Effect of Botanicals for the Management of Insect Pests in Cereal Crops

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Cereal crops play a pivotal role in global food systems, yet they are highly vulnerable to damage caused by insect pests. Conventional reliance on synthetic pesticides has led to numerous ecological and health-related concerns, including pest resistance, biodiversity loss and chemical residues in food and water. In response, botanical insecticides have gained attention for their eco-friendly properties and efficacy in pest suppression. This chapter explores the historical development, active ingredients and mechanisms of action of botanicals such as neem, pyrethrum, nicotine, rotenone, sabadilla, ryania and others. Emphasis is placed on their roles in pest management strategies for cereal crops. The chapter also evaluates challenges such as formulation stability, regulatory constraints and commercialization barriers, alongside opportunities for integration within sustainable agricultural practices. Botanical insecticides, with their biodegradable and target-specific nature, offer a viable component of integrated pest management systems for ensuring safer cereal production.

Keywords: *Botanical insecticides, Plant-based pesticides, Azadirachtin, Pyrethrum, Phytochemicals, Antifeedants, Repellents, Cereal crops, Sustainable agriculture, Integrated pest management (IPM).*

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Introduction

The use of plant-derived substances, now commonly referred to as botanical insecticides, has a long-standing history in agriculture, with documented applications dating back over two millennia in ancient civilizations such as China, Egypt, Greece and India (Thacker, 2002). Even in Europe and North America, the use of botanicals for pest control has been documented for over 150 years, predating the development of major synthetic insecticide classes, such as organochlorines, organophosphates, carbamates and pyrethroids, between the 1930s and 1950s (Ware, 1983).

However, the rise and widespread adoption of synthetic insecticides during the 20th century significantly diminished the prominence of botanicals, relegating them to a marginal role in crop protection strategies. The growing global demand for food, driven by an ever-increasing population, has led to the widespread use and dependence on synthetic chemical pesticides as a fast and effective means to control crop pests and diseases. Although synthetic insecticides initially revolutionized agricultural productivity, their overuse and misuse have brought significant environmental and health concerns (Perry et al., 2013) These include toxicity to non-target organisms, reduction in biodiversity and persistent residues that accumulate in soil and groundwater, leading to environmental pollution and contributing to ozone layer depletion. Chronic human health issues, resulting from both direct exposure and consumption of pesticide-contaminated food, have also been linked to synthetic pesticides. Furthermore, synthetic compounds are often non-biodegradable and can persist in ecosystems, disrupting ecological balance and contaminating food chains. The history of pesticide use is marked by unintended consequences, such as acute and chronic poisoning of applicators, farmworkers and consumers, destruction of aquatic and terrestrial wildlife, disruption of natural biological control mechanisms and pollinator populations and the development of pesticide resistance in pest species (McLaughlin, 1997). In response to these concerns, various governments implemented regulatory actions aimed at curbing the most hazardous pesticide products. This led to the banning or restriction of numerous synthetic insecticides and the formulation of policies favoring the use of safer alternatives (Gerland et al., 2014). In the United States, for instance, the Environmental Protection Agency (EPA) introduced the concept of “reduced risk” pesticides in the early 1990s, granting these products a more favorable regulatory status. Furthermore, the enactment of the Food Quality Protection Act in 1996 significantly altered the pesticide regulatory landscape. By reassessing acceptable pesticide residue levels in food, this legislation indirectly phased out many synthetic insecticides developed before 1980. These regulatory shifts have stimulated a renewed interest in the development of alternative pest management strategies, particularly those with reduced human and environmental toxicity. Among these, botanical insecticides have emerged as promising candidates (Regnault-Roger, 2005). Derived from plant sources, botanical pesticides offer several advantages: they are biodegradable, inexpensive, exhibit diverse modes of action, are readily available and generally pose low toxicity risks to non-target organisms. Scientific interest in plant-derived insecticidal compounds has increased significantly over the past 25 years. A substantial body of literature now documents the isolation of hundreds of plant secondary metabolites with insecticidal, antifeedant or repellent properties under laboratory conditions (Dev, (2017, Kostyukovsky, 2002).

Historical background

Throughout history, humans have drawn inspiration from nature, observing that certain plants possess inherent mechanisms to deter pests more effectively than others. This understanding led to the early use of plant-derived substances now known as botanical pesticides for crop protection. Long before the advent of synthetic chemicals, botanical formulations were employed in ancient civilizations. References to the use of such botanicals appear in early Egyptian hieroglyphs, as well as in ancient Chinese, Greek and Roman texts. In India, the neem tree (*Azadirachta indica* Juss., family Meliaceae) holds a prominent place, with its pesticidal properties documented in the Vedas sacred Sanskrit scriptures believed to be over 4,000 years old (Philogene et al., 2005). The earliest use of botanical pesticides and naturally occurring allelochemicals was largely based on readily accessible plant materials. These substances were initially employed to manage insect pests, which were easier to detect and identify compared to plant pathogens. As a result, early pest control efforts focused more on insects than on microbial threats. In recent years, a number of comprehensive reviews and publications have explored the development and application of plant-based biopesticides (Thacker, 2002; Regnault-Roger et al., 2005).

Prior to the Second World War, pest management primarily relied on four major groups of naturally derived compounds: nicotine and other alkaloids, rotenone and related rotenoids, pyrethrum and its active pyrethrins, as well as various vegetable oils. Despite their effectiveness, some of these substances presented limitations such as nicotine's toxicity to non-target organisms and the chemical instability of pyrethrum under environmental conditions. With the advent of World War II, the development and widespread adoption of synthetic insecticides such as organochlorines, organophosphates and carbamates began to replace botanical alternatives. These synthetic compounds were more stable, cost-effective and easier to use, leading to a marked decline in the application of plant-based pesticides. This trend persisted until the emergence of environmental concerns in the 1960s (Alburo & Olofson, 1987). However, growing awareness of the adverse effects of synthetic pesticides on non-target organisms and the environment led to a resurgence of interest in botanical alternatives. Despite the predominant focus on developing new synthetic compounds, significant research continued in the field of plant-based biopesticides throughout the latter half of the 20th century. These efforts aimed to enhance the stability of botanical products and identify novel bioactive molecules or new plant sources. Notable examples include the synthesis of pyrethroids stable, chemically modified versions of natural pyrethrins and the extensive development of neem-based formulations from plants in the Meliaceae family.

