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Allelopathy for weeds management in Sustainable Agriculture

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ABSTRACT

Weeds management using herbicides is necessary to get higher yield of crops. Allelopathy is promising alternative for weeds control. Many plants have allelopathic herbicidal potential; hence, it is essential to evaluate them to integrate into sustainable weed management strategies. This review aimed to explore the allelopathic potential of plants for weed control. The allelopathic management has gained popularity to reduce environmental contamination and minimize the use of herbicides for weed control. Natural herbicides, offer an environmental friendly alternative to present synthetic herbicides.

Keywords: Agriculture, allelochemicals, allelopathic plants, herbicides, sustainable agriculture, weeds management

INTRODUCTION

The term "allelopathy" was coined by Molisch in 1937 (108). It is derived from two Greek words "Pathos" (suffering) and "Allelos" (mutual) (133). Allelopathy involves interactions that affect the target and surrounding organism in both negative and positive

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*Correspondence author, [1]Dept Mechanical Engineering [2]Dept Biotechnology, Ambala College of Engineering and Applied Research, Devsthali, Ambala-133 001, India ways (122). Allelopathic effects can be antagonistic, synergistic, or additive. It includes chemical interactions and communication among various organisms. The study of allelochemicals-interactions between plants may help in developing agrochemicals to replace synthetic pesticides (38,63). Several active chemical compounds present in extracts of leaves, stems, roots, seeds and fruits and in volatiles released by plants have been identified and classified (9,15,135). The allelopathic effects are largely influenced by phytotoxic effects of allelopathic plants that reduces the plant's growth (53). This supports Bais's "Novel weapons hypothesis," which suggests that success of an invasion is largely driven by allelopathy. It also indicated that plants can effectively suppress the growth of competing plants by releasing phytotoxic chemicals into a shared ecosystem (35).

International Allelopathy Society (IAS), defined allelopathy as "the study of any process involving secondary metabolites produced by plants, algae, bacteria and fungi that affects the growth and development of agricultural and biological systems" (92). How to differentiate the allelopathy from the competition? As these two mechanisms cannot be clearly separated in natural environments, scientists recognize allelopathy as a part of the competition for resources. Muller's term "interference," referring to the general impact between plants, encompasses both allelopathy and competitiveness (109). In contrast to allelopathy, competition involves the removal of growth resources and environmental factors essential for other plants that share the same habitat (9). Competition involves the acquisition of various resources, such as root space, pollinators, nutrients, food, light and water. One effective strategy to survive in resource-scarce environment is to prevent competing plants from growing in their vicinity, thereby reducing the competition for limited resources from competitors.

Interference between plants typically refers to either competition for resources (e.g., nutrients, light, water) or chemically-mediated interference i.e., allelopathy (102,136). Traditionally, resource competition has been regarded as the most important driver of plant community diversity and dynamics (137). However, recent researches have shown that allelopathy can also affect the patterning of plant communities (140,141). In this process, phytochemicals released into the environment inhibited the germination and growth of neighboring plants by altering their metabolism or impacting their soil community mutualists. Most of these studies have focused on plant invasion and the Novel Weapons Hypothesis (NWH). According to the NWH, allelopathic effects are strongest on species lacking historic exposure to the particular allelochemicals (19,143). A limited conceptual framework exists for the role of plant chemicals in the natural dynamics of co-evolved native species (131,144), but it has been suggested that allelopathic interference may prove as important as competition for resources in modulating plant community function and dynamics. Therefore, it is crucial to evaluate the relative importance of these two plant interference mechanisms resource competition and allelopathy.

2. ALLELOPATHY IN WEEDS MANAGEMENT

2.1. WEEDS MANAGEMENT

One of the most difficult issues adversely affecting agricultural production worldwide is weeds. Weeds hinder crop growth and productivity by competing for space, light, nutrients and water. Furthermore, weeds are home to bacterial, fungal, viral and insect pests, all these reduce crop yields. By 2050, there will likely be more than 9 billion people on the earth; hence, lower food production cannot be afforded due to weeds competition (37). Synthetic herbicides are the primary tool used in agriculture in developed nations to manage weeds. Heavy weedicides use gave rise to various problems: (a) the natural weed flora changed to grass species because of herbicidal control of broadleaf weeds, (b) *Phalaris minor* developed resistance to its recommended herbicide isoproturon (70) (c) human health hazards appeared during herbicide spraying and (d) groundwater became contaminated. An alternative for overcoming these problems is to use allelopathic strategies for weed management for sustainable agriculture. These strategies include (i) using weed-smothering crops, (ii) using crop residues for weed control, (iii) using phytotoxins from plants or microbes as herbicides and (iv) using synthetic derivatives of natural products as herbicides. Because these weed management strategies do not cause the problems associated with herbicides, they could lead to more sustainable agriculture (40, 93). Concerns is growing in public about these negative effects of indiscriminate use of weedicides. A sustainable, environmentally acceptable method of managing weeds is required because of the emergence of herbicide-resistant weeds and growing public awareness of synthetic herbicides (Table 3).

