Chapter 3
Role of Allelopathy in Weed Management

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Introduction

Weeds cause substantial yield loss of crops and pose a severe threat to food security for future generations. Controlling weeds in field crops is therefore imperative, but this is a hard nut to crack. However, wise management is quite effective in achieving the target weed control. Several methods of weed management, with varying degrees of effectiveness, are practiced according to the climatic conditions, cropping systems and socioeconomic conditions of the region. Manual and mechanical methods of weed control have been practiced for centuries, but these are inefficient methods, labor intensive and weather dependent [1, 2].

Chemical means of weed control are far cheaper, the most prevalent, and quite effective [2]. Nonetheless, continuous and indiscriminate use of herbicides is posing environmental hazards [3], may cause development of herbicide-resistant weed biotypes [4, 5], and is also creating human health concerns [6–8]. For example, babies born to families living near wheat farms, with continuous use of chlorophenoxy herbicides for weed control, may have 65% greater risk of birth defects related to

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the circulatory/respiratory system [9]. This situation demands to develop environmentally friendly technology for weed control.

Allelopathy, a naturally occurring ecological phenomenon of interference among organisms, involves the synthesis and release of plant bioactive compounds which are known as allelochemicals [10, 11]. These allelochemicals are capable of acting as natural pesticides and can resolve problems of soil and environmental pollution, resistance development in weed biotypes, and health defects caused by the indiscriminate use of synthetic herbicides [11].

Allelopathy may be employed for weed management in field crops through mix cropping intercropping [12], use of surface mulch [13], soil incorporation of plant residue [14], allelopathic aqueous extracts [12, 15], combined application of allelopathic aqueous extracts with lower herbicide doses [16, 17], and crop rotation [11, 18, 19]. In addition, smothering crops, such as rye (*Secale cereale* L.), buck wheat (*Fagopyrum esculentum* Moench), black mustard (*Brassica nigra* L.), and Sorghum–Sudan grass hybrids can also be used for controlling different weeds [20]. Conventional breeding and modern biotechnological approaches can be used to breed the crop cultivars having more weed-suppressive ability through allelopathy.

Most plants with allelopathic properties, including wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), sorghum (*Sorghum bicolor* [L.] Moench), oat (*Avena sativa* L.), rye, and pearl millet (*Pennisetum glaucum* [L.] R. Br.), belong to the family Poaceae. However, plants from other families, including *Brassica* spp., alfalfa (*Medicago sativa* L.), eucalyptus (*Eucalyptus* spp.), tobacco (*Nicotiana tabacum* L.), sesame (*Sesamum indicum* L.), sweet potato (*Ipomoea batatas* [L.] Lam.), sunflower (*Helianthus annuus* L.), and mulberry (*Morus alba* L.), also possess allelopathic properties [21–26].

In this chapter, potential application of allelopathy for weed management in field crops is discussed. Furthermore, role of conventional breeding and biotechnology in improving the allelopathic activity of crop genotypes for weed suppression is also included.

Intercropping

Intercropping, growing of two or more crops together at the same time in the same field, can be used as an effective weed management strategy [27]. Recent studies have suggested to use intercropping allelopathic crops as an effective element for integrated weed management, particularly in low-input farming systems [11, 28, 29]. Allelopathic intercrops suppress the weeds by shade effect, weed–crop competition, and by the release of certain allelochemicals [27, 28, 30]. In addition to weed suppression, intercropping may provide several other benefits, including increase in net returns and biological diversity, less chance of complete failure of crop, better use of resources, and suppressive effects on diseases and insect pests [30].

Intercropping maize with fodder legumes like Spanish tick-clover (*Desmodium uncinatum* [Jacq.] DC.) and green leaf desmodium (*Desmodium intortum* [Mill.]

Urb.) significantly reduced giant witchweed (*Striga hermonthica* [Del.] Benth) infestation in maize compared to sole maize crop [31]. In another field study, intercropping sesame, soybean (*Glycine max* [L.] Merr.), and sorghum in cotton (*Gossypium hirsutum* L.) suppressed the density and total dry biomass of purple nutsedge (*Cyperus rotundus* L.) [32]. Intercropping sorghum, sunflower, mungbean (*Vigna radiata* [L.] R. Wilczek; Table 3.1) [33], bean species (Table 3.1) [34], cassava (*Manihot esculenta* [L.]) Crantz) [35], horse gram (*Macrotyloma uniflorum* [Lam.] Verdc.) [36], groundnut (*Arachis hypogaea* L.), sweet potato [37], and legumes [38] with maize reduced the densities and dry biomass of many weed species. Maize–legume intercrop is also effective in reducing weed density and weed biomass compared to sole crops [39]. Bansal found that intercropping of linseed (*Linum usitatissimum* L.) with wheat suppressed corn buttercup (*Ranunculus arvensis* L.; Table 3.1) [40]. Bitter bottle gourd (*Cucurbita pepo* L.) intercropping in maize at lower density also decreased weed biomass (Table 3.1) [41]. In general, crop yield increases with simultaneous decrease in weed growth if the intercrops are more effective than sole crops in usurping resources from weeds [42]. Intercropping sorghum with fodder cowpea (*V. unguiculata* [L.] Walp.) suppressed densities and total biomass of several weeds [43]. Growing leek (*Allium porrum* L.) and celery (*Apium graveolens* L. var dulce [Mill.] Pers.) as intercrop shortened the critical period for weed control in the intercrop compared to pure stand of leek [44]. Likewise, pea (*Pisum sativum* L.) intercropped with barley, instead of sole crop, increased the competitive ability towards weeds [45]. Similarly, intercrops of wheat–canola–pea and wheat–canola provided better weed suppression than each individual crop grown alone [46].

