



Importance of allelopathy in agriculture: Bioavailability and functions of allelochemicals in soil environment

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ABSTRACT

Weed invasion and subsequent infestation represents a major problem in crop production. Chemical weed control is the major management tactic used in conventional agriculture. Complementary strategies to herbicides are increasingly being investigated. The importance of allelopathy has been considered for weed management over the years. However, the relevance of allelopathy has been highly discussed due to the lack of phytotoxic concentrations of allelochemicals under field conditions. *Avena fatua*, *Brassica nigra*, *Fagopyrum esculentum*, *Secale cereale*, *Sorghum bicolor*, *Triticum aestivum* and other cover crops have been used in weed management on a limited basis. Crop residues from existing crop or rotational crops can provide selective weed suppression through their physical presence on the soil surface and/or through the release of allelochemicals. Some of the allelochemicals have been reported to play a role in weed management, including phenolic acids, DIBOA, DIBOA-glycoside, and BOA, dhurrin, fatty acids, hydroxamic acids, isoflavonoids, isothiocyanate, juglone, momilactone, scopoletin, and sorgoleone. The soil system, a living and dynamic, influences the fate and functions of allelochemicals in time and space. The bioavailability of allelochemicals in the soil is dependent on processes such as adsorption, leaching and degradations by abiotic and biotic factors. The clay types, organic matter, and soil pH can affect the bioavailability of allelochemicals in the soil. Thus, the allelopathic potential of many compounds may not be expressed in some soils because of the chemical adsorption to soil colloids. The resulting concentrations (sub-toxic) of any of these allelochemicals in soil matrix may have a variety of functions that influence seed germination, seedling emergence, plant growth suppression, nutrient acquisition or soil microbial activity. Examples of such compounds are benzoic acid, catechin, coumaric acid, dihydroxyphenylalanine, ferulic acid, hydroxybenzoic acid, sorgoleone, vanillic acid, and others.

In my view, future allelopathic research should be focused on mechanisms facilitating persistence of allelochemicals in soil environment and characterization of complementary roles of these compounds in plant growth and development. The bioavailability of allelochemicals under field conditions must be established for its effective role in weed management. Currently, we face challenges and opportunities in using allelopathy as a part of weed management strategies in today's production agriculture.

INTRODUCTION

An Austrian plant physiologist, Hans Molisch coined term allelopathy in 1937. Later, allelopathy was defined as the effect(s) of one plant (including microorganisms) on another plant through the release of a chemical compound(s) into the environment (Rice 1984). This definition includes both inhibitory and stimulatory effects, depending on the

concentration of the compound(s). However, inhibitory effects of plants or crop residues are of great importance in relation to weed management. Allelopathic research through the last several decades has demonstrated many aspects of allelopathy, including the applied nature of allelopathy in weed management. To demonstrate allelopathy, one must identify one or more phytotoxins produced by the

putative allelopathic plant or identify a compound(s) produced by the donor plant that is converted to a phytotoxin in the soil complex. The compound(s) must be present in sufficient quantity (in time and space) in the soil for allelopathic effects in controlling weeds. Allelochemicals are generally weak phytotoxins. Most of the allelochemicals are present at low concentrations, and undergo rapid chemical and biological degradation in the soil. The focus of this presentation is to discuss (i) the importance of cover crops residues in weed management, (ii) the nature of allelochemicals, and (iii) the role of soil factors in allelopathic activity, and iv) challenges in implementing allelopathy in weed management.

Cover crops residues

Cover crop residues such as *Avena fatua*, *Brassica nigra*, *Fagopyrum esculentum*, *Secale cereale*, *Sorghum bicolor*, *Triticum aestivum*, *Vicia villosa* and others have been used in weed management on a limited basis. Crop residues from existing crop or rotational crops can provide selective weed control through their physical presence on the soil surface and through the release of allelochemicals (Fay and Duke 1977, Bhowmik and Doll 1982, Alsaadawi *et al.* 1986, Teasdale 1993, Weston 1996, Barker and Bhowmik 2001, Jabran *et al.* 2015). The allelochemicals are concentrated and exuded through roots or are released during decomposition of plant litter (Siqueira *et al.* 1919, Bonanomi *et al.* 2006).

