Allelochemicals and crop management: A review

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Abstract: The allelochemicals have diverse applications in agriculture, especially in weed management in crop systems as growth regulator, weed management and as pesticides etc. In allelopathy bioactive compounds are employed for growth regulation, weed infestation control and pest management and are safer than synthetic chemicals and their use preclude the health defects and environmental pollution of synthetic chemicals. Most of the studies asserted the inhibitory action of allelochemicals as well explored known dimension of allelopathy on the weed and pest management with the use of allelochemicals. In this study, the applications of allelochemicals for weed management for different crops as well as types and methods are reviewed. Moreover, mode of action and effect on soil properties, plant composition, photosynthesis, water uptake and limitation are highlighted.

Introduction

Ongoing population growth has introduced the food security as a challenge for farming community and agriculturist today. Crop diseases, insects and pests, weeds and unfavorable climate changes are the major hindrance for sustainability both of aquatic and terrestrial ecosystem and of food production, and are the major threats for the Agriculture sector especially in the area of crop production. Agricultural practices elevate the food production level to meet this target. With these practices, global crop production has increased mainly from greater inputs of pesticides and insecticides to cope with crop diseases. In this regard also the fertilizers and weed management have enhanced production yield. All such practices have raised the crop yield undoubtedly to meet the need but at the cost of food nutrition and quality. Application of synthetic chemicals left the residues on the food crops that impure the food and contaminates the environment. All this scenario need immediate shift to sustainability of production (Tilman et al., 2002). Innovation in methods and techniques for sustainability of ecosystem and agriculture will probably prove crucial if we want to increase the yield without imparting risks to public health and environmental integrity. Allelopathy offers a unique and eco-friendly solution of growth regulation, weed management and disease control at the same time to enhance the safe global per capita food

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supply (Arora et al., 2015). In general, allelopathy affected the growth and development of the neighboring plants by releasing the chemicals in the environment (Lux-Endrich et al., 2005). According to Rice (1984), allelopathy is the influence of one plant over the other plant by releasing the secondary metabolites or principle metabolic byproducts during different physiological process in its surrounding environment via leaching/decomposition, vitalization or root exudation thereby, affecting the growth of neighboring plant. Although secondary metabolites of plants are mostly associated with defense mechanism of plants but these valuable compounds can be involved in ecological functions. There is a strong evidence suggesting the involvement of metabolic compounds in communication of plants (Bertin et al., 2003; Weir et al., 2004). It was first time introduced by Molisch, an Austrian plant physiologist in 1937, who considered it chemical interaction among micro-organisms and plants (Hussain and Reigosa, 2011). It is a natural phenomenon in which different plants or organisms release the secondary metabolites to affect the function of other plants or organism in their positive or negative vicinity (Cheema et al., 2012; Farooq et al., 2011). These unique compounds, identified as allelochemicals, are flavonides, alkaloids, phenolics, monilactone, jasmonates, glucosinolates, hydroxamic acid, brassinosteriods, amino acids, terpenoids and carbohydrates (Adaramola et al., 2016; Asif, 2015a, b, c, d, e, f, 2016). These chemicals are non-nutritional and can be synthesized in any part of the plants i.e. roots, seeds, bark or leaves (Bonanomi et al., 2006; Rice, 1984).

