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Botanical Insecticides: A Sustainable Alternative for Eco-Friendly Insect Pest Management

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ABSTRACT: Botanical insecticides, derived from plant extracts, essential oils, or other plant-based substances, offer a sustainable and eco-friendly alternative to conventional chemical insecticides. These natural agents have been used in pest management for centuries and are valued for their effectiveness and reduced toxicity to humans, animals and other non-target beneficial organisms. The active compounds in botanical insecticides disrupt insect physiology by affecting their nervous systems, altering feeding behavior, or interfering with reproductive processes, thereby serving as effective tools for insect pest management. This review paper highlights the potential of several prominent botanical insecticides, including pyrethrins, neem oil and rotenone, with a particular focus on their mechanisms of action, efficacy and safety. The growing popularity of plant-derived insecticides is largely driven by increasing awareness of the environmental and health hazards posed by synthetic chemicals. Consequently, botanical insecticides are gaining attention as a key component of sustainable agricultural practices. In addition to their advantages, the paper also addresses challenges associated with the use of botanical insecticides, such as issues related to formulation stability, variability in effectiveness due to environmental factors and the potential development of pest resistance. Understanding and overcoming these limitations is essential for improving the reliability and widespread adoption of botanicals in integrated pest management (IPM) systems. Overall, botanical insecticides represent a promising and environmentally sound strategy for pest management and continued research in this area will be vital to maximizing their potential and ensuring their effectiveness in modern agriculture.

Keywords: Botanical Insecticides, IPM, Plant derived compounds, Sustainable agriculture.

INTRODUCTION

Botanical insecticides, derived from plant extracts and secondary metabolites, have been used since ancient times to protect crops and stored products from insect pests. Long before the commercial rise of synthetic insecticides in the 1940s, traditional farming systems across civilizations in Egypt, China, Greece and India relied heavily on botanical formulations for pest control (Ware, 1983; Thacker, 2002). Historical texts including the *Vedas* of ancient India, dating back over 4,000 years mention the use of plant-derived insecticides such as *Azadirachta indica* (neem) for crop protection (Philogène *et al.*, 2005). With the advent of synthetic insecticides like organochlorines, organophosphates, carbamates, pyrethroids and neonicotinoids, the use of botanicals significantly declined, especially in industrialized countries, due to the synthetic compounds high efficacy, rapid action, ease of application and cost-effectiveness (Isman, 2008). However, concerns over the ecological, toxicological, and resistance related drawbacks of synthetic pesticides have rekindled global interest in botanical alternatives.

Botanical insecticides are plant-derived substances that exhibit insecticidal, repellent, antifeedant, fungicidal or nematicidal activity (Regnault-Roger *et al.*, 2005; Isman, 2006). Prominent botanical products include pyrethrum, rotenone, neem, and essential oils, while others such as ryania, nicotine and sabadilla also have historical significance. Essential oils, in particular, serve crucial ecological functions in plants ranging from defense against herbivores and pathogens to attracting pollinators (Isman, 2000; 2006). These botanicals exert their effects through multiple mechanisms, including the inhibition of acetylcholinesterase, modulation of GABA-gated chloride channels and interference with nicotinic acetylcholine receptors, octopamine and tyramine receptors and sodium channels (Pavela and Benelli 2016; Regnault-Roger *et al.*, 2012). Such multifaceted action reduces the risk of resistance development, making them highly suitable for integrated pest management (IPM) programs.

The Northwestern Himalayan region, particularly Jammu and Kashmir, harbors a rich diversity of medicinal plants with potent insecticidal, antifeedant and repellent properties. Species such as *Artemisia absinthium*, *Achillea millefolium*, *Acorus calamus*, *Digitalis purpurea* and *Plectranthus rugosus* are part of the indigenous flora and have shown significant efficacy against major pests like *Helicoverpa armigera*, *Sitophilus oryzae* and *Corcyra cephalonica* (Yaseen *et al.*, 2025). These plants not only offer bioactive molecules for pest control but also represent an underutilized resource for developing eco-friendly, plant-based pesticides suited for temperate climates.

