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Botanical Biopesticides for Climate Resilient Agriculture: From Phytochemicals to Agroecosystems-A Review

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ABSTRACT: Global agricultural systems face mounting pressure from climate change and insect pest damage, which destroys 20-40% of global crop production annually. Synthetic chemical pesticides, the conventional response, have incurred high ecological costs through environmental contamination, toxicity to non-target organisms and the rapid evolution of resistance in pest populations. Botanical biopesticides, derived from the rich phytochemical arsenals of medicinal plants, offer a scientifically validated alternative for building climate-resilient agricultural systems. This review synthesises current knowledge on three critical dimensions: (1) the chemical complexity of plant secondary metabolites, including terpenoids, alkaloids and phenolics, which confer multi-target mechanisms of action against pests; (2) advanced formulation technologies such as microencapsulation and nano-formulations that enhance field persistence and climate resilience; and (3) strategic integration into integrated pest management (IPM) systems for insecticide resistance management. Evidence demonstrates that botanical biopesticides, when formulated and deployed strategically, provide broad-spectrum efficacy across insect pests, fungal pathogens and nematodes. Significant barriers, including climate-driven variability in phytochemical composition, inherent instability under environmental stressors and regulatory frameworks designed for single-molecule synthetics, currently limit widespread adoption. A coordinated advance across molecular biology, formulation science and regulatory reform is essential to realise the full potential of botanical biopesticides in sustainable, climate-adaptive agriculture.

Keywords: Biopesticides, Climate change, Formulation technology, Insecticide resistance management, Integrated Pest Management, Phytochemicals.

1. INTRODUCTION

1.1. The Imperative for Sustainable Pest Management in a Changing Climate

Global agricultural systems confront an unprecedented crisis, namely ensuring food security for a growing population while adapting to the profound impacts of climate change (Dhillon & Gujar, 2010; Harvey et al., 2023). Insect pests represent a persistent and significant biotic threat, destroying an estimated 20-40% of global crop production annually (Skendi et al., 2021). Rising global mean temperatures are expected to increase crop losses by an additional 10-25% per degree Celsius for staple crops including rice, maize and wheat (Furlong & Zalucki, 2017). As ectothermic organisms, insects respond to climate warming through accelerated development rates, increased voltinism (number of generations per season), poleward range expansion and extended activity periods (Furlong & Zalucki, 2017 and Harvey et al., 2023).

For over five decades, intensive application of synthetic chemical pesticides has been the primary response to pest threats. While delivering short-term gains in crop protection, this paradigm has incurred severe environmental costs: soil and water contamination, toxicity to non-target organisms, including vital pollinators and natural enemies, and direct health risks to agricultural workers and consumers (Stehle & Schulz, 2015; Rezende-Teixeira et al., 2022). Furthermore, the relentless selection pressure exerted by single-target synthetic pesticides has driven the rapid evolution of resistance in hundreds of pest species (Hawkins et al., 2019). This chemical-dependent paradigm is itself vulnerable to climate change. Warmer temperatures and altered precipitation patterns accelerate volatilisation, photodegradation and wash-off of synthetic pesticides, reducing persistence and necessitating more frequent or higher-dose applications (Chen & McCarl, 2001; Koleva & Schneider, 2009; Delcour et al., 2015).

1.2. Botanical Biopesticides: A Scientifically Grounded Alternative

These concerns have catalysed global demand for safer, more sustainable alternatives, creating fertile ground for renewed scientific interest in botanical insecticides derived from medicinal and aromatic plants (Isman, 2006). Medicinal plants have evolved over millennia to produce complex arsenals of secondary metabolites, specifically terpenoids, alkaloids and phenolics, as natural defences against herbivory and pathogens (Isman & Grieneisen, 2014). The fundamental advantage of botanical agents lies in their inherent chemical complexity. Unlike single-molecule synthetics, crude plant extracts or essential oils contain a variety of bioactive compounds that act on multiple physiological and behavioural targets in pests simultaneously (Koul et al., 2008). This multimodal action significantly reduces the likelihood of resistance development, a crucial attribute given that shorter pest generation times may accelerate resistance evolution in warming scenarios (Matzrafi, 2019). The diverse biological activities of selected botanical agents are illustrated in Table 1, and field-level practices of botanical biopesticide application are shown in Figure 1.

The novelty of this review lies in its integrative, climate-focused perspective. Unlike earlier reviews that addressed botanical biopesticides in isolation, the present work specifically examines how climate change simultaneously

Table 1. Major classes of phytochemicals in botanical biopesticides with representative examples and primary modes of action

Compound class	Representative example	Source plant	Primary mode of action	Target insect pest/Pathogen
Terpenoids	Azadirachtin	*Azadirachta indica* A. Juss.	Insect growth regulator; antifeedant; endocrine disruption (ecdysone and JH antagonism)	Broad-spectrum insects (aphids, caterpillars, beetles)
	Pyrethrins	*Chrysanthemum cinerariifolium* (Trevir.) Bocc.	Voltage-gated sodium channel modulation; rapid knockdown	Aphids, mosquitoes, stored product pests
	1,8-Cineole	*Eucalyptus* spp. L.	Fumigant; membrane disruption; ROS induction in fungi	Stored product weevils; Alternaria spp.; fungi
	Menthol/ Menthone	*Mentha spp.* L.	Contact neurotoxin; GABA receptor modulation; repellent	Diverse insect orders
	Toosendanin	*Melia azedarach* L.	Antifeedant; insect growth disruption	Lepidopteran pests
Alkaloids	Nicotine	*Nicotiana tabacum* L.	nAChR agonist; continuous depolarisation; paralysis	Soft-bodied insects; aphids
	Phytolacca alkaloids	*Phytolacca dodecandra* L'Her.	Contact and ingestion toxicity	Termites; molluscs
Phenolic Compounds	Eugenol	*Syzygium aromaticum* (L.) Merr. & L.M. Perry	AChE inhibition; mitochondrial Complex I inhibition; fungal membrane disruption	Mites; fungi; insects
	Flavonoids	Various medicinal plants	Antifeedant; digestion inhibitor; antioxidant interference	Herbivorous insects
	Tannins	Various plant families	Protein precipitation; digestive enzyme inactivation; nutrient absorption reduction	Herbivorous insects; nematodes

