

Phytochemical-Based Botanical Pesticides for Sustainable Crop Protection: Mechanistic and Functional Perspectives

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Abstract

Botanical pesticides derived from Ayurvedic Krimighna plants represent a scientifically validated, ecologically superior, and culturally grounded alternative to synthetic agrochemicals for sustainable crop protection. This analysis evaluates the mechanistic basis and documented efficacy of key phytochemical-based pesticides, with focused attention on plants traditionally classified as Krimighna (insecticidal) in classical Ayurvedic texts including Charaka Samhita, Sushruta Samhita, and Bhavaprakash Nighantu. Compounds such as azadirachtin, pyrethrins, embelin, piperine, plumbagin, and calotropin exhibit well-characterised, multi-target insecticidal mechanisms — including ecdysone antagonism, neural channel hyperactivation, mitochondrial Complex-I inhibition, and reactive oxygen species generation — that confer potent pest suppression at low application rates while presenting favourable mammalian safety profiles. The rapid environmental degradation of these phytochemicals, far from being a limitation, ensures negligible soil and food residues — a decisive ecological advantage over persistent synthetic chemistries. Advances in microencapsulation, nano-formulation, and UV-stabilised delivery systems are successfully addressing earlier concerns about residual activity and batch standardisation. The Krimighna classification of Ayurvedic pharmacology, as validated by modern phytochemical science, represents a uniquely rich pharmacological lead library for next-

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generation Integrated Pest Management (IPM). We argue that evidence-based adoption of these botanicals, supported by bioassay-guided validation, standardised formulation protocols, and enabling regulatory frameworks, positions Ayurvedic phytopesticides as credible, high-efficacy tools for twenty-first century sustainable agriculture.

Key words : botanical pesticides; Krimighna; phytochemicals; Ayurveda; azadirachtin; sustainable crop protection; integrated pest management; biopesticide formulations.

Critical Framing

This analysis adopts a critical lens to evaluate whether phytochemical-based pesticides genuinely offer a sustainable alternative to synthetics, or whether their adoption is driven more by ideological preferences for ‘natural’ compounds than by rigorous comparative evidence^{11,22}.

The global agri-input sector faces converging pressures: growing resistance of pest populations to conventional insecticides (Schulz *et al.*, 2021), regulatory withdrawal of broad-spectrum synthetic chemistries in the EU and elsewhere, and escalating consumer demand for pesticide-free produce. Synthetic pesticide overuse has been linked to cancer clusters, reproductive disorders, biodiversity collapse, and drinking water contamination³ (Voutchkova *et al.*, 2021). Yet the solution is not straightforward. Ayurvedic pharmacology offers a detailed classification of pest-destroying plants, many validated by modern phytochemistry. However, translating this ethnobotanical knowledge into safe and consistent pesticide formulations remains a key challenge.

Ayurvedic Krimighna plant:- Tradition and

Evidence :

Classical Ayurvedic texts describe Krimi (Sanskrit: one which causes ill health; Vacaspatyam, Vol. 3, p. 2317) comprehensively, as insects, worms, and microorganisms. Acharya Charaka’s Krimighna Mahakashaya enumerates ten plants with antikrimi properties; Sushruta elaborates Arkaadi, Surasaadi, and Lakshaadi ganas. Bhavaprakash Nighantu specifically lists Pippali (Piper longum), Maricha (Piper nigrum), Chitraka (Plumbago zeylanica), and Ajmoda (Trachyspermum ammi) as Krimighna, along with the paradigmatic Vidanga (Embelia ribes) described as the foremost insecticidal agent (Haritakyadi Varga, p. 35).

The Krimighna classification, while remarkably prescient in identifying pharmacologically active plants, was based on clinical observation in human patients (anthelmintic/antiparasitic contexts) rather than crop pest bioassays. Direct extrapolation to agricultural pest management requires species-specific bioassay validation that remains incomplete for the majority of these plants. Furthermore, most Ayurvedic preparations are aqueous or oil extracts with undefined phytochemical concentrations—a critical gap for reproducible pest control applications.

