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Eco-Friendly Management of Insect Pests and Plant Diseases Using Botanical Extracts

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Abstract: *Insect pests and plant diseases are major constraints to global crop production, causing severe yield losses, economic costs, and environmental degradation. Conventional reliance on synthetic pesticides has generated resistance in pests and pathogens, contamination of ecosystems, and health risks to humans and beneficial organisms. Botanical extracts, derived from plants rich in bioactive compounds such as azadirachtin, pyrethrins, and essential oils, provide promising eco-friendly alternatives. These extracts act through diverse mechanisms, including repellency, feeding inhibition, growth disruption, antimicrobial activity, and induction of plant defense pathways, thereby reducing the risk of resistance development. Case studies in cereals, legumes, and vegetables demonstrate their effectiveness under greenhouse and field conditions, with commercial formulations of neem, pyrethrum, and essential oils already in use. Advantages include biodegradability and low toxicity to non-target species, but challenges such as short residual activity, variable efficacy, high production costs, and regulatory hurdles limit wider adoption. Advances in formulation technologies (nanoemulsions, encapsulation), exploration of underutilized plant species, and integration with biological and cultural practices within integrated pest management (IPM) frameworks offer pathways to overcome these barriers. This review highlights the potential* *role of botanical extracts in sustainable agriculture and emphasizes the need for interdisciplinary research, farmer-oriented innovations, and supportive policies to accelerate their global adoption.*

Keyword: Botanical extracts, Azadirachtin, Pyrethrins, Essential oils, Sustainable agriculture,, Insect repellency, Antifungal activity, Plant defense mechanisms

Introduction

Crop production worldwide is severely constrained by insect pests and plant diseases, which cause yield reductions of up to 30-40% in staple crops such as wheat, rice, and maize (Godfray *et al*., 2016). Insects such as aphids, whiteflies, and lepidopteran larvae damage crops directly and transmit viral and bacterial pathogens, while fungi and bacteria such as *Xanthomonas spp*. *Fusarium spp*. further intensify losses (Savary *et al*., 2019; Oerke, 2006). These damages translate into billions of dollars in annual economic losses, disproportionately affecting smallholder farmers in developing countries. Ecologically, pest-induced crop failures often lead to land expansion and deforestation, accelerating biodiversity decline (Dudley & Alexander, 2017). Synthetic pesticides, though effective in the short term, are increasingly unsustainable. Their overuse has resulted in resistance in more than 500 insect species and numerous fungal pathogens (Gould *et al*., 2018; Shaw, 2016). Additionally, chemical residues persist in soil and water, harming pollinators, aquatic organisms, and human health (Goulson, 2013; Aktar *et al*., 2009). Consequently, there is an urgent need for alternative approaches that are both effective and environmentally sound. Botanical extracts, rich in natural bioactive compounds such as azadirachtin, pyrethrins, terpenoids, and phenolics, provide a sustainable option. Their multiple modes of action-including repellence, antifeedancy, antimicrobial activity, and induction of systemic resistance reduce the likelihood of resistance and fit well into integrated pest management (IPM) systems (Isman, 2020).

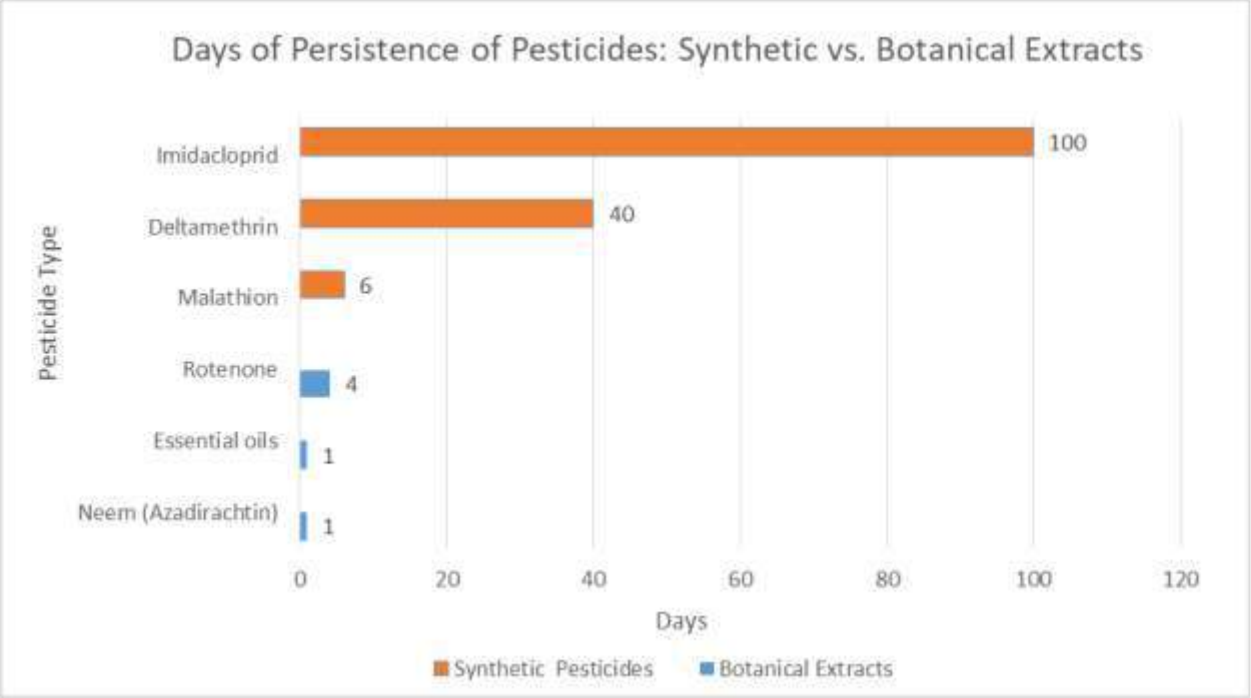

FIGURE I: COMPARING DAYS OF PERSISTENCE OF SYNTHETIC PESTICIDES AND BOTANICAL EXTRACTS

Sources: (Kumar *et al*., 2025; Ngegba *et al*., 2022; Smith & Perfetti, 2020)

