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Impact of Allelochemicals in Crop Protection Management: A Review

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ABSTRACT

One of the most serious issues is biotic stress in plants produced by insect pests, which results in production losses. Synthetic pesticides continue to play an important role in crop protection. Yet, the environmental consequences and health risks caused by excessive or improper use of synthetic pesticides compelled authorities to ban some dangerous ones. As a result, there is an urgent need for unique and alternative insect pest management strategies. Allelopathy is a naturally occurring ecological phenomenon of organism interaction that can be used to manage weeds, insect pests, and illnesses in field crops. Allelopathy can be utilized in field crops after rotation, using cover crops, mulching, crop smothering, and plant extracts for natural pest management. Allelochemicals in soil are adsorbed on soil solids and decomposed during soil movement by chemical and biological reactions. Its behavior is influenced by soil characteristics such as soil texture, organic and inorganic matter, moisture, and organisms, all of which have an impact on phytotoxic activity in soil. Although allelochemicals are produced throughout the plant, root exudation is the principal source of chemical release into the soil environment. Therefore, this review will focus on the role of insect-pest management, factors affecting production and release of allelochemicals, their activity and limitations in insect-pest management.

Keywords: *Allelochemicals in soil are adsorbed on soil solids and decomposed during soil movement by chemical and biological reactions*

Introduction

In different Agro-climatic zones, insect communities interact both favourably and unfavourably with a variety of plants [80]. The development of numerous chemical complex defence mechanisms has been prompted by negative interactions with insects that harm plants [34]. Insect diversity is determined by plant diversity and evolution. Allelochemicals, a class of secondary plant metabolites, are especially important in the interactions between plants and insects [43].A twofold increase in food production is predicted to be required to meet the world's demand by the year 2050 [66].Arthropod pests' yield loss is one of the causes of less intensive production [28]. Globally, the annual yield loss is greater than 15% [62].Numerous serious issues are brought on by the widespread use of pesticides, such as non-target adverse effects on individuals and beneficial organisms, like insect pollinators [35], natural enemies, pest resurgence, the emergence of secondary pests, biotypes, high costs associated with both active ingredients, and the application and development of pesticide resistance by target pests [30]. All these reasons necessitate the development of a more convenient, environmentally friendly, and low-input driven efficient strategy for pest control. In order to address the problems of environmental pollution and herbicide resistance, allelopathy is becoming increasingly popular as a sustainable weed management method [37].

The occurrence of allopathy has long been documented in natural ecosystems, dating back to prehistoric times and before agriculture. Allelopathy was only associated with deleterious chemical interactions among plant species since it was discovered in the agroecosystem through observations of what was called "soil sickness" or through the detrimental influence of some plant species on others (mostly crops). Although theories on allelopathy may date back to 600 B.C. and the discovery of intrinsic plant defence systems dates back more than 2000 years [32]. The word allelopathy comes from two Greek words: 'allelon', which means 'of each other', and 'pathos', which means 'to suffer'. Austrian plant physiologist Molsch coined the word "allelopathy" and first used it to describe the chemical interaction between plants and microbes (Molsch, 1937). It is a phenomenon in which an organism secretes biochemicals (referred to as allelochemicals), which can interfere with the growth and development of other species in either a positive or negative way [2].However, the word allelopathy was coined by Molisch and recognised by certain researchers to apply to both negative and positive chemical interactions between plants in nature. According to Whittaker and Feeny the ideal definition of allelochemicals is chemicals that allow organisms of one species to influence the development, well-being, behaviour, or population biology of organisms of another species (with the exception of compounds consumed solely as food by the second species). Allelopathy uses plant-derived secondary metabolites in the disease and pest control as a defence mechanism.In cropping systems, allelopathy can provide a strong bio-rational pest management option. When grown in intercropping systems, allelopathic plants release allelochemicals into the environment through root exudates, volatilization from above-ground plant components, and leaching or decomposition of plant debris [75].

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Allelochemicals are primarily secondary metabolites that are produced as byproducts during a variety of physiological processes in plants [45]. They mainly include phenolics, flavonoids, terpenoids, alkaloids, momilactone, jasmonates, salicylates, hydroxamic acids, brassinosteroids, polysaccharides, glucosinolates, and amino acids [33].

Allelochemicals having stimulatory effects on plants can be used to produce biofertilizers [7], whereas those with inhibitory effects can be used as herbicides and disease control agents [53]. Allelochemicals can sometimes influence targets more effectively when used in combinations than when used alone. The application of allelopathic plant water extracts and the powder of allelopathic plants may be highly effective for the management of insect pests (field and storage insect pests). Allelochemicals have an impact on the development of unwanted plants (e.g., weeds) via modifications to their cellular structure, suppression of cell division and elongation, rupturing of membranes, interference with the processes of water and nutrient intake, and photosynthesis [9].Different types of allelochemicals produced by different plants along with their target insect-pest is listed in Table 1. The analysis of allelopathic potential of plant genetic variations among cultivars to outpace crops and weeds, identification of allelochemicals, the status of allelopathy in ecosystems, and the prospects of utilising allelopathic crops for pest control in field crops are all included in numerous research works on allelopathy. Currently, in this study, the potential use of allelopathy as a substitute for insecticides for managing insect pests, especially in small-farm intensive agricultural systems is being discussed. This review work has been lucidly written with a broad objective of exploring the mechanism of action of allelochemicals, method of pest control through allelochemical, factors affecting the production of allelochemicals and potential of allelochemical in pest control.