Factors affecting use of botanical pesticides

- Raw material availability.
- Standardization of botanical extracts containing a complex mixture of active constituents.
- Solvent types, plant species and part of plant.
- Rapid degradation.
- State registration.
- Market opportunities for botanical pesticides.
- Weather conditions.

Current status of botanicals pesticides in India

In India, the use of pesticides for agricultural or other purposes requires mandatory registration under the Insecticides Act, 1968, in accordance with the guidelines established by the Central Insecticides Board and Registration Committee (CIBRC), operating under the Department of Agriculture and Farmers Welfare. As per current regulations, only three botanical pesticides have received official approval for commercial use: Azadirachtin (derived from neem), Pyrethrum and Eucalyptus leaf extract. Among these, neem-based formulations containing azadirachtin are the most widely utilized in agricultural pest management, followed by Pyrethrum and Eucalyptus leaf extract (Thongni,2023).

Mode of action of botanicals

Nicotine: Nicotine’s insecticidal properties were identified as early as the 16^{th} century. This compound is not found free in the plant but in the form of maleates and citrates. It is essentially a non-persistent contact insecticide (Kumbhar, 2020). Nicotine, a pyridine alkaloid predominantly extracted from the foliage of *Nicotiana tabacum* and related species, has been extensively utilized as a botanical insecticide due to its potent neurotoxic properties. Along with structurally analogous compounds such as nor-nicotine and anabasine, nicotine acts as a synaptic neurotoxin by serving as an agonist at nicotinic acetylcholine receptors (nAChRs) in the insect central nervous system.

This mode of action results in sustained neuronal excitation, leading to convulsions, paralysis, and eventual death. The symptomatology and mechanism closely parallel those observed with synthetic acetylcholinesterase inhibitors such as organophosphates and carbamates (Hayes, 1982; Regnault-Roger & Philogene, 2008). Due to the high toxicity of pure nicotine to mammals (rat oral LD50 of 50 mg/kg) and its quick absorption through human skin, its use has decreased over time. It is now mainly employed as a fumigant in greenhouses targeting soft-bodied insect pests (Casanova et al., 2002).

NICOTINE	
Source	*Nicotiana tabacum*
Active ingredients	Nicotine
Action mechanism	Mimics the neurotransmitter Acetylcholine
Mode of application	Foliar spray

Nicotine is a fast-acting neurotoxin that disrupts nerve signal transmission in both insects and mammals by binding to nicotinic acetylcholine receptors (nAChRs). This leads to continuous nerve firing, causing the failure of systems dependent on controlled neural input. While broadly neurotoxic, nicotine exhibits selective toxicity in insects, affecting certain species more than others (El-Wakeil, 2013).

Rotenone: Rotenone is a plant-based insecticide with broad-spectrum activity, obtained from the roots and stems of tropical legume species such as *Derris* (*D. elliptica*, *D. involuta*), *Lonchocarpus* (*L. utilis*, *L. urucu*) and *Tephrosia virginiana***.** (Weinzierl,1999). Rotenone is a contact and ingestion compound, which acts as a repellent too (Kumbhar, 2020). Rotenone functions as both a contact and systemic insecticide (Fields et al.,1991). It primarily acts as a stomach poison by inhibiting cellular respiration in insects. Specifically, it blocks the transfer of electrons between NAD^+ and coenzyme Q in the mitochondrial electron transport chain, leading to a disruption in ATP production and cellular metabolism (Ware & Whitacre, 2004). The compound mainly targets nerve and muscle tissues, causing a swift halt in feeding activity. Insect mortality typically occurs within a few hours to several days following exposure (El-Wakeil, 2013).

ROTENONE	
Source	*Derris* spp., *Lonchocarpus* spp. and *Tephrosia* spp.
Active ingredients	Rotenone
Action mechanism	Disrupts energy metabolism in mitochondria in nerve axons
Mode of application	Dried root powder, spray

Sabadilla: This compound is derived from the seeds of *Schoenocaulon officinale*, a plant native to South America and belonging to the Liliaceae family. The seeds are rich in alkaloids, which are responsible for the plant's toxic effects. The purified active constituents, known as cevadine-type alkaloids, are highly toxic to mammals, with a rat oral LD50 of approximately 13 mg/kg. However, commercial formulations usually contain less than 1% of the active substance, offering a reasonable safety margin (El-Wakeil, 2013).

SABADILLA	
Source	*Schoenocaulon officinale*
Active ingredients	Veratridine, Cevadine
Action mechanism	Interferes with Ns & k ion movement in nerve axons
Mode of application	Foliar spray – Dust or Liquid formulation

In insects, the toxic alkaloids present in sabadilla interfere with the normal functioning of nerve cell membranes, leading to disruption of nerve activity, paralysis and eventual death. While some insect species succumb quickly after exposure, others may remain paralyzed for several days before dying. The insecticidal efficacy of sabadilla can be significantly enhanced when combined with synergists such as piperonyl butoxide (PBO) or MGK 264.

Ryania: Ryania is another botanical insecticide whose use has declined over time. It is derived by pulverizing the wood of *Ryania speciosa*, a shrub native to the Caribbean and belonging to the family Flacourtiaceae. The powdered material contains less than 1% of ryanodine, a potent alkaloid known to disrupt calcium ion release in muscle cells, thereby affecting muscular function (National Research Council, 2000). Although its usage is now limited, it is still occasionally employed by apple producers for managing the codling moth (*Cydia pomonella*).