The **Figure I** compare persistence of synthetic pesticides and botanical extracts. highlight respective durations of efficacy of synthetic pesticides and botanical pesticides in days. Synthetics pesticides showed significantly longer persistence. Imidacloprid persisted for hundred days followed by Deltamethrin and Malathion. On the other hand, botanical extracts showed relatively lower persistence. Rotenone persisted for four days followed by Neem plant extracts and Essential oils extracted from plants. This literature suggest that botanical plant extracts provide sustainable alternative with minimal impact on environment (Kumar *et al*., 2025; Ngegba *et al*., 2022; Smith & Perfetti, 2020). This review aims to summarize bioactive compounds and their mechanisms against pests and pathogens, evaluate performance in greenhouse and field trials, explore integration with other sustainable practices, and identify future research needs and policy measures for scaling adoption.

Botanical Extracts: Sources and Composition

TABLE 1: REPRESENTATIVE PLANT FAMILIES, BIOACTIVE COMPOUNDS, AND THEIR ROLES IN ECO-FRIENDLY PEST AND DISEASE MANAGEMENT

Plant family	**Representative species (common name)**	**Major bioactive compounds**	**Primary activity**	**Citations**
Meliaceae	*Azadirachta indica* (neem)	Azadirachtin, other limonoids	Antifeedant, growth disruption, broad antimicrobial activity	(Wylie & Merrell, 2022)
Asteraceae	*Chrysanthemum cinerariifolium* (pyrethrum)	Pyrethrins (pyrethrin I/II)	Fast contact insecticidal activity (neurotoxic to insects)	(Hodoșan *et al*., 2023)
Lamiaceae	*Ocimum tenuiflorum* / *Ocimum sanctum* (holy basil)	Eugenol, methyl eugenol, linalool	Repellency and insecticidal effects	(Raveau *et al*., 2020)
Lamiaceae	*Thymus vulgaris* (thyme)	Thymol, carvacrol	Strong antifungal activity, insect repellency	(Ranjbar *et al*., 2022)
Lamiaceae	*Ocimum basilicum* (basil)	Methyl chavicol, linalool, eugenol (varies)	Repellent activity against stored-product pests and mosquitoes	(Rodríguez-González *et al*., 2019)
Lamiaceae	*Mentha piperita* (peppermint)	Menthol, menthone, 1,8-cineole	Insect repellency and antifungal effects	(Raveau *et al*., 2020)
Lamiaceae	*Origanum vulgare* (oregano) / *Thymus* spp.	Carvacrol, thymol	antifungal activity	(Aoujil *et al*., 2025)
Lamiaceae	*Rosmarinus officinalis* (rosemary)	1,8-cineole, camphor, other monoterpenes	Antifungal and insect-repellent effects	(Houzi *et al*., 2024)
Myrtaceae	*Eucalyptus* spp.	1,8-cineole (eucalyptol)	Antimicrobial and insecticidal repellent	(Raveau *et al*., 2020)
Myrtaceae	*Syzygium aromaticum* (clove)	Eugenol	Antifungal and antimicrobial	(Batiha *et al*., 2020)
Fabaceae	*Tephrosia vogelii*	Rotenoids (rotenone, deguelin)	Insecticidal activity	(Tembo *et al*., 2018)

Plant family	Representative species (common name)	Major bioactive compounds	Primary activity	Citations
Verbenaceae	*Lippia javanica*	Linalool, other volatiles	Antifungal	(Kushaha *et al*., 2024)
Apiaceae	*Coriandrum sativum* (coriander)	Linalool, other terpenoids	Antimicrobial/repellent	(Raveau *et al*., 2020)
Amaryllidaceae	*Allium sativum* (garlic)	Allicin and sulfur volatiles	Broad antibacterial and antifungal activity	(Bedir *et al*., 2025)
Rutaceae	*Citrus* spp.	Limonene, citral	Repellency and insecticidal effects	(Sanli *et al*., 2025)

Table 1 summarizes key plant families and their representative species that produce bioactive compounds with significant pesticidal and antimicrobial potential. (*Azadirachta indica*) species of Meliaceae family contains azadirachtin that disrupts feeding and reduces insect growth and shows potential antimicrobial activity (Wylie & Merrell, 2022). *Chrysanthemum cinerariifolium,* of Asteraceae family contain pyrethrins that are known for their rapid neurotoxic action against insects (Hodoșan *et al*., 2023). Lamiaceae family is one of the largest family of plants that are used as botanical extracts that include Ocimum, Thymus, Mentha, Origanum, and Rosmarinus species. These plant contain terpenoids and phenolics like eugenol, thymol, carvacrol, and menthol that confer insect repellency, antifungal activity, and insecticidal properties (Aoujil *et al*., 2025; Houzi *et al*., 2024; Ranjbar *et al*., 2022; Raveau *et al*., 2020; Rodríguez-González *et al*., 2019). Similarly, *Eucalyptus spp* and *Syzygium aromaticum* of Myrtaceae family are rich sources of essential oils that are rich in eucalyptol and eugenol with strong antimicrobial and antifungal activities (Batiha *et al*., 2020;Raveau *et al*., 2020). Further, *Tephrosia vogelii* of Fabaceae family provides rotenoids with potent insecticidal properties (Tembo *et al*., 2018), and *Allium sativum* of Amaryllidaceae family contain sulfur-based volatiles that are effective against a wide range of pathogens (Bedir *et al*., 2025). Plants from Rutaceae and Apiaceae family *Citrus spp* and *Coriandrum sativum* provide limonene, citral and linalool with insect-repellent and

antimicrobial effects (Sanli *et al.*, 2025; Raveau *et al.*, 2020). **Table 1** highlights the diverse chemical arsenals of botanical extracts that are sustainable and eco-friendly alternatives to synthetic pesticides in integrated pest and disease management strategies.