Earlier reports have shown that weed control could be achieved by growing cover crop of rye, barley, wheat or sorghum to a height of 40–50 cm, then desiccating the crop by either contact herbicides or winter freezing, and allowing their residues to remain on the soil surface (Putnam *et al.* 1983, Barker and Bhowmik, 2001). Barnes and Putnam (1983) reported that *Secale cereale* residue used as mulch reduced total weed biomass by 63%. It was found that disappearance of rye allelochemicals was more closely related to weed suppression than to the disappearance of rye residues. Duration of cover crops residue on the soil surface often determines the extent of an effective weed control period. Yenish *et al.* (1995) studied the disappearance of *Secale cereale* residue and allelochemicals, DIBOA (2,4-dihydroxy-1,4-benzoxazin-3-one), DIBOA-glycoside and BOA from *Secale cereale* residues. These authors found that 50% of the initial content of *Secale cereale* residue disappeared by 105 days after clipping. However, the combined active compound concentrations of DIBOA-glycoside, DIBOA, and BOA disappeared 168 days after clipping.

Allelopathy can play a beneficial role in various cropping systems (Haramoto and Gallandt 2005, Macias *et al.* 2014, Jabran *et al.* 2015). In a 5-yr field study with *Helianthus annuus* and *Avena fatua* rotation, the weed density increase was significantly less in sunflower plots than in control plots (Leather, 1983). It was found that sunflower plants possess chemicals, which inhibit the growth of common weed species.

Allelochemicals for weed management

Thousands of allelopathic substances have been isolated from plants and their chemical structure has been determined. However, the mode-of-action (MOA) has only been elucidated for a limited number of allelochemicals (Vyvyan 2002). Some of the allelochemicals such as allyl isothiocyanate (*Brassica* sp., black mustard), fatty acids (*Polygonum spp.*), isoflavonoids and phenolics (*Trifolium spp.*, *Melilotus spp.*), phenolic acids and scopoletin (*Avena sativa*), hydroxamic acids (*Triticum* sp.), phenolic acids, dhurrin, and sorgoleone (*Sorghum bicolor*) have been reported for weed control (Duke *et al.* 2002). Artemisinin, a sesquiterpenoid lactone, has been shown to inhibit the growth of *Amarantus retroflexus*, *Ipomoea lacunosa*, *Artemisia annua* and *Portulaca oleracea* (Duke *et al.* 1987). The phytotoxic activity of sorgoleone against weed species was first reported by Einhellig and Souza (1992). Mushtaq and Siddiqui (2010) reported that plants belonging to Asteraceae family are the most studied species for allelopathic potential to control weeds in India. Some of the species including *Parthenium hysterophorus*, *Ageratum conyzoides* and others received more attention.

Allelopathic activity in soil environment

The soil system, a living and dynamic, influences the fate and functions of allelochemicals in time and space. The bioavailability of allelochemicals in the soil is dependent on processes such as adsorption, leaching and degradations by abiotic and biotic factors. The clay types, organic matter, and soil pH can affect the bioavailability of allelochemicals in the soil. An excellent review in this area has been published by Kobayashi (2004).

The allelopathic activity of many compounds is not expressed in some soils because of the chemical adsorption to soil colloids. For instance, sorgoleone binds strongly to soil colloids because it is a highly lipophilic allelochemical, with a logP (log octanol-water partition coefficient) of 6.1 (Trezzi *et al.* 2016). The allelopathic compounds 1-3,4dihydrox

phenylalanine and catechin are also strongly adsorbed by soil colloids, possibly due to the catechol group present in these molecules (Furubayashi *et al.* 2007). Reduced allelopathic potential of benzoxazinoid compounds 2-aminophenoxazin-3-one and DIBOA (2,4-dihydroxy-(2H)-1,4-benzoxazin-3(4H)-one) have been reported due to their adsorption by soil colloids (Teasdale *et al.* 2012). The chemical compounds that are not adsorbed onto colloids or minerals are usually in the soil solution. Thus, they can be absorbed by plants or leached (Kobayashi 2004, Kong *et al.* 2007, Li *et al.* 2013). Kong *et al.* (2007) reported that flavonoids with a high mobility in the soil profile were less phytotoxic than those with reduced soil mobility with rice plants. Similarly, an analysis of ten potential allelochemicals revealed an inverse relationship between soil mobility and their toxic effect on target plants (Li *et al.* 2013).

