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Weeds Cause Losses in Field Crops through Allelopathy

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Abstract

A large number of weeds are known to be associated with crops and causing economic losses. Weeds interfere with crops through competition and allelopathy. They produce secondary metabolites known as allelochemicals, which belong to numerous chemical classes such as phenolics, alkaloids, fatty acids, indoles, terpens etc. However, phenolics are the predominant class of allelochemicals. The allelochemicals release from weed plants takes place through leaf leachates, decomposition of plant residues, volatilization and root exudates. Weeds leave huge quantities of their residues in field and affect the associated, as well as succeeding crops, in various cropping systems. Liberation of allelochemicals from weeds affects the germination, stand establishment, growth, yield and physiology of crop plants. They cause substantial reduction in germination and growth of the crop plants by altering various physiological processes such as enzyme activity, protein synthesis, photosynthesis, respiration, cell division and enlargement, which ultimately leads to a significant reduction in crop yield. In crux, allelopathic weeds represent a potential threat for crop plants and cause economic losses.

Keywords: allelochemicals, crop physiology, crop yield, germination and growth, weed allelopathy, phenolics, secondary metabolites

Introduction

Weeds are associated with many crops and are a major threat to crop production in many cropping systems. Losses due to weeds have been estimated to be even more than those caused by insect pests and diseases. It has been observed that weeds may cause a reduction up to 25-30% in the yield of wheat (Chaudhary *et al*., 2008; Marwat *et al*., 2008), 35-40% reduction in rice yield (Oerke and Dehne, 2004), 35-80% reduction in maize (Dangwal *et al*., 2010) and 20-40% reduction in sugarcane yield (Ibrahim *et al*., 1984; Khan *et al*., 2004), depending upon weed density, types of weeds, duration of competition, management practices and weather conditions. Weeds cause a reduction in the growth and yield of crops by interfering with different metabolic processes (Hajizadeh and Mirshekari, 2011). The interference of weeds with crops may be the consequence of competition and/or allelopathy.

Allelopathy is regarded as any process whereby secondary metabolites produced by plants, microorganisms, viruses and fungi influence the growth and development of agricultural and biological systems, including positive and negative effects (Torres *et al*., 1996). The ability of various plant species to induce allelopathic impacts on plants in their surroundings has been documented since ancient times. The most primitive writings on allelopathy are accredited to the Theophrastus (300 BC) who detected the detrimental effect of cabbage over the growth of a vine and proposed that such effects were occurred by odours from cabbage plants (Willis, 1985). The term allelopathy was coined by a German plant physiologist named Molisch (1937), deriving from the Greek word “allelon” which means of “each other”, while “pathos” means “to suffer”. Allelochemicals are secondary metabolites which are liberated from plants and affect the germination and growth of recipient plants (Kruse *et al*., 2000; Asaduzzaman *et al*., 2010). Allelochemicals are released through volatilization, root exudation, residues decomposition and leaching from leaf litter, and they act upon by various modes of actions. Seed germination and plant growth is interrupted by the disturbance of a variety of physiological functions occurring within plant bodies. The plant functions of prime importance which are affected by allelochemicals include respiration, photosynthesis, cell division and enlargement, metabolic activities, protein synthesis and enzyme actions (Lin *et al*., 2004).

A large number of allelopathic weeds have been documented in the literature as they affect crop plants right from their emergence till maturity and cause considerable economic losses. Weeds allelopathy has been found responsible for perturbation of emergence and stand establishment, growth, yield and physiology of crop plants.

To best of our knowledge, limited review is available in specialized literature that emphasized the injurious allelopathic effects of weeds on crops. Within the present review, an attempt has been made to elucidate the weeds containing potentially active allelochemicals, weeds allelochemicals mode of release and their harmful effects on germination, stand establishment, crop growth and development, crop yield and alterations in crop physiological processes.