Botanical extracts contain a variety of bioactive compounds that play important role in pest and disease management. These compounds include terpenoids, alkaloids and phenolics. Monoterpenes (limonene and thymol) and sesquiterpenes (azadirachtin), are common essential oils. These repel insects, work as antifeedants, and exert antimicrobial activity through the disruption of cellular membranes and enzyme functions (Regnault-Roger *et al.*, 2012). Thymol extracted from thyme extract work as antifungal against *Botrytis cinerea*, through the disruption of hyphal structures (Mishra *et al.*, 2016). Alkaloids extracted from *Nicotiana tabacum* and *Cinchona spp*., show insecticidal activity. These selectively inhibit acetylcholine receptors in insects inducing neurotoxic activity (Pavela, 2016). Flavonoids and tannins extracted from tea (*Camellia sinensis*) are Phenolics that deter insects and inhibit pathogens by inducing oxidative stress or inhibiting microbial enzymes. Compounds extracted plants have fewer chances of resistance development (Isman & Grieneisen, 2014).

The extraction process plays a key role in determining the efficiency and scalability of botanical extracts. Solvent extraction methods use solvents like hexane or ethanol for extraction. It is prevalent for the extraction of non-volatile compounds such as azadirachtin from neem seeds, give high yields but require careful solvent removal to avoid residue (Mordue & Blackwell, 1993). Steam distillation is widely used for the extraction of essential oils from Lamiaceae family plants. It retains volatile compounds like linalool and thymol and results in lower yields for thermolabile molecules (Regnault-Roger *et al.*, 2012). Supercritical CO_2 extraction is a leading-edge technology, produces high-purity extracts with low environmental impacts, pyrethrins extraction, although high cost restricts scalability for small-scale producers (Isman, 2020). Cold pressing, widely used for citrus oils, preserves bioactive compounds but shows reduced efficiency in industrial-scale production. The choice of each extraction process impacts bioactivity; for instance, neem oil from solvent extraction harbors a broader limonoid range compared to cold-pressed oil, thus increasing its insect-repellent and antifungal activities (Pavela, 2016). Scalability is also limited by plant material availability, process costs, and regulatory approval for extract standardization, requiring the establishment of optimized processes for large-scale agricultural applications (Bouizgma *et al*., 2025).

Mechanisms of Action Against Insect Pests and Plant Pathogens

Botanical extracts often suppress insect feeding and oviposition through mechanisms acting as antifeedants and repellents through secondary metabolites that act to modulate the behavior of insects. Chemicals such as azadirachtin derived from the neem tree (*Azadirachta indica*) act as potent antifeedants by altering the perception of taste and palatability and hence effectively deter insects such as *Spodoptera litura* from feeding on treated plant material (Mordue & Nisbet, 2000). Similarly, plant volatile oils such as those of rosemary (*Rosmarinus officinalis*) and peppermint (*Mentha piperita*) containing monoterpenes such as 1,8-cineole and menthol release volatile compounds that repel insects by disrupting olfactory receptor cues, as demonstrated in experiments with aphids (*Myzus persicae*) (Hori, 1998). The extracts also suppress oviposition, neem-based formulations prevent egg-laying in *Helicoverpa armigera* by disrupting host selection cues (Pavela, 2016). Repellent activities tend to operate in a dose-response mode and are based on the chemical composition of the extract, and hence they are effective in deterring crop damage without inducing direct mortality, hence minimizing ecological disturbance (Regnault-Roger *et al*., 2012).

Botanical extracts are insecticidal through toxic and growth-disrupting activity that targets a variety of physiological processes of insects. Pyrethrins from *Chrysanthemum cinerariifolium* cause neurotoxicity by binding to sodium channels in insect neurons, causing paralysis and death, as documented on pests like *Tribolium castaneum*. Azadirachtin, a neem limonoid, acts as a growth disruptor by inhibiting ecdysteroid biosynthesis, causing failure to moult and larval death in insects like *Plutella xylostella* (Mordue & Blackwell, 1993). Other chemicals, rotenone from Derris spp., target mitochondrial respiration, resulting in rapid knockdown in insects like Sitophilus oryzae (Isman, 2020). Botanical extracts target multiple physiological pathways preferentially, thus reducing the likelihood of resistance compared to single-mode synthetic insecticides. Growth-disrupting action is highly effective against immature instars, and botanical extracts are therefore highly useful for long-term suppression of pest populations in integrated pest management programs (Pavela, 2016).

Apart from their toxic potential, botanical extracts induce sublethal effects that alter insect behavior as well as physiological processes, thus exerting pest control through the reduction in reproductive efficiency and host-seeking effectiveness. For instance, sublethal levels of azadirachtin drastically reduce fecundity and fertility in *Bemisia tabaci* by inhibiting ovarian development and egg viability (Mordue & Nisbet, 2000). Essential oils, especially those of *Thymus vulgaris* containing thymol as a component, negatively influence host-seeking activity of pests like Aphis gossypii by disrupting chemosensory processes, consequently inducing depressed feeding and locomotion (Hori, 1998). Physiologically, such compounds as eugenol from clove (*Syzygium aromaticum*) induce oxidative stress and inhibit enzymatic activity, thus leading to the weakening of insects and reduction in lifespan (Regnault-Roger *et al.*, 2012). Such sublethal effects also enhance the effectiveness of natural antagonists as weakened insects are more vulnerable to predation or parasitism. Through disruption of both behavioral and physiological processes, botanical extracts offer an integrated approach towards pest control, thus minimizing the reliance on lethal control measures alone (Isman, 2020).

