Allelopathy for Weed Management

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Abstract

A large number of plant and weed species produce secondary metabolites known as allelochemicals, and the process is known as allelopathy. Allelochemicals can be used to control weeds in agricultural systems by using allelopathic crops for intercropping, crop rotation, or mulching. A few important examples of crop species with high allelopathic potential may include (but not limited to) wheat, rice, sorghum, rye, barley, and sunflower. The naturally produced allelochemicals in these crops could be manipulated to suppress weeds and witness an environment-friendly and sustainable agricultural production system.

Keywords

Allelopathy · Weed control · Allelopathic crops · Crop rotation · Intercropping · Cover crops

1 Introduction/Importance of Allelopathic Weed Control

Sustainable weed control is critical to ensure food security for future generations. Chemical weed control has been the most effective among the various weed management methods that have been used to control weeds in different crops and ecological conditions. However, the sustainability of chemical weed control is at stake due to evolution of herbicide resistance in weeds, environmental concerns, and damages to human health.

Allelopathy, a biochemical interaction among living organisms, can provide an effective environment-friendly alternative to chemical weed control [1, 2]. Various natural herbicidal compounds have been identified from different microbes and crop species [1, 3, 4]. These natural phytotoxins could be applied directly as natural herbicides or could be used to develop novel herbicide mode of actions [5]. Allelopathy can be used to manage weeds in field crops through intercropping, cover cropping, crop rotation, mulching and residue incorporation, and allelopathic extract and by utilizing hormetic potential of allelochemicals [2, 6].

In this chapter, we have discussed the potential allelopathic crop and weed species and the possible ways to utilize allelopathic potential for weed management in field crops. Moreover, challenges to allelopathic weed control and future directions are also discussed.

2 Rich Sources of Allelochemicals

2.1 Allelopathic Crops

Various crop species have shown allelopathic potential that can be used to manage weeds in field crops by using them as cover crops, surface mulch and/or residue incorporation, intercropping, and rotation and using crop extract with reduced dose of herbicides [7]. Researchers have screened various crop cultivars with strong allelopathic traits. Common field crops including rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), sunflower (*Helianthus annuus* L.), maize (*Zea mays* L.), canola (*Brassica napus* L.), sorghum (*Sorghum bicolor* L.), millet (*Pennisetum glaucum* (L.) R.Br.), and buckwheat (*Fagopyrum esculentum* Moench) possess variety of allelochemicals that can be used to suppress weeds [1, 7]. Alfalfa (*Medicago sativa* L.) a common fodder crop cultivated worldwide provided significant control (up to 80%) to various weeds of rice ecosystem [8]. Rice a major cereal also possess various herbicidal compounds; Xuan et al. [9] reported that rice allelopathy can provide up to 88% control of weeds. Similarly, buckwheat residues caused up to 80% weed control in rice field [10]. Furthermore, allelochemicals released from sunflower, rye (*Secale cereale* L.), wheat, and sorghum could be utilized to provide effective weed control in various crops [1, 11–19]. Allelopathic potential of crops against weeds varies among crop species. For example, Batish et al. [91] tested the weed control potential of 35 crops; all tested crops showed weed suppression potential; some common crops including rice, wheat, maize, sugarcane, alfalfa, and vegetable crops (cucumber (*Cucumis sativus* L.), soybean (*Glycine max* [L.] Merr.), fennel (*Foeniculum vulgare* Mill.), and carrot (*Daucus carota* L.)) showed strong allelopathy and even caused autotoxicity under some conditions. Various allelochemicals having inhibitory effects against the weeds have also been identified from different common crop species [7, 20].

Different genotypes of the same crop may have different allelopathic potential. Thirty eight wheat cultivars were tested for their allelopathic effect on *Lolium rigidum* Gaud. Wheat cultivars showed differential allelopathic potential [84]. The above discussion indicates that the allelopathic potential of a number of field crops has been established in the last decades. These crops can be potentially used to manage weeds in agroecosystems in different ways to ensure sustainable weed control.