increases the need for botanicals and complicates their deployment through phytochemical plasticity and formulation challenges. It bridges the gap between molecular mechanisms, advanced delivery technologies and agroecosystem-based IPM strategies, offering a comprehensive roadmap that is particularly relevant to tropical and subtropical agricultural contexts such as India, where climate variability and biodiversity of medicinal plants converge.

1.3. Scope and Structure of This Review

However, the transition from promising laboratory results to widespread field adoption is fraught with challenges: variability in chemical composition driven by climate change, rapid environmental degradation and regulatory frameworks designed for single chemical entities have historically limited commercial success (Isman & Grieneisen, 2014). This review critically examines the state of the art of botanical biopesticides within the context of climate change, providing deep mechanistic understanding of their potential while addressing the scientific, technological and regulatory dimensions essential for mainstream adoption.

Key hypotheses addressed: (1) Complex phytochemistry provides intrinsic advantages for resistance management; (2) Advanced formulation technologies can adequately address environmental instability; and (3) Strategic integration into IPM systems represents the pathway to climate-resilient pest management.

2. METHODOLOGY

This review was conducted following the broad principles of systematic and narrative review methodology as given by PRISMA (Figure 2).

Review articles were consulted for contextual background, but primary research studies, book chapters and technical reports were preferentially used for specific data and mechanistic claims. The review is organised thematically, covering phytochemical diversity (Section 3), molecular mechanisms of action (Section 4), broad-spectrum efficacy and climate effects (Section 5), formulation technology (Section 6), IPM integration (Section 7) and regulatory and commercial dimensions (Section 8).

3. THE PHYTOCHEMICAL PROPERTIES OF PLANTS

Plants, through a co-evolutionary arms race with

Figure 1. Integrated sustainable agriculture: Bio-Pesticide preparation, field application, agroforestry, and crop cultivation systems. The composite image illustrates the complete workflow of an eco-friendly farming system, beginning with the step-by-step extraction of natural neem leaf bio-pesticides (top centre) and their manual application in the field using protective gear (top right). It showcases the practical integration of sustainable land management through agroforestry plantations (top left) alongside diverse crop cultivation practices, including well-maintained field crops (bottom left) and organized row cropping near greenhouse facilities (bottom right)

herbivores and pathogens, have developed a capacity for chemical defence mediated by secondary metabolites that are not directly involved in primary growth and reproduction but are crucial for environmental interactions. This phytochemical arsenal comprises tens of thousands of unique structures, representing a rich, largely untapped reservoir for the discovery of novel biopesticides (Isman & Grieneisen, 2014). The major classes of these compounds, along with representative examples, are summarised in Table 1.

3.1. Terpenoids

Terpenoids, derived from the five-carbon isoprene unit, constitute the largest and most diverse class of plant secondary metabolites, with structural diversity spanning physicochemical properties and biological functions (Isman, 2006; Bakkali et al., 2008).