Preferential absorption allelochemicals in soil

Use of allelopathy is gaining its application in current agricultural science. However, the role of sorption to soil in modifying the bioavailability of components in complex allelochemical mixtures is still not well understood. Soils are capable of altering the phytotoxicity of plant secondary metabolites by changing their bioavailability, persistence, and fate under field conditions. Sorption is one of the prominent factors affecting the phytoavailability of allelochemicals in soil.

In one of our studies, the role of preferential sorption to soil in altering the chemical composition of plant exudates was studied in a silt loam soil using representative mixtures of plant phenolic acids, namely, hydroxybenzoic acid, vanillic acid, coumaric acid, and ferulic acid Tharayil *et al.* (2006). Removal of organic matter substantially decreased the sorption affinity of all phenolic acids. Direct competition for sorption sites was observed even at low concentrations of phenolic acids. The K_d value of hydroxybenzoic acid was decreased more than 90% in the presence of coumaric acid. About 95% of sorbed vanillic acid was displaced into the soil solution in the presence of ferulic acid. Hydroxybenzoic acid did not affect the sorption affinity of other phenolic acids significantly, whereas ferulic acid showed low displacement by other phenolic acids. The displacement pattern indicated directional sorption of phenolic acids with -OH and -COOH groups. Soil organic matter was associated with preferential sorption. The preferential sorption to soil can alter the availability of plant exudates in mixtures and thus may mediate their phytotoxic effects (Tharayil *et al.* 2006).

Soil sorption can also protect compounds from microbial degradation and thus indirectly alter their phytotoxic effects (Dalton, 1989, Wauchope *et al.* 2002). The soil sorption properties of some individual allelochemicals have previously been studied. Various soil components such as organic matter, sesquioxides, and clay minerals have been found to affect the phytoavailable concentration of allelochemicals (Dalton *et al.* 1989, Ohno, 2001, Wang *et al.* 1978). Considering the fact that compounds in the soil solution are more phytoavailable than those sorbed to the soil matrix (Lehman and Blum, 1999, Ito *et al.* 1998), the varied sorption affinity of compounds in a mixture will change the composition of plant exudates that become bioavailable. Different compounds in plant exudates differ widely in their phytotoxicity (Wu *et al.* 2002, Uren, 2001) and therefore preferential sorption to soil could in turn alter the phytotoxicity of these exudates.

Microbial degradation in soil

Biotic processes are involved in determining the fate of allelopathic compounds in soil. Microorganisms produce enzymes which catalyze the oxidation and polymerization reactions of phenolic acids (Huang *et al.* 1999, Lou *et al.* 2016). Microbial activity will alter phenolic compounds in soil and subsequently alter the expressed level of phytotoxicity (Blum 1998).

Phenolic acids are readily converted from one structure to another with different phytotoxicities (e.g., ferulic acid to vanillic acid) by soil-borne microbes (Blum 1998). Schmidt and Ley (1999) suggested that carbon-limited soil organisms would rapidly mineralize phenolic compounds due to their higher energy content on a per weight basis than simple sugars. Zikmundová *et al.* (2002) studied the biotransformation of the phytoanticipins BOA and HBOA by four endophytic fungi isolated from *Aphelandra tetragona*. It was shown that the metabolic pathway for HBOA and BOA degradation leads to o-aminophenol as a key intermediate.

Microorganisms play important roles in releasing additional allelochemicals bound up in the recalcitrant fractions of cover crop residues (Barnes *et al.* 1987). These insoluble allelochemicals can constitute a significant fraction of total allelopathic potential of a cover crop residue (Harper and Lynch 1982), so microbes may slowly release residue-derived allelochemicals, extending the longevity of a cover crop's effectiveness. Microbes can deactivate water soluble allelochemicals released soon after

cover crop residue incorporation (Jilani *et al.* 2008). As agricultural soils are not sterile, it is important to understand how microbial activity moderates allelopathic potential of cover crop residues (Blum 1998, Inderjit 2005). Mohler *et al.* (2012) recently showed that unsterilized live soil (*i.e.*, with a natural microbial community) reduces seedling germination rates when cover crop residues are incorporated, and the combined effect of residues and live microorganisms is greater than the effect of either of these components alone.