2.2 Allelopathic Weeds

A large number of allelochemicals that can suppress the growth of other plant species have been identified in various weeds. Similar to crops, weed species also produce allelochemicals; these allelochemicals are supposed to be more toxic because weeds normally grow under stress conditions. Different weed species including *Chenopodium album* L., *Medicago denticulata* L., *Melilotus indica* L., *Convolvulus arvensis* L., *Vicia hirsute* L., *Lathyrus aphaca* L., and *Rumex acetosella* L.

showed strong herbicidal potential to control *Phalaris minor* Retz. [21]. *Acroptilon repens* L., a commonly found weed in the western United States, showed herbicidal potential against *Echinochloa crus-galli* (L.) P. Beauv., *Agropyron smithii* Rydb., and *Bromus marginatus* Steud. [22]. Aqueous extract of different plant parts of *Croton bonplandianum* Baill. exhibited herbicidal potential against the weeds including *Melilotus alba* L., *Vicia sativa* L., and *Medicago hispida* Gaertn. [23]. Two weed species, i.e., *E. crus-galli* and winter cherry (*Withania somnifera* (L.) Dunal), were tested for their potential to control *Avena fatua* L., and allelopathic extracts from both the weeds inhibited the germination and seedling growth of *A. fatua* [24]. However, rare studies are available on identification and extraction of herbicidal compounds from weed species.

D'Abrosca et al. [25] identified 24 different phytotoxic compounds in *Sambucus nigra* L. belonging to various groups including lignans, cyanogenins, phenolic glycosides, and flavonoids. These phytotoxic compounds showed strong inhibitory effects on germination and growth of lettuce (*Lactuca sativa* L.), onion (*Allium cepa* L.), and radish (*Raphanus sativus* L.) [25]. Honeyweed (*Leonurus sibiricus* L.) contained various phytotoxic compounds that showed an inhibitory effect on rice, wheat, and mustard [26]. Aqueous extract of *Conyza canadensis* L. showed a strong inhibitory effect on various crops due to the presence of different phenolics, including gallic acid, syringic acid, catechol, and vanillic acid [27]. Sasikumar et al. [28] stated that the strong inhibitory effect of different plant parts of *Parthenium hysterophorus* L. on the germination and growth of various crops was due to the presence of phenolic acids identified in this weed. Similarly, *Chenopodium ambrosioides* L. and *E. crus-galli* also contain various phytotoxic compounds that were found to inhibit the germination and growth of different crop species [29, 97]. Zohaib et al. [30] reviewed more than 30 weed species containing phytotoxic compounds that showed strong inhibition against various crops and weeds; the phytotoxic potential of these weeds can be explored to manage weeds. The most commonly found phytotoxic compounds in weeds were alkaloids, fatty acids, phenolics, terpenoids, indoles, lignans, cyanogenins, flavonoids, and coumarins [30]. Furthermore, allelopathic compounds released from aquatic weeds showed more phytotoxic activity against various terrestrial weeds and crop plants [31], because plants of a certain ecosystem might be well adapted to the allelochemicals compared to the ones of any other ecosystem [31, 32]. Thus, phytotoxic compounds released from aquatic weeds can be identified and used as potential bio-herbicides. In crux, the use of weeds to make herbicides can be an environment-friendly option to control weeds in crops for sustainable crop production.