Table 1. Allelochemicals produced by different plants, their target insect-pest along with their potential mortality rate

Allelopathic source	Application Rate	Target Insect-pest	Mortality	References
Neem	Seed kernels water extract (2%)	Pod borer	32%	[1]
Tomato	Leaf water extract (2%)	Flowetthrip	12%	[12]
Hot Pepper	Fruit Water Extract (4%)	Flowetthrip	31%	[14]
Kalonji	Oil extract (10%)	Red flour beetle	48%	[50]
Clove	Oil extract (10%)	Red flour beetle	47.5%	[53]
Olive	Oil extract (10%)	Red flour beetle	46%	[81]
Datura	Leaf powder (10%)	Asian citrus psyllid nymphs	31.5%	[74]
California pepper tree	Water extract (5.6% w/v)	Elm leaf beetle	28%	[42]
Eucalyptus	Oil volatiles	Rice moth	67-78%	[67]
Fig-leaf goosefoot	Ethanol extract (5%)	Aphid	86%	[20]
Birbira seed crude extract	---------------	Sorghum chaffer	45-60%	[46]
Sunflower	Water extracts (16%)	Aphids	52.5%	[80]

Allelochemicals released into environment through four methods:

1. Leaching: From plant leaves and stems. Allelochemicals in the leaves of the Black walnut, *Juglansnigra*, for example, are washed away by rain can impede the growth of vegetation beneath the walnut tree [9].

2. Volatilization compounds: From the stem and leaves of a plant, e.g. *Salvia leucophylla* [55].

3. Phytotoxic chemicals: Derived from decaying plant matter. When utilised as a mulching medium, the decomposing plant residue releases a range of allelochemicals such as Rye (*Secale cereale*) [26].

4. Root exudation: chemicals emitted from plant roots; for example, living Rice plants can selectively limit pest growth [36].

Allelochemicals either have a direct or indirect mode of action, which is referred to as true or functional allelopathy [3], respectively.Allelochemicals may harm the target directly (direct allelopathy) or alter the microenvironment indirectly (indirect allelopathy) by degrading into secondary degradation products in the soil after release. It is impossible to distinguish the dominance of direct allelopathy over indirect allelopathic effects in field conditions because there may be countless biotic and abiotic factors influencing the fate of allelochemicals released into the soil environment [75].Therefore, from an ecological perspective, indirect allelopathy is thought to be more significant. The mechanism of action of allelochemicals for agricultural pest management has been detailed in the following lines.

1. Changes in cell strucure: The cell structure and its shape are affected by the allelochemicals found in various plant components. In addition to nuclear anomalies within the vacuole, volatile allelochemicals (such as monoterpenes, eucalyptol, and camphor) can cause the root cells to expand or shorten [70]. For instance, the use of maize (*Zea mays* L.) pollen extract decreased the activity of mitotic cells in watermelon (*Citrullus lanatus*by more than 50%. Additionally, it inhibited the growth of the radicle and hypocotyl and increased the irregularities of nuclear and pyknotic nuclei [16]. White mustard (*Sinapis alba* L.) cell walls were damaged by the allelochemicals from barley (*Hordeum vulgare* L.) roots (hordenine and gramine), which also increased cell organelle disorganisation and autophagy [56]. Similar to this, an allelochemical called "cinnamic acid" distorts the ultrastructure of the chloroplasts and mitochondria in cucumber (*Cucumis sativus* L.) (89).Allelochemicals produced by catmint (*Nepeta meyeri* Benth.) and field bindweed (*Convolvulus arvensis* L.) have also been shown to affect the random amplification of the polymorphic DNA profiles of diverse plants [50]. An allelochemical called citral has a significant impact on the disruption of microtubules in the roots of wheat (*Triticum aestivum* L.) and Arabidopsis (*Arabidopsis thaliana* L.) [17]. In Arabidopsis, the citral cell reduced intercellular communication, altered the ultrastructure, and promoted cell-wall condensation [39].

2. Effect on cell multiplication and elongation: It is hypothesised that the inhibition of mitosis and disordered organisation of cell organelles produce the reduction in plant growth brought on by the production of allelochemicals [58]. Allelochemicals, mainly monoterpenoids.

(i.e camphene, beta-pinene, camphor, alpha-pinene, and 1,8-cineole), have an impact on DNA synthesis and cell proliferation in plant meristems [63]. Due to their capacity to obstruct energy transmission and reduce ATPase activity in the cell membrane and chloroplasts, these substances manifest such harmful consequences [11] Allelochemical exposure has also been associated with a reduction in the mitotic process, particularly in lettuce (*Lactuca sativa* L.) [81]. In a study, sorgoleone, an allelochemical found in sorghum (*Sorghum bicolor* (L.) Moench), reduced the number of cells during each phase of cell division, causing damage to tubulins and polyploidy nuclei in bean plants (*Phaseolus vulgaris* L.) [41]. It has been noted that allelochemical DIBOA (2, 4 dihydroxy-1,4 (2H)-benzoxazin-3-one) released by rye (*Lolium rigidum* Gaud.) decreases cucumber root cap cell regeneration along with slow growth [9]. When jimson weed (*Datura stramonium* L.) allelopathic water extracts were applied to soybean (*Glycine max* (L.) Merr.), they suppressed root tip cell division, increased chromosomal aberration in micronucleus index, inhibited the length and density of root hairs, and reduced primary/lateral root elongation [15]. Polyphenolic chemicals extracted from dodder plants suppressed the mitotic activity of barley seedlings and onion root meristematic cells, with results resembling those of treatments with 8-Hydroxyquinoline, a popular cytotoxic drug [29].

