

Allelopathy for pests (Insects, Nematodes, Pathogens) management in sustainable Agriculture

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ABSTRACT

Sustainable pests (insects, nematodes, pathogens) management is necessary due to environmental drawbacks caused by use of pesticides for pests control. Allelopathy is promising alternative for pests control. Many crops have allelopathic pesticide potential; hence, it is essential to evaluate them to integrate into sustainable pests management strategies. This review aimed to explore the allelopathic potential of plants for crop pests control. The allelochemicals present in essential oils of medicinal plants (Thyme, oregano, rosemary, lavender, fennel and laurel) are fungitoxic against both foliar and soil-borne pathogens. Natural pesticides, offer an environmental friendly alternative to present synthetic pesticides.

Keywords: Agriculture, allelochemicals, allelopathic plants, fungitoxic, insects, medicinal plant, nematodes, pathogens, pests management.

1. INTRODUCTION

Allelopathy is a natural phenomenon in which organisms produce chemicals through various mechanisms to inhibit the growth of other nearby organisms (4). Plants possess an innate ability to defend themselves using naturally occurring chemical molecules that interfere with the growth, metabolism and development of crop pests (weeds, insects, nematodes, pathogens). This subfield of chemical ecology, investigates how various compounds secreted by plants or microorganisms influences the germination, growth and

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distribution of surrounding flora and microfauna in both agricultural and natural ecosystem (46). Since ancient times, allelopathy has been recognized as an important ecological phenomenon in agricultural practices and has gained widespread use in plant ecology in past few decades (64). Willis (62) cited the literature discussing allelopathy from ancient times till 1957 in his book '*The History of Allelopathy*'. In mid-1950s, 3-books on allelopathy were published (i). Grummer (1955) Monograph (German) (ii). *Impacts of Allelopathic Chemicals in Agriculture* (Russian) and (iii) Hubert Martin (1957) '*Ecology's Chemical Aspects in Relation to Agriculture*' (23). Since, the mid-1990s, allelopathy research has progressed rapidly and being studied in fields related to Agriculture, Botany, Ecology, Environmental, Science and Edaphology (11). Allelopathy research is currently gaining attention in field of crop production.

Allelopathy involves interactions that affect the target and surrounding organism in both negative and positive ways. It can be antagonistic, synergistic, or additive. It includes chemical interactions and communication among various organisms. Allelochemicals involved in allelopathy against competing plant species and defensive molecules involved in defence functions against natural enemies, including herbivores and diseases, are also present in several invasive plant species (40). The ability of plant species to defend themselves against herbivore insects as natural enemies is one of the most important requirements for their survival during invasion. Plant growth, development and regeneration are seriously harmed by herbivore insects (6). To protect themselves from their natural predators, several plant species have evolved a chemical defence mechanisms (31).

2. ALLELOPATHY IN INSECT-PESTS MANAGEMENT

According to Narwal and Haouala (42), sustainable agriculture seeks to minimize negative environmental effects, while maintaining agricultural output and natural resources over the long term. It focusses on optimal crop production with minimal external inputs, minimizing reliance on commercial inputs (pesticides and fertilizers), utilizing internal resources, and anticipating sustainable methods that could sustain productivity over time. Allelopathic techniques may be able to satisfy these needs; as a significant advancement in agriculture. Consequently, an alternate strategy for managing pests might be to employ allelopathic methods (32). This review examined how allelopathy may be used, instead of pesticides to control diseases and insect pests, especially in intensive small-farm agricultural systems (53). Thus, this review's evaluated the allelopathy's contribution to pest management in sustainable agriculture.

2.1. INSECT-PESTS MANAGEMENT

Insects attacks are primary factors to reduce yields of cereals, pulses, fiber crops, fruits and vegetables. To combat these pests, chemical pesticides are widely used, but they severely impact natural ecosystems. Moreover, the increasing resistance of insects to these chemicals forces farmers to apply higher doses, compounding the issue. Biotic stressors (viruses, bacteria, nematodes, fungi, insects and other herbivores) are the primary causes of plant damage. Plants have developed numerous defence systems, chemical barriers for protection against insect pests (41). A wide variety of pests and diseases harm plants,

triggering the plant's defence mechanisms to generate a range of chemical compounds "weapons" (terpenoids, phenolics and nitrogen compounds), these are pesticidal, antifungal and antibacterial, which are induced by pest attacks (22).