RYANIA	
Source	*Ryania speciosa*
Active ingredients	Ryanodine
Action mechanism	Activates Ca ion release channels & causes paralysis in muscles
Mode of application	Foliar spray

Ryania functions as a slow-acting stomach poison. While it does not induce immediate paralysis or rapid knockdown effects, it leads to feeding cessation shortly after ingestion. Detailed studies on its precise mode of action in insect physiology are limited. However, it is known that its efficacy can be enhanced when combined with synergists like piperonyl butoxide (PBO) and it tends to perform best under warm or hot climatic conditions.

Pyrethrum: Pyrethrum is a widely utilized botanical pesticide in India and globally, obtained from the dried and powdered flower heads of the daisy *Chrysanthemum cinerariaefolium* (family Asteraceae) (El-Wakeil, 2013). This plant contains its highest concentration of active compounds in the flowers, with minimal amounts in other plant parts (Rhoda, 2006; Sola, 2014). The term "pyrethrum" refers to the crude flower powder itself, whereas "pyrethrins" denotes the six naturally occurring insecticidal constituents found within these flowers. A significant portion of the global pyrethrum supply is cultivated in Kenya, making it a key center for production.

PYRETHRIUM	
Source	*Chrysanthemum cinerariaefolium*
Active ingredients	Pyrethrin I and II, Cinerin I and II, Jasmolin I and II
Action mechanism	Interfere with Na & K ion movement in nerve axons
Mode of application	Flower extracts as a spray or dust

Pyrethrins, a class of natural insecticidal compounds, exert their toxic action by interfering with the voltage-gated sodium channels in insect nerve axons, thereby disrupting the normal exchange of sodium and potassium ions. This interference leads to impaired nerve impulse transmission, resulting in rapid paralysis or “knockdown” of the insect. Although pyrethrins act quickly, many insects possess metabolic enzymes capable of detoxifying these compounds, allowing them to recover from the initial paralysis.

To enhance efficacy and prevent detoxification, pyrethrin-based formulations are commonly combined with piperonyl butoxide (PBO), a synergist that inhibits insect metabolic enzymes and prolongs the toxic effect (Rattan, 2010).

Neem based botanical pesticide: Two primary types of botanical pesticides are derived from the seeds of the Indian neem tree, *Azadirachta indica* (family Meliaceae) (Schmutterer, 1990; 2002). Neem oil, obtained through the cold pressing of seeds, is effective against soft-bodied insects and mites and is also used in the management of phytopathogens. In addition to its physical mode of action on pests and fungi, the bioactivity of neem oil is attributed in part to disulfide compounds present in the oil (Dimetry et al., 2010; Dimetry, 2012). More highly valued than neem oil are the medium-polarity extracts obtained from the seed residue left after oil extraction. These extracts are rich in the complex triterpenoid azadirachtin. Neem seeds contain over a dozen azadirachtin analogs; however, azadirachtin itself is the predominant form, with minor analogs contributing little to the overall efficacy of the extract. In addition to azadirachtin, neem seed extracts contain other triterpenoids such as salannin, nimbin and their derivatives. While the roles of these additional compounds have been debated (El-Sayed, 1982–1983a, b) most evidence indicates that azadirachtin is the principal active component responsible for pesticidal activity (Isman et al., 1996). Typically, neem seeds contain 0.2–0.6% azadirachtin by weight. Therefore, solvent partitioning or other chemical processing techniques are necessary to concentrate the active ingredient to levels of 10–50%, as found in technical-grade formulations used in commercial neem-based products (Sallena, 1989; Schmutterer, 1990). Azadirachtin a principal bioactive compound derived from neem (*Azadirachta indica*), exerts multiple detrimental effects on insect physiology and behavior. At the hormonal level, azadirachtin inhibits the biosynthesis and release of ecdysteroids (molting hormones) from the prothoracic glands, leading to disrupted molting and incomplete ecdysis in immature stages. In adult females, the same mechanism results in reproductive failure and sterility (El-Wakeil, 2013). In addition to its hormonal action, azadirachtin functions as a potent antifeedant, deterring feeding behavior in a wide range of insect species. Compounds such as azadirachtin, salannin and melandriol induce anti-peristaltic activity in the insect alimentary canal, triggering a vomiting-like reflex that reinforces feeding deterrence. Furthermore, neem compounds exhibit oviposition deterrent properties, preventing egg-laying behavior in female insects.

At the biochemical level, azadirachtin and other limonoids in neem inhibit ecdysone 20-monooxygenase, the enzyme responsible for converting ecdysone to its active form, 20-hydroxyecdysone, a key hormone regulating insect metamorphosis. This interference likely results from the disruption of microtubule assembly in rapidly dividing cells, further impairing growth and development (Morgan, 2009; Campos et al., 2016). Furthermore, azadirachtin inhibits the release of prothoracicotropic hormone (PTTH) and allatotropins from the brain corpus cardiacum complex, leading to reduced fertility and fecundity in insects (Campos et al., 2016; Su & Mulla,1999). It also interferes with mitosis in a manner similar to colchicine and causes direct histopathological effects on the insect gut, epithelial cells, muscles, and fatty tissues. These effects collectively result in restricted movement and reduced flight activity (Wilps et al., 1992; Qiao et al., 2014).

AZADIRACHTIN (Neem based botanical pesticide)	
Source	Neem tree (*Azadirachta indica*)
Active ingredients	Azadiractin, Salanin, Melandriol and other limonoids
Action mechanism	Mitotic inhibitor, damages the hormonal system, food poison, feeding deterrent, oviposition deterrent and impairs metamorphosis and reproduction, mortality
Mode of application	Neem Extract Cakes, Neem oil, Kernel Extract

Eucalyptus essential oil: Eucalyptus oil is a complex mixture of various phytochemicals such as monoterpenes, sesquiterpenes, aromatic phenols, oxides, ethers, alcohols, aldehydes and ketones. The composition and proportion of the chemical constituents vary with the species.