As the demand for residue-free produce, eco-friendly agriculture and sustainable farming practices increases, botanical insecticides are re-emerging as key tools for modern pest management. Their integration into organic farming and IPM systems supports both crop protection and environmental conservation, aligning with the goals of sustainable agriculture and biodiversity preservation.

BOTANICAL INSECTICIDE

A botanical insecticide is a plant-derived substance used to control or repel pests. These botanical insecticides are used in various ways, depending on the target pest and application method and they provide a more eco-friendly alternative to synthetic chemicals.

Here are some types of botanical insecticides**:**

1. Pyrethrin: The mixture contains six active compounds: pyrethrin I and II, cinerin I and II, jasmolin I and II. Pyrethrin I, cinerin I and jasmolin I are chrysanthemic acid esters, while pyrethrin II, cinerin II and jasmolin II are pyrethric acid esters (Head, 1973). Pyrethrin extract typically contains pyrethrins, cinerins and jasmolins in proportions of 10:3:1 (Crombie, 1995). The ratio of pyrethrin I to pyrethrin II is approximately 1.0 but can range between 0.5 and 3.5 in some breeding lines (Bhat, 1995). Pyrethrins are primarily found in flower heads with minor amounts present in other plant parts. Pyrethrin I and pyrethrin II are predominant and the most active components (Head, 1966; Casidaand Quistad, 1995) while cinerin I, cinerin II and jasmolin I and II are present in lower concentrations and characterized with noticeable lower bioactivity (Chen and Wang 1996). Pyrethrin I acts in minutes and alone is toxic while pyrethrin II has a high knock-down effect appearing a few hours after its application.

Source Plant: This product is made from powdered and dried flower heads of the pyrethrum daisy specifically, *Chrysanthemum cinerariaefolium* but also obtained from *C. coccineum* and *C. marshalli.*

Active Compound: *Pyrethrins*

Target Pests: These products are effective against a variety of insects, including Mosquitoes, sawfly larvae, caterpillars, leafhoppers, spider mites, bugs, cabbage wormsand Beetles as well as *Culicoides variipennis* (Woodward *et al.*, 1985; Casida (1973); Glynne-Jones (2001)), House flies (Sheppard and Swedlund, 1999) and Rosy apple aphid (Grdisa and Grsic 2013).

Mode of Action: Pyrethrum can cause toxicity in insects by penetrating their cuticles and reaching their nervous systems. Pyrethrins found in pyrethrum bind to sodium channels in nerve cells. Sodium channels transmit nerve signals by allowing sodium ions to flow throughout the nerve cell. Pyrethrins can obstruct sodium channels, leading to hyperexcitation and loss of function in nerve cells. Exposure to pyrethrins often leads to insect nervous system shutdown and death (Soni and Anjikar 2014).

2. Nicotine: In chemistry, it is also referred to as I-methyl-2,3 (pyridyl) pyrrolidine. It is tobacco primary alkaloid. A naturally occurring heterocyclic nitrogenous base that is optically active has a comparatively high molecular weight and demonstrates discernible physiological activity is commonly referred to as an alkaloid. Nicotine is present in 2–14% of *Nicotinica rustica* and *Nicotinana tabacam* leaves. Approximately 97% of the twelve alkaloids present in tobacco are nicotine (Mandal, 2024).

The other two have insecticidal properties and are known as

(i) Nornicotine ($C_9 H_{12} N_2$) 2-(3-pyridyl pyrrolidine).

(ii) Anabusine (nornicotine, 3-(2-piperdyl) pyridine).

Source Plant: Leaves of tobacco plants *Nicotiana tabacum* and similar species.

Active Compound: *Nicotine*

Target Pests: Nicotine is toxic to insects particularly those with soft bodies like Aphids, thrips, caterpillars (Casanova *et al.,* 2002).