In another study, after first weeding in rice, black gram (*Phaseolus mungo* [L.] Hepper) was seeded as intercrop, which effectively controlled rice weeds (Table 3.1) [47]. Banik et al. found that intercropping wheat and chickpea (*Cicer arietinum* L.) decreased the total weed density and weed biomass compared to monocrop of both crops (Table 3.1) [48]. In a two-year study, intercropping pea with false flax (*Camelina sativa* [L.] Crantz) suppressed the weeds by 52–63% more than sole crop of pea [49]. Similarly, intercrop of finger millet (*Eleusine coracana* [L.] Gaertn.) and green leaf desmodium decreased the density of giant witchweed more than monocrops of these crops [50]. Intercropping wheat with canola (*B. napus* L.) significantly reduced density and fresh/dry weight of littleseed canarygrass (*Phalaris minor* Retz.), broad-leaved duck (*Rumex* obtusifolius L.), swine cress (*Coronopus didymus* [L.] Sm.), and common lambsquarters (*Chenopodium album* L.) than the sole crops of both (Table 3.1) [51]. Similarly, intercropping canola with wheat suppressed annual ryegrass (*Lolium rigidum* Gaud.) and common lambsquarters [52]. In a two-year study, growing one strip of canola between two strips of wheat caused substantial decrease in weed density and dry weight than sole wheat crop [53]. Similarly, weed population was also significantly suppressed when either one strip of lentil or chickpea was planted between two strips of wheat [53].

Although intercrops are able to suppress weeds through the release of allelochemicals, the use of intercropping as a strategy for weed control should be approached carefully.

Table 3.1 Effect of different intercrops on weed suppression

Main crop	Intercrop	Weeds suppressed	Reference
Linseed (*Linum usitatissimum* L.)	Wheat (*Triticum aestivum* L.)	Corn Buttercup (*Ranunculus arvensis* L.)	Bansal [40]
Maize (*Zea mays* L.)	Hyacinth-bean (*Lablab purpureus* (L.) Sweet), Jack-bean (*Canavalia ensiformis* (L.) DC.), Butterfly pea (*Pueraria phaseoloides* (Roxb.) Benth.)	Itchgrass (*Rottboellia cochinchinensis* (Lour.) W.D. Clayton)	Cruz et al. [34]
Rice (*Oryza sativa* L.)	Black gram (*Phaseolus mungo* (L.) Hepper)	Junglerice (*Echinochloa colona* (L.) Link.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.), yellow foxtail (*Setaria glauca* (L.) Beauv.)	Midya et al. [47]
Wheat (*Triticum aestivum* L.)	Chick pea (*Cicer arietinum* L.)	Bermudagrass (*Cynodon dactylon* (L.) Pers.), wild oat (*Avena fatua* L.), purple nutsedge (*Cyperus rotundus* L.), common lambsquarters (*Chenopodium album* L.), sweet clover (*Melilotus indica* (L.) Pall.), honey clover (*Melilotus albus* Medik.), scarlet pimpernel (*Anagallis arvensis* L.), swinecress (*Coronopus didymus* (L.) Sm.)	Banik et al. [48]
Pea (*Pisum sativum* L.)	False flax (*Camelina sativa* (L.) Crantz)	Black bindweed (*Fallopia convolvulus* (L.) Á.Löve), common sowthistle (*Sonchus oleraceus* L.), chamomile (*Matricaria chamomilla*L.)	Saucke and Ackermann [49]
Maize (*Zea mays* L.)	Bitter bottle gourd (*Cucurbita pepo* L.)	Pigweed amaranth (*Amaranthus retroflexus* L.), field bindweed (*Convolvulus arvensis* L.)	Fujiyoshi [41] Fujiyoshi et al. [168]
Cotton (*Gossypium hirsutum* L.)	Sesame (*Sesamum indicum* L.), Soybean (*Glycine max* (L.) Merr.) and Sorghum (*Sorghum bicolor* (L.) Moench)	Purple nutsedge (*Cyperus rotundus* L.)	Iqbal et al. [12]

Table 3.1 (continued)