3. Effect on cell membrane integrity and permeability: The cell membrane, which is a crucial part of the cell and acts as a partition between the interior and exterior environments. To protect the cell from harmful external environmental factors, the membrane's integrity is essential [93]. Electrolyte leakage and lipid peroxidation are brought on by allelopathy-induced changes in membrane permeability and polarisation, which reduce mineral nutrient uptake [58]. Plant tissues either grow slowly or die as a result of such modifications in membrane permeability that cause cell contents to leak out [55]. Malonaldehyde (MDA), a product of lipid peroxidation, is frequently employed as a marker of the integrity of cell membranes. Early research on allelochemicals including benzoic and cinnamic acids, which are frequently present in soil, revealed lower catalase and peroxidase activity and increased electrolyte leakage in soybean seedlings [10]. For example, by increasing lipid peroxidation, the application of allelopathic water extracts made from barley's aerial plant parts reduces the growth of wild mustard (*Sinapis arvensis* L.) and wild barely (*Hordeum spontaneum* L.) saplings [31].Due to the leakage of biological membranes, the application of non-sterile wheat aerial parts and water foxtail (*Alopecurus aequalis* L.) increases the ROS (reactive oxygen species) activity and leaf malondialdehyde contents in seedlings of non-transgenic and transgenic potato (*Solanum tuberosum* L.) [89]. The biological membranes of barnyard grass (*Echinochloa crussgalli* (L.) were damaged as a result of the application of lemongrass (*Cymbopogon citratus* L. (DC) Stapf) essential oil [70]. Cinnamic acid treatment increased the generation of ROS, which increased lipid peroxidation and decreased membrane H+ -ATPase activity in cucumber seedlings [27].

4. Effect on activities of different enzymes and the production of endogenous hormones: The production of allelopathic chemicals from weeds and other plants that are planted close to important crops causes the plant's enzymatic systems to become suppressed [92].

The mechanism of phenolic compound-related allelopathy has been thoroughly investigated and the results revealed that phenolics interfere with a several physiological processes and rate-limiting enzymes in plants. For example, benzoic and cinnamic acids block the action of hormones respiration, photosynthesis, membrane permeability, and the creation of organic compounds. According to reports, the allelopathic chemicals block Pectolytic enzymes, catalases, cellulases, phosphorylases, ATPases, peroxidases, phosphatases, proteinases, invertases, decarboxylases, and other enzymes are all found in the plant system. [16] reported that diethyl phthalate suppresses glutamine synthetase isoenzymes in nitrogen for nitrogen absorption and antioxidant enzymes found in larger duckweed (*Spirodela polyrhiza* L.). Additionally, [56] revealed that tomato's morphological, physiological, and biochemical responses are improved by peppermint water extracts. The inhibitory activity on proline, soluble sugar, and starch was stronger at an extract concentration of about 10% (v/v). Additionally, the phenolic components in the extract demonstrated greater ascorbate peroxidase, catalase, peroxidase, and superoxide dismutase (SOD) enzyme activity levels. According to other studies, the alkaloids may prevent the growth of plants through a number of different processes, including interference with DNA, enzyme activity, protein synthesis, and membrane integrity in developing crops. Allelochemicals may disrupt the balance of several phytohormones or alter the composition of plant growth regulators, which inhibits plant growth and development, including seed germination and seedling growth. Indole acetic acid (IAA) oxidase activity may be increased by phenolic allelochemicals, and the interaction between peroxidase and IAA may be inhibited [84]. Application of rice (Oryza sativa L.) aqueous extracts reduced IAA levels and immediately increased IAA oxidase activity in barnyard grass, which adversely affected seedling growth [55]. Application of cyanamide (1.2 mM) to tomato (*Lycopersicon esculentum* L.) led to an imbalance in auxin and ethylene [72]. According to a previous study by Chou (1980), a variety of allelochemicals may block the IAA-oxidase enzyme. Allelopathy stress increased the synthesis of ethylene and ABA (abscisic acid) [5].

5. Effect on photosynthesis: A reduction in photosynthesis or the breakdown of the photosynthetic apparatus can be used to illustrate how allelochemicals primarily affect plant photosynthesis.The pigment content of the photosynthetic apparatus then decreases, interfering with the power and electron transfer, ATP synthesis, enzyme activity, and stomata, ultimately slowing down photosynthesis [93]. Allelochemicals mostly interfere with ability of PS II to carry out photosynthesis [87], followed by D1 protein damage [88]. According to reports, sorgoleone reduces the Fv/Fm, weed growth, and the quantity of active reaction centres in the electron transport chain [82]. A larger application of the essential oil from lemongrass leaves greatly hindered the metabolism of the photosynthetic process in barnyard grass, the alpha-amylase activity in seeds, and the green pigments (i.e., chlorophyll a and b, carotenoids) in leaves [83]. Application of cucumber root extracts, root exudates, derivatives of cinnamic and benzoic acids, and stomatal conductance decreased the net photosynthetic rate, transpiration, intercellular CO2 concentration, and stomatal conductance in cucumber (Yu *et al*., 2006). An allelochemical in sorghum called sorgoleone inhibits PSII [4] which prevents plastoquinone from attaching to the DI protein [59].

Various other allelochemicals present in sorghum, like 5-ethoxysorgoleone, have also been noted to decrease PSII activity [48].