Mode of Action: In both insects and mammals, nicotine acts as a highly rapid nerve toxin. It competes with acetylcholine, the primary neurotransmitter, by attaching to acetylcholine receptors at nerve synapses, leading to uncontrolled nerve activation. This interference with normal nerve impulse activity causes a swift malfunction of body systems that rely on nervous input for their proper operation. In insects, nicotine effects are relatively specific, impacting only certain categories of insects (Ishaaya and Degheele 1998).

3. Rotenone: Rotenone makes up about 5% of dried derris roots (Ling, 2003). Since the 1930s, rotenone has been employed as a selective fish poison to control freshwater fisheries and maintain the intended species balance (Whitehead and Bowers 1983; Ray, 1991). It is regarded as one of the most environmentally friendly pollutants that can be used to manage fisheries. The insects rapidly cease feeding after being exposed to rotenone and they die a few hours to several days later.

Source Plant: *Derris* spp., *Lonchocarpus* spp.

Active Compound: *Rotenoids*

Target Pests: A variety of insect species such as Caterpillars, Aphids, Thrips and other pests present in fruits and vegetables such as the Colorado potato beetle, Plum curculio, Diabrotica and Acalymma species (Weinzierl, 1998) are effectively killed by this contact and stomach poison. Rotenone also effective against bugs, aphids, potato beetles, spider mites, carpenter ants (Cabras *et al.,* 2002; Cabizza *et al.,* 2004).

Mode of Action: Rotenone inhibits respiratory enzymes including NAD+ (a coenzyme involved in metabolic redox reactions) and coenzyme Q (which transports electrons) leading to respiratory function failure (Ishaaya and Degheele, 1998).

4. Ryania: Ryanodine and 9,21-dehydro-ryanodine are the two most potent ryanoids. Less than 1% of ground stem wood contains ryanoide (Khater, 2012).

Source Plant: The wood of the Caribbean shrub *Ryania speciosa* (Flacourtiaceae) is obtained by grinding it.

Active Compound: *Ryanodine*

Target Pests: Codling moths, potato aphids, onion thrips, corn earworms, silkworms (Copping and Menn 2000); (Isman, 2006).

Mode of Action: In insects, these compounds activate calcium release channels that are sensitive to ryanodine. Ryania extracts are highly toxic to fish but have a weak effect on mammals (Mandal, 2024). Ryania is a gradual acting toxin for the stomach.

5. Sabadilla: Sabadila produces alkaloids known as veratrine. Cevadine and veratridine are the most active veratrines, occurring in a 2:1 ratio (Dayan *et al.,* 2009) and found that ripe and aged Sabadilla seeds contain approximately 0.3% alkaloids. Veratrin is produced by several other species, including European white hellebore, *Veratrum album* L. (Ujvary *et al.,* 1991).

Source Plant: The wood of the Caribbean shrub *Ryania speciosa* (Flacourtiaceae) is obtained by grinding it.

Active Compound: Veratridine and other alkaloids

Target Pests: It is effective against cabbage loopers, squash bugs, grasshoppers, codling moths, armyworms, aphids (Bloomquist, 1996; 2003).

Mode of Action: Toxic alkaloids found in sabadillas impair the function of nerve cell membranes in insects, leading to paralysis, death and loss of nerve function. Certain insects are instantly killed by sabadilla, while others may remain paralyzed for a few days before passing away (El-Wakeil, 2013).

6. Neem: Neem insecticides are derived from *Azadirachta indica* A. Juss. (Syn. *Melia azadirachta* L.) a tropical and subtropical tree that is scientifically classified in the Meliaceae family. It is also known as neem and Indian lilac. Neem plants originated in Southern and Southeast Asia and are now found in tropical and subtropical regions of Africa, North-South America and Australia. The main active ingredient in neema tetranortriterpenoid limonoid is *azadirachtin* (Mordue and Blackwell 1993).

Neem oil which is produced by cold pressing seeds is helpful in controlling phytopathogens as well as softbodied insects and mites. Since the active ingredient in neem seeds is normally only 0.2% to 0.6% by weight solvent partitions or other chemical processes is needed to concentrate it to the 10–50% level found in the technical grade material used to make their products (Sallena 1989; Schmutterer 1990).