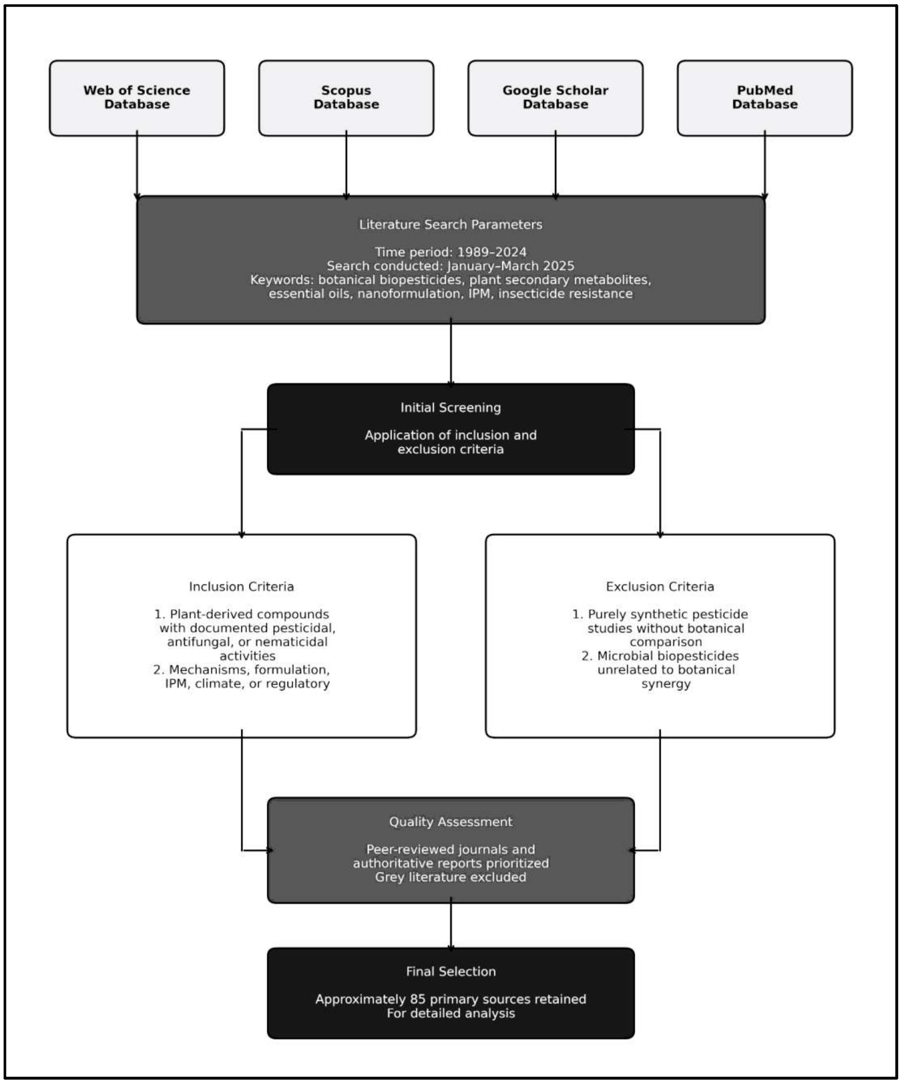

Figure 2. Flowchart of the systematic literature search and selection methodology. Primary databases (Web of Science, Scopus, Google Scholar, and PubMed) were queried using predefined parameters and keywords for the period 1989–2024. The retrieved literature was systematically refined through rigorous inclusion and exclusion criteria, followed by a quality assessment to prioritise peer-reviewed and authoritative reports, ultimately yielding approximately 85 primary sources for detailed analysis

Volatile monoterpenes and sesquiterpenes comprise primary constituents of essential oils. Menthol and menthone from *Mentha* spp. L. (Lamiaceae), 1,8-cineole from *Eucalyptus* spp. L. (Myrtaceae) and citral from *Cymbopogon* spp. Spreng. (Poaceae) are characterised by low molecular weight and high vapour pressure, making them effective fumigants, repellents and contact toxins (Bakkali et al., 2008). Their volatility, beneficial for enclosed space fumigation, contributes to short residual activity in open applications, a challenge exacerbated by rising temperatures.

Non-volatile terpenoids, particularly limonoids (tetranortriterpenoids) abundant in the Meliaceae family, function as potent antifeedants and insect growth regulators. The most studied limonoid is azadirachtin from *Azadirachta indica* A. Juss. (Meliaceae), which acts as a powerful feeding deterrent and disrupts insect endocrine systems through interference with moulting and development (Mordue Luntz & Blackwell, 1993). Other limonoids, such as toosendanin from *Melia azedarach* L. (Meliaceae), also exhibit significant antifeedant and growth regulatory effects (Chen et al., 2005).

3.2. Alkaloids

Alkaloids are structurally diverse nitrogen-containing compounds derived from amino acids that exhibit broad-spectrum pharmacological and toxicological effects (Koul et al., 2008). Nicotine from *Nicotiana tabacum* L. (Solanaceae), historically used since the 17th century, acts as an agonist of the nicotinic acetylcholine receptor in insect nervous systems, causing paralysis and death (Soderlund & Bloomquist, 1989 and Jansen et al., 2010). Its mode of action inspired the development of synthetic neonicotinoids, which are among the most widely used modern insecticides (Bai et al., 1991). Alkaloids from *Phytolacca dodecandra* L'Her. (Phytolaccaceae), known as endod or soapberry, demonstrates potent antitermitic and molluscicidal properties.

3.3. Phenolic Compounds

Phenolic compounds, characterised by hydroxyl groups attached to aromatic rings, include simple phenols, flavonoids and complex tannin polymers with multifaceted defence roles (El-Wakeil, 2013). Eugenol from *Syzygium aromaticum* (L.) Merr. & L.M. Perry (Myrtaceae) and *Ocimum sanctum* L. (Lamiaceae), key essential oil components, possess strong insecticidal, antifungal and neurotoxic properties (Bakkali et al., 2008). Flavonoids act as feeding deterrents, digestive inhibitors, and antioxidants, thereby reducing herbivore performance. Tannins (high molecular weight polyphenols) bind and precipitate proteins; when ingested, they inactivate digestive enzymes and reduce nutrient absorption, impairing herbivore growth and development.

3.4. Phytochemical Plasticity: How Climate Change Alters Plant Defences

The phytochemical bioactivity of plants is not static but highly plastic, responding dynamically to environmental cues. Rising atmospheric CO_2, elevated temperatures and altered precipitation patterns modulate plant secondary metabolism, with profound implications for the consistency and efficacy of botanical biopesticides (Zvereva & Kozlov, 2006 and Gherlenda et al., 2016).

Elevated atmospheric CO_2 often stimulates photosynthesis in C3 plants, increasing carbon availability relative to nitrogen. According to the carbon-nutrient balance hypothesis, this excess carbon is allocated to carbon-based secondary metabolites (phenolics and terpenes) (Ibrahim et al., 2011). Temperature and water availability exert powerful control over phytochemical production; plants respond to heat stress and drought by synthesising protective compounds (antioxidants and osmoprotectants), thereby altering overall metabolic profiles and disrupting normal growth cycles and flowering times (Zvereva & Kozlov, 2006).

This climate-induced phytochemical plasticity presents a fundamental paradox. The environmental drivers that make botanicals more necessary simultaneously introduce variability and unpredictability into their chemical composition (Gherlenda et al., 2016; Applequist et al., 2020). Standardisation of extracts becomes complicated, quality control is compromised and regulatory agencies accustomed to consistent active ingredients face evaluation challenges, affecting the entire value chain from cultivation to commercial formulation.