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Allelochemicals in weeds

A large number of allelochemicals, which affect the recipient plants in various ways, have been found and identified in weed plants. These allelochemicals have been classified into different groups depending upon their properties. Phenolics, terpenes, fatty acids and indoles are the most commonly occurring allelochemicals in plants (Noguchi, 2008). Similar to other plant species, weeds produce a large number of allelochemicals that influence the crop plants in their vicinity. *Sambucus nigra* contains at least 24 allelochemicals which belong to lignans, cyanogenins, phenolic glycosides and flavonoids. These compounds were used in a bioassay study to examine their effects on lettuce, onion and radish. Cyanogenins showed inhibitory effect, while lignans stimulated the plants' growth (D'Abrosca *et al.*, 2001). *Leonurus sibiricus* root exudates contains phenolics such as caffeic acid. Mandal (2001) observed that it has inhibitory effect on different crops. *Conyza canadensis* water extract was observed to contain vanillic acid, gallic acid, syringic acid and cathecol, as determined by chromatographic analyses. Germination and seedling growth of okra, bitter gourd, tomato and onion was reduced by water extract of dry plants of *Cyperus rotundus* (Ameena and Sansamma, 2002). They reported that the phenolic acids which were present in water extracts of dry plant organs were the cause of inhibition of germination and seedling growth of test crops. Sasikumar *et al.* (2002) reported inhibitory effect of *Parthenium hysterophorus* plant organs containing phenolic compounds (caffeic acid, p-coumaric acid, p-hydroxy benzoic acid and vanillic acid) on cowpea, blackgram, green gram, horse gram and pigeon pea. The mixture of these phenolic acids, as well as their role as individual compounds, inhibited the germination and vigor index of all tested crops. Shaukat *et al.* (2003) noted that *C. canadensis* imposed inhibitory effect on radish, tomato, corn, wheat, mung bean and bulrush millet. Addition of shoots for decomposition in the sandy loam soil also inhibited the germination and growth of bulrush millet. Rahman (2005) reported that the aqueous extracts from inflorescences, stem and leaves of *P. hysterophorus* containing parthenin, caffeic acid and p-coumaric acid resulted in a reduction of the germination percent, low growth of radical and plumule, as well as low dry weight of *Cassia tora* seedlings. Shao *et al.* (2005) determined three sesquiterpenoids named deoxymikanolide, dihydromikanolide and 2,3-epoxy-1-hydroxy-4,9-germacradiene-12,8:15,6-diolide and found that they exhibit allelopathic activity on the germination and growth of *Acacia mangium*, *Lactuca sativa*, *Pinus massoniana* and *Eucalyptus robusta*. Hegazy and Farrag (2007) analyzed the water, methanol and oil extracts of *Chenopodium ambrosioides* and found that it contained flavonoids, alkaloids, terpenoids and volatile oils. Water extract of *C. ambrosioides* was observed to be inhibitory to the percent germination of *Beta vulgaris, Lycopersicon esculentum, Sonchus oleraceus* and *M. indicus*. The methanol and oil extracts were found inhibitorier than water extract. Khanh *et al.* (2008) found that *Echinocloa crusgalli* infested soil contained 18 compounds belonging to terpenes, derivatives of cinnamic acid and ferulic acid, long chain fatty acids and steroids, and thus affected rice.

Table 1 summarizes many classic and novel candidates for allelochemicals produced by some important weeds in world.

Allelopathic weeds produce a large number of allelochemicals belonging to diverse chemical classes, depending upon their characteristics. In general, the allelochemicals released from the weeds belong mostly to the phenolics, terpenoids, alkaloids, fatty acids, indols, lignans, cyanogenins, phenolic glycosides, flavonoids and coumarins. Furthermore, a large number of novel allelochemicals have also been discovered from several weeds.

Allelochemicals release modes

Allelochemicals can liberate from plants through different modes, depending upon species and environmental conditions. Their release takes place through leaching from the leaves or other plant parts, decomposition of plants residues, volatilization and root exudation (Bertin *et al.*, 2003).

Leachates

Water soluble allelochemicals such as phenolics, alkaloids and terpenoids are released from different plant organs in the form of leachates and affect the germination and growth of accepter plants (Das *et al.*, 2012). Plant leachates suppress the germination of seed and vegetative propagules, as well as radical and plumule growth (Casado, 1995). Leaf leachates of *Hyptis suaveolens* investigated for their effects on the germination and biochemical attributes of *Parthenium hysterophorus* revealed that leachates exert inhibitory effects on *P. hysterophorus* seedlings (Kapoor, 2012). Jinhu *et al.* (2012) reported that *Eupatorium adenophorum* leaf leachates exerted inhibitory as well as promoting effects on the membrane permeability, germination and dry matter accumulation of *Amaranthus retroflexus* and *C. glaucum* seedlings. Higher concentrations substantially reduced the biosynthesis of chlorophyll content and enzyme activity, while increasing the malondialdehyde (MDA) accumulation. However, lower concentrations of leachates showed promoting allelopathic effect. *Echinochloa colona* leaf leachates significantly reduced the germination and growth of rice seedlings in different media viz. soil, filter paper and soil plus activated charcoal (Swain *et al.*, 2012).