TABLE 2: MECHANISMS OF ACTION OF SELECTED BOTANICAL EXTRACTS IN PEST AND DISEASE MANAGEMENT

Botanical extract / key compound	**Major compounds**	**Targets**	**Mechanisms of action**	**Citations**
Azadirachta indica extracts	Azadirachtin, other limonoids	Insects, some fungi	Anti-feedant, growth disruption, reduced fecundity; repellent effects; enzyme inhibition in pathogens.	(Su *et al.*, 2023)
Chrysanthemum cinerariifolium	Pyrethrin I & II	Insects (broad)	Neurotoxicity via binding to voltage-gated sodium channels, paralysis, knockdown	(Hodoșan *et al.*, 2023)

Botanical extract / key compound	Major compounds	Targets	Mechanisms of action	Citations
extracts				
Thymus extracts	Thymol, carvacrol	Fungi, bacteria, insects	Disruption of cell membranes (fungi/bacteria), loss of membrane integrity and leakage; inhibition of ergosterol synthesis (fungi) and spore germination; repellency/antifeedant.	(Nazzaro *et al.*, 2017)
Rosmarinus officinalis extracts	1,8-cineole, camphor, other monoterpenes	Fungi, insects	Volatile olfactory disruption, membrane damage to microbes; antifungal inhibition of hyphal growth.	(Abd Rashed *et al.*, 2021)
Syzygium aromaticum extracts	Eugenol	Fungi, bacteria, insects	Cell membrane disruption, increased permeability, inhibition of biofilm formation and virulence	(Ulanowska & Olas, 2021)
Allium sativum extracts	Allicin, diallyl sulfides	Bacteria, fungi, nematodes,	enzyme inactivation, membrane damage, antibiofilm/antiquorum sensing activity, broad-spectrum antimicrobial effects.	(Nakamoto *et al.*, 2020)
Tephrosia spp extracts	Rotenone and related rotenoids	Insects; aquatic organisms	Inhibits mitochondrial electron transport (complex I), blocks ATP production, rapid knockdown / mortality	(Zhang *et al.*, 2020)
Citrus peel oils (limonene, citral)	Limonene, citral	Insects, fungi	Disruption of insect cuticle and respiratory function, membrane effects on microbes, knockdown and repellency.	(Abd Rashed *et al.*, 2021)
Mentha spp. extracts	Menthol, menthone, 1,8-cineole	Insects, fungi	Olfactory disruption, membrane disturbance in microbes, potential	(Nazzaro *et al.*, 2017)
Ocimum spp. extracts	Eugenol, methyl eugenol, linalool	Insects, microbes	Olfactory/behavioural disruption, contact toxicity, membrane damage in microbes, fumigant effects in stored-grain tests.	(Said *et al.*, 2020)
Salix extracts	Salicylic-acid analogs, phenolics, other elicitors	Plant immune system (pathogens indirectly)	Induction of systemic acquired resistance (SAR) and induced systemic resistance (ISR): upregulation of PR proteins (chitinases, glucanases), JA/ET signaling activation, priming for faster responses to pathogens.	(Yu *et al.*, 2022)

Table 2 highlights the diverse mechanisms through which botanical extracts exert insecticidal, antifungal, and antibacterial effects, reinforcing their role as eco-friendly alternatives to synthetic pesticides. Extracts of *Azadirachta indica* (azadirachtin) disrupt insect growth, feeding, and reproduction, while also inhibiting pathogenic enzymes (Su *et al*., 2023). *Chrysanthemum cinerariifolium* produces pyrethrins that target insect nervous systems, causing rapid knockdown (Hodoșan *et al*., 2023). Essential oil-rich plants such as *Thymus* and *Rosmarinus officinalis* act primarily through membrane disruption, inhibition of ergosterol synthesis, and olfactory interference, leading to impaired microbial and insect survival (Abd Rashed *et al*., 2021; Nazzaro *et al*., 2017). Similarly, *Syzygium aromaticum* (eugenol) and *Allium sativum* (allicin) compromise microbial cell integrity, inhibit biofilm formation, and inactivate key enzymes (Ulanowska & Olas, 2021; Nakamoto *et al*., 2020). Extracts from *Tephrosia spp.* demonstrate potent insecticidal effects by blocking mitochondrial electron transport, whereas citrus peel oils disrupt insect cuticles and microbial membranes (Abd Rashed *et al*., 2021; Zhang *et al*., 2020). Members of *Mentha* and *Ocimum* species further enhance pest suppression through repellency, contact toxicity, and fumigant properties (Said *et al*., 2020; Nazzaro *et al*., 2017). Uniquely, *Salix* extracts function indirectly by activating plant immune responses through systemic acquired resistance and induced systemic resistance (Yu *et al*., 2022). Collectively, these mechanisms illustrate the multifaceted potential of botanical extracts in integrated pest and disease management systems, offering both direct biocidal activity and indirect plant defense enhancement.