Allelopathy involves the synthesis of bioactive compounds capable of growth regulation, weed infestation control and pest management that resolve the problem of health defects and environmental pollution caused by ruthless use of synthetic chemicals (Dayan et al., 2009; Macías et al., 2007). Most of the studies asserted the inhibitory action of allelochemicals as well explored known dimension of allelopathy on the weed and pest management with the use of high concentrations of such chemicals (Farooq et al., 2009). Figure 1 depicts the importance of this hot issue that is the allelopathic application for the weed management Allelopathic crops, when used as smother crops, intercrops or green manure, mulch or cover crops can encounter biotic stresses. Thus, increasing the fertility of soil and reducing the erosion resulting in enhanced yield (Jabran et al., 2007; Khanh et al., 2005). This inhibitory action is attributed to interruption in various physiological process and blockage of important metabolitic within the plant (Iqbal et al., 2007). But some studies have been reported the promotory effect of allelochemicals when used in low concentrations especially foliar that imparts immunization against various abiotic stresses that improve the plant growth (Narwal, 2000). The foliar application of low concentration allelochemicals poses significant impact on crucial physiological process by improving cell elongation and cell division, photosynthesis etc. to enhance crop yield. Phytochemicals from plant extracts are innocuous to beneficial insects and grazing animals (Jamil et al., 2009), are easily degradable due to short half-life with no unnatural and toxic ring structures and low halogen substitution usually have different mode of action than dangerous synthetic agrochemicals (Cheema et al., 2009; Jabran et al., 2007; Jabran et al., 2010b; Kordali et al., 2009).

Previous reviews and reports on application of allelochemicals in agriculture including importance of allelopathy in ecosystem (Khanh et al., 2005; Kruse et al,
2000; Rizvi et al., 1999), applications of allelopathy in fields for weed management (Bhowmik, 2003; Macías et al., 2007; Weston and Duke, 2003), applications of allelopathic crops as pesticides, suppression of weeds and crops through genetically different cultivars (Weston and Duke, 2003) has been discussed. In this review, identification of allelochemicals in allelopathic crops for the weed management is highlighted.

**WEED MANAGEMENT**

The diversity in weedy species is an adverse factor to achieve the targeted yield of desired crop (Blackshaw et al., 2002). These weeds compete with cultivated crops and retard their growth by releasing the growth inhibiting chemicals. *Parthenium hysterophorus* L. is a huge proliferated weed that releases the Parthenin in the neighboring environment and inhibits the growth and shoot length of *Crotalaria mucronata* L., *Oscimum basilicum* L., and barley (De La Fuente et al., 2000). *A. repens* is diversified problematic weed that inhibits the yield of *Lactuca sativa, Medicago sativa, Echinochloa crusgalli* and *Panicum miliaceum* by absorbing the nutrients and releasing the toxic chemicals that affect the growth of crop (Bhadoria, 2011). Allelopathy is economical and eco-friendly solution to control such weed infestation. Allelochemical are found in different parts of the plants with varying concentration and composition and their pathways to release these compounds into the environment are specie dependent (Gatti et al., 2004).

Natural plants and their products with their structural and chemical diversity are widely used for the herbicides and weed management. Toxicological effects of these plants on the weeds are associated with the presence of phytochemicals in the leaves and/or other parts of plant. Identification and isolation of such specific phyto-toxic and biological active allelopathins has substantial importance to investigate the interaction phenomenon. (Putnam, 1988) described the 6 classes of allelochemicals, ethylene, benzoxazinones, alkaloids, cyanogenic compounds, cinnamic acid derivatives and other flavonoids, isolated from aquatic and terrestrial plants. These allelochemicals damage the normal growth of weed by affecting metabolic pathways like ‘Cnicin’ inhibits the chlorophyll production, ‘sorgoleone’ disturbs the respiration process, ‘juglon’ (5-hydroxy-1,4-napthoquinone) invades redox reactions and free radical mechanism (Weston and Duke, 2003). ‘Artemisinin’ in *Artemisia annua* is the main allelootoxin that strongly reduces the growth of roots of neighboring plant and causes extreme chlorosis. This phytotoxin disturbs the mitochondrial oxygen evolution process and inhibits mitosis. The monoterpenes, cineole and its derivative cimminin exhibits remarkable phytotoxicity and is a well known bioherbicides (Khan et al., 2005).