Decomposition

Large amount of allelochemicals add up in the soil by decomposition of plant residues and affect the target plants on exposure (Matloob *et al.*, 2010). Allelochemicals are released directly or by the action of microbes from plants residues. In field conditions, the release of allelochemicals mostly occurs from residues decomposing (Singh *et al.*, 2001). Allelochemicals accumulate in the soil through discharge by decomposition of plant residues and cause soil sickness. The accumulation of allelochemicals in soil leads to a reduction in seed germination and plant growth, decreased primary roots and increased secondary roots, chlorosis, poor nutrient absorption, maturation delayed and reproduction failure (Narwal *et al.*, 2005). Residues of *Chromolaena odorata* incorporated in soil showed inhibition of *L. esculentum* seedling germination and growth characteristics at all the concentrations of residues incorporated in soil (Enyi, 2001). Soil amended with residues of *P. hysterophorus* was tested by Singh *et al.* (2005) and it was observed that incorporation of residues at the rate of 40 g per kg of soil decreased the size and biomass of *B. oleracea, B. campestris* and *B. rapa* upon decomposition. These results were credited to the phenolics released into the soil with water from decomposing residues of *P. hysterophorus*. The influence of *Lantana camara, A. conyzoides* and *E. adenophorum* residues addition in soil at 5% and 10% concentrations, was found inhibitory on emergence and shoot growth of wheat, rice and maize. The effect was proportional to the concentration of the incorporated residues (Katoch *et al.*, 2012).

Volatilization

The release of volatile allelochemicals from plants and the impact upon receptor plants takes place by direct absorption in vapours form from atmosphere or through absorption along with dew or rain water. Camphor, camphene, dipentene, cineole, alpha and beta pinene are the most common volatile compounds that are released from plants (White *et al.*, 1989). Obaid and Qasem (2005) reported that volatiles extracted from shoots of *Convolvulus arvensis, A. gracilis, Portulaca oleracea* and *L. serriola* caused a reduction in the growth of cabbage, cucumber, squash, onion, pepper, tomato and carrot. However, the volatiles from *C. arvensis* and *L. serriola* caused mostly inhibitory effect. Volatiles from shoots of *Cardaria draba* and *Salvia syriaca* caused inhibitory effects on cabbage, carrot, cucumber, squash, onion, pepper and tomato. Germination and seedling growth characteristics of several test crops were reported to be affected by volatiles (Qasem, 2001).

Table 1. Classic and novel candidates for allelochemicals found in some important weeds considered worldwide