4. MOLECULAR MECHANISMS

An advantage of botanical biopesticides is their ability to engage multiple molecular targets and physiological pathways, making resistance development significantly less likely than with single-target synthetics (Sparks & Nauen, 2015). Understanding these mechanisms at molecular and cellular levels is crucial for optimising their use, guiding the discovery of new agents and designing effective insecticide resistance management (IRM) strategies (Sparks et al., 2019).

4.1. Neurotoxic Disruption

Many fast-acting botanical insecticides function as neurotoxins, interfering with nerve impulse transmission and leading to paralysis and death.

4.1.1. Pyrethrins and voltage gated sodium channels

Extracted from flowers of *Chrysanthemum cinerariifolium* (Trevir.) Bocc. (Asteraceae), Pyrethrins and their synthetic analogues (pyrethroids) are potent neurotoxins targeting voltage-gated sodium channels in nerve cell membranes (Jansen et al., 2010 and Sparks et al., 2019). These channels are essential for action potential generation and propagation. Pyrethrins slow both activation (opening) and inactivation (closing) kinetics, causing prolonged sodium ion influx during nerve excitation, resulting in membrane depolarisation, repetitive hyperexcitability and nerve block leading to paralysis and death (Soderlund & Bloomquist, 1989 and Mordue Luntz & Blackwell, 1993).

4.1.2. Nicotine and nicotinic acetylcholine receptors

Nicotine from *Nicotiana tabacum* acts as a potent agonist of insect central nervous system nicotinic acetylcholine receptors (nAChRs) (Jansen et al., 2010 and Sparks et al., 2019). By mimicking acetylcholine, nicotine induces continuous depolarisation and permanent excitation, leading to muscular paralysis and death.

4.1.3. Essential oils and multiple neurological targets

Essential oil components exhibit neurotoxic effects through diverse mechanisms. Eugenol inhibits acetylcholinesterase (AChE), the enzyme degrading acetylcholine in synaptic clefts. AChE inhibition causes acetylcholine accumulation, leading to nervous system hyperexcitation and paralysis, similar to the mechanisms of organophosphates and carbamates (Koul et al., 2008; Sparks et al., 2019). Monoterpenoids act as antagonists or allosteric modulators of GABA-gated chloride channels and octopamine receptors, contributing to broad neurotoxic profiles (Tong & Coats, 2010).

4.2. Endocrine Disruption and Growth Regulation

Many botanical compounds function as insect growth regulators (IGRs), interfering with endocrine systems governing moulting and metamorphosis (Isman & Grieneisen, 2014).

4.2.1. Azadirachtin

Azadirachtin from neem represents the archetypal botanical IGR, exerting effects multi pronged disruption of insect endocrine systems. Its primary action involves antagonism of key developmental hormones (ecdysone and juvenile hormone). Azadirachtin's structure mimics the steroid moulting hormone ecdysone, interfering at multiple levels of signalling. Centrally, it blocks the release of prothoracicotropic hormone (PTTH) from the corpus cardiacum complex (Mordue Luntz & Blackwell, 1993). PTTH is the neuropeptide that signals the prothoracic gland to synthesise and release ecdysone; by inhibiting PTTH release, azadirachtin effectively halts ecdysone production, preventing moulting and trapping insects in larval stages or causing fatal moulting defects. Azadirachtin also interferes with juvenile hormone through blockade of allatotropin release; this disruption creates developmental chaos, resulting in malformed pupae and often sterile, non-viable adults.

4.3. Metabolic and Cellular Disruption

Botanical compounds target fundamental cellular processes, including energy metabolism and membrane integrity. Beyond its neurotoxic effects, eugenol is a potent metabolic poison. A key molecular target in mites is NADH-ubiquinone oxidoreductase. Eugenol binds the MTND2 subunit, inhibiting function, disrupting electron flow, halting ATP production and leading to cellular energy failure and death. Molecular docking studies show eugenol binds effectively to mite MTND2 but not human homologues, providing a molecular basis for selective toxicity. Rotenone, another botanical insecticide, inhibits respiratory enzymes by disrupting electron transport between NAD and coenzyme Q (Mordue Luntz & Blackwell, 1993).

The monoterpene 1,8-cineole, the major eucalyptus oil component, powerfully compromises fungal cell structural and functional integrity. Its lipophilic nature allows it to intercalate into fungal plasma membranes, disrupting fluidity and permeability and causing leakage of essential ions and metabolites. Concurrently, 1,8-cineole induces massive reactive oxygen species (ROS) bursts within fungal cells, creating severe oxidative stress and widespread cellular damage, while downregulating ergosterol biosynthesis genes; ergosterol is a fungi specific sterol essential for membrane function.

4.4. Behavioural Modification

Many botanical compounds protect plants by modifying pest behaviour rather than directly killing pests (Isman & Grieneisen, 2014). Azadirachtin exhibits potent antifeedant activity through both immediate primary and delayed secondary mechanisms. Primary antifeedancy is immediate and taste mediated, where azadirachtin stimulates specialised deterrent chemoreceptors on mouthparts.

Secondary antifeedancy is delayed and post-ingestive, where sublethal consumption causes physiological distress and learned taste aversion. This dual-pronged behavioural modification provides robust crop protection by preventing feeding damage from initiation.

The power of botanical biopesticides lies not in single modes of action but in synergistic disruption portfolios. Single applications simultaneously launch multi-pronged assaults with neurotoxins, metabolic poisons, repellents, and antifeedants, representing an evolutionarily robust, integrated strategy that poses formidable adaptation challenges for pests and constitutes a cornerstone of sustainable resistance management.