Main crop	Intercrop	Weeds suppressed	Reference
Finger millet (*Eleusine coracana* (L.) Gaertn.)	Green leaf desmodium (*Desmodium intortum* (Mill.) Urb.)	Giant witchweed (*Striga hermonthica* (Del.) Benth)	Midega et al. [50]
Maize (*Zea mays* L.)	Sorghum (*Sorghum bicolor* (L.) Moench), Sunflower (*Helianthus annuus* L.) and mungbean (*Vigna radiate* (L.) R. Wilczek)	Purple nutsedge (*Cyperus rotundus* L.), field bindweed (*Convolvulus arvensis* L.), horse purslane (*Trianthema portulacastrum* L.)	Khalil et al. [33]
Wheat (*Triticum aestivum* L.)	Canola (*Brassica napus* L.)	Annual ryegrass (*Lolium rigidum* Gaud.), common lambsquarter (*Chenopodium album* L.)	Khorramdel et al. [52]
Wheat (*Triticum aestivum* L.)	Canola (*Brassica napus* L.)	Littleseed canarygrass (*Phalaris minor* Retz.), Broad-leaved dock (*Rumex obtusifolius* L.), Swine cress (*Coronopus didymus* (L.) Sm.), common lambsquarter (*Chenopodium album* L.)	Naeem [51]

Crop Rotation

Accumulation of autotoxins and spread of plant pests are the major limitations of monoculture cropping systems [23, 54, 55]. Crop rotation, growing of different crops in sequence in a particular field over a definite time period, can be helpful in overcoming the autotoxicity and decreasing the pressure of plant pests, including weeds, pathogens and insects [11, 19].

Inclusion of allelopathic crops in crop rotation may be useful to control weeds [27]. In crop rotation, the allelochemicals released in the rhizosphere by plant roots and decomposition of previous crop residues help in weed suppression [56, 57]. For instance, in the crops following sorghum, weed population is significantly reduced due to the release of sorghum allelochemicals [58]. Therefore, in rice–wheat system, growing of allelopathic crops after wheat harvest and prior to rice transplantation may be useful to control weeds in rice.

A 10-year study on different crop rotations, viz. maize–soybean, continuous maize, and soybean–wheat–maize, indicated a significant decrease in giant foxtail (*Setaria faberi* [R.] Hermm.) density in the succeeding crop following wheat [59]. Likewise, in sunflower–wheat rotation, density and dry biomass of wild oat (*Avena fatua* L.) and Canada thistle (*Cirsium arvense* [L.] Scop.) were decreased

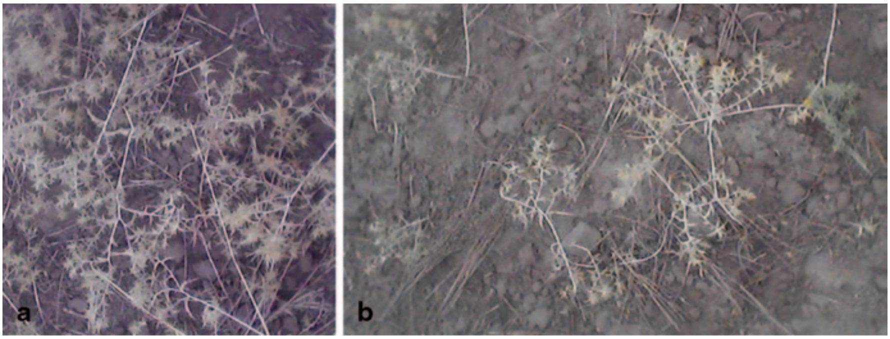

Fig. 3.1 Wild safflower infestation in field previously occupied by wheat and chickpea field. **a** After wheat harvest. **b** After chickpea harvest

significantly in the succeeding wheat crop after sunflower [60]. In a rotation study conducted in Russia, weed suppression of up to 40% was noted in crops raised in rotation with rapeseed [61]. Al-Khatib et al. noted that weed suppression in peas varied between different green manure crops [62]. One month after planting, the highest weed population was in green pea following wheat, whereas the lowest was in green pea following rapeseed. Wild safflower (*Carthamus oxyacantha* [M.] Bieb.) is a noxious weed of the rainfed areas of Pakistan. However, its population in field vacated by wheat is always higher than in the chickpea-vacated fields (Fig. 3.1), owing to release of certain allelochemicals from the chickpea roots. Thus, proper rotation of crops in any cropping system in a specific region can be used as a successful strategy to control weeds without reliance upon chemical, manual, and mechanical methods used for centuries.

Mulching

In mulching, crop residues (or other materials) are applied on soil surface and/or incorporated into the soil. Mulching inhibits the germination and seedling growth of weeds through the release of certain allelochemicals [63, 64], producing microbial phytotoxins during decomposition, and physically obstructing the growth of seedlings [65]. Mulching also increases the soil's water-holding capacity [66].

In 1979, Lockerman and Putnam floated the idea to use allelopathic crop residues as mulch [67]. Afterward, several researchers have evaluated the potential use of allelopathic crop residues as surface-applied or soil-incorporated mulches for weed suppression in field crops [13, 58, 68]. Sorghum is the most-studied crop in this regard. For example, surface-applied sorghum mulch (10–15 t ha^{-1}) in maize at sowing provided weed control of about 26–37% [69], whereas in cotton, surface-applied sorghum mulch (3.5–10.5 t ha^{-1}) reduced the weed density by 23–65% [13]. In aerobic rice, incorporation of sorghum residue (8 t ha^{-1}) reduced the weed density and total dry biomass by 50% [70].