3 Ways to Use Allelopathic Potential for Weed Management

3.1 Intercropping

Growing of crops together at the same time in the same field is an important strategy to increase input (land, fertilizer, and water) use efficiency and to enhance crop yield and economic returns [33]. In addition, intercropping especially with allelopathic crops can provide eco-friendly alternative to chemical weed control [34]. Recent studies have explored the effectiveness of intercropping with allelopathic crops as a good alternative to chemical weed control [6]. Intercropping of fodder legumes in maize helped to control the giant witchweed (*Striga hermonthica* [Del.] Benth) invasion than the sole maize crop [99]. Intercropping of various allelopathic crop species in maize was effective to control different narrow- and broad-leaved weed species [35]. Infestation of purple nutsedge (*Cyperus rotundus* L.) in cotton crop was significantly reduced with intercropping of sesame (*Sesamum indicum* L.), soybean, and sorghum on alternate rows [100]. In another field trail, the intercropping of white clover (*Trifolium repens* L.), black medic (*Medicago lupulina* L.), alfalfa, and red clover (*Trifolium pratense* L.) in wheat crop was effective to control various weed species and to enhance wheat yield [101]. Similarly, intercropping of pea (*Pisum sativum* L.) with barley (*Hordeum vulgare* L.) [102], sorghum with cowpea (*Vigna unguiculata* (L.) Walp.) [36], wheat with canola [37], and wheat with chickpea (*Cicer arietinum* L.) [38], reduced the weed infestation as compared to sole crop and enhanced farm income. Therefore, intercropping of allelopathic crops with the main crop has potential to control weeds through release of allelochemicals.

3.2 Cover Crops

Cover crops with allelopathic properties can provide effective weed control in addition to their other benefits including protection from soil erosion, snow trapping, nitrogen fixations, and improvement of soil structure and fertility [39]. The weed suppression potentials of cover crops including physical suppression, shade effect, decrease in temperature, and competition with weeds for inputs can be further increased through selection of strong allelopathic crops as cover crops. Furthermore, the release of allelochemicals from cover crops through root exudates, leaf shading, and washing by rain will help to decay the weed seedbank. The weed control efficiency of cover crops depends on its allelopathic potential and duration in the field; strong allelopathic crop for long duration in the field will provide more efficient weed control [40]. The weed control efficiency of cover crops also depends on weed species, e.g., sorghum as cover crop provides effective control of broad-leaved weeds; however narrow-leaved weeds were not controlled [41]. Environmental factors also influence weed control potential of cover crops by changing allelopathic potential, e.g., rye grown under nutrient stress conditions was more phytotoxic as compared to rye grown under high fertility [42]. Herbicide-resistant weeds, which are a major problem for sustainable weed management, may be controlled with allelopathic cover crops. The allelopathic crops that can be used as cover crops include rye, barley, sorghum, oat, wheat, canola, black mustard, buckwheat, clover species, and hairy vetch [39, 2]. In a recent study, allelopathic cover crops such as buckwheat and hairy vetch were effective in controlling apricot weeds [39].

3.3 Crop Rotation

Crop rotation is system in which different plants are grown in a sequence in a specific field for definite time period. It is important to reduce pest (weeds, pathogens, and insects) pressure, to overcome autotoxicity, and to sustain soil fertility [6, 43, 92]. Diversified rotation is key for sustainable weed control as it creates unstable conditions for weeds and helps to reduce weed seedbank [44]. Allelopathic crop in a rotation can potentially suppress its associated weeds and reduce weed infestation in the crop following in the rotation [45]. Both root exudates and decomposing crop residues an allelopathic crop in the rotation add allelochemicals to the soil that help to reduce weed pressure [46]. For example, weed infestation is reduced in wheat crop if grown following the sorghum crop due to release of allelochemicals from sorghum [47]. For instance, in sunflower-wheat rotation, the weed infestation in wheat crop grown after sunflower was considerably reduced [6]. Inclusion of rapeseed in rotation caused about 40% reduction in weed density in the subsequent crop in rotation [46].

Weed seed germination inhibition potential of allelopathic crop in rotation can also negatively affect the seed germination of subsequent crop in rotation. For example, wheat germination was delayed when it was grown in rotation with sorghum [48]. However, wise use of allelopathic crops in rotation and tillage timing can help to reduce the inhibitory effect on crop [49]. Therefore, good crop rotation with inclusion of allelopathic crop can help to avoid autotoxicity and to reduce weed problem with minimum dependence on chemical weed control method.