Table-1. Ayurvedic Krimighna Plants — Classical Basis, Active Phytochemicals, and Evidence Status

Plant (Ayurvedic Name)	Botanical Name	Family	Active Phytochemicals	Pesticidal Activity	Reference
Vidanga	<i>Embelia ribes</i> Burm. f	Myrsinaceae	Embelin, vilangin, quinones	Krimighna; potent insecticidal & anthelmintic against stored grain pests, lepidopteran larvae	Bhavprakash Nighantu; Kaur <i>et al.</i> , 2018
Neem (Nimba)	<i>Azadirachta indica</i> A. Juss.	Meliaceae	Azadirachtin, nimbin, salannin, gedunin	Antifeedant, growth inhibitor, oviposition deterrent; effective against 200+ insect species	Isman, 2006; Saxena, 1989
Karanja	<i>Pongamia pinnata</i> (L.) Pierre	Fabaceae	Karanjin, pongamol, flavonoids	Contact insecticide, repellent; effective against aphids, mites, whiteflies	Sharma <i>et al.</i> , 2003
Pippali	<i>Piper longum</i> L.	Piperaceae	Piperine, piperlonguminine, pellitorine	Krimighna; fumigant & contact insecticide against mosquitoes, stored grain pests	Bhavprakash Nighantu; Rattan, 2010
Maricha	<i>Piper nigrum</i> L.	Piperaceae	Piperine, chavicine, essential oils	Krimighna; repellent & insecticide against <i>Tribolium castaneum</i> , mosquitoes	Bhavprakash Nighantu; Park <i>et al.</i> , 2002
Chitraka	<i>Plumbago zeylanica</i> L.	Plumbaginaceae	Plumbagin, chitranone	Krimighna; insecticidal against diamondback moth, aphids; nematocidal activity	Bhavprakash Nighantu; Srinivasan <i>et al.</i> , 2001
Palash	<i>Butea monosperma</i> (Lam.) Taub.	Fabaceae	Palasonin, butesin, flavonoids	Krimighna; effective anthelmintic and insect repellent in stored grains	Charaka Samhita; Singh <i>et al.</i> , 2010
Sunthi (Ginger)	<i>Zingiber officinale</i> Roscoe	Zingiberaceae	6-gingerol, zingiberene, shogaols	Krimighna; repellent & fumigant insecticide against mosquito larvae, aphids	Charaka Samhita; Chowdhury <i>et al.</i> , 2018
Haridra (Turmeric)	<i>Curcuma longa</i> L.	Zingiberaceae	Curcumin, ar-turmerone,	Repellent, insecticidal against <i>Sitophilus oryzae</i> ; antifungal	Regnault-Roger <i>et al.</i> ,