The allelopathic interactions between crops and weeds indicate potential to develop, organic herbicides to control weeds species, providing natural and sustainable alternative to synthetic herbicides (131). Recently, allelopathic management has gained popularity to reduce environmental contamination and minimize the use of herbicides for weed control (68) to reduce the reliance on herbicides (Figure 1).

Crops are being grown since ancient times without damage to the environment but the use of herbicides during the short span of last 50 years have raised serious doubts about their continuous use. Prior to invention of herbicides, weeds were controlled through mechanical and cultural practices. Allelopathy may help in weed control through inhibition of weed seed germination and seedling growth. Present understanding of the plant biochemistry, physiology, morphology, inter and intra-plant interactions and chemistry of natural products have shown that smothering crops, trap crops, tree litter and allelochemicals may be used in weed control, overcoming the problems associated with herbicides. This review briefly outlines these potential areas for weed control.

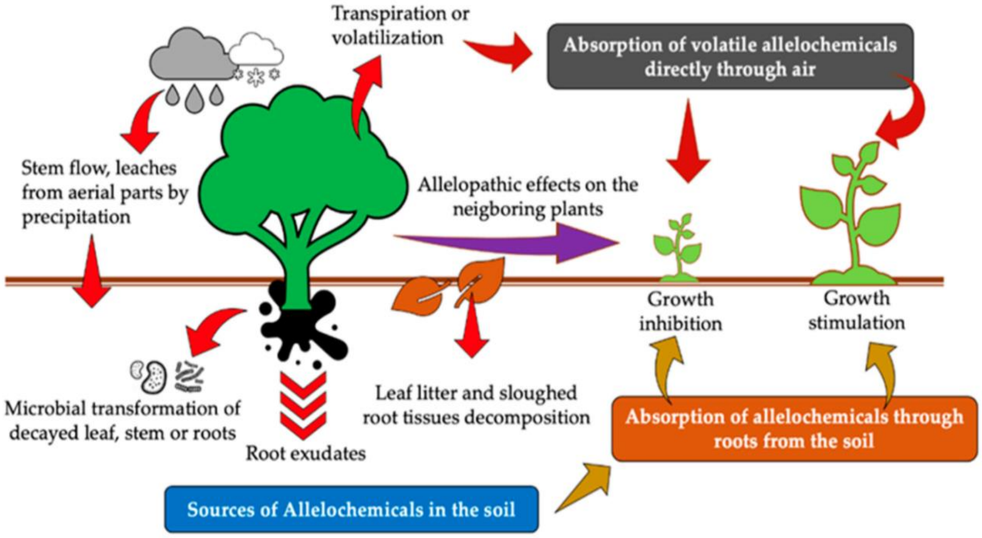

Figure 1**.** Routes of Allelochemicals release and movement into environment and its effect on neighbouring plants.

Allelopathic crops can be utilized as smother crops, green manure, or cover crops to suppress weeds growth. These crops [*Oryza sativa* L., *Solanum Lycopersicon* L., *Triticum aestivum* L. and *Sorghum bicolor* (L.) Moench], reduce the germination of targeted weed species (36). Due to advancements in crop breeding, new varieties exhibit allelopathic traits, for weeds management (75). These crop varieties may be used to suppress weeds growth by mulching and sowing them as intercrops to create a natural barrier to weed proliferation (99). Two new cultivars of *Medicago sativa* L., ‘Yuba’ and ‘Rasen’ and *O. Sativa* cultivar ‘Rondo’ have greater weed suppression effects (42,102). Allelopathic crops may effectively control weeds and reduces use of chemical herbicides (122).

Allelopathic substances in phytotoxic plant extracts are effective on target weeds (110,116). Allelopathic chemicals are better suited for use as bioherbicides because of their biodegradable nature, which makes them environmental friendly and reduces the long-term impact on ecosystems (44,91,121). *Helianthus annuus* L. and *S. bicolor* (L.) Moench, phytotoxic water extracts, ‘Sorgaab and Sunfaag’ are the well-known natural bioherbicides, they suppress weeds without reducing crop yields (37,151). The aqueous extract of *S. bicolor* (L.) Moench, increased the productivity of *O. sativa* by 18% while reducing the *Echinochloa crusgalli* (L.) P. Beauv weed's biomass by 40 % (11,144). To manage *Cyperus rotundus* L., in *Gossypium hirsutum* L. field, glyphosate + aqueous extracts of *Brassica napus* L., *S. bicolor* (L.) Moench and *H. annuus* L. were sprayed (7). The glyphosate + aqueous extracts of *B. napus* L. and Sorgaab increased the yield of cotton by 15-21 % and also decreased the dose of glyphosate (67-75 %) to control *C. rotundus* L. weed (165).

Allelopathic plants have residual inhibitory effects on weed germination. When these plants residues are mixed in the soil, their decomposition releases phytochemicals, which suppress the germination and development of weeds (81). Rice weed, *Echinochloa colona* (L.) is employed as a test plant in conjunction with S. *bicolor* (L.) Moench, *H. annuus* L., and *Brassica juncea* (L.) Czern to evaluate the allelopathic effects on *Echinochloa colona* (L.) in the soil. Keeping, the biomass of *E. colona* (L.) Link in field significantly impacted negatively (23). *E. colona* control may include several management options, such as mechanical, cultural (utilizing resistant rice phenotypes), allelopathic control etc. However, in many cases its control is mainly dependent on synthetic herbicides, either pre-emergent (including metribuzin, pendimethalin etc.) or post-emergent. (71).