EUCALYPTUS	
Source	*Eucalyptus* spp.
Active ingredients	8-Cineole (eucalyptol), citronellal, citronellol, citronellyl acetate, p-cymene, eucamalol, limonene, linalool and α-pinene
Action mechanism	Antifeedent, Repellant, ovicidal, larvicidal, pupicidal and adulticidal
Mode of application	Extracts as a spray or dust

The bioactivity of essential oils is influenced by the chemical composition of the oil, which varies based on the type, nature and concentration of individual constituents. These factors are, in turn, affected by species-specific traits, as well as environmental conditions such as season, geographic location, climate, soil type and the method of extraction and processing of plant material (Brooker & Kleinig, 2006). Among the constituents, 1,8-cineole, a major component in Eucalyptus essential oil, has been identified as having the strongest pesticidal activity (Batish et al., 2008). Eucalyptus oil functions as a natural insect repellent and antifeedant, exhibiting efficacy against a wide range of insect pest species.

Potential new botanicals

Annonaceous acetogenins: Botanical pesticides have traditionally been derived from the seeds of tropical *Annona* species, which belong to the custard apple family (Annonaceae). Notable examples include sweetsop (*Annona squamosa*) and soursop (*Annona muricata*), both which are significant sources of fruit juices in Southeast Asia. Extensive research during the 1980s led to the identification of several long-chain fatty acid derivatives, collectively known as acetogenins, which are responsible for the insecticidal activity of these plants. The primary acetogenin isolated from *A. squamosa* seeds is annonin I, also known as squamocin, while a structurally related compound, asimicin, has been extracted from the bark of the American pawpaw tree (*Asimina triloba*) (McLaughlin et al., 1997; Johnson et al., 2000). Mikolajczak et al. (1988) were granted a U.S. patent for insecticides based on acetogenins derived from *A. triloba*, while Bayer AG (Germany) holds a similar patent for acetogenins extracted from *Annona* species (Moeschler et al., 1987). The acetogenins derived from *Annona* species act primarily as slow-acting stomach poisons, showing notable efficacy against chewing insect pests, including lepidopteran larvae and the Colorado potato beetle (*Leptinotarsa decemlineata*). Among these compounds, asimicin has been extensively studied for its mode of action. Experimental evidence indicates that asimicin significantly inhibits mitochondrial respiration. In fourth instar larvae of *Ostrinia nubilalis*, asimicin was found to reduce oxygen consumption, as determined using a constant volume manometer. Further analysis using mitochondria isolated from the midgut tissues of fifth instar larvae revealed that asimicin causes a substantial reduction in state 3 respiration, particularly when malate and pyruvate were used as substrates. The concentration required to achieve 50% inhibition (IC_{50}) was determined to be 0.55 nmol/mg protein, as measured via polarographic techniques (Lewis et al., 1993). These findings suggest that asimicin disrupts oxidative phosphorylation in insect mitochondria, contributing to its insecticidal effect.

Sucrose esters: In the early 1990s, researchers at the U.S. Department of Agriculture identified sugar esters present in the foliage of the wild tobacco plant *Nicotiana gossei* as having insecticidal activity against certain soft-bodied insects and mites. Although these compounds were patented for their pesticidal potential, commercial-scale extraction from plant biomass proved unfeasible. This challenge led to the development of synthetic analogs sucrose esters produced by combining sugar with fatty acids derived from vegetable oils (Pittarelli et al.,1993).

AVA Chemical Ventures (USA) subsequently patented and registered an insecticidal/miticidal formulation composed of mono, di and triesters of sucrose octanoate and sucrose di octanoate, primarily using C8 and C10 fatty acids. Registered in 2002, this formulation contains 40% active ingredient (Farone et al., 2002). Mechanistically, it functions similarly to insecticidal soaps particularly those developed in the 1980s containing potassium oleate acting as a contact insecticide. These compounds exert their effect by suffocating target pests (blocking spiracles) or disrupting the protective wax and membrane structures of the insect cuticle, leading to desiccation. While these sucrose ester-based products have demonstrated utility in domestic and greenhouse settings, their broader application in large-scale agriculture remains under evaluation. In terms of mode of action, this formulation shows minimal functional distinction from the pesticidal soaps developed in the 1980s, particularly those based on fatty acid salts such as potassium oleate. Acting as a contact pesticide, it targets soft-bodied insects and mites by causing suffocation through the blockage of spiracles or by disrupting the protective cuticular waxes and membrane structures of the integument, ultimately resulting in desiccation (Buta et al., 1993; Isman, 2006). While these formulations have proven effective in ornamental gardening and greenhouse environments, their broader applicability and efficacy in large-scale agricultural systems remain to be fully evaluated.

Melia extracts: The discovery of the potent bioactivity of azadirachtin, a compound derived from the Indian neem tree (*Azadirachta indica*), spurred interest in identifying similar natural pesticides within related plant taxa. This led researchers to explore the genus *Melia*, a close relative of neem. Notably, the seeds of the chinaberry tree (*Melia azedarach*) were found to contain a group of triterpenoids known as meliacarpins, which, although structurally related to azadirachtins, are chemically distinct. These compounds have also demonstrated insect growth-regulating properties (Kraus, 2002), highlighting their potential as botanical pest control agents.

The primary concern regarding the use of chinaberry (*Melia azedarach*) seed extracts is the presence of additional triterpenoid compounds, notably the meliatoxins, which have been shown to exhibit toxicity to mammals (Ascher et al., 2002). The extract is rich in several triterpenoids structurally related to toosendanin, a bioactive compound reported to function as a stomach poison with notable efficacy against chewing insect pests (Chiu, 1988). subsequent research has shown that the compound primarily functions as a feeding deterrent. Additionally, it has been found to act as a synergist when used in combination with conventional insecticides (Chen et al., 1995; Feng et al., 1995).