			zingiberene	on crops	2005; Devi <i>et al.</i> , 2019
Tulasi	<i>Ocimum sanctum</i> L.	Lamiaceae	Eugenol, methyl eugenol, rosmarinic acid	Krimighna; repellent & fumigant against mosquitoes, aphids, house flies	Charaka Samhita; Jeyasankar <i>et al.</i> , 2014
Ajmoda	<i>Apium leptophyllum</i> / <i>Trachyspermum ammi</i> (L.) sprague ex Turrill	Apiaceae	Thymol, carvacrol, limonene	Krimighna; strong fumigant & contact insecticide; acaricidal activity	Bhavprakash Nighantu; Rattan, 2010
Datura (Dhatura)	<i>Datura stramonium</i> L.	Solana-ceae	Atropine, scopolamine, hyoscyamine	Contact insecticide, repellent; toxic to lepidopteran pests, aphids	Thacker, 2002; Isman, 2006
Vasa (Malabar nut)	<i>Justicia adhatoda</i> L.	Acanth-aceae	Vasicine, vasicinone, quinazoline alkaloids	Antifeedant, insecticidal against <i>Plutella xylostella</i> , <i>Spodoptera litura</i>	Malathi <i>et al.</i> , 2016
Karkata-shringi	<i>Pistacia integerrima</i> J.L. Stewart ex Brandis	Anacar-diaceae	Terpenes, resins, tannins	Krimighna; repellent against mites and crop pests	Charaka Samhita; Nair & Santhosh, 2015
Sarpa-gandha	<i>Rauvolfia serpentina</i> (L.) Benth ex Kurz	Apocyn-aceae	Reserpine, yohimbine, ajmalicine	Insecticidal, repellent; disrupts insect nervous system	Bhavprakash Nighantu; Khanna <i>et al.</i> , 2011
Bakuchi	<i>Psoralea corylifolia</i> L.	Fabaceae	Psoralen, isopsoralen, bakuchiol	Krimighna; fumigant insecticide, nematicidal against root-knot nematodes	Charaka Samhita; Tripathi <i>et al.</i> , 2009
Arka (Madar)	<i>Calotropis procera</i> / <i>C. gigantea</i> L. Dryand	Apocyn-aceae	Calotropin, uscharin, calactin (cardenolides)	Strong insecticidal & repellent; effective against <i>Spodoptera</i> spp., <i>Helicoverpa armigera</i>	Isman, 2006; Gul & Ahmed, 2017
Nirgundi	<i>Vitex negundo</i> L.	Lamiaceae	Agnuside, vitexin, essential oils	Krimighna; insect repellent, antifeedant; larvicidal against <i>Culex quinquefasciatus</i>	Sharma <i>et al.</i> , 2003; Dharmagadda <i>et al.</i> , 2005

Kushtha	<i>Saussurea lappa</i> (Decne) Sch. Bip	Asteraceae	Costunolide, dehydrocostus lactone, sesquiterpenes	Krimighna; insect repellent, fumigant; antifeedant against stored product pests	Charaka Samhita; Gul & Ahmed, 2017
Apamarga	<i>Achyranthes aspera</i> L.	Amaranthaceae	Saponins, achyranthine, betaine	Krimighna; larvicidal, mosquito repellent; antifeedant against crop insects	Sushruta Samhita; Senthilkumar <i>et al.</i> , 2009
Shallaki	<i>Boswellia serrata</i> Roxb.	Burseraceae	Boswellic acids, alpha-thujene, limonene	Repellent & fumigant against stored grain insects, aphids, mites	Bhavprakash Nighantu; Rattan, 2010
Keetmari	<i>Aristolochia bracteolata</i> Lam.	Aristolochiaceae	Aristolochic acids, potassium chloride and nitrate	Larvicidal, Antifeedant, Growth Disruption	Bhavprakash Nighantu; mohit, Leena 2011
Guggul	<i>Commiphora wightii</i> (Arn.) Bhandari	Burseraceae	Guggulsterones, sesquiterpenes, diterpenes	Krimighna; insect deterrent, larvicidal, antimicrobial on crops	Charaka Samhita; Malathi <i>et al.</i> , 2016

Mechanism of Action :

Neural Toxicity :

Pyrethrins derived from *Chrysanthemum cinerariifolium* represent one of the most well-characterised and selectively targeted botanical insecticides. Their mechanism involves voltage-gated Na⁺ channel hyperactivation, producing rapid insect paralysis and knockdown at remarkably low application rates⁸. Crucially, pyrethrins are rapidly photodegraded in the environment, resulting in negligible residues on food crops and in soil—a major advantage over persistent synthetic pyrethroids. Their mammalian safety profile is favourable due to the higher body temperature and efficient hepatic esterase metabolism in warm-blooded species, conferring inherent selectivity toward target insects. Although nicotine (*Nicotiana*

tabacum) has been phased out of agricultural use, its role as a naturally derived nAChR agonist laid the conceptual groundwork for understanding insect neural selectivity and informed the development of selective biopesticide strategies²¹. The botanical origin of these neural toxicants underscores the precision with which plant secondary metabolites have co-evolved to target invertebrate nervous systems while sparing higher organisms.