Purple nutsedge is one of the most noxious weeds. Allelopathic mulching has also been very effective in managing this cumbersome weed. For instance, surface-applied and soil-incorporated sorghum mulch (15 t ha^{-1}) reduced the purple nutsedge density by 40–45% [71]. In another study, Ahmad et al. reported that sorghum residues suppressed the broad-leaved dock, littleseed canarygrass, field bind weed, common lambsquarters, purple nutsedge, and scarlet pimpernel (*Anagallis arvensis* L.) [72].

Other than sorghum, several other allelopathic mulches also provide a good weed control. For example, sunflower mulching suppressed the germination and seedling growth of several weeds [73]. Likewise, application of rye mulch and its root residues controlled redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters, and common ragweed (*Ambrosia artemisiifolia* L.) by 90% in tobacco, sunflower, and soybean in no-tilled system [74]. Mulching of subterranean clover (*Trifolium subterraneum* L.) and rye suppressed different weeds in tobacco, sorghum, sunflower, maize, and soybean [75]. Likewise, application of rice mulch provided a good control of several weeds in wheat [76].

Use of wheat residues as surface mulch suppressed the density and dry weight of several weeds in maize–legume intercropping [64]. Likewise, soil incorporation of wheat straw suppressed the horse purslane (*Trianthema portulacastrum* L.) growth [77]. Soil incorporation of mint marigold (*Tagetes minuta* L.) suppressed purple nutsedge and barnyard grass (*Echinochloa crus-galli* [L.] P. Beauv.), the two most problematic weeds of rice [78], whereas application of root and leaf powder of Malabar catmint (*Anisomeles indica* L.) mulch reduced the density and dry mass of littleseed canarygrass in wheat field [79].

Combined application of more than one allelopathic mulch has been found more effective in weed management than their sole application. For instance, mulching residues of *Brassica,* sunflower, and sorghum suppressed the horse purslane and purple nutsedge; nonetheless, combined application of these residues provided better weed control than sole application of these crop residues [14, 80]. Sunflower mulch applied on soil surface alone or in mixture with legume and buckwheat suppressed weeds; however, the mixed application was more effective in this regard [81]. In another study on wheat, surface application of sorghum, sunflower, or *Brassica* substantially suppressed weeds; however, combined application was more effective [53]. Thus, allelopathic crop mulches, either surface applied or soil incorporated, can be used to control various weed biotypes in different agro-ecological regions of the world.

Use of Cover Crops

Cover crops are widely used for weed management in field crops [82, 83]. Cover crop suppresses weeds by covering the soil surface [84] through competition, release of allelochemicals, stimulation of microbial allelochemicals, shading effect, and through alteration in soil physicochemical properties [85], or weed germination inhibition through physical barriers [86–88]. Most of the crops used as cover crops—including cowpea, sunhemp (*Crotalaria juncea* L.), alfalfa, yellow sweet clover (*Melilotus officinalis* [L.] Pall.), ryegrass, and velvet bean (*Mucuna pruriens* [L.] DC.)—belong to the legume family [89]. Use of leguminous crops as cover crop substantially decreased the population of barnyard grass [90], while use of barley as cover crop suppressed many weed species in soybean [91].

Rye and oat are also considered as potential cover crops. For instance, rye residues reduced the emergence of common ragweed, green foxtail (*Setaria viridis* [L.] P. Beauv.), redroot pigweed, and common purslane (*Portulaca oleracea* L.) by 43, 80, 95, and 100%, respectively [92]. Barnes et al. reported 90% reduction in weed biomass in a cover crop of rye compared to unplanted controls [93]. Similarly, different oat cultivars reduced the germination of common lambsquarters from 10 to 86% [94]. Rye as cover crop inhibited the seedling emergence of yellow foxtail (*Setaria glauca* [L.] Beauv.) [95]. Hoffman et al. reported that due to increase in the density of rye plantation, leaf number, growth, and dry matter production of barnyard grass seedlings were suppressed owing to allelopathy other than weed–crop competition [96].

Sudex hybrid (sorghum × Sudan grass) is often used as summer cover crop due to its rapid growth habit and strong ability to suppress different weed species [97]. Red spiderlily (*Lycoris radiata* [L'Hér.] Herb.) can also be used as ground cover crop to suppress weeds because its dead leaves contain lycorine, an allelochemical with strong suppressive ability against several rice weeds [98]. In Mexico, morning glory (*I. tricolor* Cav.) is used as an important summer cover crop for controlling weeds in sugarcane fields during fallow periods. Peters and Zam opined that tall fescue (*Festuca arundinacea* Schreb.) can be grown as a cover crop for controlling large crabgrass (*Digitaria sanguinalis* [L.] Scop.) weed in multiple crops [99]. In crux, inclusion of cover crops, especially leguminous crops in different cropping systems, can be useful to manage different weed genotypes, depending upon the socioeconomic conditions of the farmers.