By targeting important phases of fungal growth like spore germination and mycelial development, botanical extracts show great antifungal capabilities and are therefore effective against a variety of fungal pathogens. High in compounds such thymol and carvacrol, essential oils from plants such as thyme (*Thymus vulgaris*) and oregano (*Origanum vulgare* inhibit spore germination in fungi including Botrytis cinerea and Fusarium oxysporum by destroying cell membrane integrity and halting ergosterol synthesis, an important component of fungal membranes (Mishra *et al*., 2016). For instance, clove oil

(*Syzygium aromaticum*), containing eugenol, has been shown to reduce mycelial growth of *Rhizoctonia solani* by up to 80% in vitro (Pavela, 2016). Neem (*Azadirachta indica*) extracts, with azadirachtin and other limonoids, also demonstrate antifungal activity by interfering with fungal enzyme activity and cell wall formation, effectively controlling pathogens like *Alternaria spp*. (Mordue & Blackwell, 1993). In organic agriculture, these extracts are especially helpful as their wide spectrum antifungal activity and poor environmental persistence make them practical substitutes for synthetic pesticides (Isman, 2020).

Through methods including membrane damage, enzyme inhibition, and interaction with pathogen replication, botanical extracts fight bacterial and viral plant pathogens. Phenolic compounds, those present in garlic (*Allium sativum*) and tea (*Camellia sinensis*) break bacterial cell membranes, causing leakage of cellular contents and death in pathogens like *Xanthomonas* campestris and Pseudomonas syringae (RegnaultRoger *et al*., 2012). Allicin from garlic extracts, for instance, inhibits important bacterial enzymes including cysteine proteases, therefore lowering the virulence of Erwinia carotovora (Curtis *et al*., 2004). Botanic extracts like those from Eucalyptus spp. containing 1,8cineole combat viral pathogens by obstructing viral protein synthesis, as seen in experiments on Tobacco Mosaic Virus (TMV) (Bishop, 1995). Although direct antiviral effects are less researched, some extracts, neem oil decrease viral transmission by repelling insect vectors like aphids, which are important for spreading viruses like Potato Virus Y. These varied activities show how botanical extracts could be used to control viral and bacterial infections in crops (Pavela, 2016).

By activating defense mechanisms to strengthen plant immunity, botanical extracts can improve plant resistance to pathogens by triggering systemic acquired resistance (SAR) or induced systemic resistance (ISR). Substances like salicylic acid analogs in willow (Salix spp.) extracts and phenolic compounds in rosemary (*Rosmarinus officinalis*) encourage SAR by upregulating pathogenesis-related (PR) proteins, such as chitinases and glucanases, thereby breaking down fungal and bacterial cell walls (Vallad & Goodman, 2004). For instance, by enhancing PR gene expression (Mishra *et al*., 2016), neem extracts have been shown to cause SAR in tomato plants and so lessen Fusarium wilt severity. Similarly, essential oils from *Mentha piperita* activate ISR through jasmonic acid and ethylene pathways, hence boosting resistance to Phytophthora infestans in potato crops by promoting the synthesis of defensive enzymes like polyphenol oxidase (Isman & Grieneisen, 2014). These triggered resistance mechanisms provide both direct protection and long-term advantages by priming plants against future infections, therefore making botanical extracts a sustainable tool for integrated disease management (Regnault-Roger *et al*., 2012).

Case Studies and Applications

Neem (*Azadirachta indica*) extracts containing azadirachtin have been widely tested in rice cultivation, where they reduce populations of the brown planthopper (*Nilaparvata lugens*) and suppress rice blast caused by *Pyricularia oryzae* (Isman, 2020). Field studies in South Asia reported up to 60% reduction in planthopper populations following neem application. However, many of these trials compared neem extracts only with untreated controls rather than synthetic standards, making it difficult to assess competitiveness under commercial farming. Furthermore, repeated applications were often required due to rapid degradation, raising concerns about labor and cost for smallholder farmers. Despite these limitations, neem remains one of the most widely adopted botanicals in Asia, partly because local communities can produce crude extracts at low cost, improving accessibility (Isman, 2020). In East Africa, neem and *Lippia javanica* extracts at 10% w/v increased bean yields by 350 kg/ha by suppressing *Colletotrichum boninense* and aphids (Mkindi *et al*., 2021). While promising, these trials were conducted under smallholder conditions with limited replication, raising questions about scalability to commercial systems. Moreover, yield gains were partly attributed to reduced pest pressure, but environmental factors such as rainfall and soil fertility were not fully controlled, making it difficult to isolate the direct effect of the extracts. Larger multi-location trials are needed to confirm consistency across environments. Rosemary (*Rosmarinus officinalis*) essential oil suppressed *Alternaria* infection by 70% and reduced whitefly infestation in greenhouse-grown tomatoes (Mishra *et al*., 2016). Greenhouse experiments demonstrated that rosemary (*Rosmarinus officinalis*) essential oil suppressed *Alternaria* infections by 70% and repelled whiteflies (*Bemisia tabaci*), leading to improved tomato yields (Mishra *et al*., 2016). The strength of these findings lies in the dual antifungal and insect-repellent activity. However, greenhouse conditions (stable humidity and reduced UV exposure) may have inflated performance relative to field settings, where essential oils degrade rapidly. Consequently, while rosemary oil shows high potential in controlled environments, its field application requires formulation improvements (e.g., encapsulation) to ensure persistence and cost-effectiveness. T*ephrosia vogelii* extracts reduced aphid and pod borer damage in cowpea, producing yields comparable to synthetic insecticides (Tembo *et al*., 2018). Yet, the requirement for weekly reapplications at *ephrosia vogelii* extracts reduced aphid and pod borer damage in cowpea, producing yields comparable to synthetic insecticides (Tembo *et al*., 2018). Yet, the requirement for weekly reapplications at 10% w/v due to rapid degradation imposes labor and cost challenges for smallholder farmers. This questions the practicality of large-scale adoption without advances in formulation or extension support for local extract preparation.10% w/v due to rapid degradation imposes labor and cost challenges for smallholder farmers. This questions the practicality of large-scale adoption without advances in formulation or extension support for local extract preparation (Hongo and Karel, 1986).