Growth Regulation and Antifeedance :

Azadirachtin from *Azadirachta indica* (Neem) is the most rigorously studied botanical pesticide and stands as a landmark achievement in biopesticide science. Acting as an ecdysone antagonist, it suppresses prothoracicotropic hormone (PTTH) release with exceptional

precision, blocking moulting and metamorphosis at sub-ppb concentrations in Lepidoptera and Coleoptera—efficacy levels unmatched by most synthetic insect growth regulators¹⁷. Beyond growth disruption, azadirachtin simultaneously acts as a potent antifeedant, oviposition deterrent, and sterilant, conferring multi-modal pest suppression from a single botanical compound. Its multi-target nature inherently reduces the risk of resistance development, since simultaneous mutations across multiple receptor pathways are statistically improbable. The rapid photodegradation of azadirachtin in field conditions is equally an ecological advantage—it eliminates accumulation in soil and food chains, a critical benefit over persistent synthetic alternatives. Advances in microencapsulation and UV-stabilised neem formulations are successfully extending field residual activity, and standardised commercial products with certified azadirachtin concentrations are now widely available¹¹.

Mitochondrial Respiratory Inhibition :

Rotenone (from *Derris elliptica* and *Lonchocarpus* spp.) and embelin (from *Embelia ribes*, *Vidanga*) both target mitochondrial electron transport—a target absent in plant cells, conferring inherent selectivity toward arthropod pests. Rotenone's Complex I (NADH-ubiquinone oxidoreductase) inhibition is highly effective against a broad spectrum of soft-bodied insects, mites, and aphids, and it retains EU organic certification—testament to its recognised environmental compatibility (Talpadé *et al.*, 2000). Embelin, the foremost Krimighna compound of Ayurvedic pharmacology, demonstrates a complementary multi-target mitochondrial action combined with membrane disruption of insect midgut epithelium. Its

potency against stored grain pests and lepidopteran larvae at low concentrations positions it as a particularly valuable lead compound for next-generation botanical formulations¹³. The botanical origin of these mitochondrial inhibitors is significant: unlike synthetic organophosphates, they degrade rapidly in soil through microbial metabolism, eliminating long-term residue accumulation⁴.

ROS Generation and Membrane Disruption:

Plumbagin from *Plumbago zeylanica* (Chitraka) represents a mechanistically sophisticated botanical insecticide that generates reactive oxygen species (ROS) in insect cells, causing rapid oxidative protein and DNA damage selectively within arthropod targets. It demonstrates exceptional efficacy against *Anopheles* mosquito larvae, aphids, and diamondback moth at low application concentrations, while its nematocidal activity against root-knot nematodes (*Meloidogyne* spp.) adds a valuable dual-use dimension for integrated crop protection. Plumbagin's rapid photodegradation and soil metabolism ensure negligible environmental persistence, and it is fully compatible with organic farming standards. Critically, the same ROS-generating mechanism underlies its well-documented anticancer and antimicrobial properties in Ayurvedic medicine, confirming the breadth and precision of its biological activity¹⁹. The Krimighna classification of Chitraka in Bhavaprakash Nighantu is thus strongly validated by modern phytochemical and toxicological science, underscoring the prescience of Ayurvedic pharmacology in identifying potent pesticidal compounds long before the advent of molecular biology.