2.1.1 Rice allelopathy for weeds management

Allelopathy is postulated as one mechanism by which weeds affects crop growth and it occurs widely in natural plant communities (137). In addition, some crops also possess allelopathic activity or weed-suppressing activity, including rye rice (*Oryza sativa* L.) (121), (*SecaLe cereale* L.) and wheat (*Triticum aestivum* L.) (69), sunflower (*Helianthus annuus* L.) (70), oat (*Avena sativa* L.) (34), barley (*Hordeum vulgare* L.) (57), tobacco (*Nicotiana tabacum* L.) (65). Putnam and Duke (1974) suggested that “wild types” of existing crops may have possessed high allelopathic activity and this character was reduced or lost as they were hybridized and selected for other characteristics. (148,154)

(i). Rice crop: More than 50 weed species infest direct-seeded rice and cause major losses in U.S. rice production (56). Ducksalad [*Heteranthera limosa* (Sw.) Willd.], an aquatic weed that reduced rice yield by 27-30 % when competing with rice in a water-seeded culture (8). It is second weed only to barnyard grass [*Ehinochloa crusgalli* (L.) Beauv.] as the most frequently reported weed in rice fields, followed by hemp sesbania [*Sesbania exaltata* (Raf.) Cory], bulrushes (*Scirpus* spp.), red rice (*Oryza sativa* L.), broadleaf signal grass [*Brachiaria platyphylla* (Griseb.) Nash] and sprangletop (*Leptochloa* spp.) (128).

Purvis (1990) reviewed the potential of allelopathy for weed control. Allelopathic rice cultivars could supplement the use of herbicides in direct seeding (70). Cultivars showing allelopathy against important rice weeds have been identified in the United States (118), Japan (40), Egypt (93) and the Philippines (144). Some allelopathic cultivars strongly inhibit root elongation of barnyard grass [*Echinochloa crusgalli* (L.) P. Beauv.], but weakly affects the shoot (73). In Egypt, Hassan (1995) identified rice varieties that expressed allelopathic effects after plants reached the 3-leaf stage and such varieties inhibited root development and emergence of the first or second leaf of *E. crusgalli*. (68).

(ii). Rice crop residues: The phytotoxic potential of crop residues could be exploited in managing various weeds in agro ecosystems (133). Dilday (1992) reported that allelochemicals were present in rice straw of accessions that showed allelopathic activity in the field around *Heteranthera limosa* (Sw.) Willd. (50) The use of rice germplasm that contains high allelopathic activity, combined with incorporating straw

> into the soil, controlled *Cyprus iria* L. almost as effectively as a tank mixture of propanil + bentazon (156). Khan and Vaishya (1992) reported that residues of Sarjoo- 52 rice incorporated 5-6 cm deep at 5 t^{ha} reduced the population and biomass of *Echinochloa colona* (L.) Link and broadleaf weeds (*Ammannia bacifera* L., *A. multiflora* Roxb. and *Phyllanthus fraternus* Webster), whereas the residues stimulated germination and biomass production of *Fimbristylis dichomato* (L.) Vahl and *F. ovata* (Burm. f.) Kern. (7). Allelopathic potential has been reported in some of the world's worst weeds (52). In Thailand, Harada (1992) found that *A. bacifera* controlled weeds when incorporated into the soil before seeding. (51).

In the past two decades, with the expansion of irrigation facilities in northwestern India (the states of Punjab, Haryana, and Uttar Pradesh), area under rice has increased substantially. In this region, rice is grown during the summer rainy season; as a result, weeds are a major problem (132). The rice crop is harvested from late October to mid-November; by this time, the sowing of most winter crops, except wheat, is over. The rice-wheat rotation is popular with farmers in irrigated areas because it is high-yielding. Rice weeds are also a major problem in wheat. Therefore, most herbicides in these states are used in the rice-wheat rotation. This gave rise to various problems: (a) the natural weed flora changed to grass species because of herbicidal control of broadleaf weeds, (b) *Phalaris minor* developed resistance to its recommended herbicide isoproturon (70) (c) human health hazards appeared during herbicide spraying and (d) groundwater became contaminated. An alternative for overcoming these problems is to use allelopathic strategies for weed management for sustainable agriculture. These strategies include (i) using weed-smothering crops, (ii) using crop residues for weed control, (iii) using phytotoxins from plants or microbes as herbicides and (iv) using synthetic derivatives of natural products as herbicides. Because these weed management strategies do not cause the problems associated with herbicides, they could lead to more sustainable agriculture. (40).