Identified compounds, 1H-indole-3-carboxaldehyde, p-coumaric acid, p-Coumaric acid and 1H-indole-5-carboxylic acid found in the rice inhibited the *Echinochloa crusgalli* L. germiantaion (Rimando et al., 2001). Black walnut (*Juglans nigra*) is a woody species which decreases the yield by wilting and death of sensitive crops like vegetables, legumes etc. The toxic effect of Black walnut is attributed to juglone and naphthoquinone that oxidize to toxic form on exposure to air (Weston and Duke, 2003). Juglon and other allelochemicals like 2,6-dimethoxybenzoquinone present in walnut have the abilities to interfere photosynthesis and respiration by generating dangerous free radicals (Matvienko et al., 2001). Sorghum is well known cover crop for weeds management with major phytochemicals, “sorgeolone” characterized as p-benzoquinone (2-hydroxy-5-methoxy-3-pentadecatriene) is potent bio-herbicide for broadleaf and grass weeds (Nimbal et al., 1996). Some of these biodegradable products contain in them halogens that possess potent herbicidal action. It has been noticed that growth of weeds was suppressed by employing the allelopathic species as cover crop, intercropping, crop rotation or their foliar spray directly.

**COVER CROPS**

Cover crops have the key importance in the sustainable agriculture management due to reduced soil erosion, improved surface residue, water holding capacity and effective weed suppression in the field. Cover crops suppress the weed establishment through different mechanisms that leave some residues to kill or inhibit the weed growth. These residues release the phytotoxic compounds acting as physical barrier to emergence of weed seedlings that inhibit germination and growth of weeds (Ekeleme et al., 2004; Kramberger et al., 2009).

Table 1 describes the importance of allelochemicals as cover crops for the weed management include cyclic hydroxamic acids in ryegrass (*Lolium perenne* L.), Sorgoleone in sorghum, Glucosinolates in Black Mustard (*Brassica nigra* L.) to eradicate weeds through selective cover cropping. Legume crops such as jack bean (*Canavalia ensiformis* L.), jumbie bean (*Leucaena leucocephala* Lam.) de Wit and velvet beans used preferably as cover crops in maize field, reduced the weed crops, substantially barnyardgrass population (Lins et al., 2006). The smothering effect of hyacinth bean (*Lablab purpureus* L.), jack beans and velvet beans control mission grass effectively, a congestion weed in rubber fields. In the field of soybean, barley (*Hordeum vulgare* L.) is grown as cover crop for craggrass suppression and its herbicidal effect is attributed to the presence of DIMBOA (2,4-dihydroxy-7-methoxy-1,4-benzoazin-3-one). Dead leaves of Spiderlily (*Lycoris radiate* L.), a ground cover crop incorporated into soil as mulch, contain lycorine (0.08%) (Iqbal et al., 2006). Most of the cover crops include star-of-Bethlehem (*Ornithogalum umbellatum* L.), European pennyroyal (*Mentha pulegium* L.), Roman chamomile (*Chamaemelum nobile* L) and trefol have been used for the growth suppression of lettuce (*Lactuca sativa* L.).