5. BROAD-SPECTRUM EFFICACY AND ENVIRONMENTAL VARIABLES

The chemical diversity of secondary metabolites translates into exceptionally broad-spectrum biological activities, making medicinal plants versatile pest management tools (Isman, 2006 and Bakkali et al., 2008). Utility extends beyond direct toxicity to include behavioural modification and growth regulation, offering multiple avenues for integration into sustainable programmes. However, field performance is significantly influenced by environmental variables that are now being altered by climate change (Dhillon & Gujar, 2010). The range of documented biological activities and representative botanical sources are summarised in Table 1.

5.1. Climate-Dependent Efficacy

Translation of lab-demonstrated bioactivity to reliable field performance critically depends on environmental conditions, which are becoming more extreme and unpredictable due to climate change (Chen & McCarl, 2001; Dhillon & Gujar, 2010) (Table 2).

These climate-induced vulnerabilities underscore the critical need for robust predictive models. Future pest management decision-making requires models that integrate regional climate projections, pesticide degradation kinetics, pest phenology, and crop growth stages to optimise the timing, formulation, and application rates of botanical biopesticides in dynamic agricultural landscapes (Delcour et al., 2015).

6. ADVANCED FORMULATION FOR ENHANCED FIELD PERSISTENCE AND CLIMATE RESILIENCE

Despite potent and diverse botanical biological activities, widespread adoption has been significantly hampered by practical field level limitations. Properties making essential oil components effective fumigants, namely high volatility and susceptibility to UV radiation, heat and moisture degradation, result in short residual activity (Koul et al., 2008). These challenges are intensified by more extreme climate change-associated weather conditions (Dhillon & Gujar, 2010 and Acheuk et al., 2022). Bridging the critical lab-to-field gap requires advanced formulation and delivery systems that protect active ingredients, control release and enhance environmental stress resilience (Nuruzzaman et al., 2016 and Kumar et al., 2019).

6.1. The Formulation Challenge

Advanced formulation primary goals are creating

Table 2. Impact of climatic factors on botanical efficacy

Abiotic factor	Observed impact & mechanism	Specific compound/ context	Source
Temperature	Persistence vs Acute Toxicity Trade-off: Elevated temperatures increase component volatility, leading to rapid dissipation and reduced residual field activity. Conversely, it increases the metabolic rate of ectothermic insects, accelerating toxin uptake and potentially increasing acute efficacy.	Essential oil components (General)	Boina et al., 2009, Dhillon & Gujar, 2010
UV Radiation	Photodegradation: Acts as a primary degradation driver, causing significant loss of biological activity (e.g., antifeedant and IGR effects). *Azadirachtin* half-life is reduced to 48 minutes under direct 254 nm UV, compared to 2.47–3.98 days under natural conditions.	Azadirachtin; Pyrethrins	Sundaram, 1996,Jansen et al., 2010, Kookana et al., 2014
Precipitation & Humidity	Physical Wash-off & Synergism: Heavy rainfall physically washes formulations off plant surfaces, limiting efficacy. Conversely, high humidity promotes the germination and infectivity of entomopathogenic fungi, offering potential for synergistic application with botanicals.	Botanical formulations (General); Entomopathogenic fungi	Koleva & Schneider, 2009, Dhillon & Gujar, 2010

protective barriers around bioactive cores, shielding them from premature degradation while ensuring target-site availability over desired periods. Ideal formulations should enhance physical and chemical stability, improve solubility (especially lipophilic oils in aqueous sprays), increase plant surface adhesion and provide controlled or sustained release profiles (Kumar et al., 2019). Microencapsulation and nano-formulations represent the two most promising technologies (Camara et al., 2019).

6.2. Microencapsulation for Stability and Controlled Release

Microencapsulation involves surrounding tiny core material particles or droplets (for example, essential oils) with continuous polymeric films, forming microcapsules (1-1000 micrometres in diameter). Polymer shells act as physical barriers, protecting cores from volatilisation and environmental degradation while modulating release (Nuruzzaman et al., 2016). Common techniques include interfacial polymerisation, in which oil and water phase polymer precursors react at emulsion interfaces to form solid polymer shells (for example, polyurea) around oil droplets, and spray drying, a scalable industrial process wherein core material-wall material emulsions are atomised into hot air streams, leaving solid microparticles with entrapped cores.

By entrapping active compounds, microencapsulation significantly enhances shelf life and field persistence. Studies show that microencapsulated repellents maintain high efficacy for considerably longer periods than non-encapsulated formulations. Release is triggered by various mechanisms (diffusion, rupture, and biodegradation), enabling the design of predictable release kinetics (Nuruzzaman et al., 2016).

6.3. Nano-formulations: Enhancing Bioavailability and Climate Resilience

Nanotechnology offers sophisticated botanical pesticide delivery solutions, with the global nanopesticides market projected to exceed USD 2 billion by 2032 (Coherent Market Insights, 2025 and Precedence Research, 2025). Nano-formulations (nanoemulsions and nanocapsules) reduce active ingredient particle or droplet sizes to nanometre scales (typically less than 100 nm) (Kumar et al., 2019).

Nanoemulsions are kinetically stable colloidal dispersions of immiscible liquids (for example, essential oils-water) stabilised by surfactants. Extremely small droplet sizes provide key advantages: dramatically increased surface area-to-volume ratios enhancing bioavailability and biological activity, improved lipophilic oil solubility and water dispersibility and better hydrophobic plant cuticle adhesion and wettability (Anjali et al., 2010 and Kumar et al., 2019). Nanocapsules and polymeric nanoparticles enclose active ingredients within nanoscale polymer shells or matrices. Nanoencapsulation provides superior environmental degradation protection compared to microencapsulation, enables highly targeted and controlled release and enhances photoprotection of sensitive compounds (Camara et al., 2019). Biopolymers like chitosan and alginate increasingly serve as shell materials due to their biodegradability and biocompatibility (Wani & Khan, 2016).