During the past 10 years, there is an acute shortage of labour at harvest of rice and wheat; hence, harvest of these crops is often done by Combines. In areas with cropping intensity of 300 % or higher, only 7-10 d are available between the harvest of the previous crop and the sowing of the next crop. Farmers therefore burn the rice and wheat straw to prepare a seedbed for the next crop. Putnam and DeFrank (129) reported a high potential of crop residues for weed control, so we incorporated rice and wheat crop residues to explore their potential for weed control under Indian conditions. Weed-smothering crops suppress weeds through interference, that is, competition and allelopathy (82). Narwal (1984) mentioned several weed-smothering crops for the summer season (sorghum, sudangrass, pearl millet, hemp, soybean, cowpea and alfalfa) and winter season (barley, rye, oat, buckwheat, sweet clover and rapeseed) (114).

Bioengineering and transgenics hold promise for developing crops with enhanced allelopathic traits, potentially reducing herbicide use and improving sustainability (4). Engineering crops to produce specific allelochemicals could reduce weed competition and minimize herbicide use (74). Developing crops with enhanced allelopathic traits could also improve resistance to environmental stresses. Bioengineered crops with allelopathic traits could contribute to more sustainable agricultural practices (112).

2.1.2. Rice Allelopathy Research in USA

Studies on allelopathic rice, which inhibits the germination and growth of weeds such as barnyard grass (*Echinochloa* spp.) and ducksalad [*Heteranthera limosa* (Sw.) Wild], have been strongly conducted in USA, Philippines, Japan, Korea and other countries since the 1980s. Weed-suppressing rice plants can compete with weeds for light and mineral nutrients by their rapid and dense growth characteristics and probably also by their allelopathic effects. It was suggested that allelopathic properties were inherited from parents (110). Different screening methods for finding allelopathic rice simply and rapidly have been proposed. In contrast, stimulative allelopathy in rice, which promotes germination of the dormant and dormancy-awakened seeds of *Monochoria vaginalis* (Burm. F) Kunth var. *vaginalis*, has been investigated by the authors since the 1990s. Rice seeds promoted the germination in the dark and in light under submerged conditions. Our experiments suggested that rice seeds, hulls, plants and straw contain stimulatory substance(s) that promote seed germination of *M. vaginalis* (153).

In attempts to control weeds in rice, much effort has been focused on rice allelopathy research for more than 30 years. Among screening methods that have been developed, the allelopathic potential of various rice cultivars in a limited in time and space, which is less costly and can be conducted year-round (40). Rice allelopathy activity is variety dependent and origin dependent, where Japonica rice shows greater allelopathic activity than Indica and Japonica-Indica hybrids (86,145). Allelopathic characteristics in rice are quantitatively inherited and several allelopathy-involved traits have been identified. Numerous phytotoxins such as cytokinins, diterpenoids, fatty acids, flavones, glucopyranosides, indoles, momilactones (A and B), oryzalexins, phenols, phenolic acids, resorcinols and stigmastanols have been identified and determined as growth inhibitors in rice. But, the modes of action of these compounds are not well understood. The rice allelopathy attributes to the interactions of all allelochemicals present in rice plants (157). Although locating genes determining or involving allelopathy in rice having attracted much effort, the introduction of these genes into target rice cultivars has not yet been achieved. Success in breeding new rice cultivars having excellent weed-suppressing ability would benefit farmers in rice-cultivating countries and play a significant role in sustainable agriculture (134).

Effective, affordable weed control is a challenge to sustainable rice production in U.S. In the 1980s, evaluation of the allelopathic potential of rice germplasm in drill-seeded systems was initiated in Stuttgart, AR, USA. These efforts led to the identification of several foreign lines with allelopathic activity against aquatic weeds and some of these lines (e.g. PI 312777) also suppressed barnyard grass (*Echinochloa crusgalli*; BYG) more effectively and economically under reduced herbicide inputs than commercial cultivars. These suppressive rice lines appear to produce greater root mass near the soil surface compared to non-suppressive cultivars (118,160). Because plant type and grain quality of these lines have often been inadequate for the U.S. rice industry, a breeding program was initiated to combine the desirable characteristics of Katy long grain rice with several high yielding, suppressive lines. The F_5 or later generations from selections of the pedigree PI 338046/Katy//PI 312777 have been evaluated for several years (162). Some selections have produced acceptable yield and quality, but often yielded or suppressed BYG less than did parental lines or other standards. Several 'competitive' *indica* lines from Asia (e.g. 4593 from China) and commercial hybrids from the U.S. (e.g. XL8) have yielded as much or more than elite U.S. cultivars and controlled BYG similar to the most suppressive rice lines. Thus, these germplasm lines may be useful in weed suppressive systems for U.S. rice (133).

2.1.3. Rice allelopathy research in China

There are around 50,000 rice accessions in the China Rice Germplasm Bank, including 4,500 wild rice accessions (76). It has three foci of genetic diversity and is one of the origins of rice (133). We may be able to choose germplasm with significant allelopathic potential thanks to this vast and varied gene pool. Numerous studies have been conducted in fields, greenhouses and labs to assess possible allelopathic rice cultivars or lines (5,8,66,77,98). Both contemporary cultivars and certain wild rice lines exhibited significant allelopathy against weeds (122). Target weeds' root growth was more susceptible to rice's allelopathic effects than their shoot growth (54).