Weeds	Allelochemicals	Reference
Alternanthera philoxeroides	4-Hydroxy-3- methoxybenzoic acid, m-coumaric acid, p-coumaric acid	Mehmood *et al.* (2014)
Alternanthera sessilis	Chlorogenic acid, ferulic acid, gallic acid, vanilic acid	Mehmood *et al.* (2014)
Avena fatua	Vanillic acid, scopoletin, ellagic acid, chlorogenic acid, caffeic acid, p-coumaric acid, ferulic acid, p-hydroxy-benzoic acid	Schumacher *et al.* (1983); Qureshi *et al.* (1987)
Bothriochloa laguroides	E,E-farnesol, hexadecane, n-dodecane, 1-tetradecene	Scrivanti (2010)
Chenopodium album	Chlorogenic acid	Mallik *et al.* (1994)
Chenopodium ambrosioides	Limonene, α-terpinene, ascaridole (1-methyl-4(1-methylethyl)-2-3-dioxabicyclo[2.2.2] oct-5-ene)	Hegazy and Farrag (2007)
Chenopodium murale	Benzoic acid, p-coumaric acid, ferulic acid and vanillic acid	Batish *et al.* (2007a)
Cirsium arvense	Vanillic acid, caffeic acid, ferulic acid, p-coumaric acid, chlorogenic acid, p-hydroxybenzoic acid	Hussain *et al.* (1987)
Convolvulus arvensis	p-Hydroxybenzoic acid, p- coumaric acid, pyrogallic acid, protocatechuic acid, resorcinol, chlorogenic acid, caffeic acid, syringic acid, ferulic acid, salicylic acid, cinnamic acid	Hegab and Ghareib (2010)
Conyza stricta	Chlorogenic acid, ferulic acid, m-coumaric acid	Abbas *et al.* (2014)
Cyperus esculentus	Ferulic acid, p-hydroxybenzoic acid, syringic acid, vanillic acid, p-coumaric acid	Tames *et al.* (1973)
Cyperus rotundus	Catechol tannins, sesquiterpenes	Komai and Ueki (1975)
Echinochloa crusgalli	m-Coumaric acid, p-coumaric acid, vanilic acid	Abbas *et al.* (2014)
Eclipta alba	Vanillic acid, ferulic acid, benzoic acid, p-coumaric acid	Gulzar and Siddiqui (2015)
Eichhornia crassipes	Isocyanatoethyl acetate, propane amide, 2-2-dimethyl cyclopentane	Jin *et al.* (2003)
Lathyrus aphaca	Gallic acid, caffeic acid, syringic acid, m-coumaric acid	Zohaib *et al.* (2014)
Medicago polymorpha	4-Hydroxy-3-methoxybenzoic acid, p-coumaric acid, vanilic acid, m-coumaric acid	Zohaib *et al.* (2014)
Melilotus indica	Caffeic acid, ferulic acid, chlorogenic acid	Zohaib *et al.* (2014)
Parthenium hysterophorus	Parthenin, caffeic acid, coronopilin acid, vanillic acid, chlorogenic acid, ferulic acid, anisic acid, saponins, tannins, cardiac glycosides, myrcene, ocimene, β-pinene	Tanveer *et al.* (2015)
Polygonum barbatum	Caffeic acid, chlorogenic acid, m-coumaric acid, p-coumaric acid	Abbas *et al.* (2014)
Ruta graveolens	a-Pinene, camphene, b-pinene, heptane-2-one, p-cymene, limonene, 1,8-cineole, n-octanol, terpinolene, valeric acid, non-2-ene, nonan-2-one, linalool, phenylethyl alcohol, nonan-2-ol, octanoic acid, methyl salicylate, decan-2-one, decan-2-ol, octyl acetate, undecan-2-one, undecan-2-ol, dodec-2-ene, tridecane, decyl-2-acetate, dodecan-2-one, tridecan-2-one, α-copaene, β-caryophyllene, α-humulene, Δ-cadinene, hexadecane, α-eudesmol, pentadecan-2-one, heptadecane, pentadecanol, 1-hexadecanol, xanthotoxin, furocoumarins, flavonoids	Aliotta *et al.* (1999); Feoa *et al.* (2002)
Sorghum halepense	Chlorogenic acid, phenolic compounds, p-hydroxybenzeldehyde, p-coumaric acid	Abdul-Wahab and Rice (1967)
Terminalia catappa	2-Pentadecanone, syringic acid, vanillic acid, ferulic acid, palmitic acid, p-coumaric acid, stearic acid, 3,3',4-tri-O-methyl ellagic acid, β-sitosterol-3-O-β-D-glucoside	Baratelli *et al.* (2012)
Trigonella polycerata	4-Hydroxy-3-methoxybenzoic acid, syringic acid, m-coumaric acid	Zohaib *et al.* (2014)
Vicia sativa	Ferulic acid, 4-hydroxy-3-methoxybenzoic acid, p-coumaric acid	Zohaib *et al.* (2014)
Nigella sativa	Thymoquinone, thymohydroquinone, thymol, dithymoquinone, carvacrol, nigellidine, nigellicine, α-hederin	Randhawa and Al-Ghamdi (2002); Gali-Muhtasib *et al.* (2006); Al-Saleh *et al.* (2006)
Stauranthus perforates	Pyranocoumarins [xanthyletin and 3-(10,10-dimethylallyl)-xanthyletin], furanocoumarins [chalepensin, ammirin, chalepin and 20-isopropyl-psoralene], lignans [asarinin and fargesin], sesquiterpene [4,5-epoxi-b-caryophyllene], alkamide [pellitorine]	Anaya *et al.* (2005)
Stellera chamaejasme	Neochamaejasmin B, mesoneochamaejasmin A, chamaejasmenin C, genkwanol A, daphnodorin B, dihydrodaphnodorin B	Yan *et al.* (2014)
Sphenoclea zeylanica	Epi-zeylanoxide A, zeylanoxide A, zeylanoxide B, epi-zeylanoxide B	Hiraia *et al.* (2000)