The degradation of allelochemicals in the soil may be altered, reducing their efficacy. In non-sterilized soil, for instance, DIBOA showed a half-life of 43h. However, 2-aminophenoxazin-3-one (APO), the final degradation product of DIBOA, has a low mineralization rate and therefore, a half-life greater than 90 days (Macías *et al.* 2005). In addition, some flavonoid glycoside molecules exuded by rice plants can suffer high mineralization by soil microorganisms, resulting in a glycosylated compounds. Flavonoid glycosides and a glycoside have a half-life of 2 h and 30 h, respectively, suggesting a higher allelopathic activity for the second group (Kong *et al.* 2007). The biodegradation of the sorgoleone quinone ring is relatively slow, with only 21% being mineralized 77 d after incubation in soil. However, the sorgoleone methoxy group was biodegraded within a few days, particularly in soils with a low colloid content (Gimsing *et al.* 2009).

Bioavailability of allelochemicals

Soils may also influence the relative activity of allelochemicals in combination(s). Because allelochemicals are generally exuded in mixtures of metabolites that often include other allelochemicals (Wu *et al.* 1999, Uren *et al.* 2001), preferential sorption of compounds onto the soil matrix could further alter availability.

The persistence of allelochemical mixtures may be enhanced in soil environment. In one of our studies, we found that one compound in combination can make the bioavailability and half-life of others greater in soil, because of competitive sorption and preferential degradation. Allelochemicals may also help plants to acquire nutrients in infertile soils which give competitive advantage to the donor plant over its neighbors.

The interaction of allelochemicals in the soil matrix remains as one of the least understood areas in the research on allelopathy (Tharayil *et al.* 2006). Most of the allelopathic interactions take place in the soil, where allelochemicals are concentrated and

exuded through roots (Bias *et al.* 2003) or are released during decomposition of plant litter (Bonanomi *et al.* 2006, Siqueira *et al.*, 1991). Thus, soil matrix forms the primary medium for the transport of allelochemicals from a donor to a receiver plant. During this transportation, the soil matrix is capable of altering the bioavailability of allelochemicals by various processes including sorption and chemical and microbial degradation (Tharayil *et al.* 2006, Ohno 2001). Because allelochemicals are secreted in quantities far less than needed to overwhelm the soil processes, at the field level, the soil matrix becomes the governing factor in the allelopathic activity. Thus, in many cases allelochemicals are not found in phytotoxic quantities under field conditions (Perry *et al.* 2007, Blum 1992).

A less attention has been made in the fact that the allelochemicals may be released as mixtures with other compounds (Wu *et al.* 2002). The degradation pattern of individual allelochemicals in soil matrices has been studied before (Dalton 1989, Ohno 2001). The disappearance of allelochemicals was delayed when present in a multi-solute mixture from both soils. This slow disappearance of allelochemicals in a mixture could be due to the combined effect of preferential degradation, where compounds with a stable ring structure and without a 3-C (acrylic) side chain are less susceptible to degradation, and competitive sorption, where less hydrophobic molecules are displaced into soil solution (Tharayil *et al.* 2006).

Microbial degradation of substrate in soil matrix is related to biological activity of the compound, where toxic compounds are degraded slowly (Kurt-Karakus *et al.* 2007). Addition of a more soluble and energy-efficient carbon source has been shown to reduce the microbial decomposition accompanying complex substrates (Pue *et al.* 1995). Competition for sorption sites arises if the same sites can be occupied by more than one non identical molecule (Xing *et al.* 1996, Tharayil *et al.* 2006). This competition for sorption sites in a soil matrix could increase the effective concentration of phenolic acids in soil solution (Tharayil *et al.* 2006).

Litter decomposition of *Centauria maculosa* in sandy loam soil yielded five phenolic acids, namely, hydroxybenzoic, vanillic, protocatechuic, p-coumaric, and ferulic acids (Tharayil *et al.* 2008). The degradation studies were conducted by exogenous application of catechin, the primary allelochemical exuded by *C. maculosa*, and the phenolic acid co-solutes in a sandy loam and silt loam soil. Compared to a single-solute system, in a multi-

solute system the persistence of individual allelochemicals was significantly increased in both soils. Oxidation and sorption were primarily involved in the disappearance of allelochemicals. Catechin rapidly underwent polymerization to form procyanidin dimer both in soil and in bioassay medium, resulting in reduced persistence and phytotoxicity. Hence, catechin phytotoxicity could occur only under conditions that would inhibit these condensation reactions. This study clearly demonstrates that various soil mechanisms including competitive sorption and preferential degradation would increase the persistence of allelochemical mixtures in a soil matrix (Tharayil *et al.* 2008).