3.4 Mulching and Residue Incorporation

In allelopathic mulching, the crop or weed residues are applied on soil surface or incorporated in the soil. Mulching with allelopathic crop/weed residues inhibits weed germination and growth due to release of allelochemicals in the rhizosphere, physical suppressing and depriving weed seeds from light [50–53]. In addition to weed control, mulching increases water holding capacity, increases soil fertility, enhances organic matter, and works as buffer to maintain soil temperature [54–56]. Commonly, farmers use economic parts of the crop while incorporating the remaining crop parts in the field as organic matter. The allelopathic plant parts left in the field inhibit the weeds. Recently, many studies have been done to explore the weed control potential of allelopathic mulches and residue incorporation in field crops. For instance, application of sorghum crop straw as surface mulch in maize provided up to 37% weed control [57], while in cotton and rice, about 60% and 50% weed control, respectively, was achieved with sorghum surface mulch [58] Sorghum residue incorporation or surface mulches provided effective control of various noxious weed species including *C. rotundus*, broad-leaved dock (*Rumex obtusifolius* L.), *P. minor*, *C. arvensis*, *C. album*, and scarlet pimpernel (*Anagallis arvensis* L.) [59, 60]. In another field study, it was observed that maize residues added in the field after maize harvest caused significant reduction in weed infestation in the succeeding broccoli (*Brassica oleracea* L.) crop [61]. Similarly, sunflower residues and surface mulches have potential to control various weed species in the field crops [62]. In another study, application of barely mulch in maize provided up to 80% weed control and 45% increase in maize grain yield over control [63]. Abbas et al. [50] reported that the mulches of allelopathic crops including rice, maize, sorghum, and sunflower at 12 t ha^{-1} provided effective control of herbicide-resistant *P. minor* in wheat. Mulches and residues of various crops including rye, clover, rice, maize, and canola have been reported for their potential as weed control [1, 7, 11–18].

Combined use of different allelopathic mulches can enhance their weed control potential due to the availability of diverse allelochemicals. Furthermore, allelochemicals have been known for their synergistic effect [6]. For example, combined use of canola, sunflower, and sorghum mulches provided more efficient weed control in maize as compared to the sole use of individual mulch material [64]. Therefore, residues of allelopathic crops can be used either as surface mulch or soil residue incorporation to control weeds in different crops.

3.5 Development of Herbicides from Allelochemicals and Their Derivatives

Herbicides with new modes of actions are badly needed due to fast-increasing herbicide resistance in weeds against all the major herbicide groups [65]. In addition, weed management in organic production systems is a great challenge [66]. Various natural herbicidal compounds have been identified from different microbes and crop species [1, 3, 4, 11]. These herbicidal compounds can be categorized in two major groups: phenolics and terpenoids [67]. These natural phytotoxins offer a great opportunity to be directly used as natural herbicides and to develop novel herbicide mode of actions [5]. The toxicity of allelopathic compounds depends on various factors including cultivar, plant part, concentration of extract, donor plant growth stage, and environmental conditions [68]. In this regard, several crop and weed species are now getting importance as a potential weed-controlling agent because of having various allelochemicals [1, 11–18].

In conclusion, allelochemicals from various crop and weed species can be directly used as herbicides or can provide basis for development of herbicides with new modes of actions.

3.6 Utilizing Hormetic Potential of Allelochemicals to Enhance Crop Competitiveness

The phytotoxic response of allelochemicals is dose dependent; allelochemicals cause growth enhancement (hormesis) at their low concentrations. The growth-promoting response of allelochemicals can be used to enhance crop growth. It will provide crop plants a competitive advantage over weeds. Allelochemicals can cause up to 50% and 42% increase crop growth under laboratory and field conditions, respectively [69, 90]. The hormetic response of allelochemicals varied depending on the type of allelochemicals, source of allelochemicals, time of application, and crop trait [90]. For example, aqueous extracts of sorghum, maize, and rice at low concentrations caused up to 35% increase in maize grain yield; each extract caused different levels of enhancement [70]. Similarly, the sorghum extract at 3% w/v concentration caused up to 42% increase in canola and maize yield, respectively [71]. Allelochemicals from various sources have been reported for their hormetic effect on different crop species in field conditions both under normal and stress environments [90].