The surroundings and methods of evaluation have an impact on the allelopathic activity of the examined rice accessions. Despite their strong inhibition of barnyard grass (*Echinochloa crusgalli*) growth in the laboratory, the majority of rice accessions did not exhibit allelopathic effects on weeds in fields (43). The inhibitory impact was weaker at high weed density than at low weed density, even with the same amount of extracted allelochemicals (95). In contrast to favourable conditions in the fields, Lin's research (45) showed that heterosis in rice allelopathic effects on barnyard grass were significantly higher in low temperatures and weak sunlight. Recent research, however, suggests that the rice cultivar "Huahang No.1" exhibited greater allelopathic potential at high irrigation, fertility and sunshine levels (116).

2.1.4. Wheat (*Triticum aestivum* L.)

The allelopathic potential of wheat has been well investigated, much like that of rice and sorghum. The allelopathic potential of seedlings, straw, weed residues and aqueous extract has been investigated (149,158). According to Steinsiek *et al*. (147), the aqueous extract from wheat was phytotoxic to pitted morning glory (*Ipomoea lacunosa* L.), velvetleaf (*Abutilon theophrasti* Medic.) and ivyleaf morning glory (*Ipomoea hederacea* (L.) Jacq.). Polyphenols and hydroxamic acids are two main allelochemical groups found in wheat (85,119). P-hydroxybenzoic, vanillic, p-coumaric, syringic and ferulic acids were the main phenolic acids found in wheat mulch and the soil around it (91). The primary allelochemicals in wheat have also been found: H acids (benzoxazinoids) and lactams, including 2, 4-dihydroxy-1,4-benzoxazin-3-one (DIBOA), 2,4-dihydroxy7-methoxy-1, 4-benzoxazin-3-one (DIMBOA), 2-hydroxy-1,4-benzoxazin-3-one (HBOA) and 2-hydroxy-7-methoxy-1,4-benzoxazin-3-one (HMBOA). Benzoxazolin 2-one (BOA), a more potent molecule, was produced by further metabolizing DIBOA. In many plant species, BOA has been demonstrated to decrease germination and reduce seedling development. According to Burgos and Talbert (2000), DIBOA was seven times more harmful to weed species' ability to develop roots than BOA. Due to the existence of several allelochemicals, wheat exhibits allelopathic potential; however, further research is necessary to fully understand the genetic control of wheat allelopathy. Furthermore, greater effort needs to be put into choosing and developing wheat cultivars that have a stronger allelopathic effect on weed species.

2.1.5. Sorghum (*Sorghum bicolor* (L.) Moench)

The presence of hydrophilic chemicals (phenolic acids and their aldehyde derivatives, as well as hydrophobic molecules, such sorgoleone), gives sorghum its potential to suppress weeds (49). Sorgoleone was separated from hydrophobic sorghum root exudates by Netzly and Butler (117). Sorgoleone accounts for over 90 % of chemicals found in sorghum root exudates (49). Sorghum's root hair cells produce sorgoleone (161). Due to its ability to inhibit a wide variety of weed species, sorgoleone has been described as a powerful bioherbicide. Its activity has been demonstrated to be higher than other phenolics, terpenoids and allelochemicals such as juglone (153). There are several ways (intercropping, extract spray, surface mulch and soil mixing) to use sorghum to suppress weeds. Adding sorghum roots, stems and leaves to the soil reduces weed biomass by 25-50 % (39). Sorgaab, a foliar supplement of sorghum water extract, enhanced maize yield by 44 %, while decreasing purple nutsedge's density and dry weight by 44 % and 67 %, respectively (38). Uddin *et al.* (153) created a wettable powder formulation that contained sorgoleone, an active component, at 4.6 % concentration. The germination and growth of Indian jointvetch (*Aeschynomene indica* L.), Japanese dock (*Rumex japonicus* Houtt.), fake cleavers (*Galium spurium* L.) and common amaranth were all totally inhibited by 0.2 g sorgoleone, active component. The wettable powder's post-emergence treatment suppressed weed growth by 20-25 % more than its pre-emergence application. Cheema (19) isolated 9-more allelochemicals: Benzoic, p-hydroxybenzoic, vanillic, m-coumaric, p-coumaric, gallic, caffeic, ferulic and chlorogenic acids (39). There is need to develop a multidisciplinary strategy using allelochemicals, sorghum crops, or residues for strategic weed control.