While it is considered relatively non-toxic to mammals, uncertainties remain regarding its continued commercial production and whether it possesses sufficient efficacy to be used independently as a crop protectant. Neem-based products are complex blends of multiple biologically active compounds, making it challenging to isolate and define the precise modes of action of individual extracts or formulations. Among insects, neem exhibits its most consistent activity as a feeding deterrent. Depending on its formulation and mode of application, neem-based products can exhibit multiple insecticidal actions, functioning as a repellent, feeding deterrent, insect growth regulator, oviposition suppressant, sterilant or direct toxin. As a repellent, neem deters insects from initiating feeding activity. When acting as a feeding deterrent, it may cause insects to cease feeding either immediately upon contact with treated surfaces due to unpalatable chemical cues or shortly afterward due to secondary hormonal or physiological disruptions (Salama & Sharaby, 1988). Neem also exhibits properties of an insect growth regulator (IGR), interfering with normal insect development, particularly by inhibiting chitin synthesis, which is essential for cuticle formation and molting. The degree of susceptibility to these effects varies markedly among different insect species, reflecting species-specific physiological and biochemical responses.

Insect antifeedants and repellents
Antifeedants

The concept of utilizing insect antifeedants or feeding deterrents gained considerable attention during the 1970s and 1980s, largely due to the demonstration of the potent deterrent effects of azadirachtin and neem seed extracts against a wide array of pest species. Beyond the triterpenoids found in neem (*Azadirachta indica*), significant research has also focused on clerodane diterpenes from the Lamiaceae family (Klein Gebbinck et al., 2002) and sesquiterpene lactones from the Asteraceae (Gonzalez-Coloma et al., 2002) as potential natural antifeedants. Despite this progress, no crop protection products have been commercialized based solely on feeding or oviposition deterrence. Two major challenges hinder the agricultural adoption of antifeedants (Isman, 2002):

Interspecific variation in behavioral response: Even closely related insect species can exhibit markedly different responses to the same deterrent. A substance that effectively deters one pest species may be neutral or even attractive to another (Isman, 1993). This specificity limits the broad-spectrum utility of many antifeedants in field conditions.

Behavioral plasticity and habituation: Insects possess the capacity to rapidly habituate to antifeedants, often within hours of exposure. This behavioral adaptation has been documented for both pure compounds, such as azadirachtin (Bomford & Isman, 1996) and complex plant extracts (Akhtar et al., 2003). While mobile insects may abandon a host plant upon initial contact with an antifeedant, less mobile stages such as larvae may remain long enough for the deterrent effect to diminish. This behavioral flexibility is critical in cases where feeding deterrents lack toxicity upon ingestion. Many natural compounds that act as antifeedants do not cause physiological harm unless ingested in sufficient quantities or applied directly. An important exception is azadirachtin, which causes significant physiological disruptions even after ingestion. In contrast, other compounds may demonstrate strong initial deterrent activity without causing any lasting toxic effects when applied topically (Bernays, 1991).

The antifeedant index (AFI) is calculated from the formula:

$$AFI = \left[\frac{C - T}{C + T}\right] \times 100$$

Where: C = Consumption of control
T = Consumption of treated disks (Pavela & Vrchotova, 2008)

Repellents: DEET (N, N-diethyl-m-toluamide) is still the most effective and long-lasting repellent against mosquitoes and biting flies, even after decades of research (Peterson & Coats, 2001). Due to safety concerns, especially for children, several plant oils are now used as natural alternatives. Products often include citronella, eucalyptus or cedarwood oils. Others use 2-phenethylpropionate (from peanut oil) and p-menthane-3,8-diol (from mint). While these offer some protection, their effects usually last less than an hour (Fradin & Day, 2002). In tropical regions with mosquito-borne diseases like malaria or dengue, DEET is still the most reliable choice. Citronella oil or citronellal is also used in mosquito coils for outdoor use. Plant oils are found in pet treatments too like d-limonene from citrus peels for fleas and ticks. Essential oils are also being tested to keep termites away from buildings, cockroaches out of kitchens, and flies from barns (Maistrello et al., 2004). In beekeeping, menthol is used in the U.S. and thymol in Europe, to control Varroa mites (Floris et al., 2004). Also, *Francoeria crispa* extract showed repellent and toxic effects on *Eutetranychus orientalis* (Abdel-Khalek et al., 2010).

Phytochemical composition on botanical pesticides: Research on the chemical nature of many plant families has been sparked by the growing interest in natural plant products in agriculture, medicine and the food sector (Jnaid et al., 2016; Plata-Rueda et al., 2017). The secondary metabolites of plants usually alkaloids, tannins, terpenes, phenols, flavonoids and resins, which have antifungal, antibacterial, antioxidant, or insecticidal characteristics (Ahmad et al., 2017). For instance, the leaves of *Mentha piperita* contain tannins and flavonoids as the main bioactive chemicals (Pramila et al., 2012), whereas the seed kernels of *Jatropha carcus* have significant levels of phenolics, esters and flavonoids (Oskoueian et al., 2011), Certain plant species are efficient against a particular class of pests due to the specific chemicals found in those species. The bioactive chemicals found in plants also influence the mode of action against the target pests (Table 1).

Table 1. Source of botanicals with active ingredient containing insecticidal activities.

Source plant	Active ingredient	Mode of action	Target pest	References
Neem (*Azadiracta indica)*	Azadirechtin	Binding to acetylcholine receptors thereby disrupting the nervous system Repellence, Feeding deterrence, Inhibition of oviposition, egg hatching and molting	Lepidopteran and sucking insects	Isman, 2006
Turmeric (*Curcuma langa*)	ar-turmerone and turmerone	Inhibitory activity on insect growth, antifeedant	Cabbage looper, *Trichoplusia ni*	de Souza Tavares et al., 2016
Lemon grass	Citronellal	Fumigant and contact insecticidal property. It interferes with the neuromodulator: octapamine and GABA-gates chloride channels. (Volatile thus, limited persistence in field)	Gram pod borer *(H. armigera*)	Papulwar et al., 2018
Tanacetum cineariaefolium	Pyrethrum daisy	Neurotoxic: causes rapid knockdown effect, along with hyperactivity and convulsions. Pyrethrum blocks voltage-gated sodium channels in nerve axons (Half-life: 2 h)	*Western Flower Thrips, Frankliniella occidentalis*	Isman, 2006
Ferula asafoetida (Hing)	Asafoetida (oleo-gum-resin)	It acts as an insect repellent and consists of a characteristic. unpleasant smell	*Pomegranate fruit moth, Ectomyelois ceratoniae*	Kavianpour et al., 2014
Allium sativum	Allicin (gives the pungent characteristic odor to crushed garlic)	Antifeedant, repellent, inhibitor of molting and respiration, cuticle disruption and fecundity reduction	*Tenebrio molitor*	Plata-Rueda et al., 2017