Although, some side effects of cover crops such as, delay germination and planting owing to excess soil moisture, damaging effects of phytotoxic chemicals on major crops, enhance the nitrogen immobilization. These draw backs, however, be avoided through the selection of optimized integrated cover crops with good management practices in cropping system.
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<th>Allelophatic source</th>
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<th>Weed specie</th>
<th>Allelochemicals</th>
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<tr>
<td></td>
<td></td>
<td><em>Elymus repens</em></td>
<td>cyclic, hydroxamic acids+</td>
<td>(Ringselle et al., 2015)</td>
</tr>
<tr>
<td>Fagopyrum tataricum (L.) Gaertn.</td>
<td>Cover crop+foliar</td>
<td><em>Amaranthus</em>, <em>Setaria</em> spp.</td>
<td>gallic acid, chlorogenic acid and rutin</td>
<td>(Saunders Bulan et al., 2015; Uddin et al., 2012)</td>
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<tr>
<td>Lablab purpureus</td>
<td>Cover crop</td>
<td><em>Paraknoxia parviflora</em> and <em>Portulaca quadridfida</em></td>
<td>cyclic hydroxamic acids+</td>
<td>(Bernstein et al., 2014)</td>
</tr>
<tr>
<td>Secale cereal</td>
<td>Cover crop</td>
<td><em>Abutilon theophrasti</em> M., <em>C. album</em></td>
<td>cyclic hydroxamic acids+</td>
<td>(Dube et al., 2012)</td>
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<tr>
<td>Hairy vetch + oat</td>
<td>Cover crop</td>
<td><em>Datura stramonium</em> L., <em>E. indica</em>, <em>D. sanguinalis</em>, <em>A. retroflexus</em></td>
<td>Cyanamide+ Scopoletin</td>
<td>(Moran and Greenberg, 2008)</td>
</tr>
<tr>
<td>White mustard</td>
<td>Cover crop</td>
<td><em>C. album</em>, <em>A. blitoides</em></td>
<td>Glucosinolates</td>
<td>(Alcântara et al., 2011)</td>
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<tr>
<td>Black Mustard (Brassica nigra L.)</td>
<td>mulching</td>
<td>wild oat (<em>Avena fatua</em> L.)</td>
<td>Glucosinolates</td>
<td>(Turk and Tawaha, 2003)</td>
</tr>
<tr>
<td>Hairy vetch + bristle oat</td>
<td>Cover crop</td>
<td><em>P. oleracea</em>, <em>A. palmeri</em>, <em>Helianthus annuus</em> L.</td>
<td>Scopoletin</td>
<td>(Christenson, 2015)</td>
</tr>
<tr>
<td>Barley + Rye</td>
<td>Cover crop</td>
<td><em>Conyza canadensis</em> L.</td>
<td>Gramine, hordinine+cyclic hydroxamic acids</td>
<td>(Christenson, 2015)</td>
</tr>
<tr>
<td>winter pea+ winter triticale</td>
<td>Cover crop</td>
<td><em>Kochia scoparia</em> L.</td>
<td>Pisin+ p-coumaric acid,</td>
<td>(Petrosino et al., 2015)</td>
</tr>
<tr>
<td>Sorghum + Brassica + sunflower</td>
<td>Foliar</td>
<td>Sorgoleone+ Glucosinolates+</td>
<td>coumaric acids, ferulic acid, and vanillic acids</td>
<td>(Arif et al., 2015)</td>
</tr>
<tr>
<td>Rice</td>
<td>Roots exudates</td>
<td><em>Heteranthr alimosa</em></td>
<td>Ethanolamine, Hydrazinecarboxamide 3-Carene</td>
<td>(Smith and Dilday, 2003)</td>
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<td>Tinospora tuberculata</td>
<td>Foliar+mulching</td>
<td>Barnyard grass,</td>
<td></td>
<td>(Aslani et al., 2015)</td>
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<tr>
<td>Brassica rapa</td>
<td>mulching</td>
<td>Small-seeded weed</td>
<td>2-phenylethyl-ITC(Isotiocyanate) and 3-butenyl-ITC</td>
<td>(Petersen et al., 2001)</td>
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<tr>
<td>Pueraria thunbergiana</td>
<td>foliar</td>
<td>Lettuce</td>
<td>Xanthoxins,</td>
<td>(Fujii, 1994)</td>
</tr>
<tr>
<td>White tephrosia (Tephrosia candida L.)</td>
<td>mulching</td>
<td><em>Monochoria vaginalis</em> L.</td>
<td></td>
<td>(Huang et al., 2007)</td>
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Table 1: Continue..............