These advanced formulations represent transformative steps. By systematically addressing primary botanical compound weakness of environmental instability, these technologies can enhance field performance, improve cost-effectiveness and make botanicals more reliable and competitive for mainstream, climate-resilient agriculture (Camara et al., 2019). Smart formulations tailored to specific pest-crop combinations and climate zones represent the next frontier in botanical biopesticide development.

7. STRATEGIC INTEGRATION INTO CLIMATE-SMART INTEGRATED PEST MANAGEMENT SYSTEMS

The ultimate value of botanical biopesticides is realised not as simple one-to-one synthetic replacements, but when they are strategically integrated into holistic IPM programmes (Pedigo, 2002). IPM is an ecosystem-based strategy focusing on long-term pest prevention through combined techniques, using pesticides only when monitoring indicates necessity at established thresholds. Within this framework, botanical pesticides serve as powerful, multifunctional tools that enhance sustainability, manage resistance, and improve overall programme efficacy, contributing to climate-smart agricultural system development (Rao et al., 2022).

7.1. A Cornerstone of Insecticide Resistance Management

One of the most critical roles of botanical pesticides in modern agriculture is insecticide resistance management (IRM) (Hawkins et al., 2019 and Matzrafi, 2019). Relentless single-target synthetic insecticide use creates intense selection pressure driving rapid resistant pest population evolution, potentially accelerated in warming climates through shorter generation times and larger population sizes.

Botanical pesticides counter this threat in two fundamental ways. First, many products, particularly crude extracts and essential oils, are complex bioactive compound mixtures engaging numerous pest molecular targets simultaneously (Koul et al., 2008). For pest resistance evolution, multiple independent resistance mechanisms must develop simultaneously, a far less probable event than single-target chemical resistance (Matzrafi, 2019). Second, even single botanical compounds such as azadirachtin and eugenol often exhibit multiple action modes (antifeedant and growth-regulating, or neurotoxic and metabolic). Consequently, rotating or tank-mixing single-target synthetics with complex multi-modal botanicals represents a highly effective IRM strategy, extending the useful lifespan of all available control products (Georghiou & Taylor, 1977).

7.2. Synergistic Applications

Beyond IRM, botanical pesticides combine with other control agents to produce synergistic effects, in which combined efficacy exceeds the sum of the individual components (Srivastava et al., 2011). This approach builds multi-layered, robust defence systems more resilient to pest adaptation and environmental volatility.

7.2.1. Synergy with synthetic pesticides

Botanicals can enhance the potency of synthetic pesticides, often enabling reduced application rates (Pavela, 2014). This frequently occurs through inhibition of detoxification enzymes. Certain plant oils inhibit the pest oxidase and glutathione S-transferase (GST) enzymes, which normally metabolise and detoxify synthetic insecticides such as pyrethroids and organophosphates (Srivastava et al., 2011). An azadirachtin-pyrethroid (cypermethrin) mixture showed a significantly lower lethal concentration (LC50) against red flour beetles (*Tribolium castaneum* Herbst [Coleoptera: Silvanidae]) than either compound alone, indicating a potent synergistic interaction.

7.2.2. Synergy with microbial control agents

Botanical pesticides can be compatible with and enhance microbial biopesticide efficacy, such as entomopathogenic fungi (Wraight & Ramos, 2005 and Surekha & Reddy, 2016). Azadirachtin demonstrates synergistic effects when combined with *Beauveria bassiana* (Balsamo) Vuill. (Fungi: Cordycipitaceae). Botanicals may weaken the immune system or disrupt the cuticle, thereby increasing susceptibility to fungal infections. Matrine demonstrates synergistic interactions with *Akanthomyces attenuatus* (Entomopathogenic Fungi) against thrips, with combined applications significantly lowering pest defensive enzyme activity (Wang et al., 2021). However, compatibility is key; some synthetic fungicides routinely used inhibit beneficial fungal growth and the efficacy of *B. bassiana* (Surekha & Reddy, 2016).

7.2.3. Synergy with entomopathogenic nematodes

Recent research explores botanical compatibility with soil-dwelling biological control agents such as entomopathogenic nematodes (EPNs) (Oso et al., 2021). Studies show Alepidea amatymbica Eckl. & Zeyh. and Elephantorrhiza elephantina (Burch.) Heine extracts are compatible with several strains of Steinernema and Heterorhabditis nematodes. Surviving nematodes retained

Table 3. Case studies of botanical integration in integrated pest management (IPM)

Crop / context	Target pest	IPM intervention / botanical strategy	Outcome & efficacy	Source
Brinjal (Eggplant)	Brinjal shoot and fruit borer (*Leucinodes orbonalis*)	Mechanical removal of infested shoots + Neem-based product sprays	Significantly lower pest infestation and higher marketable yields.	Wang et al., 2021
Tomato	Tomato fruit borer (*Helicoverpa armigera*)	Neem seed kernel extract (NSKE) + Nuclear polyhedrosis virus (NPV)	Demonstrated synergistic effects against the borer.	Verma et al., 2021
Meta-analysis (153 field trials on organic insecticides)	Several key pests	Pyrethrin-azadirachtin combination products	Provided >75% control of the targeted key pests.	Pavela, 2014
Maize & Cabbage	General pests (Large-scale IPM programs)	Biological controls (Bacillus thuringiensis & Trichogramma spp.) + Cultural practices	Led to >10% yield increases and significant reduction in chemical pesticide use.	CABI, 2015

virulence against target pests, suggesting soil-applied botanical-EPN combinations could improve control compared to individual applications, targeting pests in different environmental niches (foliar and soil) simultaneously.