2.1.6. Barley (*Hordeum vulgare* L.)

Allelopathic compounds are a well-known characteristic of barley (*Hordeum vulgare* L. ssp. *vulgare*). The allelopathic ability of its seeds (90), residues (63) or root exudates (30) against certain crop or weed species has been investigated. Barley is a good crop model to study allelopathy because, Baghestani *et al*. (17) and Ma *et al*. (95) reported that it had a greater range of allelopathic chemicals than wheat germplasm, including phenolic acids (17,96). By reducing its own seed germination or seedling development (130), barley was also discovered to be autotoxic (28), which is an intra-specific type of allelopathy. Barley is susceptible to a significant 'allelopathic risk' in barley-barley cropping sequences, according to these research' findings (124). In barley crop, autotoxicity was defined as the repressive effects of their residues; however, it was never investigated if root exudates from intact plants also had an allelopathic influence on barley growth. Protocols designed to achieve this goal were never used to compare the allelopathic inhibition and auto inhibition activities. Barley has significant genetic diversity in allelopathic activity (17,45,67,125). Variations in the profiles and amounts of secondary metabolites are related to this variability (29). Only 44 substances from various chemical classes-such as polyamines, cyanoglucosides, alkaloids and phenolics-were found to be putative allelochemicals that support barley's allelopathic efficacy (84). Gramine and hordenine, two alkaloids, were the first allelochemicals to be suggested as the cause of barley's allelopathic actions (89,126). White mustard (*Sinapis alba* L.) and barley (*Hordeum vulgare* L.) were evaluated for allelopathic effects using modified bioassays that minimized other environmental factors. At a density of 0.5 barley seed/cm2, white mustard radicle lengths were considerably reduced and germination was delayed in a Petri dish bioassay (126). White mustard radicle elongation was not hindered one day after sowing in a "siphoning" bioassay apparatus, when the two species were sown together, but it grew more and more inhibited as the bioassay period increased (94). In a hydroponic environment, barley allelochemicals were released from the roots till 70 days from the start of barley germination. White mustard growth was inhibited and germination was delayed by solutions taken from the hydroponic barley growing system (87).

2.1.7. Brassica spp. (*Brassica oleracea* L.)

With over 375 genera and more than 3200 species, the Brassicaceae family of plants is significant and diverse. Around 100 plant species in the genus Brassica, such as Indian mustard (*Brassica juncea* L.), cabbage (*Brassica oleracea* L.) and rapeseed/canola (*Brassica napus* L.), are common vegetable or oilseed crops and are commonly cited as being very allelopathic (46,115). Because of its quick development and capacity to absorb nutrients, the Brassicaceae family is very effective at producing biomass (46). Because of their allelopathic character, some scientists have identified wild or cultivated Brassica spp. as weed suppressive (55,129,164). Numerous allelochemicals produced by *Brassica* species greatly influence the growth and development of their target plants (Table 1). Brassinosteroids, a significant class of steroidal chemicals essential to plant growth and development, are produced endogenously by *Brassica* species (105). Brassinosteroids were initially isolated from rapeseed pollen by Grove *et al*. (62). Since then, a number of studies have verified the beneficial effects of brassinosteroids on the growth and development of various plant species, such as adzuki beans (*Vigna angularis* (Willd.), field peas (*Pisum sativum* L.), mung beans (*Vigna radiata* L.) and maize (61,104,163). In addition to enhancing the development and productivity of many crops, brassinosteroids also increase tolerance to abiotic challenges, such as pesticides (146,159), heat (147), heavy metals (6,13) and salt stresses (127).

2.1.8. Sunflower (*Halianthus annuus* L.)

The Asteraceae family's sunflower (*Halianthus annuus* L.) has several bioactive allelochemicals that have allelopathic effects on other plants, making it a potential allelopathic plant (100). Flavonoids, terpenoids, and phenolic compounds are the main allelochemicals found in sunflower (58,97). When these substances leak into the surrounding rhizosphere, they significantly hinder the germination and growth of other plants and may alter nearby flora in many ways. Allelochemicals are typically released into the environment as rain leachates, exudates, or residual components (16). Depending on the type and concentration of the released allelochemicals, these substances can then have an inhibitory or stimulatory allelopathic effect on plants (31,111). The sunflower allelopathic effects are well-known on weeds and other crops (101). Aqueous extracts of sunflower aerial parts and root were found to have a low germination rate for maize (*Zea mays* L.), tomato (*Lycopersicon esculentum* Mill), soybean (*Glycine max* L.) and bean (*Phaseolus vulgaris* L.) (27). When sunflower and sorghum aqueous extracts were combined, the biomass of various weeds (*Rumex dentatis* L., *Chenopodium album* L., *Coronopus didymus* (L.) Sm. and *Fumaria parviflora* Lam.) decreased, while the wheat yield increased (41). *Cyamopsis tetragonoloba*, *Sorghum vulgare*, *Pennisetum americanum* and *Zea mays* cultivated in fields with sunflower residues showed decreased growth and yield (26). When applied to mustard (*Sinapis alba* L.), sunflower leaf extracts at varying doses demonstrated inhibitory effects on the tested plant's seed germination and seedling growth (32). Sunflower water extracts and residues decreased wild barely (16) seed germination, seedling development and biomass. The biomass of four wheat types exhibiting substantial allelopathic activity of sunflower was dramatically reduced by varying doses of aqueous extracts of sunflower (12). Nikneshan *et al*. (120) investigated the allelopathic effects of several quantities of air-dried sunflower leaf powder on wheat and other target plants. The higher doses reduced the germination indices of wheat and other plants. When applied to rice, grass and sedge weeds, various aqueous extracts of sunflower and other plants decreased biomass accumulation, root and shoot length, chlorophyll concentrations and lateral plant spread (80).