In addition to growth enhancement of crop plants, allelochemicals can suppress the weed growth directly by acting as herbicide. The selectivity can be achieved by applying allelochemicals at crop tolerant stage and weed sensitive stage (early growth stage) [90]. Therefore, hormetic potential of allelochemicals can be used to suppress weeds by providing crop plants competitive advantage over the weeds.

4 Challenges in Implementing Allelopathic Weed Control

Establishing allelopathic weed control as tool for weed management in field crops might be a difficult task as other interference appliances (competition for inputs, soil microbial impact, and nutrient immobilization) work in parallel [72]. Estimation of herbicidal potential of allelochemicals after their entry in soil is an important task because various allelochemicals only showed inhibitory effect in bioassays, but no inhibition occurs when applied with soil [72]. Moreover, various types of stresses in the ecosystem also influence the allelopathic effect [73]. Hence, it is difficult to prove the mechanism of allelopathy [74]. Type and concentration of allelochemicals released by any specific plant species depend both on plant factors (species, growth stage, and plant part) and environmental factors (soil fertility, moisture level, temperature, climatic conditions, etc.) [75]. Furthermore, fortune of allelopathic effect in soil is not well known [76]. Soil environment affects the activity of allelochemicals due to various physical, chemical, and biological interactions [77, 78]. Furthermore, in the complex agroecosystem, allelochemicals do not reproduce and are susceptible to chemical and microbial degradation. Herbicidal potential of allelochemicals is a collective/synergistic response of various chemicals in the mixture and not due to any particular chemical [75]. Thus, type of allelochemicals and their integrated effects in the mixtures is important to be considered.

High production cost (e.g., tentoxin), low efficacy, and poor selectivity are also major limitations in using allelochemicals as potential weed control agents [4]. These herbicides might be toxic to nontarget crop species, for example, a natural plant-released phytotoxin alpha-terthienyl extracted and isolated from common marigold (*Tagetes erecta* L.) roots for use as a herbicide was equally toxic to crop plants in addition to weeds [77]. Generally, allelochemicals have short half-lives [79], and additionally the nature of allelochemicals, soil type, allelochemical concentration, and soil enzymatic and microbial community are also important [72]. Moreover, allelochemicals can be toxic to animals, e.g., fumonisin is toxic to animals and sorgoleone causes dermatitis [77]. Furthermore, allelochemical concentration (10^{-2}–10^{-5} M) that causes herbicidal effect is higher than the ideal concentration (10^{-5}–10^{-7} M) of natural herbicidal compounds according to environment safety standards [80]. In simple, issues regarding development of natural herbicides that form allelochemicals are much complicated and uneconomical as compared to synthetic herbicides. Additionally, less stability, low weed control efficacy, poor selectivity, and high cost are major limitations for development of natural herbicides by industries. However, the artificial modifications in the structure of plant-released herbicidal compounds may help to increase their selectivity and weed control efficacy. In addition, experiments considering the change in allelopathic effects with application of nitrogen fertilizers, activated charcoal, and environmental stresses may help to understand the fate of allelochemicals in soil.