Source Plant: *Azadirachta indica*

Active Compound: *Azadirachtin*

Target Pests: Mites, psyllids, scales, bollworms, aphids, thrips, leaf miners, caterpillars, Armyworms, cutworms, stemborers, whiteflies, leafhoppers (Dimetry *et al.,*1993; 2010)

Mode of Action: Neem is primarily a feeding deterrent for insects but it also acts as a repellent, growth regulator, oviposition suppressant, sterilizant and toxin. Neem acts as an insect repellent, preventing them from feeding. It acts as a feeding deterrent, preventing insects from feeding. Feeding occurs either immediately after the first "taste" (Salama and Sharaby 1988) or shortly after ingesting the food (due to secondary hormonal or physiological effects of the deterrent substance). Neem, growth regulator, is thought to disrupt normal development by inhibiting chitin synthesis. Neem effects on different species vary (Gour and Sridevi 2012).

7. Quassia: Quassia (*Quassia amara* L.), another name for the bitter wood tree, is a tropical forest shrub that is rarely small. It is a member of the family Simaroubaceae. Quassinoids from *Soulamea soulameoides* and *Simaba multiflora* were tested against *Helicoverpa virescens* and *Spodoptera frugiperda*. Their capacity to inhibit insect growth matched their cytotoxic and antileukemic effects (Mandal, 2024).

Source Plant: *Quassiaamara*

Active Compound: *Quassin*

Target Pests: Effective against aphids and sawflies (McIndoo and Sievers, 1917).

Mode of Action: Their cytotoxic and antileukemic properties were complemented by their ability to inhibit insect growth. Act as a deterrent and growth inhibitor (Verma *et al.*, 2023).

8. Kaempferol: *Artemisia absinthium***,** commonly known as wormwood, is a temperate medicinal plant naturally distributed in the Kashmir region of Jammu and Kashmir at altitudes ranging from 1500 to 2700 meters above sea level. It belongs to the family Asteraceae and is well known for its traditional medicinal use and insecticidal properties. The plant contains several bioactive compounds such as α-thujone, camphor, 1,8-cineole and kaempferol**,** which exhibit strong insecticidal, antifeedant and acetylcholinesterase inhibiting activity. Owing to its rich phytochemical profile and abundance in Kashmir's forest ecosystems, *Artemisia absinthium* holds significant promise as a source of eco-friendly botanical insecticides for sustainable pest management.

Source Plant: *Artemisia absinthium* L. (Common name: Wormwood)

Active Compounds: Kaempferol, Diosmetin, Pipecolic acid, 1,7-Bis (4-hydroxyphenyl) heptan-3-one, NP-021018 (identified via HR-LCMS)

Target Pests: *Corcyra cephalonica* (Rice moth), *Sitophilus oryzae* (Rice weevil), *Helicoverpa armigera* (Gram pod borer).

Mode of Action: The insecticidal activity is attributed mainly to kaempferol, which showed the highest binding affinity to the acetylcholinesterase enzyme of *H. armigera* (−9.0 kcal/mol), surpassing even the synthetic reference Malaoxon (−5.6 kcal/mol). The mode of action involves the inhibition of acetylcholinesterase, toxicity and mortality to larvae through contact exposure (Yaseen *et al.*, 2025).

9. β-asarone: *Acorus calamus*, commonly known as sweet flag**,** is a perennial aromatic herb belonging to the family Acoraceae**.** It grows abundantly in marshy areas of temperate regions, including parts of Jammu and Kashmir**,** India. Traditionally used in Ayurveda and folk medicine, *Acorus calamus* is also known for its insecticidal, antifungal and antimicrobial properties. The rhizome contains potent bioactive compounds like β-asarone, which exhibit strong repellent, antifeedant and contact toxicity against a variety of insect pests. Due to its natural origin and efficacy, it is considered a promising candidate for use in **botanical pesticides** and **grain storage pest management.**

Source Plant: *Acorus calamus* L. (Common name: Sweet flag)

Active Compounds: β-asarone (primary bioactive compound), α-asarone, calamenene, Eugenol, Methyl Eugenol