Use of Allelopathic Water Extracts

Benefits of using crop allelopathic water extracts have been explored in several studies for their good efficacy to control several weed types. These water-soluble allelochemicals are extracted in water and then are utilized for managing weeds [100]. Application of sorghum water extract (*Sorgaab*) has been very effective in suppressing weeds [19, 101–104]. For instance, *Sorgaab* application suppressed common lambsquarters, broad-leaved dock, swine cress, Indian fumitory (*Fumaria parviflora* Lam.) [101], wild oat, field bindweed, and littleseed canarygrass [103, 104] in wheat. Other than wheat, *Sorgaab* application also suppressed the weeds in rice [105], cotton [106], canola [15, 107], mungbean [102], sunflower [108], soybean [109], and maize [69, 110].

In soybean, *Sorgaab* application at 25 and 50 days after sowing (DAS) reduced the total weed dry weight by 20–42% [109], whereas in maize, *Sorgaab* application reduced the total weed density and total weed dry weight by 34–57 and 13–34%, respectively [110]. In sunflower, *Sorgaab* application 20 DAS decreased the density of purple nutsedge and horse purslane by 10–21% and dry weight of weeds by 18–29%, respectively with yield increase of 25% [108].

Combined application of allelopathic water extracts may be a better option to control weeds than the individual application of these extracts. For example, combined application of sunflower, sorghum, and eucalyptus (*Eucalyptus camaldulensis* Dehnh.) water extracts was more effective for weed suppression in wheat than their sole application [111]. In another study in wheat, mixed application of *Sorgaab* and sunflower water extract was more effective in suppressing the littleseed canarygrass and wild oat than the individual extracts [26]. Mixed application of *Sorgaab* and sunflower and *Brassica* water extracts reduced the total weed dry weight by 55% in wheat [53].

Although complete weed control has not been achieved by the application of allelopathic water extract, there exists a great scope for its use in organic agriculture.

Combined Application of Allelopathic Water Extracts with Reduced Doses of Herbicides

Though weed management through the use of allelopathic water extracts is economical as well as environmentally friendly, the decrease in weed biomass is less than the target. Nonetheless, these allelopathic water extracts may be applied in combination with reduced rates of herbicides for effective weed control [11, 19].

Herbicides applied along with allelopathic compounds could have supportive action, affecting the same or different weed species. A reduced level of herbicide may be feasible to provide weed control when it operates simultaneously with allelopathic compounds [112]. Cheema et al. evaluated the combined effect of concentrated *Sorgaab* with a reduced dose of herbicide in maize crop [113]. Various doses of atrazine (50, 100, and 150 g a.i. ha^{-1}) were combined with *Sorgaab* (12 L ha^{-1}), while atrazine at 300 g a.i. ha^{-1} was sprayed as standard dose. Combined application of atrazine at 150 g a.i. ha^{-1} and *Sorgaab* at 12 L ha^{-1} was as effective as atrazine at 300 g a.i. ha^{-1} alone in controlling weeds such as horse purslane, field bindweed, and purple nutsedge. In another study, combined application of concentrated *Sorgaab* at 12 L ha^{-1} and pendimethalin at 0.5 g a.i. ha^{-1} at sowing decreased the horse purslane density and biomass by 72 and 76%, respectively. Similarly, application of *Sorgaab* at 12 L ha^{-1} + S-metolachlor at 1.0 kg a.i. ha^{-1} enhanced yield of seed cotton by 70% over control [114]. In a similar study, application of *Sorgaab* at 10 L ha^{-1} combined with reduced doses of pendimethalin reduced total weed dry weight by 53–95% [115]. Use of reduced doses of pendimethalin (413 g a.i. ha^{-1}) in combination with sorghum/sunflower water extract (15–18 L ha^{-1} each) was effective in complete suppression of common lambsquarters (Table 3.2) [116].

Iqbal et al. found that application of glyphosate (575–767 g a.i. ha^{-1}) combined with *Sorgaab* + *Brassica* water extracts (15–18 L ha^{-1} each) reduced purple nutsedge dry biomass by 89% (Table 2) [106]. Weeds were controlled successfully with the combined use of allelopathic crop water extract with reduced doses (50–67%) of herbicide in canola crop (Table 3.2) [15, 107]. Similarly, use of reduced doses of S-metolachlor (715–1,075 g a.i. ha^{-1}) combined with sorghum water extract (12–15 L ha^{-1}) reduced purple nutsedge dry biomass by 81% in cotton [16]. Combined application of various crop water extracts and herbicides reduced the dry biomass of many weed species in wheat [17, 117], rice [118, 119], and maize [120, 121].

In another study on mungbean, combined application of S-metolachlor (preemergence) at 1.15 kg a.i. ha^{-1} or pendimethalin at 165 g a.i. ha^{-1} and *Sorgaab* (conc.) at 10 L ha^{1} reduced weed dry weight compared with the control [122]. Cheema et al. reported that combined application of one-third dose of S-metolachlor at 667 g a.i. ha^{-1} or pendimethalin at 333 g a.i. ha^{-1} with concentrated *Sorgaab* at 10 L ha^{-1} provided as good weed control as was achieved by a full dose of these herbicides, that is, S-metolachlor at 2 kg a.i. ha^{-1} and pendimethalin at 1 kg a.i. ha^{-1} [115]. Cheema et al. indicated that *Sorgaab* combined with a lower dose of MCPA (2-methyl-4-chlorophenoxyacetic acid) at 150 g a.i. ha^{-1} and fenoxaprop-p-ethyl at 375 g a.i. ha^{-1} provided effective weed control in wheat crop [123]. Moreover, *Sorgaab* at 12 L ha^{-1} + isoproturon at 500 g a.i. ha^{-1} produced almost equal wheat grain yield as was obtained with a full dose of isoproturon (1,000 g a.i. ha^{-1}), which clearly revealed that the isoproturon dose can be reduced by 50% in combination with *Sorgaab* at 12 L ha^{-1}. Additionally, combined application of *Sorgaab* with a reduced dose of herbicide controlled weeds by 85% than control (Table 3.2) [124].