Table 1. Insect-Pests management methods using essential oils and plant extracts.

S. No.	Component	Target Pest	Effectiveness	Ref
Oils				
1.	Neem <i>Azadirachta Indica</i> L. Oil	Strawberry aphid nymphs and adults	Anti-feedant properties	36
		Huge pine weevils	Inhibits feeding	51
2.	Essential Oil (<i>Mentha citrata</i> , <i>Pogostemon cablin</i>)	<i>Spodoptera littoralis</i> larvae	Toxic effect	18
3.	<i>Chenopodium ambrosioides</i> L. Essential Oil	<i>Aedes aegypti</i> L. and <i>Anopheles arabiensis</i> Patton	Larvicidal effects	19
Extract				
4.	<i>Ageratum conyzoides</i> L. Extract	<i>Anopheles gambiae</i> , <i>Chilopartellus</i> , <i>Sitophilus oryza</i> , <i>Leptocorisa chinensis</i>	Insecticidal activity	18
5.	<i>Salvia Sclarea</i> L. Extract	Whiteflies	56.6 % mortality	25
6.	<i>Satureja Montana</i> L. extract	Greenhouse whiteflies	Insecticidal properties	25
7.	Sorghum Water Extract	Aphids	62.5 % mortality at 8 % conc	54
8.	Sunflower Water Extract	Aphids	52.5 % mortality at 16 % conc	54

Excessive use of synthetic pesticides has detrimental impacts on the environment, human and animal health and insect resistance. Hence, researchers are looking into natural insecticides. Allelochemicals offer amoreeco-friendly alternative in modern agriculture. Bio insecticides derived from natural compounds in medicinal plants, present a sustainable solution. For instance, the aqueous extract of *Satureja montana* L., exhibits insecticidal properties, against greenhouse whiteflies, with no adverse effects on pepper seedlings (25). A comprehensive understanding of allelochemicals provides valuable alternatives to reduce reliance on chemical pesticides (Table 1). For example, lower concentrations of *Salvia sclarea* L., aqueous extracts induces lipid peroxidation in roots of black nightshades (*Solanum nigrum* L.) and exhibit toxic effects on whiteflies (*Trialeurodes vaporariorum* Westwood), resulting in 56.6 % mortality (25). The essential oils from Lamiaceae family like *S. sclarea* L., repels many insect species, including common house insects (14). When used in fumigation, the essential oils of *Mentha citrate* Ehrh., *Pogostemon cablin* (Blanco) Benth., *Mentha pulegium* L., *Thuja occidentalis* L., *Nepeta cataria* L., *Thymus mastichina* L. *Origanum majorana* L., *Salvia sclarea* L., *Origanum compactum* Benth., *Origanum vulgare* L., *Melissa ofcinalis*, L. and *Lavandula angustifolia* Chaix., proved extremely toxic to *Spodoptera littoralis* larvae (57). *Aedes aegypti* L. and *Anopheles*

arabiensis Patton are susceptible to the larvicidal effects of essential oils of *Chenopodium ambrosioides* L. and *Ocimumlami folium* Hochst. Ex Benth. (19). The (*Azadirachta indica* L.) seed oil has anti-feedant characteristics against strawberry aphid nymphs and adults (*Chaetosipho nfragaefolii* (Cockerell) (36). It also inhibits feeding of huge pine weevil (*Hylobiusabietis* L.) in conifer plantations (51). The allelochemicals (salannin, nimbin and azadirachtin) in neem oil have been identified (33).

Decomposing crop residues increases soil nutrients and also released allelochemicals that greatly reduces soil-borne pathogens and plant pests (19,24). Allelopathic water extracts of mustard, sunflower and sorghum, as well as combinations of mulberry (*Morus alba* L.) and sorghum and sunflower, were tested for their ability to effectively suppress dominating aphids. The post-embryonic development and adult emergence of rice lepidopterans (*Corcyra cephalonica* St.) were considerably impacted by exposure to volatile oils derived from eucalyptus (*Eucalyptus globulus* L.) during their larval stages. Sorghum water extracts were most effective (62.5 % aphid mortality) at concentration of 8 % and sunflower water extracts (16 % concentration) resulted in 52.5 % aphid mortality. Combined water extracts (16 %) of sorghum and mulberry resulted in 45.7 % aphid mortality and sorghum and sunflower had 57.5 % mortality.