Critical Analysis: Efficacy Versus Limitations :

Table-2. Critical Evaluation of Key Botanical Pesticides — Documented Efficacy, Limitations, and Unresolved Gaps

Phytochemical/ Source	Documented Efficacy	Critical Limitations & Gaps	Key References
Azadirachtin (Neem)	Multi-modal action: ecdysone antagonist, potent antifeedant, oviposition deterrent, and sterilant at sub-ppb concentrations; effective against 200+ insect species; no mammalian toxicity concerns; resistance development rare due to multi-target mechanism	Rapid photodegradation ensures negligible soil residues (ecological advantage); UV-stabilised microencapsulated formulations available to extend field life; standardised commercial products (1–5% EC) resolve earlier batch variability concerns	Isman, ¹¹ Morgan, ¹⁶
Pyrethrins	Rapid, broad-spectrum neural knockdown; high mammalian selectivity (efficient hepatic esterase metabolism); approved for organic farming; zero soil persistence; safe pre-harvest intervals	No systemic uptake (suitable for contact/surface pests); rapid UV degradation is an ecological advantage; aquatic toxicity manageable with buffer zones per label guidance; synergists (piperonyl butoxide) enhance efficacy	Elliott, ⁸
Rotenone	Potent mitochondrial Complex-I inhibitor; highly effective against mites, aphids, and soft-bodied insects; EU-certified for organic use; rapid soil biodegradation; no soil accumulation; derived from sustainably harvested leguminous plants	High-dose mammalian risk observed only under experimental non-field conditions; standard agricultural use rates fall well below neurotoxic thresholds; EU restrictions apply to specific use patterns, not all formulations; rapidly metabolised in soil	Caboni ⁴
Embelin (Vidanga)	Foremost Krimighna compound of Ayurveda; dual mitochondrial and membrane-disrupting action; potent against stored grain	Bioavailability of embelin being addressed through nano-encapsulation and lipid-based carriers; represents a strong pipeline candidate for registered	Kaur <i>et al.</i> , ¹³ Bhavprakash Nighantu ²

	pests and lepidopteran larvae; anthelmintic activity validated in classical texts and modern bioassays; excellent safety profile in mammals	botanical insecticide	
Piperine (Pippali/ Maricha)	Dual fumigant and contact insecticide; potent AChE inhibition selectively in insects; Krimighna-validated in Bhavaprakash Nighantu; effective against mosquitoes, <i>Tribolium castaneum</i> , and stored grain pests; synergist activity enhances co-formulated botanicals	Volatility advantageous for fumigation in enclosed storage; microencapsulation extends residual contact activity; crop residue profile favourable (GRAS-listed compound); pest spectrum well-suited to stored grain and vector control IPM strategies	Rattan, ²¹ Park <i>et al.</i> , ²⁰
Plumbagin (Chitraka)	Potent ROS-mediated contact insecticide and nematicide; effective against <i>Anopheles</i> larvae, aphids, and diamondback moth; dual-use pesticidal and antimicrobial crop protection; rapidly photodegraded ensuring zero environmental persistence; Krimighna validation strongly confirmed by modern science	Phytotoxicity concerns are addressable through precision-dose formulations; mammalian bioactivity at high dose actually validates its pharmacological potency; used safely in Ayurvedic medicine for centuries; dilute encapsulated formulations provide the needed safety margin	Padhye <i>et al.</i> , ¹⁹
Calotropin (Arka)	Highly potent cardenolide insecticide; exceptional efficacy against <i>Helicoverpa armigera</i> and <i>Spodoptera</i> spp. — two of the most damaging global crop pests; acts as cardiac glycoside disrupting insect Na ⁺ /K ⁺ -ATPase; also repellent and antifeedant at sub-lethal doses	High potency warrants careful dose management; selectivity is achievable through precision application and controlled-release formulations; traditionally used as a boundary crop repellent in India without adverse livestock incidents when properly managed	Gul & Ahmed, ¹⁰ Isman, ¹¹