In conclusion, combined application of allelopathic water extracts with reduced doses of herbicides can control weeds as efficiently as standard dosing of a sole herbicide, thus reducing production costs and protecting the environment.

Improving the Allelopathic Potential of Crops

Conventional Breeding

Interest is increasing among researchers to breed crop cultivars with high weed-suppressive ability because of the development of resistance against herbicides in major weed flora as well as environmental concerns related to herbicide usage [125]. In the current scenario, it is of utmost importance to breed smothering crops with the ability of efficient weed suppression, thus lowering reliance upon herbicide usage. Crop cultivars suppressing weed communities can be used as an alternative to herbicides, often herbicide performance being superior when competitive cultivars are used [126]. Different crop species vary for their capabilities to suppress weeds [127]. Even variability in the genotypes of the same species to suppress weeds has been observed in rice [128], oat [129], *Brassica* [130], and pearl millet [131].

Laboratory and greenhouse bioassays controlling for genotypic variation in competition for light, water, and nutrients should be considered as an initial screening

Table 3.2 Effect of allelopathic water extracts applied in combination with reduced doses of herbicides on weed control

Crop	Allelopathic extracts + herbicides	Percent decrease over control	Weeds suppressed	Reference
Wheat (*Triticum aestivum* L.)	Isoproturon (400–500 g a.i. ha^{-1}) + *Sorgaab* (12 L ha^{-1})	85.5	Littleseed canarygrass (*Phalaris minor* Retz.), yellow sweet clover (*Melilotus parviflora* (L.) Pall.), swine cress (*Cronopus didymus* (L.) Sm.)	Cheema et al. [124]
Canola (*Brassica napus* L.)	Pendimethalin (400–600 g a.i. ha^{-1}) + Sorghum/*Brassica*/ Rice water extracts (15 L ha^{-1})	70.76	Purple nutsedge (*Cyperus rotundus* L.), horse purslane (*Trianthema portulacastrum* L.), common lambsquarters (*Chenopodium album* L.), swine cress (*Cronopus didymus* (L.) Sm.)	Jabran et al. [15]
Cotton (*Gossypium hirsutum* L.)	S-metolachlor (715–1,075 g a.i. ha^{-1}) + Sorghum water extract (12–15 L ha^{-1})	81.25	Purple nutsedge (*Cyperus rotundus* L.)	Iqbal and Cheema [16]
Sunflower (*Helianthus annuus* L.)	Pendimethalin (413 mL a.i. ha^{-1}) + Sorghum/Sunflower (15–18 L ha^{-1} each)	72	Common lambsquarters (*Chenopodium album* L.), sweet clover (*Melitotus indica* (L.) Pall.)	Awan et al. [116]
Cotton (*Gossypium hirsutum* L.)	Glyphosate (575–767 g a.i. ha^{-1}) + *Sorgaab* + *Brassica* water extract (15–18 L ha^{-1} each)	89.38	Purple nutsedge (*Cyperus rotundus* L.)	Iqbal et al. [106]
Wheat (*Triticum aestivum* L.)	Metribuzin (52.5 g a.i. ha^{-1})/ Isoproturon (315 g a.i. ha^{-1})/ Fenoxaprop (57 g a.i. ha^{-1})/ Idosulfuron (36 g a.i. ha^{-1})/ Idosulfuron (4.32 g a.i. ha^{-1}) + Sorghum/Sunflower water extract (18 L ha^{-1} each)	86.02	Swine cress (*Coronopus didymus* (L.) Sm.), littleseed canarygrass (*Phalaris minor* Retz.)	Razzaq et al. [17]

Table 3.2 (continued)