Effect on on the uptake of water and nutrients: The allelochemicals also have an impact on how nutrients and water are absorbed by plant roots. The roles of Na+/K+ -ATPase in the uptake and transportation of ions at the plasma membrane, which are inhibited by allelochemicals, are well documented. According tostudies, allelochemicals (cinnamic acid and p-hydroxybenzoic acid) significantly decreased root dehydrogenase capacity and ATPase activity, which in turn inhibited potassium, nitrate, and phosphorus uptake [52]. Sorgoleone and juglone have an impact on the uptake of water and solutes in the soybean, maize, and peas (*Pisum sativum L.*), and they also inhibit H+ -ATPase action across the root cell plasma membrane [40]. Numerous allelochemicals, including p-coumaric acid, ferulic acid, and trans-cinnamic acid, have been found to influence nitrate absorption and H+ - ATPase activity in the plasma membrane in maize seedlings [3]. Sunflower (*Helianthus annuus* L.) residues have an impact on the radish (*Raphanus raphanistrum* L.) plants' development, absorption, and translocation of nutrients [6]. In a study on wheat, [93] found a correlation between the application of allelochemicals (such as 4-tertbutyl benzoic acid, ferulic acid, and benzaldehyde) and the uptake of nitrogen. However, compared to nitrate form of nitrogen, the correlation was more negative for ammonical form of nitrogen. In addition, [6] discovered that the application of cinnamic acid and the cucumber seedlings' root exudates resulted in a decrease in the uptake of nitrate, sulphate, potassium, calcium, magnesium, and iron. It's noteworthy to notice that the concentration and kind of allelochemical have an effect on how much ion uptake occurs. For instance, a small amount of the allelochemical dibutyl phthalate may increase nitrogen absorption while decreasing potassium and phosphorus uptake. However, the absorption of potassium, phosphorus, and nitrogen declines when this allelochemical is present in higher concentrations. The same is true for tomato roots, where low concentrations of the allelochemical "diphenylamine" promote nitrogen absorption while discouraging phosphorus absorption [10].

Effect on soil microbial activity: The rhizospheric soil's microorganisms are affected in a variety of ways by the allelochemicals. These interactions between plants and bacteria can either stimulate plant development or impact microbe growth. Numerous studies have been conducted on the allelopathic effects of *Alliaria petiolata* (Alliaria) on mutualistic bacteria. According to a study, breakdown chemicals produced during the breakdown of glucosinolate released by Alliaria may be detrimental to mycorrhizal fungus [13]. Later, a number of research were carried out supporting the detrimental impact Alliaria has on mycorrhizal species [11]. However, the age shift in the plant population affects how the community structure of soil micro-organisms changes in response to allelopathic plant species [17]. There is also no shortage of evidence demonstrating how allelopathic plant species harm beneficial soil microbes. Early research by [59] demonstrated that *Bradyrhizobium japonicum* nodulation was suppressed by shoot extracts of various weed species, including *Chenopodium album*, *Cyperus esculentus*, and *Helianthus annuus*. Numerous symbiotic (*Rhizobium*) and free-living (*Azotobacter*) bacteria have been reported to have their growth inhibited in the presence of plant allelochemicals [65]. When competing with plants that are symbionts with such bacteria, these plant species will have an advantage due to the link between beneficial rhizospheric microbes and allelopathic plant species [16]. However, it must be kept in mind that the detrimental effects of allelopathy on soil microbes will also have an impact on the development of allelopathic plants, as they commonly take advantage of the ecosystem services that these helpful bacteria offer [19]. Plants that experience allelopathy undergo a number of physiological and biochemical alterations. Understanding the diverse allelochemicals' modes of action may help in getting the fundamental knowledge about the structure and biochemical forms of various allelochemicals for creating new bio-herbicides.

Methods of allelopathy-mediated insect biotic stress management:

A. Plant-based approaches:

1. Inter-cropping and crop rotation: For a high yield and economic advantage, compatible crops are planted together in intercropping. Intercropping also improves the efficiency of resource utilisation and aids in weed control. If the allelopathic crops are employed in intercropping, in particular, the weed population can be decreased and the crop production could be increased. Intercropping is thought to enhance the interactions between allelopathic weeds and cover crops and, as a result, increasing the phytotoxic effects by broadening the variety of the soil microbial community and encouraging the transport of allelochemicals into the soil [10]. It has been discovered that common mycorrhizal networks function as "superhighways" that carry allelochemicals to target plants while also directly connecting plants below. For example, intercropping sesame, soybean, and sorghum with cotton [39], intercropping pea with false flax [38], and intercropping maize with fodder legumes have all been shown to reduce weed density and biomass production. For instance, when maize and cowpea (*Vigna unguiculata* [L.] Walp.) were intercropped, the weed density of jungle rice (*Echinochloa colona* (L.) Link.), jute mallow (*Corchorus olitorius* L.), common purslane (*Portulaca oleracea* L.), and crowfoot grass (*Dactyloctenium aegyptium* (L.) was reduced when maize and cowpea (*Vigna unguiculata* Walp.) were intercropped [54]. Crop rotation produces the best weed seed bank reduction effects, i.e., it keeps weed communities at low densities, prevents weed establishment in the early crop season, and is most helpful in preventing the growth of invasive or noxious weed flora [85]. Rice, wheat, sorghum, barley, rye, and sunflower are a few crops frequently utilised in rotations with allelopathic potential [86]. By producing allelochemicals that work to hinder weed seed germination and limit the establishment of weeds, the inclusion of these allelopathic crops in the cropping sequence reduces weeds [85]. According to numerous studies, various crop rotations, such as sorghum-wheat [77], winter wheat-spring barley-peas [78], and corn-soybean-oat/alfalfa-alfalfa (Hunt), successfully suppress the growth and establishment of weeds. The rice-wheat system is used extensively in several Asian nations. Herbicides are mostly used in this system to manage weeds. Growing allelopathic plants including sorghum, maize, and pearl millet (*Pennisetum glaucum* L.) is permitted under this system after the harvest of the wheat and before the planting of the rice provides efficient control for the first 45 days of the crop cycle of rice weeds [33]. Exposure to eucalyptus globulus L. volatile oils during rice significantly impacted growth larval phases post-embryonic development and adult emergence of lepidopteran (*Corcyra cephalonica* St.).