Sunflower water extracts at 16 % concentration caused 52.5 % mortality in aphids, while sorghum water (8 % conc) caused 62.5 % aphid mortality (53). The combined of mulberry and sorghum water extracts at 16 % concentration led to 45.7 % aphid mortality, whereas, the mixture of sorghum and sunflower extracts achieved 57.5 % aphid mortality (58). Allelochemicals-based pest management is a promising strategy for the natural control of harmful insects, reduce crops tolerance to insect pests and synthetic insecticides, offering an eco-friendly alternative in modern agriculture. Using aqueous solutions, methanol and other organic solvents, the whole plant extracts of *Ageratum conyzoides* demonstrated insecticidal activity against number of crop insects, including the most significant malaria vector, the mosquito (*Anopheles gambiae*), the stalk borer (*Chilopartelus*) (51), the rice weevil (*Sitophilus oryza*) and the rice bug (*Leptocorisa chinensis*) (18).

Both plant-derived extracts and conventional pesticides can be used within IPM (Integrated Pest Management) framework, which combines physical, cultural, biological and chemical controls to manage pests sustainably (39). Plant-derived extracts can offer target-specific control, reducing harm to beneficial organisms and minimizing environmental impact (17). Overuse or misuse of either type of pesticide can lead to resistance, emphasizing the need for responsible and integrated pest management strategies (24).

2.2. NEMATODES MANAGEMENT

Nematodes parasitize plant roots and feed on plants nutrients in tropical and semi-tropical countries (19). Plant parasitic nematodes reduce plants productivity. Approximately 1,200 species of plant-parasitic nematodes cause significant financial losses to wide range of hosts (8). They affect turfgrass, fruit, nut and forest trees, vegetable and crops and form knots or galls, lesions in the roots and severe branching of roots. The most harmful are root-knot nematodes (*Meloidogyne spp.*), which have a large host range

(3, 26). To control nematodes, soil fumigants (methyl radical halide, propargyl bromide, bromide or 1, 3-dichloropropylene) are used but these disrupt soil ecosystems (9).

Allelopathic studies are critical in nematological research, as plant-derived substances can influence nematode behaviours, including attraction or repulsion from plant roots. Much attention has been given to nematode-suppressive crops (Table 2). Some crops are non-hosts to nematodes and others actively reduce nematode populations by producing nematicidal chemicals (48). The potential of allelopathic crops in integrated pest management strategies, offers an environmental friendly alternative to chemical nematicides (19). It involves crop rotation, intercropping, or treatments with green manure, since it offers advantages over the current use of hazardous chemicals for nematodes control.

The marigold (*Tagetes* spp.) allelopathy controls the nematodes. It is a medicinal plant and demonstrated its allelopathic activity against nematodes (13). Numerous marigold species exhibited resistance against various worm species (28). The marigold species and cultivars, when cultivated in rotation, inter-planted with crop, or applied as soil amendment, efficiently controls nematodes in crops (17). Marigold contain α -Terthienyl nematicidal chemical derived from the roots of marigold (*Tagetes* spp.), which is used to suppress plant parasitic nematodes. α -Terthienyl, an exudate of the marigold, effectively penetrates the nematode hypodermis in *Caenorhabditis elegans* Dauer and *Meloidogyne incognita* J2 larvae and exerts nematicidal activity through oxidative stress induction (59).

Table 2. Nematode management method using allelopathic plants and their extracts.