7.3. Evidence from the Field: Case Studies in IPM

Various case studies across different regions of the globe demonstrate the use of botanicals as effective tools for pest management against a wide range of pests (Table 3).

8. GLOBAL COMMERCIALISATION

Despite compelling evidence of efficacy and ecological benefits, botanical biopesticides currently represent only a small fraction of the global pesticide market (Damalas & Koutroubas, 2018). This significant gap between scientific potential and commercial reality results from a complex interplay of economic, logistical, and regulatory barriers that collectively hinder widespread adoption (Villaverde et al., 2014). Bridging this lab-to-field gap requires understanding these challenges and developing strategies to overcome them.

8.1. Economic Viability and Farmer Adoption Barriers

The path from a promising plant extract to a commercially viable product on the farmer's shelf is fraught with practical difficulties. Biopesticide production often involves plant material cultivation, extraction and purification, potentially more complex and costly than conventional chemical synthesis (Damalas & Koutroubas, 2018). While many botanicals exhibit high pest specificity, an ecological advantage, this translates to smaller niche markets, making recovery of research and development investment difficult. Inherent instability and short shelf-life of many botanical active ingredients also pose significant logistical challenges, requiring specialised formulations and more complex supply chain management than those for robust synthetic chemicals (Pathma et al., 2021).

Farmers operate in high-risk environments, often hesitant to abandon the predictability of synthetic pesticides in favour of newer technologies. However, growing evidence demonstrates botanical economic viability. Field studies show botanicals can be highly cost-effective; neem seed extract (NSE) for Pakistani tomato pest management generated a cost-benefit ratio of 19.26 (significantly higher than 13.23 for synthetic emamectin benzoate) while achieving comparable marketable yields (Akhter et al., 2023). This demonstrates that, despite potentially higher initial costs or slower action, lower input costs of crude extracts can yield higher net profits for smallholder farmers (Mkindi et al., 2020; Verma et al., 2021).

8.2. The Regulatory Maze: A Comparative Global Analysis

Perhaps the most formidable barrier to botanical biopesticide commercialisation is the complex, costly and time-consuming regulatory approval process (Chandler et

Table 4. Comparative overview of regulatory frameworks for botanical biopesticides in major markets

Country/region	Regulatory body	Key legislation/framework	Timeline for biopesticides	Key features for botanicals
United States	EPA (Environmental Protection Agency)	FIFRA; Biopesticide Registration Programme	12 to 18 months	Dedicated biopesticide pathway; reduced data requirements; lower registration fees
European Union	EFSA; Rapporteur Member States	Regulation EC No. 1107/2009	120 days (low-risk) to 12 months	Stringent two-tier system; no separate biopesticide category; high data burden
China	MARA (Ministry of Agriculture and Rural Affairs)	Pesticide Administration Regulations (2022)	18 to 24 months	Streamlined pathway for biopesticides; growing acceptance of botanicals
Brazil	MAPA/ANVISA/IBAMA	Law 14.785/2023 (New Pesticide Law)	Significantly reduced	Most biopesticide-friendly major market; expedited approval for botanicals
India	CIB&RC (Central Insecticides Board and Registration Committee)	Insecticides Act, 1968; Schedule IV provisions; National Biopesticide Policy	24 to 36 months (conventional); reduced for approved botanicals	Schedule IV lists approved botanicals; CIBRC subcommittee for biopesticides; state-level registration for local botanicals; emphasis on neem products (EC 9%); GAP certification under NPOP
Australia	APVMA (Australian Pesticide and Veterinary Medicines Authority)	Agricultural and Veterinary Chemicals Code Act 1994	12 to 24 months	Reduced data requirements for low-risk botanicals; pathway for essential oil products

al., 2011). Most regulatory frameworks were designed to evaluate the risks of single synthetic chemical molecules, creating a fundamental paradigm mismatch when applied to complex, multi-component botanical extracts (Bailey et al., 2010; Villaverde et al., 2014). The very property giving botanicals their key biological advantage, phytochemical complexity, becomes their greatest regulatory disadvantage. A comparative overview of key regulatory frameworks is provided in Table 4.

8.2.1. India: Regulatory framework for botanical biopesticides

India presents a particularly relevant regulatory context for botanical biopesticides given the country's rich biodiversity of medicinal plants and the scale of its agricultural sector. The primary regulatory authority is the Central Insecticides Board and Registration Committee (CIB&RC), which operates under the Insecticides Act, 1968, and its subsequent amendments. Botanical biopesticides, including neem-based formulations, pyrethrum extracts and essential oil products, are listed under Schedule IV of the Insecticides Act, which provides a degree of regulatory facilitation compared to synthetic chemicals.

Neem-based products have received special attention under Indian regulation. The Bio-pesticides Sub-Committee of the CIB&RC reviews and approves botanical products, and neem formulations meeting minimum specifications (Neem based Pesticides containing Azadirachtin at 0.03% EC and above) are registered with relatively streamlined documentation. The National Policy on Biopesticides aims to promote the adoption of biopesticides, and the Ministry of Agriculture and Farmers Welfare has included biopesticides in flagship schemes such as the National Mission for Sustainable Agriculture (NMSA) and the Paramparagat Krishi Vikas Yojana (PKVY). Several Indian states also maintain state-level registration provisions for locally used botanical preparations under farmer field school and organic farming promotion programmes. The National Programme for Organic Production (NPOP) under APEDA recognises botanical pesticides compliant with international organic standards, facilitating access to export markets.