2.1.9. Oats (*Avena fatua* L.)

In Northern India, where wheat is planted in rotations of cotton-wheat, pearl millet-wheat, or fallow-wheat, wild oat (*Avena fatua* L.) is the most common weed. The wheat yield is reduced by 16-46 % when the density of wild oats is 40-60 plants/m^2 (21). It is known that wild oats and wheat compete for nitrogen (60). Herbicides are used to control wild oats and other weeds (20,103) by 40 to 45 % of wheat growers. Wheat and other crops to interfere with weeds differs (10,14). Wild oat infested fields significant by cause yield loss due to the production of toxic substances by wild oat plants that inhibit the growth and development of crops. Finding out how wild oats (*Avena fatua*) might affect spring wheat (*Triticum aestivum* var. Field) growth in the absence of plant competition was the aim of this study (106). In 250 cc beakers filled with sand medium, wild oat and spring wheat seedlings were cultivated independently. In beakers containing spring wheat in temporally similar phases of development, root exudates were taken from the wild oat medium at the 1-, 2-, 3- and 4-leaf stages of wild oat development (150). Spring wheat root and leaf dry weights were measured to determine if one or more allelochemical agents were released from wild oat roots. Exudates from wild oat plants at the 2- and 4-leaf phases of growth considerably decreased the dry weights of spring wheat leaves and roots, respectively (88). Exudates from wild oat roots at different phases of plant growth were used to isolate allelochemicals. Analysis using paper chromatography revealed the presence of at least two unidentified chemicals. The two unknown compounds' R f values in benzene-acetic acid-water (0.825 and 0.930) were comparable to those of vanillic acid (4-hydroxy-3-methoxybenzoic acid) and scopoletin (7-hydroxy-6-methoxycoumarin), respectively (64). The unknowns were also shown to be coumarin-related substances including scopoletin and vanillic acid, according to additional tests employing diazotizedp-nitraniline, ultraviolet absorption spectra, and gas chromatography analysis (47).

Table 1. Allelopathic crops and their potent allelochemicals

#	**Allelopathic crops**	**Allelochemicals**	**Ref.**
1.	Rice (*Oryza sativa* L.)	Cytokinins, diterpenoids, fatty acids, flavones, glucopyranosides, indoles, (A and B), oryzalexins, phenols, phenolic acids, resorcinols and stigmastanols	157
2.	Wheat (*Triticum aestivum* L.)	Polyphenols and hydroxamic acids; P-hydroxybenzoic, vanillic, p-coumaric, syringic and ferulic acids	85, 119, 91
3.	Sorghum (*Sorghum bicolor* (L.) Moench)	Sorgoleone, Benzoic, p-hydroxybenzoic, vanillic, m-coumaric, p-coumaric, gallic, caffeic, ferulic and chlorogenic acids	49, 19, 39
4.	Barley (*Hordeum vulgare* L.)	Phenolic acids, polyamines, cyanoglucosides, alkaloids- Gramine and hordenine	17, 84, 89, 94, 126
5	Brassica spp. (*Brassica oleracea* L.)	Phenolic compounds, isothiocyanates, thiocyanates	105
6.	Sunflower (*Halianthus annuus* L.)	Phenolic compounds, flavonoids and terpenoids	32
7	Wild oats (*Avena fatua* .L)	Phenolic acids, coumarins, alkaloids, terpenes	150

Table 2. Interactions of allelopathic crops and their allelochemicals

#	Allelopathic crops	Affected crops	Allelochemicals	Ref.
1.	Barley (*Hordeum vulgare* L.)	White mustard (*Sinapis alba* L.)	Phenolics, alkaloids, cyanoglucosides, polyamines	94
2.	Brassica spp. (*Brassica oleracea* L.)	Maize (*Zea mays* L.), mung bean (*Vigna radiate* L.), field pea (*Pisum sativm* L.) and adzuki bean (*Vigna angularis* L.)	Phenolic compounds, isothiocyanates, thiocyanates	105
3.	Sunflower (*Halianthus annuus* L.)	Maize (*Zea mays* L.), tomato (*Solanum lycopersicum*), soyabean (*Glycine max* L.) and bean (*Phaseolus vulgaris* L.)	Phenolic compounds, flavonoids and terpenoids	32
4.	Wild oats (*Avena fatua* L.)	Spring Wheat (*Triticum aestivum* L.)	Phenolic acids, coumarins, alkaloids, terpenes	150

2.1.10. Allelochemicals

As the allelochemicals avoid harmful or persistent environmental effects; they present a practical and eco-friendly alternative to synthetic chemical herbicides (18). The suppressive role of allelochemicals is due to their ability to inhibit vital metabolic and physiological processes in plants. Numerous studies have been done on suppressive effects of allelopathic plants on weeds growth (99,123). At lower concentrations, they promote growth and enhance an organism's resistance to various biotic and abiotic stresses (107). In many crops, applied aqueous extracts of allelopathic plants at lower concentrations enhances the seed germination and growth (155). Hence, allelochemicals may be used to enhance crop productivity (59). The allelochemicals concentration and activity vary in different parts of same plant and fluctuate throughout the growing season (1,24,71,134,152). The allelochemicals are released through root exudates into the rhizosphere (3,4,7), volatilization (36,86), leaching in soil (79,112) residue decomposition (2,78,99). Table 2 represent different allelochemicals released from crops having suppressive effects on weeds growth.