Momordica Charantia (Bitter Melon)	Crude leaf extract, bitter Momordin	Antifeedant	Mung bean weevil (*Callosobruchus chinensis*)	Wahyutami & Aisyah, 2022

Problems/barriers in commercialization of botanicals in India

The commercialization of botanical insecticides presents several critical challenges. Key among these is the sustainability of botanical resources, the standardization of chemically complex extracts and compliance with regulatory frameworks all of which entail substantial cost considerations. Furthermore, many botanical insecticides exhibit relatively slow modes of action, which may reduce user confidence due to the absence of an immediate knockdown effect. Additionally, the limited residual activity of most botanical formulations poses constraints on their long-term efficacy in pest management programs (Isman, 1997).

Sustainability: For the commercial-scale production of botanical insecticides, the source plant biomass must be available in large quantities through agricultural cultivation and preferably throughout the year rather than on a strictly seasonal basis. Unless the plant species is naturally abundant or already cultivated for other purposes such as *Annona squamosa* (sweetsop), grown for its fruit, or *Rosmarinus officinalis* (rosemary), used as a culinary flavoring it must be agronomically viable for large-scale farming. Plants like pyrethrum (*Chrysanthemum cinerariifolium*) and neem (*Azadirachta indica*) satisfy these criteria. Notably, neem has been widely introduced across Africa, Australia and Latin America, primarily as a shade tree, windbreak or firewood source, rather than for its insecticidal or medicinal value. While efforts to produce azadirachtin through neem tissue culture have demonstrated proof of concept, such methods have not yet proven economically viable (Allan et al., 2002). Historically, neem seed oil was used in India for soap and low-grade industrial oil production. However, with the increasing demand from extraction companies for insecticidal applications, the market price of neem seeds rose by a factor of ten. In contrast, essential oils from certain plants, widely used in fragrance and flavoring industries, are produced in such high volumes that their prices remain relatively low making them cost-effective candidates for insecticidal use (Weinzierl, 1999; Isman, 2006).

Standardization of botanical extracts: For a botanical insecticide to deliver consistent and reliable efficacy, a certain degree of chemical standardization is essential typically based on quantifiable levels of the active Ingredients. While such standardization has been successfully implemented for more refined botanical products, such as those derived from pyrethrum, neem and rotenone, crude extracts often contain low and variable concentrations of active compounds, with limited or no quantification. Achieving standardization requires access to validated analytical methods and the instrumentation necessary to monitor active ingredient levels. Additionally, producers may need to blend extracts from multiple sources to ensure uniformity, a process that necessitates appropriate storage infrastructure. This approach is further constrained by the inherent chemical stability of the active compounds during storage of either raw plant material or processed extracts (Atkinson et al., 2004).

Regulatory approval: Securing regulatory approval represents one of the most substantial obstacles to the widespread adoption of botanical insecticides. In many countries, regulatory frameworks do not differentiate between synthetic chemical pesticides and biopesticides, including those derived from plants. As a result, the high cost of registration often amounting to several million dollars becomes economically unfeasible, particularly given the relatively small market size for botanical products, which are mainly used in niche sectors such as greenhouse cultivation and organic farming. This economic imbalance may hinder the commercialization of many environmentally benign pesticides, especially in regions where their use could be most beneficial. While regulatory oversight is essential especially considering the toxicity of certain natural compounds like nicotine and strychnine, which have been associated with human poisonings (Katz et al., 1996).

It is also important to recognize that many botanical insecticides exhibit favorable safety profiles, including low toxicity to mammals, minimal effects on non-target species, and reduced environmental persistence (Coats, 1994; Trumble, 2002). Nevertheless, current regulatory priorities often focus more on limiting trace residues in food products than on safeguarding the health of applicators and farm workers, who face more immediate risks from pesticide exposure (Isman, 2006).

Advantages and disadvantages

Advantages

- Source plants are often locally available and familiar to farmers.
- Many of these plants have multiple uses, such as in traditional medicine or as household insect repellents.
- Rapid degradation reduces the risk of pesticide residues on harvested crops.
- Some botanical products can be applied close to harvest without concern for residue levels.
- Many act quickly by deterring insect feeding, even if they do not cause immediate mortality.
- Their stomach action and rapid breakdown make them more selective, sparing natural enemies.
- Generally, they are non-phytotoxic and safe for crops.
- Pests tend to develop resistance to these compounds more slowly than to synthetic chemicals.

Disadvantages

- Many are not true pesticides but act mainly as repellents or deterrents, with slower effects.
- Rapid degradation under UV light leads to short residual activity.
- Some botanicals may still be toxic to non-target organisms, including animals.
- Availability may be limited to certain seasons.
- Most lack established residue tolerance limits.
- Few have official legal registration or regulatory approval for use.
- Many recommended uses are based on traditional knowledge and lack scientific validation ((El-Wakeil, 2013).