Allelopathic crop cultivars

Researchers have screened crop cultivars for their differential allelopathic activity for the last three decades (Gealy *et al.* 2000, Wu *et al.* 1998, Kato-Noguchi *et al.* 2010, Mahmood *et al.* 2013, Mahajan and Chauhan 2013, Masum *et al.* 2018). In general, more monocot crop species have been searched for allelopathy compared to broadleaf species. Several members of the family Poaceae have been identified as allelopathic. Significant amount of literature is available on the differential production of hydroxamic acids in cereals. The main hydroxamic acids reported from cereals are DIBOA and DIMBOA (2,4-dihydroxy-7-methoxy-1,4benzoxazin-3-one); their distribution with cultivated Poaceae, however, is uneven (Niemeyer 1988). While wheat has both DIMBOA and DIBOA, *Secale cereale* contains only DIBOA.

The allelopathic activity of *Avena* species has been established by Fay and Duke (1977). They examined 3000 accessions of the USDA world collection of *Avena sp.* germplasm for their ability to exude scopoletin. Twenty-five accessions exuded more scopoletin from their roots than a standard oat cultivar, 'Garry'. They found that four accessions exuded up to three times as much scopoletin as 'Garry' oats. One of these accessions grown in sand culture for 16 days with *Brassica caber* significantly reduced Brassica plant growth more than that obtained when the weed was grown with 'Garry' oats.

Over the last decade, *Oryza spp.* accessions or cultivars have been examined for their allelopathic activity in suppressing weed species (Dilday *et al.* 1998, Hassan *et al.* 1998, Gealy *et al.* 2000, Olofsdotter 2001, Olofsdotter *et al.* 1995). Dilday and his colleagues (1998) evaluated the phytotoxic effects of 12,000 rice accessions against *Heteranthera limosa* and 5000 against *Ammannia*

coccinea. They found that 412 rice accessions developed an allelopathic zone around rice plants for *Heteranthera limosa* and 145 for *Ammannia coccinea*. A hybrid (stg 94L42-130) between p1 338046 (allelopathic) and Katy (non-allelopathic) was reported to increase the yield by almost 2000 kg/ha compared to the yield of Katy.

Eight cultivars of *Oryza sativa* inhibited shoot and root growth of *Echinochloa crus-galli* when co-cultured with rice seedlings in a bioassay medium (Koto-Noguchi *et al.* 2010). They identified momolactone A and B in the bioassay medium of all rice cultivars. The concentrations of momolactone A and B varied from 0.21-1.5 and 0.66-3.8 $\mu\text{mol/L}$, respectively demonstrating the evidence of secretion of these two compounds from all rice cultivars into the medium.

Allelopathic activity of rice species has been reported by screening 50 rice cultivars from Bangladesh against *Echinochloa crus-galli* (barnyardgrass) and *Echinochloa colona* (jungle rice) by using Equal Compartment Agar Method (Masum *et al.* 2016). They reported 7 to 37% suppression of *Lactuca sativa*, *Lepidium sativum*, and *Raphanus sativus*. Recently, Masum and his group (2018) identified four potential allelochemicals from four indigenous rice cultivars. Aqueous methanol extracts of the Bangladesh indigenous rice (*Oryza sativa* L.ssp. *indica*) variety 'Boterswar' inhibited the germination and seedling growth of *Lepidium sativum* and *Echinochloa crus-galli* which suggested that this variety may contain phytotoxic substance(s). Four biologically active compounds, syringaldehyde (4-hydroxy-3,5-dimethoxybenzaldehyde), (-) loliolide, 3 α -hydroxy-5 α ,6 α -epoxy-7-megastigmen-9-one and 3-hydroxy- α -ionone, were isolated. The biological activity of these compounds showed that concentration > 10 μM significantly inhibited the root and shoot growth of *E. crus-galli* seedlings, and the *I50* (50% growth inhibition) values ranged from 16.03 to 27.23 μM and 23.94 to 75.49 μM for root and shoot growth, respectively (Masum *et al.* 2018).