Crop	Allelopathic extracts + herbicides	Percent decrease over control	Weeds suppressed	Reference
Rice (*Oryza sativa* L.)	Butachlor (1,200 g a.i. ha^{-1})/Pretilachlor (625 g a.i. ha^{-1})/Ethoxysulfuronethyl (30 g a.i. ha^{-1}) + Sorghum/Sunflower/Rice water extract (15 L ha^{-1})	53.67	Barnyardgrass (*Echinochloa crus-galli* (L.) P.Beauv., rice flatsedge (*Cyperus iria* L.), crowfootgrass (*Dactyloctenium aegyptium* (L.) Willd.)	Rehman et al. [118]
Rice (*Oryza sativa* L.)	Ryzelan (15 mL ha^{-1}) + Sorghum water extract (7.5 L ha^{-1})	34.76	Barnyardgrass (*Echinocloa crus-galli* (L.) P.Beauv.), rice flatsedge (*Cyperus iria* L.), junglerice (*Echinochloa colona* (L.) Link., purple nutsedge (*Cyperus rotundus* L.), crowfootgrass (*Dactyloctenium aegyptium* (L.) Willd.	Wazir et al. [119]
Maize (*Zea mays* L.)	Furamsulfuron (half dose) + *Sorgaab*	57.33	Field bindweed (*Convolvulus arvensis* L.), redroot pigweed (*Amaranthus retroflexus* L.)	Latifi1 and Jamshidi [120]
Wheat (*Triticum aestivum* L.)	Sorghum + sunflower water extract (18 L ha^{-1} each) + Metribuzin (52.5 g a.i./ha)/Bensulfuron + isoproturon (315 g a.s./ha)/Metribuzin + phenoxaprop (57 g a.i./ha)/Mesosulfuron + idosulfuron (36 g a.i./ha)/Mesosulfuron + idosulfuron (4.32 g a.i./ha)	88.24	Swine cress (*Coronopus didymus* L.), littleseed canarygrass (*Phalaris minor* Retz.)	Razzaq et al. [117]
Maize (*Zea mays* L.)	Atrazine (125–250 g a.i. ha^{-1}) + Sorghum + Brassica + Sunflower + Mulberry water extracts (20 L ha^{-1} each)	74.67	Horse purslane (*Trianthema portulacastrum* L.)	Khan et al. [121]

tool for allelopathic research because some lines do not possess high competitiveness but have more allelopathic activity. Variability in traits in major crop genotypes can be used to breed cultivars that possess greater ability to suppress weeds [132, 133]. For example, Haan et al. bred a smother plant by crossing dwarf *B. campestris* with *B. campestris,* and when this plant was intercropped with maize and soybean, it suppressed the weeds for 4–6 weeks without influencing the performance of maize and soybean [134]. In another study, hybrid rice was produced by backcrossing and selfing of two lines, that is, Kouketsumochi (with allelopathic gene) and IR24 (with restoring gene). The specific hybrid rice produced by this method suppressed barnyard grass more effectively [135]. Selection of "STG06L-35-061" developed from crosses between indica (cv. Katy) and commercial tropical japonica (cv. Drew) suppressed the rice weeds, such as barnyard grass, more efficiently [136].

Continuous breeding with barley genotypes has resulted in an increase in allelopathic activity of spring wheat [137] and decrease in barley [138]. Rondo is a line of indica rice developed by mutation breeding that has high weed-suppressive ability and is high yielding [139, 140]. Similarly, present crop cultivars are more allelopathic than older ones [141]. So breeding of old cultivars with modern cultivars is of prime importance to breed crop cultivars having high allelopathic activity.

Environmental variations and environment genotype interactions can obstruct phenotypic selection by obscuring genotypic differences in weed-suppressive ability [142]. For example, Gealy and Yan studied the suppressive ability of different rice genotypes against barnyard grass [140]. Some rice genotypes suppressed barnyard grass 1.3–1.5 times greater than long-grain rice cultivars, but genotypic differences were nonsignificant. These nonsignificant differences among genotypes may be due to environmental variation. Varietal potentials for weed suppression are mostly unpredictable across different study locations [143] and growing seasons [144], indicating strong genotype by environment interactions. Therefore, screening of genotypes for their relative competiveness or allelopathic potential must be carried out in different environments, locations, and years.

Use of Biotechnology

Although less attention has been given to the biotechnological aspect of allelopathy than others, during the last decade, the role of biotechnology in allelopathy has received much attention. Wu et al. tested 453 winter wheat accessions and found a normal distribution of allelopathic activity, indicating a quantitative mode of inheritance [145]. When lines having strong allelopathy activity were crossed with the lines having low allelopathic activity, the allelopathic activity was normally distributed in resulting progenies in rice [146–148] and wheat [149, 150].

Different crop species possess different allelochemicals and each allelochemical suppresses special weed biotype. For example, scopoletin suppresses wild mustard (*B. kaber* [DC] L.; Table 3.3) [129] and hydroxamates suppress wild oat (*Avena fatua* L.; Table 3.3) [151]. Similarly, DIMBOA (2,4-dihydroxy-7-methoxy-1,4-

Table 3.3 Weed-suppressing ability of some allelochemicals

Allelochemicals	Weeds suppressed	Reference
Scopoletin	Wild mustard (*Sinapis arvensis* L. (*Brassica kaber* [DC.]) wheeler var. pinnatifida lStokes] wheeler	Fay and Duke [129]
Hydroxamates	Wild oat (*Avena fatua* L.)	Pérez and Ormemeño-Núñez [151]
DIMBOA	Foxtail amaranth (*Amaranthus caudatus* L.), garden cress (*Lepidium sativum* L.)	Pethó [153]
Gramine/Hordenine	Shepherd's purse (*Capsella bursa-pastoris* (L.) Medik.), white mustard (*Sinapis alba* L.), common chickweed (*Stellaria media* (L.) Vill.)	Overland [152], Liu and Lovett [154]
Hydroxamic acids	Wild oat (*Avena fatua* L.), henbit deadnettle (*Lamium amplexicaule* L.), common lambsquarter (*Chenopodium album* L.), knotgrass (*Polygonum aviculare* L.), black bindweed (*Fallopia convolvulus* (L.) Á. Löve)	Pérez and Ormemeño-Núñez [151], Friebe et al. [155]

benzoxazin-3-one), gramine/hordenine, and hydroxamic acids suppressed various weed biotypes in several studies (Table 3.3) [151–155].