Insect Pest Management in Cereals

Rice and wheat

In rice cultivation, some of the major insect pests include the pink stem borer (*Chilo partellus*), rice ear head bug (*Leptocorisa acuta*), leaf folder (*Cnaphalocrocis medinalis*) and the white-backed planthopper (*Sogatella furcifera*). In contrast, wheat crops are commonly attacked by the wheat aphid (*Aphis maidis*) (Atwal, 1993; Garg, 1996). Botanical insecticides have shown (Table 2) limited effectiveness against stem borers due to the internal feeding habits and concealed development of these pests within plant tissues (Prakash et al., 1989). For the control of *L. acuta*, various plant-based treatments have demonstrated effectiveness. These include a 5% aqueous leaf extract of *Andrographis paniculata* (king of bitters) a 3%

neem oil (*Azadirachta indica*) emulsion, seed extract from *Citrus reticulata* (orange) and lemon grass (*Cymbopogon citratus*) leaf extract, all of which help protect maturing rice grains (Gupta et al., 1990).
The application of 1% custard apple (*Annona* spp.) seed oil has proven effective in managing key rice pests, notably by reducing the incidence of rice leaf folder (*Cnaphalocrocis medinalis*) and green leafhoppers, as well as by suppressing the transmission of rice tungro virus (Narasimhan and Mariappan, 1980). Additionally, neem kernel extract, when combined with 0.16% teepol as a surfactant, has demonstrated juvenile hormone-mimicking activity, disrupting the larval development of *C. medinalis* (Schmutterer et al., 1983). This formulation has also been reported to be effective in reducing populations of the white-backed planthopper (*Sogatella furcifera*) (David, 1986; Rajasekaran et al., 1987; Mohan & Gopalan, 1990). In addition, foliar sprays of 1% neem oil have effectively lowered leaf folder infestations (Singh et al., 1990; Mohan et al., 1991). Incorporating de-oiled neem cake into the soil at 150 kg/ha, in combination with neem oil sprays applied at 10-day intervals, significantly suppressed *C. medinalis* infestation (Krishnaiah & Kalode, 1990).
Other botanical oils, such as those extracted from *Calophyllum inophyllum* (polang), *Madhuca indica* (mahua) and *Pongamia glabra* (karanj), used at a 1% concentration, have been reported to reduce *S. furcifera* incidence (Saxena et al., 1987). Similarly, a neem oil spray (1%) applied at 7.5 kg/ha with teepol effectively managed white-backed planthopper infestations and exhibited antifeedant effects (Sontakke, 1993; Saxena et al., 1984). A 5% neem cake extract spray also suppressed the emergence of WBPH (Ramraju & Sundarababu, 1989). For wheat, aqueous leaf extract of *Aconitum ferox* Wall. a species native to the Kumaon hills and alpine Himalayan regions, showed high toxicity against wheat aphid (*Aphis maidis*) and *Siphocornye indobrassicae*. Additionally, neem extracts and azadirachtin have been shown to influence the biology and development of brown planthopper (*Nilaparvatha lugens*) (Senthil Nathan et al., 2007). Recent studies have further demonstrated that triterpenes derived from *Dysoxylum* species can significantly impact the food consumption, utilization efficiency and detoxification enzyme activity in rice leaf folder larvae (Senthil Nathan et al., 2007).

Table 2. Pesticidal Activity of plant products tested against insect pests of paddy fields

Plant taxonomic status & (common name)	Plant part, formulation & Dose/conc.	Test insects	Biological activity	Citations
Ageratum conyzovides Linn. (Asteraceae) (Goat weed)	Precocene I & II	*Leptocorisa chinensis*	Toxic to the adults & nymphs	Lu, 1982
Androgaphis paniculata (Burn f.) Wall ex. Nees (Acanthaceae) (king of bitters)	Aqueous leaf extract	*Leptocorisa acuta*	Protect rice panicle, when sprayed with the extract	Gupta et al., 1990
Annona squamosa Linn. (Annonaceae) (Custard apple/ sweet sop/supper apple)	Leaf and fruit extracts	Green leafhopper (GLH), *Nephottetix virescens*, Brown planthopper (BPH), *Nilaparvata lugens*	Insecticidal activity	Mariappan et al., 1982 a; Epino & Saxena, 1982
	Seed oil	GLH	Effectively reduce survival of adults	Mariappan and

				Saxena, 1983
	Neem oil + custard apple (1:4) mixture or alone	GLH	Reduced population	Kareem et al., 1987a
	Seed oil	*Cnaphalocrocis medinalis* and GLH	Reduce survival of LF and Tungro transmission	Narsimhan and Mariappan, 1988, Mariappan et al.,1988
Artememisla kurramensis Linn. (Asteraceae)	Seed oil alone or in combination with organic materials	(WBPH)- *Sogatella longifurcifera, Sogata striatus, Perkinsiella insigris* and *Toya attenuate*	Insecticidal activity	Khan and Khan, 1985
Azadirachta indica A. Juss. (Meliaceae) (Neem)	10% NSKE pre- sowing seed treatment	BPH	Reduced population & enhanced seedling growth	Kareem et al., 1987a
	Neem leaf bitters (NLB)	GLH, BPH	Reduced oviposition & development of test insects, when sprayed on rice seedlings	Kareem et al., 1989a
	Fractions of methanolic extract of neem seed	RLF & *Mythimna separata*	Showed JH mimic activity to the test insects	Schmutterer et al., 1983
	Neem coated urea as soil application	GM, GLH & RLF	Reduced incidences in paddy	David, 1986
	5% aqueous neem seed kernel extract **(NSKE)**	GLH	Ovipositional by seedling root-dip for 24 hrs	Kareem et al., 1987a
	10% NSKE pre- sowing seed treatment	BPH	Reduced population & enhanced seedling growth	Kareem et al., 1987a
	Seeding Root soaking NSKE (5%) its foliar spray soil incorporation	BPH, WBPH, & GLH	Inhibited growth & development	Saxena et al., 1987
	NSKE application using ULV sprayer	BPH, RLF	Checked incidences of the test insects	Rajasekaran et al., 1987a