<table>
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<tr>
<th>Allelopathic source</th>
<th>Application mode</th>
<th>Weed specie</th>
<th>Allelochemicals</th>
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<tbody>
<tr>
<td>Sorghum (Sorghum bicolor L.)</td>
<td>Foliar</td>
<td><em>Triantema portulacastrum</em> L.</td>
<td>Sorgoleone</td>
<td>(Cheema et al., 2002)</td>
</tr>
<tr>
<td>Sunflower (Helianthus annuus L.)</td>
<td>Foliar</td>
<td><em>Avena fatua</em> L.</td>
<td>Heliannone, Guianolides,</td>
<td>(Cheema et al., 2003)</td>
</tr>
<tr>
<td>Eucalyptus (Eucalyptus camaldulensis L.)</td>
<td>Foliar</td>
<td><em>Melilotus officinalis</em> L.</td>
<td>Essential oils</td>
<td>(Jamil et al, 2009)</td>
</tr>
<tr>
<td>Piper methysticum L. (kava)</td>
<td>Root exudates</td>
<td>barnyardgrass</td>
<td>ferulic acid, protocatechuic acid,</td>
<td>(Xuan et al, 2003)</td>
</tr>
<tr>
<td>Medicago sativa L. (alfalfa)</td>
<td>mulching</td>
<td>Paddy weeds</td>
<td>Gallic acid, <em>trans</em>-ocoumaric acid,</td>
<td>(Xuan et al, 2003)</td>
</tr>
<tr>
<td>Thuja orientalis L.</td>
<td>foliar</td>
<td><em>Sinapis arvensis</em> L., <em>Phalaris paradoxa</em> L., Lolium rigidum Gaud</td>
<td>Monoterpenes (α-pinene, β-phellandrene, α-cedrol)</td>
<td>(Ismail et al., 2015)</td>
</tr>
<tr>
<td>Leucas aspera (Lamiaceae)</td>
<td>Foliar</td>
<td><em>Lepidium sativum</em>, <em>Echinochloa crus-galli</em></td>
<td>vitezagniside I</td>
<td>(Islam et al, 2014)</td>
</tr>
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**Plant leaf extracts**

Some plant leaf extracts contain the allelotoxins that are plant growth inhibitors when exogenously applied (Afzal et al., 2015), thereby preferably applied for the weed growth suppression (Bonanomi et al., 2006; Macias et al., 2007). Such natural compounds in aqueous extracts have immense potential to induce biological changes that provide great agricultural benefits in weed management. For the preparation of these extracts, air dry the leaves and tender branches, grind them to powder and make aqueous solution of desired concentration (Nweke, 2015). Another method in which plant leaves mixed with water (1:20) and boiled for 5 min following by filtration is ready for exogenous application (Lee et al., 2014).

Many researchers (Table 1) suggested the foliar application of aqueous plant leaf extracts (PLEs) in the field conditions to control weed infestation (Jabran et al., 2010a; Jabran et al., 2007; Jabran et al., 2010b; Jamil et al., 2009). In this regard, the hidden traits of plant leaf extracts of jatropha plant as growth inhibitor of corn (*Ze a mays* L.) increased potential with increase in concentration of extracts (Ma et al., 2013). This inhibitory effect is inking the presence of allelochemicals that retards the growth of targeted plant. Its GC-MS analysis proved the presence of azelaic acid in the *Jatropha curcas* that damage the growth of corn plants.

Importance of PLEs as weed suppressant is depicted in Table 1. In the wheat field, application of PLEs of sorghum improved the yield of wheat along with suppression of weeds. Combined effect of sorghum with eucalyptus and sunflower reduced the weed density up to 65% and improved the wheat yield by 5.5% when applied in various rates (Mubeen, 2002). Leaf aqueous extracts of sunflower when applied at 2.5, 5.0 and 10 % (m/v) suppressed the seed growth of mustards (*Sinapis alba*) and a complete failure of seedling growth at higher concentrations (Bogatek et al., 2006). Such herbicidal behavior of sunflower is attributed to heliannuol and leptocarpin in the leaves extracts (El Marsni et al., 2015). In the aqueous extracts of yellow sweet clover, Coumarin is responsible for phytotoxic effect and is natural weed suppressant.