There is a need to identify the genes controlling production of these allelochemicals so that gene expression for production of these allelochemicals may be improved/enhanced, resulting in increased quantity of these allelochemicals production. Some work has been done to map the allelopathic genes found in wheat [149, 156]. Hydroxamic acids are the important allelochemicals found in wheat. Niemeyer and Jerez mapped the position of genes responsible for hydroxamic acid production [156]. The quantitative trait loci (QTLs) responsible for accumulation of hydroxamic acid were identified on chromosomes 4A, 4B, 4D, and 5B. In another study, Wu et al. mapped allelopathic QTLs in a double haploid population, which was obtained from the cross of two cultivars, one being strongly allelopathic and other being less allelopathic [149]. For mapping these QTLs, they used amplified fragment length polymorphism (AFLP), restriction fragment length polymorphism (RFLP), and simple sequence repeat markers (SSRM). Scientists have found two major allelopathic QTLs on wheat chromosome 2B, based on the 189 DH lines and two parents [149].

Extensive work has been carried out for mapping allelopathic QTLs in rice. Ebana et al. mapped seven allelopathic QTLs in rice on chromosomes 1, 3, 5, 6, 7, 11, and 12 by using RFLP markers in an F2 population, which was obtained from the cross of high allelopathic genotype with low allelopathic genotype [157]. Jensen et al. identified four main-effect QTLs on chromosomes 2, 3, and 8, and these QTLs explained the 35% of the total phenotypic variation in the population of rice [158]. In another study, Jensen et al. identified 15 QTLs in a rice population, each explaining 5–11% of phenotypic variation [146]. These QTLs were identified on chromosomes 3, 4, 6, 8, 9, 10, and 12. In a similar study, Zhou et al. identified three main-effect QTLs on chromosomes 5 and 11, which collectively explained phenotypic variation up to 13.6% [147]. These QTLs were identified from different recombinant inbred lines, which were obtained from the cross of two Chinese rice cultivars, one being strongly allelopathic and other being weakly allelopathic. In short, allelopathic QTLs have been identified in multiple rice genomes but still no QTL has been identified for chromosome 2. Discovery of additional fine-resolution QTLs controlling allelopathy in rice and wheat will hopefully result in the development of effective molecular markers that can be used in marker-assisted selection for cultivars with improved allelopathic activity. Marker-assisted selection may be hindered because of the large number of minor-effect QTLs that appear to control allelopathy in various genotypes. Marker-assisted backcrossing can be used as a successful tool for breeding genotypes with high allelopathic activity if major QTLs controlling allelopathy are less than five [141].

Some researchers also suggested transgenic approaches as successful tools to enhance crop allelopathy [159]. However, before moving towards transgenic approaches, it is necessary to have a clear understanding of the genes responsible for the biosynthesis and regulation of allelochemicals and their synthesis pathway. Although QTL mapping facilitates marker-assisted selection, it seldom tells about the gene responsible for allelochemical production. Several candidate genes may be located in an individual QTL spanning 5–10 cM (centimorgans) [160] and knowledge about individual genes is necessary. Genes responsible for regulation and biosynthesis of allelochemicals can be identified through isolation, discovery [161], activation tagging [162], purification of plant enzymes, purification of related bioactive metabolites [161], and through gene knockout libraries [163]. Particular genes responsible for the biosynthesis and regulation of allelochemicals, such as momilactones [164, 165], phenolic compounds [166], and benzoxazinoids [167], have been reported. Antisense knockout techniques and overexpression of genes can be used to change the quantity and quality of secondary metabolites of allelopathic plants. Fortunately, transgenic approaches can be utilized to introduce genes from high allopathic genotypes to low or non-allelopathic genotypes, but the goal is not easy to attain due to complex genetics of allelopathy. According to Bertin et al. expression of multiple genes into crop species and its regulation should be optimized in such a way that the transformed crop will be able to produce the desired allelochemicals successfully [160].

Conclusion

Allelopathy can be used as an environmentally friendly tool to manage weeds in modern agriculture for improving crop yields without reliance on synthetic herbicides, which are posing a severe threat to our environment and human health. Allelopathic strategies, such as intercropping, crop rotation, mulching, use of allelopathic crop water extracts alone or in combination with reduced doses of herbicides, and incorporation of cover crops in cropping systems, may be used as successful tools to manage different weed ecotypes. Conventional breeding of cultivars having more allelopathic activity with cultivars having low allelopathic activity may also be useful to enhance the allelopathic activity of existing crop cultivars. Moreover, Modern biotechnological approaches should be used to identify genes responsible for allelochemical production, and then these genes should be introduced to improve the allelopathic potential of cultivars that are less allelopathic.

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