	Young rice seedling when soaked in NSKE	BPH & GLH	Reduce nymphal develop and growth inhibiting activity	Kareem et al., 1988a, b
	NSKE	GLH	Reduce survival, antifeedant	Narsimhan & Mariappan, (EI-Wakeil, 2013)1988
	NSKE	GLH	Repellant	Songkittisuntron,1989
	NSKE 5%	YSB	Reduced WEH & Insecticidal	Dash et al.,1995
	Neem oil spraying protects rice crop	BPH	Strong repellency	Balasubramanian, 1979, Saxena et al., 1979.,
	Neem kernel powder suspension	(BPH) & (WBPH)	Reduce honeydew secretion and anti-feedency	Chiu et al., 1983
	Neem kernel powder with carbofuran	Green leafhopper (GLH) and Tungro	Controlled Tungro Virus	Kareem et al., 1988b
	3% Neem kernel powder	*Nephotettix virescens*	Inhibited nymphal growth	Krishnaiah and Kalode, 1990
	5% de-oiled neem cake (DNC)	BPH & WBPH	Reduced honeydew secretion	Chiu et al., 1983
	Neem cake application	BPH	Reduced population	Saxena et al., 1984b
	Neem cake coated urea	*Hydrelhia philippina* and GLH	Reduced incidences	David, 1986
	Neem cake extracts 5% spray	BPH & WBPH	Reduce emergence	Ramaraju and Sundarababu, 1989
	Neem cake + 150 kg/ha + 3% neem oil spray	Leaf folder (LF)	Effectively checked insect infestation	Krishnaiah and Kalode, 1990
	Neem cake with urea	GLH and WBPH	Reduce population	Viswanathan & Kandiannan, 1990
	DNC application in Azolla @250 kg/ha in rice	Various (e.g., *Nymphula responsalis*)	Toxicity to larvae and pupae	Sasmal, 1991
	Neem oil spraying	GLH & RTV	Population reduction	Mariappan and Saxena,1983

Vitex negundo Linn. (Verbenaceae)	Petroleum ether leaf extract	Leaf folder (LF)	Pupal malformation	Prakash et al., 2008
Tripterygium wilifordril Hook (Celastraceae)	Root & Bark powder	Yellow stem borer (YSB) larvae	Toxicity/Antifeedant activity	Chiu, 1982
Tinospota rumphi Boel. (Makabuhai)	Root & stem incorporation with soil	Green leafhopper (GLH)	Insecticidal activity	Del Fierro & Morallo-Rajessus, 1976; Morallo-Rajessus & Silva, 1979
Tagetes patula Linn. (Asteraceae)	Aqueous root extract	GLH	Toxicity	Morallo-Rajessus & Eroles, 1978
Pongamia glabra	1% oil and 2% seed extract	Brown planthopper (BPH) & White-backed planthopper (WBPH)	Reduced emergence of the hoppers	Ramaraju & Sundar Babu, 1989
Pongamia glabra	Oil	Chilo partellus	Reduced survival of the larvae	Sharma & Bhatanagar, 1990
Mixture of pongamia & neem oil (1:1)	Oil mixture	Gall midge (GM) & Yellow stem borer (YSB)	Safely protected paddy from the test insects	Prakash et al., 2008
Rhododendron molle Linn. (Ericaceae)	Root, leaf & flower aqueous & alcohol extract	Yellow stem borer (YSB)	Toxic	Chiu, 1982
Tagetes erecta Linn. (Asteraceae)	Aqueous root extract	Green leafhopper (GLH) & Brown planthopper (BPH)	Toxicity	Morallo-Rajessus & Eroles, 1978; Morallo-Rajessus

Future opportunities

Over the past three decades, it has become evident that botanical insecticides are unlikely to challenge the dominance of conventional synthetic insecticides in industrial-scale agriculture, or to surpass microbial biopesticides in the broader biopesticide market. Nevertheless, botanicals continue to gain traction in sectors where environmental and human safety are prioritized. These include:

- Domestic and urban pest management (e.g., cockroaches, ants, bedbugs) in sensitive areas such as schools, hospitals, restaurants and warehouses.

- Ectoparasite control on food and companion animals and vector management, such as mosquito control through larvicides, misting systems and personal repellents (Norris et al., 2018).

Despite public perception particularly in affluent regions that natural products are inherently safe, examples such as nicotine and strychnine highlight the need for continued regulatory oversight, even if requirements differ from those for synthetic products (Trumble,2002). In agriculture, botanicals are gaining popularity in organic production systems and are also being used in conventional farming through rotations and tank mixes, allowing for reduced use of synthetic pesticides (Arena et al., 2018). Some essential oils even synergize the action of conventional insecticides. Although laboratory studies show possible adverse effects on beneficial organisms, field evidence often supports the selective efficacy of botanicals while preserving natural enemies (Tembo et al., 2018). Their role is especially valuable in controlled environments such as greenhouses and indoor cultivation, where spot treatments or pre-harvest applications are often needed. Botanicals will likely prove particularly effective in specific crops, sectors or regions. To optimize their use, improvements in formulation, mode-of-action awareness and farmer education remain essential.

Future issues

- Compatibility and potential synergistic interactions between botanical insecticides and both microbial and mineral-based pesticides, particularly in light of the declining use of conventional chemical insecticides due to the development of resistance and increasing regulatory restrictions.
- Comprehensive field evaluations are needed to confirm the efficacy and ecological safety of botanicals as mosquito larvicides.
- Greater field-level evidence is necessary to understand the role of behavioral effects (e.g., repellency, antifeedancy, oviposition deterrence) in crop protection.
- Harmonization of regulatory standards across major jurisdictions is essential to facilitate wider registration and use of botanical biopesticides (Isman, 2020).

Conclusion

The plant kingdom offers a vast reservoir of structurally diverse secondary metabolites that hold immense potential for the development of environmentally benign pest control agents. With increasing concerns over the ecological and health impacts of broad-spectrum synthetic pesticides, there is a clear global shift towards biodegradable and biorational alternatives.

Botanical insecticides, derived from various plant sources, align with this trend by offering targeted pest control with reduced toxicity to non-target organisms and minimal environmental persistence. Their multiple modes of action including repellency, feeding deterrence, growth disruption and neurotoxicity make them valuable components in integrated pest management (IPM) systems for cereal crops. However, challenges such as formulation stability, raw material sustainability and regulatory constraints must be addressed to enhance their large-scale adoption.

Advancing research, standardization and policy support can help unlock the full potential of botanicals, contributing to a more sustainable and resilient approach to pest management in agriculture. Integrating botanicals into cereal crop protection strategies is essential for promoting ecological balance, reducing chemical inputs and advancing sustainable agricultural development.

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