Sorghum plants have been demonstrated for allelopathic effects on weed species (Nimbal *et al.* 1996, Czarnota *et al.* 2003, Weston *et al.* 2013). Root exudates of 100 cultivars of *Sorghum bicolor* were evaluated for their potency to affect the seed germination and growth of *Amaranthus retroflexus* (Alsaadawi *et al.* 1986). Some cultivars were more toxic than others.

Allelopathic activity of 526 accessions of *Cucumis sativus* and 12 accessions of eight related *Cucumis* species, representing 41 nations of origin,

was evaluated on *Brassica hirta* and *Panicum miliaceum* (Putnam and Duke 1974). One accession inhibited growth of test species by 87%, and 25 accessions inhibited growth by 50% or more. *Helianthus annuus* has been studied over the years for allelopathic effects (Leather 1983, Macias *et al.* 1999). Some sesquiterpene lactones with germacranolide and guaianolide skeletons and helianuol from different cultivars of *Helianthus annuus* were reported (Macias *et al.* 1999). These authors discussed their potential role as natural herbicides. *Mucuna prursens* has been reported to be a candidate to smother weed species (Fujii *et al.* 1992). They identified L-DOPA (L-3,4-dihydroxyphenylalanine) in *Mucuna prursens*.

Use of allelopathic plant extracts for weed management

Use of allelochemicals from plant extracts has been searched for weed management in agriculture. In Pakistan, for example, an aqueous extract deriving from sorghum shoots with a 10% concentration is left to ferment for several weeks and is subsequently sprayed post-emergence for weed control. This fermented water extract, known as "Sorgaab", reduced weed density and weed dry weight up to 50% in field trials, depending on the weed species (Cheema and Khaliq 2000, Cheema *et al.* 2002).

Limitations of allelopathic cover crop uses in agriculture

Using residues of cover or rotational crops for weed management in the field is challenging. There are limitations in using cover crops for various cropping systems. Delayed planting, delayed crop emergence, phytotoxic effects to major crops, and increased pest pressure are some of the limitations. In addition, cover crops are not much effective in managing perennial weed species. It is also believed that regrowth of certain perennial weeds may be favored due to far-red light environment under cover crops. *Vicia villosa* has been used as a cover crop and has been demonstrated potential use in weed management. Total weed density and biomass were lower in live *Vicia villosa* treatment compared to desiccated *Vicia villosa* plots (Teasdale and Daughtry 1993). Red (660 nm) and far-red (730 nm) light ratio of transmitted light was reduced by 70% in live *Vicia villosa* and by 17% under *Vicia villosa* desiccated by paraquat. They concluded that factors such as light, soil moisture and temperature are responsible for the weed suppression by *Vicia villosa*.

The question remains whether residues from crops or cover crops can provide successful weed management (100%) in the field. Under the best management practices, it is possible to integrate allelopathic crop residues and other chemical control strategies (such as pre- or post-emergence herbicides).

Challenges in implementing allelopathic concepts

In nature, plant products represent a vast diversity of compounds with a variety of biological activity (Duke *et al.* 2002, Bhowmik and Inderjit 2003, Weston and Duke 2003, Duke 2015). The natural products represent a diverse class of chemical compounds. These allelochemicals will have impact on different species of plants.

There are limitations for using allelochemicals for successful weed management. Some of these factors in implementing natural products for effective weed management include (i) compounds are present in very low concentration, (ii) allelochemicals have generally short half-lives, (iii) narrow spectrum weed selectivity, and (v) high cost of production.

Conclusion

Numerous examples of allelopathic effects have been established decades ago. Today, we are still looking for other allelopathic plants or weed species. We have made significant advances in this direction over the last three decades. However, we still have a long way to go in terms of using allelochemicals or developing plant cultivars that would be used for complete weed management. The environmental fate of allelochemicals is a complex issue that is affected by the donor and receiver target plant species, as well as soil and environmental variables that affect the fate of the chemicals in the soil complex. Knowledge concerning the variation in these factors is essential to use the allelopathic relationship among plants in agroecosystems to promote weed control.

In spite of many challenges in implementing the allelopathic concept in weed management, there is tremendous scope for exploring allelopathy phenomena for successful weed management. Biotechnology may eventually allow for the production of highly allelopathic crop cultivars that may effectively suppress many weeds. The bioavailability of allelochemicals under field conditions must be established for its effective role in weed management. Continued research on these areas is important and we must invest our resources in exploring allelopathy as a complimentary component in successful weed management.

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