The efficacy of botanical extracts varies between field and greenhouse settings due to differences in environmental conditions, application methods, and pest/pathogen pressures. In greenhouse environments, stable temperature and humidity control improves the performance of extracts such neem oil and rosemary essential oil, which achieved 75–100% inhibition of fungal pathogens like Botrytis cinerea and *Alternaria spp*. in tomato and cucumber experiments (Mishra *et al*., 2016). Azadirachtin-based extracts decreased *Aphis gossypii* populations by 73% in hydroponic cucumbers under greenhouse conditions (Afshari *et al*., 2019; Jokar & Sheikholeslami, 2023). While this demonstrates strong efficacy, hydroponic systems do not reflect open-field realities such as UV exposure and rainfall, which degrade azadirachtin rapidly. Thus, although greenhouse studies highlight potential under protected cultivation, more field-scale trials are necessary to evaluate consistency under variable agroecological conditions. Field studies with Tephrosia vogelii on legume crops demonstrated yields equivalent to those of synthetic pesticides but necessitated weekly treatments at 10% w/v to offset fast breakdown (Tembo *et al*., 2018). Although both contexts show the possibility of botanicals under correct management, field applications call for optimized formulations with stabilizers to account for environmental change; greenhouse conditions favor consistent efficacy (Bowers and locke, 2000; Belabid *et al*., 2010).

Offering ecofriendly alternatives for organic and traditional agriculture, many commercial botanical products intended for pest and disease management are mostly based on neem, pyrethrum, and essential oils. Formulations based on neem, such as Azadirachtin EC (NeemAzal, Trilogy), are often used for their broadspectrum activity against aphids, whiteflies, and lepidopteran larvae as well as fungal pathogens like *Fusarium spp*., with uses in crops including rice, cotton, and vegetables (Isman, 2020). Derived from *Chrysanthemum cinerariifolium*, pyrethrin-based pesticides (PyGanic, EverGreen) are fast-acting contact insecticides effective against thrips and beetles in fruits, ornamentals, and field crops, usually combined with piperonyl butoxide synergists to enhance efficacy. Targeting softbodied insects and fungal diseases in greenhouse and field situations, essential oil-based products like EcoVia EC (rosemary and peppermint oils) and Requiem (chenopodium oil) are approved for organic farming by companies like OMRI even though their short persistence calls for careful application timing and, in some cases, adjuvants to improve field performance (Isman & Grieneisen, 2014).

Advantages and Challenges of Botanical Extracts

Over synthetic pesticides and fungicides, botanical extracts provide notable environmental and practical benefits, hence drawing interest for sustainable farming. Compared with synthetic chemicals like organophosphates, which may last for months (Aktar *et al*., 2009; Maksymiv, 2015), their biodegradability guarantees little environmental persistence and hence helps to minimize soil and water pollution. Under field circumstances, for instance, neem (*Azadirachta indica*) extracts including azadirachtin degrade within days, hence reducing environmental residues (Isman, 2020). Moreover, botanical extracts show minimal toxicity to nontarget species including pollinators and natural enemies; experiments indicate that rosemary (*Rosmarinus officinalis*) essential oils have almost no impact on bees (Apis mellifera) as opposed to neonicotinoids (Goulson, 2013). Unlike singletarget synthetic compounds (RegnaultRoger *et al*., 2012), botanicals with complex chemical profiles such pyrethrins and essential oils reduce the risk of resistance development in pests and pathogens owing their numerous modes of action. Virtually, botanical extracts fit organic farming regulations, allowing their application in certified systems and their adaptability in preparations (sprays, seed treatments) improve their relevance across several crops like rice, tomatoes, and legumes. These qualities define botanical extracts as the foundation of environmentally friendly pest and disease control. (Pavela, 2016).

Though they have benefits, a few obstacles prevent the general use of plant extracts in agriculture. Variable efficacy, affected by environmental conditions including UV radiation, rainfall, and temperature, lowers the botanicals' consistency relative to those of synthetic substances. Pyrethrins from *Chrysanthemum cinerariifolium*, for instance, breakdown quickly under sunshine and need to be reapplied frequently (every 3–5 days) to keep efficacy against aphids (Isman & Grieneisen, 2014). Short residual activity especially for essential oils like thyme (*Thymus vulgaris*) limits their efficacy in field circumstances where residual action of less than a week conflicts with synthetic pesticides lasting weeks (Pavela, 2016). High production costs also present a barrier since extraction methods such as supercritical CO_2 extraction for highpurity neem oil are costly and resource—intensive, hence botanicals become less inexpensive for tiny farmers in poor nations (Isman, 2020). Moreover, variation in plant material quality resulting from cultivar, harvesting time, or growth circumstances affects the efficacy of extracts, therefore complicating large-scale production (Regnault-Roger *et al*., 2012).

Adoption of botanical extracts is much affected by regulatory and standardization problems as inconsistent global rules and absence of standardized testing processes present obstacles to commercialization and usage. In several countries, botanical extracts are classified as pesticides and demand thorough registration processes similar to those for synthetic substances, which could be expensive and time-consuming. For instance, neem-based products undergo stringent evaluations under Regulation (EC) No 1107/2009 in the European Union, hence delaying market introduction in spite of their low toxicity (Isman & Grieneisen, 2014). Conversely, some areas like Africa have less stringent rules but lack of supervision can result in inconsistent product quality and effectiveness (Pavela, 2016). Another challenge is the standardisation of active ingredient levels; for instance, the azadirachtin content in neem extracts ranges widely (0.1–0.9% w/w), thereby influencing performance and calls for standardised quality control protocols (Mordue & Blackwell, 1993). Lack of globally harmonized testing techniques for bioactivity and environmental safety further complicates regulatory approval as data from one location may not be accepted elsewhere (Isman, 2020). Addressing these problems calls for international cooperation to create unified standards and simplified registration procedures to encourage the acceptance of botanical extracts in sustainable agriculture (Low *et al.*, 2017).