Root exudation

Allelochemicals ooze out from the roots in the rhizosphere and affect the plants in their vicinity (Senarathne *et al*., 2010). Root exudates of *Chenopodium murale* in agar were found to reduce the wheat seedling growth. Nearly 44% and 32% decrease was noted in root and shoot length of wheat seedlings respectively, whereas seedlings' dry weight decreased up to 52% (Batish *et al*., 2007b). *Cenchrus ciliaris* and *Bothriochloa pertusa* root exudates were used for a bioassay study to examine their effects against *Brassica campestris, L. sativa, Setaria italica* and *Pennisetum americanum*. Lower concentrations were found to have stimulatory effect or no effect on the root and shoot growth of tested crops, while higher concentrations were proved inhibitory (Hussain *et al*., 2011). Evaluation of the effect of *A. retroflexus* root exudates on growth of *Phaseolus vulgaris* exhibited the inhibition of root and shoot growth of *P. vulgaris* upon exposure to exudates (Namdari *et al*., 2012).

In conclusion weeds liberate several types of allelochemicals through various modes such as leaching through plants in the form of leachates, decomposition of weeds residues, volatilization and root exudates, and affect plants in their vicinity.

Allelopathic effects of weeds on field crops

Weeds exert a diverse range of effects on field crops through the release of allelochemicals in their surroundings. Some of the potential impacts of allelopathic weeds on field crops are reviewed in the following sections.

Germination and stand establishment

Allelopathy imposes both detrimental as well as beneficial biochemical interactions among plants and microorganisms through the release of allelochemicals. Weeds release large amounts of allelochemicals in soil, which affect the germination and stand establishment of associated as well as succeeding crops. Phenolic compounds, lignans, cyanogenins, phenolic glycosides, sesquterpenoids and flavonoids released in soil from weed plants either through exudation, leachates and/or decomposition of residues inhibit or stimulate the germination and seedling vigour of crops (D'Abrosca *et al*., 2001; Yukiko *et al*., 2001; Shao *et al*., 2005). Phenolic compounds are the most important allelopathic substances that are involved in the biochemical interactions. Weeds produce large quantities of phenolics which are most actively participating in the allelopathic interactions involving both inhibitory and promoting effects on crop plants. Leachates and decomposing residues of weeds in soil add up water soluble phenolic compounds which lower the percent and rate of emergence as well as growth of crop plants (Zohaib *et al*., 2014; Abbas *et al*., 2015). Ferulic acid, p-coumaric acid, vanilic acid, caffeic acid, chlorogenic acid, gallic acid and 4-hydroxy-3-methoxybenzoic acid are the most commonly occurring plant phenolic compounds and have been detected in many weed plants which inhibit the germination and decrease seedling vigour (Rodzynkiewicz *et al*., 2006; Muzaffar *et al*., 2012; Zohaib *et al*., 2014). The inhibition of germination by allelochemicals is the result of inhibition of respiration by interruption of respiratory enzymes and enzymes involved in oxidative pentose phosphate pathway (Muscolo *et al*., 2001).

Many studies have revealed the allelopathic effects of weeds on germination and crop stand establishment. Residues of leaves, stems, roots and whole plants of *Polygonum hydropiper, A. spinosus, C. album, C. rotundus* and *Imperata cylindrica* and their mixtures imposed an inhibitory effect on the emergence of maize seedlings. They delayed the seedling emergence and reduced the seedling vigour (Samad *et al*., 2008). Jabeen and Ahmed (2009) found that the residues of *Asphodelus tenuifolius, Euphorbia hirta* and *F. indica,* mixed thoroughly in the soil at concentrations of 10 g, 25 g, 50 g and 100 g per 500 g of soil had retarding effects on emergence and seedling establishment of maize. Fresh and dry plant material of *P. hysterophorus* was composted in soil to check possible effects on the emergence and growth rate of lettuce seedlings. The results indicated inhibitory allelopathic effects on percent emergence, radical and plumule growth of lettuce seedlings. The inhibition by fresh biomass was stronger compared with the effect of dried biomass of weed (Wakjira *et al*., 2009). Soil infested with *E. helioscopia* residues was found to inhibit the emergence of chickpea, wheat and lentil. It was further revealed that emergence was substantially delayed by *E. helioscopia* allelochemicals that were accumulated in soil (Tanveer *et al*., 2010). Inhibitory effect of *L. siribicus* was perceived on *Solanum melongena, Abelmoschus esculentus, A. tricolor* and *Cucumis sativus* seedlings. Inhibition of germination was occurred by water extract, acetone extract and methanol extract of *L. siribicus* (Sayed *et al*., 2012). *Calotropis procera* allelopathic extract proved toxic to final germination, germination index and seedling establishment of wheat in different media including sand, blotter paper and soil along with soaking of wheat seeds in water extract of *C. procera*, at same concentration (Yasin *et al*., 2012). *Calotropis procera* allelopathy was also found toxic against eggplant, tomato and cucumber germination and seedling vigour (Ghasemi *et al*., 2012). Allelopathic water extracts of *Plantago lanceolata, Anagallis arvensis, M. polymorpha, Phragmites australis, Ammi visnaga, Silybum marianum, Malcolmia africana, Emex spinosa, Calendula arvensis, Fumaria indica, C. arvense* and *Rumex crispus* showed toxicity against maize, sunflower and wheat germination. Water extracts decreased the percent germination and germination index while exaggerated the time for germination. The sunflower was more prone to inhibition, while maize was more resistive. *R. crispus* was observed inhibitorier than all other weeds (Khan *et al*., 2012).