**Mulching**

Among the other strategies mulching is also viable and preferably used as weed management technique. In this method mulch of allelophatic crop is spread over the soil surface for weed suppression. These surface mulch, interfere...
the seed germination of weeds and retard the growth through release of allelochemicals (Bilalis et al., 2003). Mulching is effective only before the seed germination of weeds, however, established weeds are difficult to manage through this treatment. Along with weed suppression, use of surface mulched of allelopathic crops benefits conserving soil moisture, controlling soil erosion, enhancing biological activities, conserving soil moisture and improving water infiltration in soil (Döring et al., 2005; Ghosh et al., 2006).

Major deleterious paddy weeds are jungle rice (Echinochloa colonaum (L.), flat sedge (C. difformis L.), purple nutseed (Cyperus rotundus L.) and barnyard grass that severely affected the yields of rice. Application of mulching crop at 1-2 tons h⁻¹ reduced the weed proliferation by more than 70% and enhanced the yield of rice crop by 20% (Xuan et al., 2005). Olive wastes when amended in soil (10cm) suppressed the weed species infestation including common chickweed (Stellaria media L.), meadow grass (Poa annua L.) and shepherd’s purse (Capsella bursa-pastoris L.) in the field of maize and wheat crops (Boz et al., 2003).

Essential oils

Essential oils are well known as bio herbicides due to their high structural diversity and advantage of biodegradability. Table 2 emphasized the importance of allelochemicals like essential oils extracted from the plants as weed infestation control in different corps that ultimately enhanced the crop productivity. Application of essential oil reduced the chemical resistance of weeds. The essential oil extracted from leaves and rhizomes of Hedychium coronarium (white ginger) (Miranda et al., 2015), showed the presence of α and β-pinene, β-caryophyllene present in leaves and 1,8-cineole and β-pinene in rhizomes of white ginger. The presences of tarpenes have great potential for growth suppression of lettuce. Herbicidal effect of essential oil from N. rtanjensis was assessed on the ragweed management. Phytotoxic effect of these essential oils are attributed to 4α, 7α, 7αβ-nepetalactone (trans,cis-nepetalactone) in N. rtanjensis (Dmitrović et al., 2015).

MODE OF ACTION

Allelochemicals affect the plant physiology through multiple functions. They inhibit weed growth, cause stomatal closure, disturb mineral uptake, influence photosynthesis, affect respiration, induce water stress and damage the enzyme activity. In some studies explore the mechanism of allelochemicals in legume crops (Baziramakenga et al., 1995; Hussain et al., 2010). Another study explained the decrease in enzyme activity in hypocotyl cuttings of P. aureus under the allelochemical action of caffeic acid (Batish et al., 2008).

Croton ciliatoglanduliferus Ort. contains highly toxic flavonoids named retusin which targets the water splitting enzymes in PSII that affects the photosynthetic electron transport chain. Quercetin (flavonoids) inhibits the germination and growth of plants Physalis ixocarpa, Lolium perenne and Trifolium alexandrinum (Morales-Flores et al., 2015).

EFFECT OF ALLELOCHEMICALS

Soil properties

Weeds were commonly known by growth retardants through preventive the approach of crops to foods and nutrients from the soil. Along with this hindrance, some weeds also inhibit the growth of neighboring crop plants by releasing the toxic chemicals. In a study, three allelotoxins, maltol, veratric acid and (−)-loliolide from the root exudates of crabgrass were identified (Zhou et al., 2013). All these roots exudates reduced the soil biomass carbon consequential inhibit the growth of maize, wheat and soybean. Lanzhou lily is blemish weeds in the crops that inhibit the crop yield. Wu found a principle autotoxin in this weed that causes the soil sickness and crop yield. In his investigations, pthalic acid was found that damage the soil fertility by inducing the auto toxicity (Wu et al., 2015).

Oxidation stress

Oxidative suppress and reactive oxygen species (ROS) generations causes transformations in physiological and biochemical process. A number of studies have been conducted on the alteration of biochemical process by the application of allelochemicals that is due to generation of ROS in the weeds.