Integration with Other Management Practices

Because of their low toxicity and selective modes of action, botanical extracts are usually compatible with biological control agents like parasitoids and predators, making them useful parts of integrated pest management (IPM). Unlike broadspectrum synthetic pesticides, which can reduce populations of beneficial insects like Trichogramma spp. by up to 90% (Goulson, 2013), botanical extracts like neem (*Azadirachta indica*) and pyrethrum (*Chrysanthemum cinerariifolium*) have minimal impact on natural enemies when applied at recommended doses. For instance, greenhouse tests showed no appreciable mortality to the parasitoid Encarsia formosa at 0.5–1% neembased solutions, although they effectively controlled whiteflies (*Bemisia tabaci*) (Pavela, 2016). Likewise, rosemary (*Rosmarinus officinalis*) essential oils shown low toxicity to predatory lady beetles (Coccinella septempunctata), hence preserving their effectiveness against aphids (Aphis gossypii)

(Regnault- Roger *et al.*, 2012). Some botanicals, such highdose pyrethrins, however, can cause transient decreases in predator activity if not timed correctly; therefore, careful application techniques, such as targeted spraying or low-concentration use, are required to keep biological control agents alive. This compatibility improves the viability of plant extracts in integrated pest management systems (Isman, 2020).

Botanical extracts can be successfully incorporated into more general pest management plans by blending them with cultural methods and resistant crop types under IPM frameworks to improve pest and disease control while limiting environmental effects. Cultural techniques like crop rotation and intercropping supplement botanical extracts by lowering insect and fungal load; for instance, intercropping maize with *Tephrosia vogelii* extracts treated with legumes decreased *Spodoptera frugiperda* infestations by 40% in field trials, hence improving yields by up to 20% over untreated controls (Mishra *et al.*, 2016). Timing and application strategies are essential, seed treatments with clove (*Syzygium aromaticum*) oil protect seedlings from early-season pathogens, whilst foliar sprays target later pest infestations, as seen in tomato IPM systems (Pavela, 2016). To achieve sustainable, long-term pest and disease control this integrated approach uses the benefits of botanicals, cultural customs, and resistant types. (Isman & Grieneisen, 2014)

Synergistic effects achieved by combining botanical extracts with other natural compounds or low-dose synthetic insecticides improve cost-effectiveness and environmental safety by increasing efficacy and lowering application rates. For instance, neem oil combined with Bacillus thuringiensis (Bt) in field trials on cabbage increased control of *Plutella xylostella* by 30% compared to either treatment alone as neem's antifeedant properties complimented Bt's gut-disrupting action (Regnault-Roger *et al.*, 2012). Similarly, combining rosemary essential oil with chitosan, a natural polysaccharide, raised antifungal activity against Botrytis cinerea in strawberries by 50% because chitosan increased the adhesion and penetration of bioactive molecules (Mishra *et al.*, 2016). Low-dose synthetic synergists like piperonyl butoxide improve pyrethrin efficacy against pests like *Tribolium castaneum* by inhibiting detoxifying enzymes, hence enabling lower pyrethrin doses. Care, though, must be taken to guarantee compatibility since some combinations like high-dose essential oils with microbial biopesticides may decrease microbial viability. These synergistic strategies maximize the performance of botanical extracts, thus rendering them more competitive with traditional pesticides in a range of agricultural systems (Isman, 2020).

Implications for Sustainable Food Systems and Agribusiness

The adoption of botanical extracts in pest and disease management has far-reaching implications for sustainable food systems. By reducing dependence on synthetic pesticides, these products contribute to food security through yield stabilization, protection of staple crops, and reduced post-harvest losses. Smallholder farmers, who face disproportionate risks from pest outbreaks and pesticide costs, particularly benefit from locally available plant resources such as neem (*Azadirachta indica*) and *Tephrosia vogelii*. When integrated into community-based pest management programs, botanical extracts can buffer food supplies against shocks while supporting low-input farming systems.

From an economic perspective, botanical extracts offer both challenges and opportunities. Their use may lower expenditure on imported synthetic pesticides and open access to high-value markets for organic and sustainably certified products. Agribusinesses are increasingly exploring botanical biopesticides as part of a growing market projected to expand by 10–12% annually (Gaylal *et al*., 2025). However, economic viability depends on scalable extraction technologies, consistent product quality, and affordable formulations. Localized value chains—where plants are cultivated, processed, and marketed regionally—can strengthen rural economies while reducing reliance on imports. Partnerships between farmers, cooperatives, and private sector enterprises will be critical to achieving both affordability and profitability.

Environmental sustainability is another central dimension. Botanical extracts, owing to their biodegradability and low toxicity to non-target organisms, align with agroecological principles and biodiversity conservation goals. By lowering pesticide residues in soil and water, they safeguard beneficial insects, pollinators, and soil microbiota essential for long-term ecosystem resilience. Moreover, their compatibility with integrated pest management (IPM) supports climate-smart agriculture, enabling reduced greenhouse gas emissions compared with intensive synthetic pesticide use.