In crux, the allelochemicals, and even more commonly the phenolic compounds, that are released from weeds affect the germination and crop stand establishment through disruption of various vital processes such as respiration and activity of enzymes that are involved in the process of germination. They also affect the crop stand establishment through reduction of seedling vigour.

Growth and development of crop plants

Allelochemicals released from weeds exhibit a decrease in growth and development of crop plants through disruption of vital physiological processes. The reduction in plant growth and development comes from the inhibition of cell division and photosynthesis due to disruption of chlorophyll cells (Shao-Lin *et al*., 2004). A large number of allelochemicals such as ferulic acid, chlorogenic acid, caffeic acid, vanilic acid, 4-hydroxy-3-methoxybenzoic acid, p-coumaric acid and gallic acid have been observed to cause hindrance of plant growth (Rodzynkiewicz *et al*., 2006; Muzaffar *et al*., 2012). Weeds release a large quantity of allelochemicals in the soil and plant environment that is enough to exert damaging effects on crop plant growth. Alam and Shaikh (2007) carried out an experiment to examine the effect of leaf water extract of nettle leaf goosefoot alone, NaCl alone and combination of both on rice growth. All treatments reduced the shoot and root growth of rice. The most affected growth parameter was root length. Dry plant residues of *Cassia angustifolia* were incorporated into the soil as powder and mulch for checking its possible allelopathic effects on rice, maize, wheat and sorghum. It was found that all the attributes pertaining to plant growth viz. seedling length, dry weight and number of leaves of all the crops were retarded except wheat in which a promotion in growth was observed (Hussain *et al*., 2007). Phytotoxicity of *Prosopsis juliflora* extract was demonstrated at two concentration levels (5 and 10%) against wheat seedlings. An inhibition of root growth of wheat was observed; the inhibitory effect was proportional to extract concentration (Siddiqui *et al*., 2009). In a different study, *Cyperus rotundus, Commelina benghalensis, Prosopis juliflora* and *P. hysterophorus* residues were augmented in soil and their impact was observed on growth of soybean, sorghum and groundnut at varying concentrations of residues (5, 10 and 20 g/kg soil). The results revealed that there was more growth inhibition of soybean than sorghum and groundnut. A substantial reduction in plant height, leaf area, stem and leaf weights were perceived in response to allelopathic weeds residues. *Cyperus rotundus* and *C. benghalensis* showed more inhibitory effect and the inhibition increased with an increase in concentration of weeds residues (Jalageri *et al*., 2010).