Despite these provisions, challenges remain. The registration process for novel botanical extracts or combination formulations under CIB&RC still demands extensive dossiers similar to synthetic pesticide registration, which is financially prohibitive for small manufacturers. Harmonisation of standards with Codex Alimentarius and alignment with Integrated Pest Management Cell recommendations would significantly accelerate the commercialisation of Indian botanical biopesticide products.

A fundamental paradigm shift is needed in global regulatory science, requiring the re-evaluation and development of methodologies for assessing the safety and efficacy of complex botanical mixtures as systems rather than as single-component entities (Villaverde et al., 2014). Greater international harmonisation of data requirements and mutual recognition of approvals would significantly reduce market-entry costs and time, stimulating innovation (AgroPages, 2023; World Bioprotection Forum, 2024).

9. CONCLUSION AND FUTURE PERSPECTIVES

Botanical biopesticides derived from medicinal plants represent a compelling, scientifically validated pathway towards more sustainable and ecologically resilient global agriculture (Fenibo et al., 2022). Grounded in sophisticated plant-herbivore chemical ecology, these natural products offer bioactive compounds with diverse, multimodal mechanisms that are fundamentally advantageous for pest resistance management in warming climates. IPM integration has demonstrated a reduction in reliance on synthetic chemicals, enhanced efficacy of other control agents through synergy, and contributed to safer food production systems (Srivastava et al., 2011).

However, the journey from promising laboratory results to widespread adoption is impeded by significant, interconnected challenges. Many botanical limitations, such as instability under heat and UV radiation, are exacerbated by climate change (Sundaram, 1996 and Dhillon & Gujar, 2010). Formidable economic barriers, farmer risk aversion and regulatory frameworks designed for different technological paradigms have stifled commercialisation and limited availability (Isman & Grieneisen, 2014 and Villaverde et al., 2014). Unlocking the full potential requires concerted, interdisciplinary effort.

9.1. Future Success Priorities

The future success of botanical biopesticides depends on the synergistic advancement of a triad of innovations encompassing molecular biology, formulation science, and regulatory science. Progress in only one or two areas is insufficient; coordinated advances across all three represent the only viable pathway elevating botanicals from niche status to mainstream, indispensable global food system components.

9.1.1. Mechanism-driven bioprospecting

Future botanical discovery should shift from random screening to targeted, mechanism-driven approaches (Sparks & Nauen, 2015). By identifying novel vulnerable pest molecular targets (chordotonal organs and specific metabolic enzymes) and screening for plant compound interactions, research becomes efficient and effective. Genomics, proteomics and computational biology advances will be instrumental.

9.1.2. Advanced formulation engineering for climate resilience

Overcoming stability and persistence issues arguably represents the most critical technological hurdle (Camara et al., 2019). Sustained investment in formulation science, particularly in scalable microencapsulation and nanoformulation technologies, is essential (Nuruzzaman et al., 2016; Kumar et al., 2019). The goal should be to develop smart delivery systems protecting active ingredients from environmental stressors (heat and UV) while providing tailored release profile optimised for specific pests and cropping systems.

9.1.3. Optimising synergistic IPM systems

Robust, large-scale field research is urgently needed to validate botanical performance in real-world, climate-smart IPM programmes (Ghosh et al., 2024). Research should prioritise synergistic combination studies and explore optimal botanical rotation and mixing with synthetic pesticides, microbial agents (Beauveria and Bacillus), and other biological controls (EPNs and parasitoids) to maximise efficacy and build system resilience (Furlong & Zalucki, 2017; Wang et al., 2021).

9.1.4. Regulatory reform and harmonisation

Future frameworks must evolve to accommodate the unique nature of complex botanical mixtures and to develop new safety and efficacy assessment methodologies. Brazil's reforms offer potential models for reducing timelines; greater harmonisation of international data requirements and mutual recognition of approvals would significantly reduce costs and time, thereby stimulating innovation (World Bioprotection Forum, 2024).

9.1.5. Integration with precision agriculture and genomics

The future of pest management involves biopesticide integration with precision agriculture technologies (drones and sensors) for targeted application, improving efficacy and reducing waste (Nuruzzaman et al., 2016 and Skendi et al., 2021). Biotechnology for selecting or genetically improving microbial agents for enhanced climate tolerance will be crucial in maintaining synergistic IPM strategy efficacy under future climate scenarios.

9.2. Realising the Potential

While challenges are substantial, they are not insurmountable. Through strategic interdisciplinary research investment, supportive policy reforms, and a commitment to closing lab-field-farmer gaps, botanical biopesticides can become foundational components of the global food system, prepared for the challenges of a changing climate. The paradigm shift from chemical-dependent, single-target pest management towards complex, multi-modal botanical integration into climate-smart IPM represents not merely incremental improvement but a fundamental transformation towards sustainable, ecologically resilient agriculture.

9.2.1. Key research hypotheses addressed.

This review demonstrated that botanical chemical complexity provides intrinsic resistance management advantages; advanced formulations can adequately address environmental stability challenges and strategic IPM integration represents the viable pathway for climate-resilient pest management. Future research must validate these hypotheses across diverse agroecologies and scales.

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CRediT authors contribution statement

Anand Jejal: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing - original draft. Samiksha Pandey: Writing - review and editing, Investigation, Methodology, validation. Anurag Saxena: Supervision, Validation, Writing - review and editing, Methodology, Validation. Magan Singh: Supervision, Validation, Writing - review and editing

Conflict of interest

The authors declare no competing interests.

Declaration of generative AI and AI-assisted

technologies in the writing process

The authors declare that no generative artificial intelligence (AI) tools or AI-assisted technologies were used in the writing, editing or revision process of this manuscript. All text was generated through original scholarly effort and critical analysis.

Data availability statement

All data generated or analysed during this study are included in this published article.

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