Use of cover crops and green manure: Allelopathic cover crops provide various benefits, including pest control, increased soil fertility, reduced soil erosion, and higher yield for succeeding crops [81]. Canola, rapeseed, brown mustard, black mustard, oats, rye, crimson clover, red clover, cowpea, fodder radish, wheat, annual ryegrass, mustard, hairy vetch, and buckwheat are the most notable cover crops, and all of these crops may be used in different cropping systems to inhibit the growth of pests due to their vigorous initial growth, space capture ability, and allelopathic effect. Investigations from farmers' fields and long-term trials have demonstrated that allelopathic cover crops lower weed populations and dry biomass because they emit allelochemicals into the rhizosphere. For instance, legume cover crops including jack beans, jumbie beans, velvet beans, and wild tamarind (*Lysiloma latisiliquum* L.) can help in lowering the density of barnyard grass in maize. Similarly, when barley was sown as a cover crop for soybeans, the population of crabgrass and barnyard grass decreased [71]. Cover crop residue improve the soil's nutrient content and allelochemicals, which inhibit plant pests and diseases brought on by soilborne pathogens [72]. Green manuring involves adding crop biomass to the soil, typically before harvesting the primary crop. Crop rotational sequences will become more diverse as a result of this green manuring practise. Through their inhibitory effect on weed growth, the aqueous extracts of various green manure crops exhibit allelopathic weed control [59]. Weed suppression is mostly accomplished by crop-specific allelochemicals. For instance, dehydropyrrolidizine alkaloids have been found in black sunn hemp roots, while isohemijunceines A, B, and C, trichodesmine, junceine, and acetylisohemijunceines have been found in the leaves, stem, and seeds [69]. The cruciferous vegetables produce a lot of glucosinolate compounds, which can inhibit weed development and establishment when degraded to isothiocyanates [66]. Green manuring generally aids in early-season weed control and lessens the use for post-emergence herbicides.

3. Allelopathic crop extracts and residues: Allelochemicals are effective alternatives to insecticides for controlling pests when extracted in water from various plant parts. Neem (*Azadirachta indica* L.) seed oil exhibits antifeedant properties against strawberry aphid nymphs and adults (*Chaetosiphon fragaefolii* (Cockerell)), and conifer plantations treated with neem oil prevent large pine weevil (*Hylobius abietis* L.) feeding activity for three months [33]. Neem oil treatment prevented the feeding weevil from killing Sitka spruce seedlings (30 cm above the root collar), in contrast to untreated seedlings that were killed by it .Neem oil contains the allelochemicals azadirachtin, nimbin, and salannin. According to [30], sunflower water extracts (16% concentration) caused 52.5% aphid mortality while sorghum water extracts (8% concentration) were the easiest to use (62.5% aphid mortality). Sorghum and mulberry combined water extracts (16%) had a 45.7% aphid mortality rate, and sorghum and flower had a 57.5% aphid mortality rate.

Synthetic allelopathic compounds

Allelochemicals as Herbicides: There is mounting evidence that natural plant compounds generated from higher plants or microorganisms, known as allelochemicals, can make great agrochemicals. At first, these chemicals were thought of as useless waste products, making it unclear why plants would invest resources in producing them. However, it is now well acknowledged that these substances serve as defensive agents against diseases, insects, and nearby plants [60]. There is evidence that different allelochemicals are released into the environment by higher plants. Despite their wide chemical diversity, phenolics and terpenoids can be used to generically categorise allelochemicals. Volatilization, root exudation, plant death and decay, and leaching from live or decomposing wastes are some of the processes that release them. Herbicide applications for allelochemicals are outstanding [25]. Due to the fact that they don't have any of the issues as with current herbicides, they can be employed as herbicides right away. Their chemistry could also be employed to create new herbicides. Natural products as sources of herbicide chemistry have gained popularity as conventional techniques of discovering and creating novel herbicides have grown increasingly challenging and expensive. Numerous secondary compounds are produced by both plants and bacteria; many of these have the potential to be used as herbicides and are phytotoxic. It is estimated that only approximately 3% of the 400,000 secondary metabolites produced by both plants and microbes are secondary metabolites.

Factors affecting production and release of allelochemicals:

1. Environmental factors: Environmental conditions can have an impact on a plant's capacity to utilize allelopathy in both direct and indirect ways. Temperature, radiation, nutrition availability, and stressors are the primary environmental elements that influence the net effect of allelopathy [61]. For example, UV radiation, nutritional inadequacy, wounding, and plant pathogen invasion all have been shown to increase phenyl ammonia lyase (PAL) activity, which is the first step in the formation of phenols [15]. Cinnamic acid released by cucumber has been identified as a precursor of phenylpropanoids, which are responsible for peroxidation and decreased H+-ATPase activity in the plasma membrane, ultimately lowering the root viability of target plants [27]. Adverse environmental conditions also increase the production and release of jasmonate. As a result, these hormones can enhance the expression of genes involved in secondary metabolism in plants [83]. The presence of other plants near sorghum can exacerbate the effect of environmental stressors on sorgoleone production [86]. Environmental stresses caused by plant interactions also have an impact on the production of diverse allelochemicals [73]. Environmental factors that affect the ease of degradation of allelochemicals in soil can reduce their efficiency.

In a research, it was found that the half-life of 2, 4-dihydroxy-2H-1,4-benzoxazin-3(4H)-one (DIBOA) in non-sterile soil was 43 hours. The final product of DIBOA and 2-aminophenoxazin-3-one (APO) showed a low mineralization rate and a half-life of more than 90 days [59]. Furthermore, soil bacteria increase the rate of mineralizationof flavonoid glycosides produced by rice plants, resulting in aglycosylatemolecules. The environmental conditions influence allelochemical synthesis, bioavailability, and impact on target species. As a result, environmental variables and other processes that affect the course of chemicals in the environment are critical for the allelopathic relationship between plants in agroecosystems, which aids insect-pest management. Substantial study findings support the concept that environmental stress can increase allelochemical production.