Determination of the effects of *C. iria* residues incorporated in soil on five varieties of rice namely MRQ74, MR84, MR211, MR220 and MR232 showed that there was significant reduction in plant height, root and shoot length, plant fresh weight of rice plants (Ismail and Siddique, 2011). Residues of *Inula viscose* leaves and flowers were mixed in soil at a concentration of 1.25 g and 2.5 g per kg and their impact was examined against radish and lettuce. There was considerable inhibitory effect of allelochemicals present in the residues of *I. viscose* on the emergence and growth of radish and lettuce. Shoot and root growth of both crops was inhibited. The effect was increased by increasing concentration of residues in soil (Omezzine *et al*., 2011). Studies were conducted by Hamidi and Ghadiri (2011) to assess the effect of root and shoot water extracts of wild barley on wheat with a result of reduction in shoot and root length, as well as the number of seminal roots of wheat plants. The inhibitory effects of root water extract were more significant at higher concentration. The most affected trait was root length in their study. Assessment of allelopathic effects of residues of *Fimbristylis miliacea* on growth of various varieties of rice was done at different concentrations including 0.5, 1 and 2% (w/w). It was found that there was an inhibitory effect of weed debris on all the attributes of growth. There was a significant reduction in the seedling length and dry matter production by the application of weed residues (Ismail and Siddique, 2012). Johani *et al.* (2012) affirmed by a bioassay study that *Malva parviflora* and *C. murale* aqueous water extracts at 25, 50, 75 and 100 percent concentrations caused a negative effect on the growth of barley. It was noted that *C. murale* caused more retarding effect on plant height, leaf area, leaf fresh and dry weight, root dry weight, number of leaves and number of tillers of barley. However, the retarding effect of *M. parviflora* was observed only on leaf growth. More growth retarding effects were observed at higher concentrations. Sultana and Asaduzzaman (2012) found out the allelopathic effects of *S. marianum* fresh and hot water extracts on ryegrass and canola at various concentration levels. It was noted that higher concentrations of both fresh and hot water extracts were inhibitory to the root and shoot growth of test crops. Allelopathic effect of leaf water extract of *Argemone mexicana* was determined by Alagesaboopathi (2013) on sorghum seedlings at varying concentrations. A significant inhibitory effect was noted on growth of sorghum plants. The radical and plumule length was significantly reduced due to the effect of water extract of *A. Mexicana*, at higher extract concentrations.

In summary, a large number of allelochemicals liberated from the weeds are involved in the inhibition of vital physiological processes such as cell division, cell elongation and photosynthesis, which are essential for growth and development of crop plants. They inhibit the root and shoot growth, and lower the dry matter production.

Crop yield

Weeds causes yield reductions through weed-crop competition and allelopathy. However, in field conditions it is difficult to differentiate the cause of crop yield reduction, as to identify if this is caused by weeds' allelopathic interactions or due to weed-crop competition. Weeds are unwanted plants which compete with the associated crop plants for space, moisture, nutrients and light, and thus obstruct the growth, eventually decreasing the yield both qualitatively and quantitatively. Most of the studies have concentrated on the determination of yield losses due to competition and critical levels of weed-crop competition (Ali *et al*., 2015). Recently, the determination of yield losses due to weed-crop allelopathic interactions has been undermined. Therefore, scanty information is available regarding the assessment of yield losses due to weeds allelopathy.

Weeds suppress the crop stand establishment and plant growth through their allelopathic effect and cause a considerable reduction in crop yield. The decrease in yield may be due to the reduction in number of productive tillers per unit area, number of seeds per spike and decrease in the seed weight due to impairment of important physiological functions of plants. The crop yield is much more dependent on the number of fertile tillers per unit area than weeds are.

Allelochemicals liberated from the weeds in crop vicinity affects the seed germination, seedling growth and stand establishment, ultimately leading to a reduced number of tillers per unit area. Further, weeds suppress the growth of crop plants rendering them to stress factors. The reproductive growth of crop plants is influenced by the vegetative growth of plants to a great extent and requires a good balance between vegetative and reproductive growth for a good yield. The allelopathic effects of weeds on crop stand establishment and plant growth has been discussed in previous sections, while the physiological processes that are impaired by weed allelopathic effects that are to be discussed hereby.

Some studies have enabled the scientists to know how the crop yield is impaired by weeds allopathic interactions. Potential allelopathic effect of wild barley residues that were deposited in the soil at different concentrations against vegetative and reproductive growth of wheat was assessed by Hamidi *et al.* (2008). No effect was found from the treatment with residues at lower concentrations. However, higher concentrations were found effective in reducing growth and yield of wheat. The decrease in yield was found to be due to lesser number of tillers per plant, while grain weight was affected by weed residues at higher concentration. Mohadesi *et al.* (2011) revealed that water extracts of barnyard grass, umbrella sedge, monochori alone and their combination lowered the rice yield. There was a reduction in growth of flag leaf and number of tillers, and also there was a decrease in days to panicle emergence and 50% flowering that may be the reasons behind lowered crop yield. Majeed *et al.* (2012) noticed a reduction in wheat yield by the effect of water extract of *C. album* at higher concentrations. They observed that growth and yield parameters of wheat were decreased by water extract at higher concentrations and increased at a lower concentration viz. 25%. The reduction of yield was due to a decrease in the number of tillers per plant, number of grains per spike and grain weight by the influence of water extracts at higher concentrations as compared to untreated control and vice versa for lower concentration.