Target Pests: *Sitophilus oryzae* (Rice weevil), *Tribolium castaneum* (Red flour beetle), *Spodoptera litura* (Tobacco caterpillar), *Helicoverpa armigera* (Gram pod borer), *Callosobruchus chinensis* (Pulse beetle)

Mode of Action:

Contact and fumigant toxicant, Disrupts**nervous system a**ctivity in insects, Causes **antifeedant, repellent** and **oviposition deterrent** effects, β-asarone inhibits enzyme activity and leads to **larval and adult mortality** (Isman 2006); Liu *et al.,* 2013; Yaseen *et al.,* 2025).

Table 1: List of botanicals and their parts used against targeted pests.

Sr. No.	Scientific Name	Part utilized	Target Pest	References
1.	*Acorus calamus* L.	Leaf, Rhizome	*Sitophilus zeamais*	(Yao *et al.*, 2012)
2.	*Allium cepa* L.	Seed	Tomato Lepidopteran Pest, *Bemisia tabaci, Pieris brassicae*	(Arora *et al.*, 2012; Debra and Misheck 2014)
3.	*Allium sativum* L.	Bulb	White fly, Thrips, Rice Weevil	(Muthomi *et al.*, 2017; Sanskriti *et al.*, 2024)
4.	*Adhatoda vasica* L.	Leaf, Root, Fruit, Flower	*Spodoptera littoralis*	(Sadek, 2003)
5.	*Annona squamosa* L.	Seed, Leaves	Diamondback moth, Cabbage looper, *Sitophilus oryzae, Tribolium castaneum, Callosobruchus maculates*	(Khalequzzaman and Sultana 2006; Kumar *et al.*, 2010; Senthilkumar *et al.*, 2014; Ismail and Sleem 2021; Muthu *et al.*, 2024)
6.	*Camellia oleifera*	Stem, Leaf	Lepidopteran pest	(Cui *et al.*, 2019)
7.	*Capsicum frutescens* L.	Fruit	Thrips, Legume pod boror	(Rosulu *et al.*, 2022)
8.	*Chromolaena odorata* L.	Leaf, Stem, Root	*Callosobruchus maculates*	(Osariyekemwen and Benedicta 2017)
9.	*Citrus hystrix* DC	Leaves	*Spodoptera litura* fabricius, *Lasioderma serricorne*	(Loh *et al.*, 2011; Ikawati *et al.*, 2017)
10.	*Coriandrum sativum* L.	Seed, Fruit	Store grain pest, *Tribolium castaneum*	(Lee *et al.*, 2018; Khani and Rahdari 2012)
11.	*Curcuma longa* L.	Root, Stem	*Spodoptera frugiperda, Spodoptera litura,*	(Cui *et al.*, 2022; Veeran *et al.*, 2019)
12.	*Rhododendron molle* G.Don	Flower	*Pieris rapae*	(Zhong *et al.*, 2001)
13.	*Zingiber officinale* Roscoe.	Rhizome	Storage pest	(Amuji *et al.*, 2012)

Table 2: List of commercial botanical insecticides, their active compounds and biological effects on insect pests.

Sr. No.	Product	Botanical Name	Main Bioactive Compound	Trade name	Effects	References
1.	Karanjin	*Derris indica* Lam.	Karanjin	Derisom	Insecticide, Acaricide	(Copping and Duke, 2007; Singh *et al.*, 2021; Verma *et al.*, 2011)
2.	Neem	*A. indica*	Azadirachtin, Dihydroazadirachtin, Triterpenoids	Ecozin, Azatrol EC,	Insecticide, Acaricide, Fungicide	(Copping and Duke 2007; Muhammad and Kashere 2020; Khater, 2012)
3.	Nicotine	*Nicotiana* spp.	(RS)-isomers and (S)-isomer of nicotine sulfate	Stalwart, No-Fid, Tobacco Dust	Insecticide	(Copping and Duke 2007; Isman and Paluch 2011)
4.	Lemongrass essential oil	*C.citratus, Cymbopogon*	Citronellal, Citral	GreenMatch, EXTM	Insecticide, Herbicide	(Fischer *et al.*, 2013; Moustafa