2. Plant factors: Root systems perform a variety of activities, including plant anchoring and water and nutrient absorption. Aside from these primary functions, roots also serve as a site for photoassimilates storage and carbon reserves, phytohormone synthesis (e.g. auxins, cytokinins, abscisic acid, gibberellic acid, ethylene) [65], synthetic activities (e.g. nitrogen fixation, synthesis of organic acids, etc.), and metabolite exudation [10]. It is believed that higher plants create approximately 10,000 allelochemicals, with significant variation in their activity and mode of action in target plants [92]. In response to biotic and abiotic challenges, the living roots of many weed and crop species continuously generate and secrete both low- and high-molecular-weight compounds into the rhizosphere [11]. The compounds excreted into the soil by roots are known as root exudates [86]. Their quantity and quality are affected by plant species, cultivar, stage of growth, and environmental stressors [9].These characteristics have been widely reported in the literature for a variety of allelopathic plants. [1], reported that rice exudation rates are lowest at the seedling stage, increase until flowering, and then decline at maturity. Root exudations in sorghum and wheat decrease with plant age and increase when the soil is stressed by compaction, drought, and nutrient deficiency [91].Actively expanding root systems emit more exudates in general, demonstrating a positive relationship between root exudation and root growth. In addition, the nature of root surface morphology (e.g. suberized or unsuberized, with or without mycorrhizal hyphae, thickness of periderm, quantity and location of root hairs, etc.) as well as the root system architecture one of monocotyledonous plants, amount of root branching, number of lateral roots, etc.) [66] are all factors involved in determining the quantitative and qualitative composition of exudates [10]. Root exudation, however, is also affected by the root zone. The zone immediately behind the root tip is thought to be the most important exudation site [68]. The root cap and root hair cells [15] are the root cells most involved in root exudation [69], followed by cortex and stellar cells [70]. Because the type of roots depends on plant age, season, and soil conditions (e.g. texture, structure, temperature, water content, pH, and so on), all of these aspects are intimately related [40].Root exudation is comprised of two distinct active processes: excretion and secretion [22]. The former is characterised by the discharge of metabolic wastes and combinations of small compounds with unknown functions, whereas the later is characterised by molecules with defined functions.Roots secretions are most likely involved in external processes (for example, nitrogen acquisition) and play an important ecological role in the rhizosphere. The majority of allelochemicals released by exudation are secretions. Excretions, on the other hand, have an impact on internal metabolic processes [38]. Several studies have been conducted on the root exudation of allelochemicals, indicating that this pathway of release is the primary source of plant allelochemicals into the rhizosphere.

Soil factors: Soil physical (texture, structure, organic matter content, moisture, and aeration), chemical (reaction, ion exchange capacity, nutrient dynamics, O_2 and CO_2 concentrations), and biological characteristics (soil microorganisms) all have an impact on the production and release of allelochemicals.Plants, too, can influence rhizosphere properties through ion, H_2O, and O_2 absorption and rhizodeposition [39]. Allelochemicals leaching and their phytotoxic effects are strongly influenced by soil texture [24]. Moreover, because clay minerals differ widely from one another, clay typology effects the availability of allelochemicals. For example,Vertisols, which are rich in montmorillonites (expanding 2:1 silicate clays), have the highest specific surface area, ion exchange capacity, water retention capacity, and thus, have the strongest retention power towards allelochemicals. [69] reported that *Eucalyptus camaldulensis*Dehnh. is more poisonous on fine soils than on coarse soils. This is most likely due to excessive evaporation, which concentrates allelochemicals on the soil surface, and low infiltration, which prevents allelochemicals from leaching out of the rooting zone. [29] found that *Medicago sativa* L. crude powder reduced total stem, leaf, and root dry matter accumulation in clay soils more than in sandy soils. On the contrary, [23] revealed that allelochemicals secreted by roots of Hordeum vulgare L. subsp. vulgar was more poisonous in a sandy substrate.Similarly, [78] found that *Conyzacanadensis* L. shoot aqueous extracts had higher phytotoxic effects in amended sandy soils, followed by loamy sand and sandy loam soils, due to little adsorption on soil particles and low microbial and chemical degradation. The effects of soil texture on allelochemical phytotoxicity are contradictory, with some scientists finding more inhibitory action in clay soils and others in sandy substrates. Clays, in fact, decrease water infiltration, enhance cation exchange capacity, and therefore restrict allelochemicals leaching, which is the most important factor influencing their phytotoxic behaviour, due to their high surface area and negative surface charges [31].Additionally, because clay soils have poorer aeration than sandy soils, aerobic bacteria decompose allelochemicals more slowly.By altering the explorable depth of roots, soil structure influences the release and spatial arrangement of allelochemicals in soil. Because it affects soil porosity, the equilibrium between soil liquid and gaseous phases, and soil organic matter content, structure can also influence the transformation process carried out by microbial communities. A well-structured soil, for example, has a high cation exchange capacity, which reduces the leaching of water-operated allelochemicals. The size and shape of soil pores have a significant impact on allelochemical adsorption [10]. There is substantial evidence that SOM influences the availability of allelochemicals in soil, particularly the adsorption-desorption process [31]. On the one hand, SOM can bind allelochemicals, rendering them inert and/or reducing bioavailability and phytotoxicity [19]. For example,[41] discovered that the concentration of *Cytisusscoparius* (L.) Link allelochemicals was higher in soils with low SOM, impeding lettuce seedling emergence, and decreased in soils with high SOM. Allelochemical adsorption is low in hot-semiarid soils, which generally have low SOM (<1%), enabling the spread and diffusion of allelopathic plants. Allelochemicals, as well as heavy metals and cations as Fe^{3+}, Al^{3+}, Mn^{2+}, and Ca^{2+}, can be chelated by SOM to prevent oxidation and boost efficiency [44]. Furthermore, SOM, particularly humus, tends to darken the O and A layers, increasing solar radiation absorption and, hence, soil temperature [32]. A higher soil temperature suggests increased microbial activity and, as a result, higher allelochemical transformation processes. The effect of soil pH on allelochemicals has been extensively studied [64]. The chemical change of allelochemicals into more or less hazardous chemicals is heavily influenced by soil reaction. [32] reported that *Sorghum bicolor* (L.) Moench seedlings cultivated in buffers produced more sorgoleone when the pH declines. [44] studied the effect of *Chenopodiummurale* L. residues on chickpea (*Cicer arietinum* L.) and pea (*Pisumsativum* L.) growth, nodulation, and macromolecule content, and discovered that the pH of the residue-amended soil changed from neutral (6.85) to slightly alkaline (7.47) with 5-40 g residue kg^{-1} soil. The ion exchange capacity includes the cation exchange capacity (CEC) and the anion exchange capacity [57]. They have a significant impact on the adsorption/desorption balance and, as a result, the retention and transport processes by influencing allelochemical leaching and availability. [54] observed that, parthenin breakdown is favoured in clay soils with high CEC.