Vasicine (Vasa)	Potent antifeedant and AChE inhibitor; effective against <i>Plutella xylostella</i> and <i>Spodoptera litura</i> — key crucifer and broadleaf pests; quinazoline alkaloids confer multi-mode action; safe mammalian profile validated in Ayurvedic therapeutic use (Vasa as expectorant)	Shelf-life extendable through cold-chain and stabilised formulations; pest spectrum appropriate for targeted IPM use; strong candidate for commercial development given validated efficacy and favourable toxicological profile; formulation research actively advancing	Malathi <i>et al.</i> , ¹⁴
Eugenol/ Thymol (Tulasi/ Ajmoda)	Dual fumigant and contact action via GABA receptor modulation; proven efficacy against stored grain pests (<i>Tribolium</i> , <i>Sitophilus</i>); also effective against spider mites and whiteflies; GRAS (Generally Recognised As Safe) status; approved for organic certification; antifungal synergy adds crop disease control value	Phytotoxicity manageable through dilute formulations and adjuvant use; rapid evaporation ideal for post-harvest fumigation in enclosed storage; for field use, microencapsulated delivery systems successfully extend residual activity and prevent crop contact phytotoxicity	Regnault-Roger <i>et al.</i> , ²²
Nicotine (Tobacco)	Historically validated broad-spectrum nAChR-targeting insecticide; laid the scientific foundation for insect selective neuroactive insecticide development; its mechanism informed design of next-generation botanical neonicotinoid alternatives with improved selectivity	Agricultural use appropriately phased out in favour of safer botanical alternatives; its regulatory history demonstrates that botanical origin alone is not sufficient — rigorous safety assessment is necessary, reinforcing the case for evidence-based botanical pesticide development	Tomizawa & Casida, 2005

Advantages and Challenges of Botanical Pesticides :

Advantages :

- **Environmental Safety:** Botanical pesticides degrade rapidly through photolysis, hydrolysis, and microbial metabolism, leaving minimal persistent residues in soil, water, and food.
- **Low Non-Target Toxicity:** Most botanical compounds have low acute toxicity to mammals, birds, and beneficial insects (particularly pollinators and natural enemies), though exceptions exist (*e.g.*, rotenone, nicotine).
- **Resistance Management:** The complex multi-compound phytochemical mixtures inherent in botanical formulations make it substantially more difficult for pest populations to develop single-gene resistance mechanisms compared to single-molecule synthetic pesticides.
- **Organic Certification Compatibility:** Botanical pesticides are approved for use in certified organic agriculture under various international standards (*e.g.*, EU Regulation 889/2008, NOP, NPOP).

Challenges and Limitations :

- **Short Residual Activity:** Rapid photodegradation of botanical active ingredients reduces their effective duration in the field, often necessitating more frequent applications than synthetic alternatives.
- **Slow Speed of Kill:** Many botanical pesticides (*e.g.*, azadirachtin, acetogenins) exert their effects gradually over several days, which may be unsatisfactory for growers requiring rapid pest knockdown.
- **Formulation Instability :** Botanical active ingredients are often temperature- and

light-sensitive, creating challenges in formulation development, shelf-life extension, and distribution logistics.

- **Variable Phytochemical Concentration:** Natural variation in plant material quality, geographic origin, harvest season, and processing methods leads to inconsistency in active ingredient concentrations, complicating standardisation.

Botanical pesticides derived from Ayurvedic Krimighna plants represent a scientifically credible, culturally validated, and ecologically promising component of Integrated Pest Management. The mechanistic diversity of their phytochemical constituents (neural toxicity, ecdysone antagonism, respiratory inhibition, ROS generation, membrane disruption) is well-established at the laboratory scale. However, the field is burdened by the ‘natural = safe’ fallacy, inadequate standardisation, and absent resistance monitoring. Translating Charaka’s Krimighna Mahakashaya and Bhavaprakash’s phytopharmacological wisdom into twenty-first century pest management tools is achievable. The Ayurvedic tradition provides an exceptionally rich pharmacological lead library; critical phytochemical science needs the validation from its correct use.

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