The major findings of allelopathy research are:

(a) Different plant families have allelopathic suppression properties that can be grown either alone or in intercropping to manage weeds.

(b) Various allelopathic techniques (crop rotation, intercropping, cover crops (used as living or dead mulches), green manuring and the application of allelochemical-based bioherbicides) can be used.

(c) These techniques are highly adaptable and more effective in integrated weed management.

(d) Recent advancements in the chemistry of allelopathy have made it easier to use allelochemicals to produce bioherbicides.

(e) Numerous biotechnologies, including genetic engineering and stress induction methods, have the potential to enhance a crop's allelopathic abilities or create allelopathic traits from scratch.

2.1.11. Intercropping

To maximize crop yields per unit area per unit of time, intercropping-the practice of growing multiple crop species together in the same field during a growing season-has been used extensively throughout history. Although it is being utilized more and more in contemporary intensive agriculture, it is still a prevalent agricultural technique in small farms, conservative agriculture and resource-constrained agricultural systems. Intercropping is cost-effective and environmentally friendly method of weed control (33). The degree of weed suppression is strongly influenced by cash and cover crop genotypes, plant density, plant arrangement, etc. Because it facilitates crop cultivation and permits greater interactions between crops, intercropping is the most commonly used method in allelopathic field studies (Table 3).

Table 3. Allelopathic crops and main crops in intercropping system (58)

#	**Allelopathic crop**	**Main crop**	**Weed species**	**Ref**
1	Barley (*Hordeum vulgare* L.)	Pea (*Pisum sativum* L.)	Common lambsquater (*Chenopodium album* L.), wild mustard (*Sinapis arvensis* L.)	48
2	Canola (*Bassica napus* L.)	Wheat (*Triticum aestivum* L.)	Littleseed canarygrass (*Phalaris minor* Retz.), broad-leaved duck (*Rumex obtusifolius* L.), swine watercress (*Lepidium didymum* L.), and common lambsquarters (*Chenopodium album* L.)	113
3	Chickpea (*Cicer arietinum* L.)	Wheat (*Triticum aestivum* L.)	Common lambsquater (*Chenopodium album* L.), burr medic (*Medicago polymorpha* L.), sweet clover (*Melilotus indicus* (L.) All.), scarlet pimpernel (*Anagallis arvensis* L.), swine watercress (*Lepidium didymum* L.)	22
4	False flax (*Camelina sativa* L.)	Pea (*Pisum sativum* L.)	Field bindweed (*Fallopia convolvulus* L.), sow thistle (*Sonchus oleraceus* L.), chamomile (*Matricaria recutita* L.)	138
5	Cowpea (*Vigna unguiculata* (L.) Walp.)	Maize (*Zea mays* L.)	Barnyardgrass (*Echinochloa colona* (L.) Link), purslane (*Portulaca oleracea* L.), tossa jute (*Chorchorus olitorius* L.), crowfoot grass (*Dactyloctenium aegyptium* (L.) Willd)	139
6	Maize (*Zea mays* L.)	Cassava (*Manihot esculenta* Crantz)	Redroot pigweeed (*Amaranthus retroflexus* L.), giant foxtail (*Setaria faberi* Herrm.), bermudagrass (*Cynodon dactylon* (L.) Pers.)	123
7	Sorghum (*Sorghum bicolor* (L.) Moench)	Maize (*Zea mays* L.)	Purple nutsedge (*Cyperus rotundus* L.), field bindweed (*Fallopia convolvulus* L.) and horse purslane (*Trianthema portulacastrum* L.)	**79**
8.	Sorghum (*Sorghum bicolor* (L.) Moench), soybean (*Glycine max* (L.) Merr.) and sesame (*Sesamum indicum* L.)	Cotton (*Gossypium hirsutum* L.)	Purple nutsedge (*Cyperus rotundus* L.)	**72**
9.	Spanish tick-clover (*Desmodium uncinatum* [Jacq.] DC.), green leaf desmodium (*Desmodium intortum* [Mill.] Urb.)	Maize (*Zea mays* L.)	Giant witchweed (*Striga hermonthica* [Del.])	**83**

In intercropping, allelopathic crops release allelochemicals into the environment by leaching from rainfall or plant debris degradation, volatilization from aboveground plant components and root exudation (142). By increasing soil microbial diversity and promoting the uptake of allelochemicals into the soil, intercropping improves allelopathic weed-cover crop interactions and in turn, the phytotoxic effects (33). Common mycorrhizal networks can serve as "superhighways" that connect plants below ground and transport allelochemicals to specific plants (25).

3. CONCLUSIONS

Allelopathy, a biological process involving chemical interactions between plants, offers a lot of potential for use as a practical and sustainable method of controlling weeds in field crops. Allelopathy can be used to manage weeds organically and lessen excessive dependence on herbicides. Another tactic for a long-term weed control campaign would be the use of allelopathic plant extracts. More allelochemicals will be discovered, examined and applied for weed control thanks to advancements in extraction techniques and contemporary biotechnological instruments. Although it is now challenging to completely replace chemical weed control, an integrated weed management strategy could be successful.

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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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