S.No.	Component	Target Nematode	Effectiveness	Ref
1.	Marigold (<i>Tagetes</i> spp.)	Plant-Parasitic nematodes	Suppresses population by α -terthienyl	13
2.	α -Terthienyl	<i>Caenorhabditis elegans</i> Dauer, <i>Meloidogyne incognita</i> J2 larvae	Nematicidal activity through oxidative stress induction	61
3.	<i>Ageratum conyzoides</i> L. Extract	<i>Meloidogyne javanica</i> , <i>Meloidogyne incognita</i>	Increases mortality, Inhibits parasitic gall production	1,49
4.	<i>Ageratum conyzoides</i> L. (Pyrrolizidine Alkaloids)	Nematodes	Potential nematicidal action	17
5.	<i>Brassica</i> crops	Plant- parasitic nematodes	Biofumigation, suppresses nematode populations	37

The mortality of *Meloidogyne javanica* (37) and *Meloidogyne incognita* (1) was increased by aqueous extracts of *Ageratum conyzoides* leaves. Additionally, *Meloidogyne incognita*'s parasitic gall production was inhibited by its aqueous leaf extracts (49). The observations imply that, *conyzoides* may contain specific compounds with nematicidal activity, even if the active compounds in the extracts have not yet been identified. The pyrrolizidine alkaloids found in *Ageratum conyzoides* are extremely poisonous to both insects and animals (17,27). Consequently, these pyrrolizidine alkaloids might contribute to the species' nematicidal action. Numerous plants and weeds have been evaluated for their chemical action against nematodes and many plant species from different plant

groups produce nematicidal chemicals. While some studies have provided clear evidence of allelopathy. This highlights the need for more rigorous research to better understand the allelopathic potential of these plants in nematode management (39).

2.2.1. Chemical pathway of α -terthienyl

The α -terthienyl is an allelochemical derived from the roots of marigold (*Tagetes* spp.), which is used to suppress plant parasitic nematodes. It's known for its insecticidal, nematicidal and antifungal properties (50). The chemical pathway of α -terthienyl involves its sensitization to UV light, leading to the generation of reactive oxygen species that damage cellular components (Table 3). Several mechanisms of α -Terthienyl activity have been elucidated. The oxygen-dependent phototoxicity of α -Terthienyl reportedly generates singlet oxygen and superoxide anion radicals (44). These reactive oxygen species (ROS) *in-vivo* are substrates for the detoxification enzymes superoxide dismutases (SODs) and catalases (CTLs). In addition, photoactivated α -terthienyl (PAT) showed significant concentration-dependent ROS-induction activity in lepidopteran ovarian Tn5B1-4 and Sf-21 cells, which decreased the activity of peroxidase (POD), SOD and CTL (50, 29). Since biomolecules oxidized by ROS also become harmful substances, phase II metabolism that employs such enzymes as glutathione S-transferases (GSTs) and UDP-glucuronosyl transferases (UGTs) (35) are important for resistance to α -terthienyl. Oxidative stress-related enzymes in the free-living model nematode *Caenorhabditis elegans* are largely controlled by the cap'n'collar transcription factor SKN-1, which is a structural and functional homolog of the mammalian Nrf2 (3). SKN-1 activity in such stress responses is negatively regulated by the WD40 repeat protein, WDR-23 (50).

Table 3. Chemical pathway, mechanism, effects and regulation of oxidative stress response of α -terthienyl.

S.No.	Mechanism	Effects	Ref
1.	UV Light sensitization	Generates reactive Oxygen species	44
2.	Oxygen-Dependent Phototoxicity	Produces singlet oxygen and superoxide anion radicals	44
3.	ROS-Induced Damage	Damages cellular components including proteins, Lipids and DNA	50
4.	Detoxification Enzymes	Superoxides mutases (SODs) and catalases (CTLs) mitigate ROS- Induced damage	50
5.	Antioxidant Defense	α -terthienyl affects peroxidases (POD), SOD and CTL activity	50
6.	Phase II Metabolism	Glutathione S- transferase (GSTs) and UDP-glucuronosyl transferases (UGTs) detoxify oxidized biomolecules	35
7.	SKN-1 Regulation	Regulates oxidative stress- related enzymes in <i>Caenorhabditiselegans</i>	44
8.	WDR- 23 Regulation	Negatively regulates SKN- 1 activity, modulating oxidative stress response	35

2.2.2. Soil mobility of α -Terthienyl

α -Terthienyl exhibits low mobility in soil, because its significant portion remains immobilized. Specifically, in one study, α -terthienyl showed approximately 93.3 % immobility after 72 h (60). This low mobility is likely due to its relatively high molecular weight and tendency to bind to soil organic matter. α -Terthienyl size and ability to interact with soil components, particularly organic matter, restrict its movement through the soil profile (25). The relatively low mobility of α -terthienyl in the soil is relevant to its use as nematicide, as it can accumulate in the rhizosphere, where it can effectively target nematodes (5). While α -terthienyl can be activated by light (photosensitization) for its nematocidal activity has been observed without photoactivation, suggesting a more direct mechanism of action in some cases, particularly in the presence of peroxidases. (10).