5 Future Directions

5.1 Germplasm Selection to Enhance Allelopathic Potential

Importance of crop cultivars with improved weed suppressive ability has highly increased due to fast-increasing herbicide resistance in weeds and environmental concerns of herbicide use. In this scenario, it is important to breed crop cultivars with high allelopathic potential to suppress weeds and reduce herbicide usage. Different crop species and even the cultivars within same crop species vary in their allelopathic potential [81]; this weed-suppressing potential can be used as an alternative to herbicides. Studies on genetics of allelochemicals have not gained much attention in the past. The variability in allelopathic traits can be used to breed crop cultivars with more weed suppressive ability, e.g., rice produced from two inbred lines one with allelopathic gene and second with restorative gene had strong suppressive ability against *E. crus-galli* [82]. Crossing between old cultivars (having high allelopathic potential) with new crop cultivars can also help to enhance allelopathic potential [83]. Marker-assisted selection can help to develop crop cultivars with enhanced allelopathic potential. For instance, two major QTLs linked with allelochemical production were identified on 2B wheat chromosome [84]; thus allelopathic potential of wheat can be increased with the discovery of markers linked with the genes that control allelopathic traits. Recently successful attempts have been made to produce rice cultivars with high allelopathic potential in the United States (Arkansas), Asia, and Africa [85]. Bertholdsson [83, 86] also improved the weed suppressive potential of wheat and barley using breeding techniques; however the developed cultivars showed low grain yield potential. Further studies are required to breed crop cultivars with enhanced allelopathic potential and good yield potential for sustainable weed management.

5.2 Exploring Hormesis to Suppress Weeds

Hormesis of allelochemicals can play an important role for sustainable weed management. The dose-response effect of allelochemicals (inhibition at higher concentrations and growth enhancement at low concentrations) can be used in crop production to enhance crop growth with inhibition in weeds [90]. For example, application of hormetic dose to crop plants can produce herbicidal effect to weeds at their growth sensitive stage (early seedling stage). Optimization of dose, source, and application time of allelochemicals to produce hormesis in crop plants and inhibition in weeds might be an effective way to control weeds on a sustainable basis. Abbas et al. [90] reviewed that the various types of allelochemicals released from different crop and weed species produced hormesis (growth enhancement) in range of crop species at low doses, the same hormetic doses produced herbicidal effect when applied to weeds at their early seedling stage. Thus hormesis of allelochemicals will increase weed suppressive ability of crop by enhancing crop growth and by inhibiting weed growth due to their herbicidal effect. Therefore, future research in this regard will open new horizons for sustainable weed management.

5.3 Allelopathy of Unexplored Fields

The allelopathy of unexplored field can help to provide novel allelochemicals with more herbicidal potential. For example, allelopathic effect of aquatic weeds was more suppressive against various types of terrestrial weed species (Abbas et al. 2017). The susceptibility of crop weeds against allelochemicals from different ecosystem (aquatic in this case) was due to low adaptability of terrestrial weeds. Thus, more studies about determination and identification of allelochemicals of aquatic weeds can help to evaluate strong natural herbicide candidates. Furthermore, secondary metabolites released from lichen showed phytotoxicity to lichen photosynthetic process both when used alone and in the form of naturally occurring mixtures [87]. Similarity, allelochemicals released from fungi showed herbicidal effect against some weed species, e.g., *P. hysterophorus* L. [88]. Further studies in these ignored fields might identify novel strong herbicidal candidates.

5.4 Understanding About Mode of Action of Allelochemicals

Studies about how allelochemicals work have prime importance in allelopathic studies and require understanding at the molecular level, e.g., the structure of binding sites of protein or DNA. The knowledge about mode of action of natural phytotoxins can help to fasten the further industrial level consideration to produce natural herbicides. Recently few research attempts have been made to understand the mode of action of allelochemicals, e.g., Ren et al. [89] revealed that β-cembrenediol an important allelochemical inhibits the receptor plants through oxidative damage due to increased production of reactive oxygen species.

6 Conclusion

Allelopathic weed control can provide environmentally friendly tool to control weeds in cropping systems without dependence on chemical herbicides, as chemical weed control causes various hazards to environment, biodiversity, and human health. The use of allelopathic weed control through intercropping, crop rotation, cover cropping, mulches, residues, and water extract alone or in combination with synthetic herbicides will not only provide sustainable weed control but also sustainable crop production due to positive effects of these strategies on soil fertility, organic matter contents, and ecosystem biodiversity. Furthermore, efforts to motivate industries to produce allelochemical-based herbicides, breeding of more weed suppressive crop cultivars, exploring the allelopathy of unexplored fields, the use of allelochemical hormesis, and understanding about mode of action of allelochemicals will enhance the efficacy of allelopathic weed control.

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