		Flexuosus				*et al*., 2021)
5.	Sabadilla	*Schoenocaulon* spp. (*S. officinale*)	Mixture of alkaloids (cevadine, veratridine)	Veratran, Red Devil	Insecticide	(Isman and Paluch 2011)
6.	Pyrethrum	*Tanacetum Cinerariaefolium*	Esters of chrysanthemic acid and pyrethric acid (pyrethrins I and II, cinerins I and II, jasmolins I and II)	Pyganic, Diatect	Insecticide, Acaricide	(Dayan *et al*., 1992)
7.	Ryania	*Ryania* spp.	Ryanodine, Ryania, 9,21-didehydroryanodine (alkaloids)	Natur-Gro R-50, Natur-Gro Triple Plus, Ryan 50	Insecticide	(Copping and Duke 2007; Isman and Paluch 2011)

Factors influencing the use of Botanical insecticides

In addition to their advantages, the use of botanical insecticides is influenced by a variety of factors that also present certain challenges, as discussed in this paper. These include formulation stability, environmental variability and the risk of pest resistance development. The following key factors affect their overall efficacy and adoption:

1. Plant Source and Active Ingredients: The insecticidal potential of botanical pesticides is directly linked to the plant species used and the concentration of its bioactive compounds. Variability in the chemical composition due to plant genotype, geographic origin, or harvest time can significantly influence efficacy. Ensuring consistent potency remains a formulation challenge.

2. Application Method: The effectiveness of botanical insecticides depends on how they are applied whether as foliar sprays, soil treatments, fumigants, or dusts. The success of each method varies depending on the crop, pest species, stage of infestation and local conditions, making standardized application difficult.

3. Environmental Factors: Meteorological conditions such as temperature, humidity, UV exposure and rainfall play a major role in the degradation, wash-off, or volatilization of active ingredients. This environmental sensitivity often leads to inconsistent results under field conditions, requiring careful timing and repeated applications.

4. Regulatory Framework and Standards: The commercialization and field use of botanical insecticides are subject to regulatory approvals, which may vary by country or region. Maximum residue limits (MRLs) and quality control requirements can affect the availability and legal use of these products in food crops.

5. Cost and Accessibility: The affordability and availability of botanical formulations influence their adoption, especially in low-income or remote agricultural settings. Some botanicals are regionally abundant and cost-effective, while others may be scarce or expensive to process and formulate.

6. Formulation and Stability Challenges: Botanical insecticides often face challenges related to shelf life, volatility and degradation during storage or after application. These factors affect product reliability and user confidence, highlighting the need for improved formulations with enhanced stability.

7. Pest Resistance Potential: Though less common than with synthetic pesticides, pests may still develop resistance to botanicals, especially when sub-lethal doses are applied repeatedly. Rotational use and integrated strategies are essential to mitigate this risk.

8. Additional Influencing Factors: Other aspects such as the age of the treated organism, climatic season, dosage, exposure duration and indirect effects also influence outcomes. As noted by Henn *et al.* (1991); Dosemeci *et al.* (2002), these variables can alter both the effectiveness and safety of botanical pesticide use.

CONCLUSIONS

Botanical pesticides are an efficient and environmentally friendly substitute for traditional chemical pesticides. They are useful instruments in contemporary agriculture because of their selective toxicity and compatibility with Integrated Pest Management (IPM). To increase their effectiveness and encourage wider adoption in sustainable pest management practices, it will be essential to address present issues like formulation stability and environmental variability through ongoing research.

FUTURE SCOPE

Botanical insecticides have the potential for long-term pest management. Future research shall focus on identifying new bioactive compounds, improving formulations using advanced technologies, and incorporating these products into Integrated Pest Management (IPM) systems. Standardization, regulatory support, and increased farmer awareness will be critical to widespread adoption. As environmental concerns grow, botanical insecticides are expected to play an important role in sustainable agriculture.

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Conflict of Interest. None.

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