Ultimately, the integration of botanical extracts into sustainable food systems requires coordinated action across science, policy, and markets. Investment in research to improve efficacy, government incentives to ease regulatory barriers, and farmer training for adoption will together determine the pace of transition. If these conditions are met, botanical extracts could contribute not only to crop protection but also to global sustainability goals, bridging agricultural productivity with environmental stewardship and economic inclusivity.

Future Research Directions

Despite promising results, the adoption of botanical extracts for pest and disease management remains constrained by scientific and practical gaps. Based on the current evidence, we propose the following **prioritized research directions**:

1. **Formulation Science (High Priority):**
   Improve stability and persistence of extracts through nanoencapsulation, microemulsions, and UV-protective carriers. This will directly reduce application frequency, lower costs, and increase competitiveness with synthetics.
2. **Standardization and Quality Control (High Priority):**
   Develop cost-effective analytical tools (e.g., portable HPTLC, near-infrared spectroscopy) to ensure consistent concentrations of active compounds across seasons and geographies. Standardization is essential for regulatory approval and farmer confidence.
3. **Field-based, Multi-location Efficacy Trials (High Priority):**
   Expand trials beyond greenhouse and laboratory studies to multi-season, multi-ecoregion field experiments. These should include **direct comparisons with leading synthetic benchmarks** and assess performance under variable climate conditions.

4. **Mode-of-Action Elucidation (Medium Priority):**
   Advance mechanistic understanding of extracts at the molecular and physiological levels, including induction of plant defense genes and synergistic interactions with beneficial microbes. Clear mode-of-action data will strengthen resistance management strategies and regulatory dossiers.
5. **Integration within IPM Systems (Medium Priority):**
   Evaluate how botanicals interact with biocontrol agents, trap crops, and cultural practices. Optimizing synergy can reduce reliance on repeated sprays and support agroecological transitions.
6. **Socio-economic and Adoption Studies (Medium Priority):**
   Conduct participatory research with farmers to assess willingness to pay, labor requirements, and perceived barriers to adoption. Coupling agronomic data with economic modeling will guide farmer-centered innovations.
7. **Environmental and Ecotoxicological Assessments (Lower Priority but Emerging):**
   Undertake long-term studies on the effects of botanical residues on soil health, pollinator dynamics, and aquatic ecosystems. This will ensure alignment with biodiversity conservation and sustainability policies.
8. **Policy and Market Research (Lower Priority):**
   Investigate pathways to integrate botanicals into certification schemes (e.g., organic, residue-free labels) and explore incentive mechanisms (price premiums, subsidies) that make adoption economically viable.

Conclusion

Botanical extracts have great potential as environmentally safe methods of pest and disease management, a precious substitute for synthetic fungicides and pesticides in agriculture. Their biodegradability, mild toxicity to non-target species, and numerous sites and modes of action such as repellence and toxicity and inducing plant resistance enable effective management of insect pests like *Spodoptera litura* and pathogens like Botrytis cinerea without ecological harm (Isman, 2020; Regnault-Roger *et al*., 2012). Empirical field trials validate their efficacy in crops like rice, tomatoes, and legumes, with neem and rosemary extracts attaining levels of pest and disease control similar to that obtained with synthetic chemicals under laboratory conditions (Mishra *et al*., 2016; Tembo *et al*., 2018). Their integration with integrated pest management (IPM) practices, which include biological control and promotion of resistant varieties, further contributes to their potential in sustainable agriculture, particularly in organic agriculture. By reducing reliance on synthetic chemicals, botanical extracts are essential to maintaining biodiversity, soil health, and long-term food security and thus are an integral part of ecologically sustainable pest and disease management practices (Pavela, 2016).

Sustained research and company policy support are necessary to overcome hurdles in the extensive application of botanical extracts, thereby ensuring their scalability and effectiveness in various agricultural systems. Research must tackle issues of variable efficacy, limited residual activity, and high costs of production, with innovation like nanoemulsions and encapsulation holding potential for enhancing stability and delivery (Isman & Grieneisen, 2014). Molecular research to illuminate plant-insect-pathogen interactions, as well as ecological evaluations of non-target implications, will further maximize their utilization and ensure safety for the environment (Vallad & Goodman, 2004). Policy interventions, such as streamlined regulation and funding incentives to the botanical sector, are needed to lower costs and ease market entry, especially for smallholder farmers in underdeveloped nations (Pavela, 2016). Harmonization of international standards for extract registration, especially in the context of issues presented by EU regulations, may accelerate acceptance. Collaboration among researchers, policymakers, and agricultural extension practitioners is required to create economically viable, standardized products and transfer knowledge, thereby ensuring that botanical extracts become an economically viable and widely accepted option (Isman, 2020).

Interdisciplinary collaboration among entomologists, plant pathologists, and agronomists is needed to develop and apply botanical extracts further, encourage innovation, and practical use. Entomologists might focus on screening newly discovered insect-repellent and insecticidal compounds from underutilized plants like Lantana camara while improving application techniques to limit impacts on beneficial arthropods (Regnault-Roger *et al*., 2012). Plant pathologists might investigate the molecular mechanisms by which extracts induce systemic resistance or inhibit pathogens like *Fusarium spp*., using tools like transcriptomics to enhance efficacy (Mishra *et al*., 2016). Agronomists might scale these findings to field-scale IPM systems, testing mixtures of botanicals with cultural control and resistant cultivars in crops like maize or cowpea, as demonstrated in African trials (Tembo *et al*., 2018). Interdisciplinary collaboration might include designing farmer training modules and open-access repositories of bioactive plants, extraction protocols, and application guidelines. By combining disciplinary expertise, such collaborations might encourage the innovation of sustainable, affordable, and effective botanical-based solutions to global agricultural problems in an environmentally friendly manner.

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