In conclusion, within field conditions is considered difficult to differentiate the cause of crop yield reduction whether it is attributable to allelopathy or competition. However, results of some studies have revealed that allelopathic weeds negatively affect the yield by influencing the crop stand establishment and reducing the number of productive tillers per unit area, as well as by decreased number of grains per spike and seed weight.

Crop physiology

Allelochemicals are responsible for the modulation of physiological processes taking place within plants. These alterations may take place in the hormonal balance, protein synthesis, enzyme activity, photosynthesis, respiration etc. Weeds alter the pattern of growth and development of crop plants through changes in the physiological processes by releasing the allelochemicals within their vicinity. The allelopathic effect of Charlock (*Sinapis arvensis*) plant organs aqueous extracts at 0.5% and 1.5% concentrations against canola (*Brassica napus*) revealed that shoot extract inhibited the protein synthesis and Hill reaction. It reduced chlorophyll *a* and total chlorophyll at 1.5% concentration. Chlorophyll *b* was reduced at 1.5% concentration of root extract. Shoot and root extracts of *S. arvensis* increased soluble carbohydrates, proline and decreased non-soluble carbohydrate contents in canola. Shoot and root extracts of *S. arvensis* at 1.5% concentration increased catalyzed oxidation of guaiacol (peroxidase activity) of canola (Haddadchi and Khorasani, 2006). Similarly, water extracts of *S. nigrum* and *P. hysterophorus* showed an increase in protein content in various varieties of soybean (Verma and Rao, 2006).

Total chlorophyll contents and the amount of proteins and carbohydrates of *Cicer arientinum* and *Pisum sativum* were reduced when both legume crops were grown in soil amended with 5, 10, 20 and 40 g residue kg^{-1} soil of *C. murale* (Batish *et al.*, 2007a). Otusanya (2008) demonstrated that leachates of *Tithonia diverifolia* inhibited the photosynthetic pigments in *Lycopersicon esculentum* and *Capsicum annum*. Chlorophyll *b* of *C. annum* was reduced by the action of allelochemicals that were present in leachates, while chlorophyll *b* and total chlorophyll of *L. esculentum* was enhanced. Allelochemicals from *C. arvensis* methanol extract at various concentrations viz. 75 ppm, 150 ppm, 300 ppm and 600 ppm imposed a stimulatory allelopathic effect on the biosynthesis and accumulation of chlorophyll and protein contents, carbohydrates and phenolic compounds of wheat. Similarly, activity of antioxidant enzymes such as peroxidase (POD), catalase (CAT), super oxide dismutase (SOD) and phenol oxidase increased, while lipid peroxidation and H_2O_2 content in wheat plants decreased by the effect of allelochemicals at lower concentrations. Higher levels of chlorophyll and antioxidants were observed at 300 ppm (Hegab and Ghareib, 2010). Hui *et al.* (2011) noted that plant material of garlic stalk upon decomposition exerted an inhibitory effect on antioxidants viz. SOD, POD and CAT of Chinese cabbage, tomato, lettuce, carrot, hot pepper and cucumber seedlings, while the MDA content increased upon decomposition. Water extracts of *Cynodon dactylon* and *Ammania baccifera* showed an inhibitory as well as stimulatory effect at different concentrations on the physiological and biochemical attributes of black gram. The stimulatory effect was observed at lower concentrations while higher concentrations were observed to cause inhibitory effect on photosynthetic pigments viz. chlorophyll *a*, *b* and total chlorophyll, protein content, amino acids, sugars, starch and proline content (Kavitha and Arumugam, 2012).

In conclusion, allelochemicals disturb numerous essential physiological processes such as protein synthesis, enzyme activity, chlorophyll synthesis and maintenance, photosynthetic rate and respiration. Furthermore, it increases the production of reactive oxygen species and reduces the activity of antioxidant enzymes that leads to lipid peroxidation and results in imbalanced plant growth and development.

Conclusions

Weeds are a diverse group of plants that grow either in association along with crops or may grow in places where they are not required. When they occur in association with crops they cause economic losses through competition or by releasing allelochemicals, in the process known as allelopathy. Weeds produce a large number of allelochemicals belonging to different chemical classes, and liberate them through different metabolic processes such as leaching, decomposition of residues, volatilization and root exudation; their effects impair the germination, crop stand establishment, growth of crop plants and reduce yield. The allelochemicals released by weeds disrupt many physiological processes of crop plants and impact upon plant growth and development. In crux, the allelopathic effects of weeds are threats to qualitative and quantitative yields and their control is crucial for economic crop production.

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