R. (2020). Invasive weeds with pesticidal properties as potential new crops. *Industrial Crops and Products*, **110**: 113–122.
- Ngegba, P.M., Cui, G., Khalid, M.Z., & Zhong, G. (2022). Use of botanical pesticides in agriculture as an alternative to synthetic pesticides. *Agriculture*, **12**(5): 600.
- Ntalli, N.G., & Menkissoglu-Spiroudi, U. (2022). Botanicals of Lamiaceae family as insecticides: An updated review. *Plants*, **11**(14): 1870.
- Olanrewaju, O.D., Opara, J.C., Nwite, O.P., Umoru, U., & Aliyu, M.S. (2023). Comparative effects of botanical powders in controlling *Sitophilus zeamais* (maize weevils) in stored maize. *Biology and Life Sciences Forum*, 2023.
- Pereira, V., Figueira, O., & Castilho, P.C. (2024). Flavonoids as insecticides in crop protection: A review of current research and future prospects. *Plants*, **13**(6): 776.
- Saikumar, T., Manideep, S., Paschapur, A.U., & Thrilekha, D. (2025). Botanical pesticides: Exploring successes, challenges, and future directions in sustainable pest management. *Journal of Plant Diseases and Protection*, **132**(6): 12-23.
- Stevenson, P.C., Isman, M.B., & Belmain, S.R. (2020). Pesticidal plants in Africa: A global vision of new biological control products from local uses. *Industrial Crops and Products*, **110**, 2–9.
- Thomine, E., & Siegwart, M. (2024). Status and prospects of botanical biopesticides in Europe and Mediterranean countries. *Biomolecules*, **12**(2): 311-322.