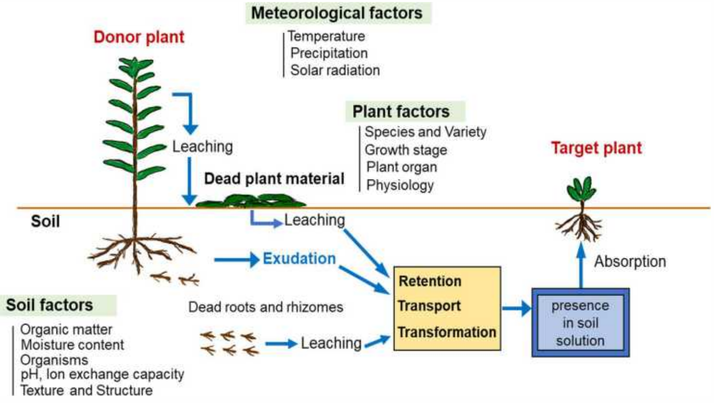

Fig. 1 Impact of climatic, soil, and plant conditions on allelochemical production in soil (from Kobayashi, 2004).

Plant Metabolites and Their Insecticidal Activity: Plant metabolites are classified into primary and secondary. Primary metabolites are compounds that are directly involved in all plant growth, development, and reproduction. These metabolites play no defensive role. Secondary metabolites play an important function in insect defense [23]. Insect populations can be suppressed by compounds such as phenol, tannin, peroxidase, polyphenol oxidase, and Bt proteins (insecticides produced by the bacterium Bacillus thuringiensis) [87, 88]. [24] reported that Alkaloids, phenolics, cyanogenic glucosides, polyacetylenes, and polythienyls have biocidal activity. These chemicals are frequently formed as by-products of primary metabolic product synthesis [58, 59]. For example,Geranium develops a unique chemical compound known as quisqualic, in its petals to fight against Japanese beetles (*Popillia japonica*) by paralysing them in 30 minutes [44]. Phytoanticipins are metabolites that are always produced in plants. They induce constitutive resistance to the corn earworm [87]. Due to the induced ability to combat *Helicoverpaarmigera* and *Spodopteralitura*, disparate metabolites are synthesized shortly after initial injury. Furthermore, after first insect pest infestation, infested cotton plants demonstrated a higher concentration of defensive proteins (e.g., proteinase inhibitors, proline-rich proteins, lipoxygenase) than other plants [88].Induced defence relies on mobile metabolites with low molecular weight that are created at minimal metabolic costs and only during or after insect attacks. Terpenoids, aromatics, and fatty acids, on the other hand, have a large molecular weight and are formed after insect infestation [49]. Quantitative metabolites are abundant, and their increased proportion in herbivore diets promotes lower eating activity [71].Insect pest management programmes require a more suitable and unique strategy (84). Plant allelochemicals derived from plant-insect interactions are either inherent or based on C or N. They can be repellents, deterrents, growth inhibitors, or direct killers [52]. As a result, insects have evolved techniques to deal with these toxins, such as avoidance, excretion, sequestration, and degradation [Table 2].

The competition between insects and plants drives coevolution, which eventually leads to speciation [43].Insect herbivores that feed on plants come into contact with potentially toxic substances that have relatively non-specific effects on proteins (enzymes, receptors, ion channels, and structural proteins), nucleic acids, secondary metabolites, bio-membranes, and specific or unspecific interactions with other cellular components [54].

Table 2. The main group of allelochemicals and their physiological effects on insects

Allelochemicals	Physiological effects on insects
Allomones	Provide adaptive benefits to the producing organisms
Repellents	Drive insects away from the plant.
Arrestants	Immobilize insects
Suppressants	Restriction on biting or piercing
Locomotor excitants	Increase movement
Digestibility reducing	Interfere with food utilisation processes
Deterrents	Prevent feeding or oviposition
Toxins	Cause chronic or acute physiologic disorders

It has been experimentally demonstrated that neem-based pesticides have adverse effects on insect physiology [63] due to the antifeedant action of biochemicalsand their growth regulatory effects [83].Terpenes from neem stimulate chemosensory receptor cells and influence receptors in other organs in lepidopteran larvae [76].