2.3. PATHOGENS MANAGEMENT

Through host-pathogen co-evolution, plants have developed a range of complex, inherent defence mechanisms to protect themselves against these microbial invaders (2). A pathogen produces degradative enzymes, forcing access through stomata or injured areas, or penetrating with specialized structures (45). Numerous secondary metabolites are produced by plants, many of these have antibacterial properties, therefore, this second line of defence mechanisms will come into contact with the pathogen (7).

Numerous diseases, especially fungus, bacteria, viruses and phytoplasmas, attack crop plants and reduces the plant growth and productivity. There is growing trend in many property systems to investigate natural and eco-friendly substitutes for such chemicals (12). One of most innovative approach to manage phytopathogens is to take advantage of plants' allelopathic capabilities (20). Allelochemicals are physiologically active substances produced and released by many plant species. Allelochemicals are released through root exudation, activity from aerial elements, especially leaves, volatile emissions and material degradation, release these compounds into the environment (63).

2.3.1. Fungal Diseases

Fungal-induced plant diseases are leaf spots, root and crown rot, rust, smut, blight, wilt, dieback and mildew and controlled by fungicides (24). These are controlled by fungicides which develop resistance in fungi and also cause environmental pollution. Allelochemicals, in aqueous extracts, oil extracts and residues, effectively manage plant diseases with minimal ecological impact (16,59). The allelochemicals in *Lawsonia inermis* L., *Decalepisha miltonii* Wight and *Mimosops elengi* L., were compared using artificial chemical fungicides, the results were identical (15). The growth of *Fusarium solani*, the causative agent of rot and wilt illnesses, was inhibited by aqueous n-hexane and methanol extracts of complete *Ageratum conyzoides* plants (30). The growth of blight and wilt-causing *Fusarium oxysporum* was inhibited by methanol extracts of shoots of *Ageratum conyzoides* (30). Furthermore, extracts from *Ageratum conyzoides*' aerial portions prevented the growth of fungi that cause rice blast (*Pyricularia oryzae*) and sugar beet root rot (*Rhizoctonia solani*). Precocene II was most potent of the four flavonoids (nobiletin, 5'-methoxynobiletin, eupalestin and 5,6,7,3',4',5'-hexamethoxyflavone) found in the extracts (43). Allelochemicals can therefore, be utilized to control pathogenic seed-borne fungal infections in an environmentally benign way (Table 4).

Table 4. Fungicidal effects of *Ageratum conyzoides* extracts

S. No	Fungal Diseases	Causative fungi	Allelochemical Management	Effects	Ref
1.	Rot and Wilt	<i>Fusarium Solani</i>	<i>A. conyzoides</i> extracts	Inhibited growth	30
2.	Blight and Wilt	<i>Fusarium oxysporum</i>	<i>A. conyzoides</i> methanol extracts	Inhibited growth	30
3.	Rice Blast	<i>Pyriculariaoryzae</i>	<i>A. conyzoides</i> extracts	Prevented growth	43
4.	Sugar Beet Root Rot	<i>Rhizoctoniasolani</i>	<i>A. conyzoides</i> extracts	Prevented growth	43

2.3.2. Bacterial Diseases

Bacterial pathogenic microorganisms cause several plant diseases (34) and are more harmful than fungi or viruses (55). Two hundred species of microorganisms cause serious, diseases in 150 plant genera. These microorganisms associated with plants are rods, with symptoms such as mosaic patterns, pustules, spots on fruits and leaves, or malodorous tuber rots leading to plant death (38).