Essential plant oils have the potential to be neurotoxic or to function as insect growth regulators, disrupting the normal process of morphogenesis [38].Certain monoterpenoids (D-limonene, myrcene, terpineol, linalool, and pulegone), which are the major components of essential oils, have been utilised against a variety of pests [72]. The toxicity of the ten most prevalent monoterpenes of Pinuscontorta against mountain pine beetles suggests that (-)-phellandrene, (+)-3-carene, myrcene, terpinolene, and enantiomers of -pinene, -pinene, and limonene were responsible for death [82]. Plant monoterpene profiles revealed a constant foliar pattern throughout the growing season, with -3-carene present in spring while bornyl acetate increasing during the growth season. Furthermore, these compounds (Himachallol and Himachalene) were highly poisonous to pulse beetles [25]. When insects consume some plant oils, they become neurotoxic. The most peculiar symptoms are hyperactivity and hyperexcitement, followed by fast knockdown and immobilisation [77].Tolerating noxious and unappealing poisons requires various physiological strategies in herbivorous insects. These techniques include the use of carbohydrates to mask the unpleasant taste of toxins, prolonged dietary exposure to some unpalatable secondary plant chemicals, and dietary exposure to poisonous compounds that stimulate the synthesis of P450 detoxication enzymes. Herbivorous insects use an integrated set of physiological processes to identify potentially harmful substances in diets and preferentially adapt to those that do not offer a severe threat to their growth and survival [79].

Limitation of uses allelochemical against pest control:

There are various constraints to inspecting allelopathic potential as a pest management strategy. The limitations are attributable to the plant itself, producing allelochemical, and the status. Many abiotic and biotic soil factors affect phototoxic levels of allelochemicals [49]. Several non-living and organic compound elements such as plant age, temperature, light-weight and soil condition, microbiota, nutritional status, and herbicide actions affect the meeting and unharnessing of allelochemicals through allelopathy, which is regarded as a genetically affected issue [93]. While acquiring soil allelochemicals, various factors concerning soil surrounds such as physical, chemical, and physicochemical properties of soil could influence allelochemical activity. While reviewing the allelopathic potential of plants, the impact of soil should not be overlooked.[90], reported that the number of nutrients available to the plant, as well as the plant's ability to use the nutrient, influence the allelopathic potentiality of the rice plant, mostly with a deficit of soil nutrients favouring the assembly of secondary metabolites. Machine cyanogenic chemicals and surroundings should have some colour force [56].

Conclusions

Current intensive farming demands new, effective and ecofriendly insect pest management. Allelochemicals are capable of acting as natural pesticides and should address issues such as pest biotype resistance, health defects, and soil and environmental pollution caused by the indiscriminate use of artificial agrochemicals. Allelopathic crops, when used as cover crops, mulch, smother crops, intercrops, or green manures, or grown in rotational sequences, can combat biotic stresses such as insect pests while also increasing soil fertility and organic matter status, reducing soil erosion and improving farm yields. Several investigations and studies have been conducted in order to exploit allelopathy of plants against pests in the agricultural field. Allelochemical structures can be employed as analogs for the production of novel pesticides. These natural product-based insecticides may be significantly less hazardous to the environment than synthetic agrochemicals. Allelochemicals are advantageous since they are biodegradable, have multiple mechanisms of action, and pests are unlikely to develop resistance to them. Yet, there are numerous limits to employing allelopathic potentially as a pest management strategy. The restrictions are caused by both the plant itself, which produces allelochemicals, and environmental factors.Moreover, allelochemicals can be produced by plants, bacteria, other soil creatures, and insects, providing new techniques for maintaining and expanding agricultural production in the future.

Future Prospects

Plants emit a vast range of chemical substances into the environment, both as a defence mechanism against biotic or abiotic stressors and as a tool for pollination to interact with neighbouring plants, soil microbes, and within the plant. The advancement of analysis procedures and technical instruments in recent years has permitted the acquisition of fresh knowledge on this topic. A greater understanding of the behaviour of allelochemicals in soil could be beneficial in agroecosystems for pest control, as well as in traditional agricultural techniques under Integrated Pest Management Systems (IPMS).Allelopathic mechanisms can be used efficiently for agroecosystem control in a variety of ways. The most important are [1] crop selection, breeding, and inclusion in crop rotations [85] the use of their residues as living mulches, dead mulches, or green manure; and [3] the selection of the most active allelopathic compounds and their use as bioherbicides [85]. However, allelopathy could be used to manage nutrient soil dynamics, improve plant nutrient use efficiency, and reduce heavy metal toxicity. Several features of these interactions, however, are unclear. The scientific community faces a significant problem in investigating the influence of soil physical and chemical properties in field conditions throughout long-term studies, especially the role of soil texture and structure on allelochemicalphytotoxicity. The influence of environmental elements on the utilization of allelopathy in the field must be researched for optimal results. The most essential component in this regard is the soil environment. The complex of plant-microorganism interactions in the rhizosphere is an area that requires much research to better understand the aboveground chemical communication and the physiological processes involved in both positive and negative interactions with microorganisms. Further, knowledge of root exudate chemistry is currently extensive, with hundreds of allelochemicals found in recent decades. Their transport pathways through the plasma membrane, on the other hand, require more study in order to clarify the behaviour of allelopathic plants and regulate the genes involved in breeding programmes. Given the complexity of the soil system and the significant heterogeneity of soils in different environments, the challenge for researchers does seem to be more difficult than in other scientific areas, necessitating the involvement of multidisciplinary research groups with expertise in botany, agronomy, biology, chemistry, ecology, and soil chemistry.

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