Plants have allelopathic ability to control plant diseases and infections caused by microorganisms (21). These have no adverse effects, intercropping garlic (*Allium tuberosum* L.) with tomato considerably reduced and delayed the occurrence of tomato microbiological wilt caused by *Pseudomonas solanacearum* Smith. Dicot trees (*Acacia nilotica*, *Phyllanthus emblica* L. and *Terminalia chebula* Retz.), effectively suppresses lesions on leaves and fruits caused by bacterium genus *X. campestris* Pammel. Application of volatile plant oil thyme camphor (2-isopropyl-5-methylphenol) decreased the incidence of *Ralstonia solanacearum* Smith (Table 5). Wilt and increased tomato yield. Extracts of leaves of *Datura stramonium* L. and *Pisum sativum* L. are antibacterial against microorganisms that cause wilting in *Ralstonia solanacearum* Smith (30).

Table 5. Bacterial diseases and their allelochemicals management using various plant sources

S. No	Fungal Disease	Causative Bacteria	Allelochemical Management	Effectiveness	Ref
1.	Tomato Microbial Wilt	<i>Pseudomonas solanacearum</i> Smith	Garlic (<i>A. tuberosum</i> L.) intercropping	Reduced and delayed occurrence	21
2.	Citrus Bacterial Canker	<i>Xanthomonas campestris. citri</i>	Dicot trees (<i>A. nilotica</i> , <i>Phyllanthusemblica</i> L., <i>Terminalia chebula</i>)	Suppressed lesions	21
3.	Bacterial Wilt	<i>Ralstonia solanacearum</i> Smith	Thyme Camphor (2-isopropyl-5- methylphenol)	Decreased incidence, increased yield	21
4.	Bacterial Wilt	<i>Ralstonia solanacearum</i> Smith	<i>Datura stramonium</i> L. and <i>Pisum sativum</i> L. extracts	Antibacterial activity	30

As an alternative to the heavy use of pesticides, is the use of allelopathy in planting systems to manage pests and decrease pesticides usage. By using allelopathy as a substitute pest management technique in property-intensive crop production, chemical consumption is further decreased. Allelochemicals have the potential as natural

insecticides. They also have shorter half-life, fewer group substituents, hence, quickly degrade (47). According to Regnault *et al.* (52), phytochemicals have a relatively high rate of degradation, different sites of action, and low or no toxicity to mammals and beneficial insects. Allelochemicals affects the vital physiological functions such as respiration, chemical reactions, biological processes and elongation, membrane fluidity, the biogenesis of macromolecules and the activity of numerous enzymes (47). By integrating allelopathy into natural and organic management techniques, fewer insecticides, and other pesticides may be applied, to lessen environmental and soil contamination and the risks of autotoxicity. There is high demand for substances that are selectively harmful and soil microbes or plants can quickly break down. Furthermore, all plant species, microbes, other soil organisms produce allelochemicals that offer fresh strategies for maintaining and improving agricultural productivity and output over the long run.

3. CONCLUSIONS

Allelopathy offers a promising approach for sustainable pest management, but its potential is constrained by several factors. Allelopathic effects can be influenced by environmental factors, such as soil type, temperature and moisture which can impact their stability and efficacy. Effective delivery systems are needed to ensure that allelopathic compounds are released in a controlled and targeted manner. The development and implementation of allelopathic pest management strategies can be costly which may limit their adoption. Allelopathy can contribute to sustainable agriculture by reducing the use of synthetic pesticides and promoting ecosystem services. Allelopathic pest management strategies can promote ecosystem health by minimizing harm to non-target organisms. By addressing the constraints and leveraging the potential of allelopathy, we can develop effective and sustainable pest management strategies that promote ecosystem health and reduce the environmental impact of agriculture.

ACKNOWLEDGEMENTS

The authors express their profound appreciation to the esteemed Directors and administrations of the Department for their unwavering support and for furnishing the indispensable materials required to carry out this scholarly pursuit.

AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration with all authors. All authors finally approved and drafted the manuscript.

DECLARATION

We declare that all authors of this manuscript have made substantial contributions. We have not excluded any author that substantially contributed to this manuscript. We have followed our ethical norms established by our respective institutions.

ETHICAL STATEMENT

In this study, we did not involve any animal and human studies.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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