Artemisinin,isolated from leaves of Artemisia annua inhibits the growth of lettuce by arresting the cell division by overproduction of reactive oxygen species (ROS) that leads to lipid peroxidation, proline peroxidation and reduction in chlorophyll contents (Yan et al., 2015). Eugenol from the essential oil of summer savory and cinnamon induced the generation of ROS that causes oxidative stress and membrane damage of roots along with damage of electrolyte regulating membrane resulting in electrolyte leakage and cell death that detached the leaves of dandelion (Tworkoski, 2009). This resulted in an increase in the malondialdehyde contents, ascorbate peroxidases and guaiacol peroxidases that ultimately retard the growth of weeds (Ahuja et al., 2015).

Alterations in Lignin composition

Lignin is the crucial component of cell wall of the plants. It is noteworthy that change in monomers of the lignin, p-hydroxyphenyl (H), syringyl (S) and guaiacyl (G), by any environmental stress alter the lignin contents consequently growth of the plants. (Parizotto et al., 2015) explored the inhibiting effect of Benzoxazolin-2(3H)-one (BOA) on the growth of soybean. In this study inhibiting effect of BOA was associated with the alteration of lignin contents that were accompanied by increase in H, S and G monomers. Application of allelochemicals increase the lignin contents 29, 44 and 40% respectively that damage the growth of plant. Germination and growth of weeds were also decreased with this growth retardant phenomenon and mode of action on the plants.
Photosynthesis disruption

Sorgoleone is well known allelochemicals which interferes the photosynthesis and inhibits the evolution of oxygen in potato (Solanum tuberosum) and groundsel (Senecio vulgaris) (Ein hellig et al., 1993). (Nimbal et al., 1996) found sorgoleone as an effective inhibitor of PSII at binding sites than atrazine, a herbicide. It inhibits the electron transfer at reducing site of photosystem (PSII) between QA and QB other studies have revealed that Sorgoleone has acted as analogue of plastoquinone (PQ) and competed the PQ-binding site on the D1 protein of photosystem II (PSII) and has shown inhibitory effect for electron flow (Czamota et al., 2001). It also inhibits hydroxyphenylpyruvate dioxygenase (HPPD), a target site for herbicides. It is an efficient inhibitor as sulcotrione, famous synthetic herbicides. Inhibition of HPPD is actually depletion of PQ that decreases the availability of PQ at binding sites of PSII (Meazza et al., 2002).

Perturbation of water uptake

Proton ATPase is crucial to plants for electrochemical gradients in plasma membrane that drive the uptake of secondary metabolites and plant response to the environment. Uptake and translocation of these allelochemicals through roots is best explained through isotope trace studies (Duke, 2003). Allelochemicals disrupt the H\textsuperscript{+}-ATPase activity in root microsomal membranes and inhibit the growth of targeted weeds due to presence of mitochondrial and tonoplast ATPases inhibitors. Proper functioning of H\textsuperscript{+}-ATPase enzyme is essential to maintain proton concentration in the rhizosphere, external to root cell membrane. Inhibition of this enzyme retards the water uptake capacity of plant. This produces an electrochemical gradient to drive the water uptake (Michelet and Boutry, 1995; Steudle and Peterson, 1998). In this way, phytotoxins disturb other fundamental functions of the plants without ever reaching there.

In other studies allelotoxins induce perturbation to plant water balance and ions uptake in roots that disturbs the normal active transport (Barkosky et al., 2000). These allelochemicals also Damage the cellular membrane increase the electrolyte leakage and lipid peroxidation that reduce the mitochondrial respiration and pigment synthesis. The presence of phytotoxin hydroquinone inhibits the enzyme activity that damages the water uptake phenomenon and leads to action of plant growth reduction (Ein hellig, 1995; Hejl and Koster, 2004; Hull and Cobb, 1998; Tu et al., 1995).

Proteomics of weeds

Vrious allelotoxins have been tested on the seeds and seedlings and their detrimental effect can produce abnormalities in the seed mechanism and inhibit the germination and growth of weeds. Light harvesting complex contains chlorophyll and binding proteins, variation in the binding proteins alter the concentration of chlorophyll pigments. This alteration in chlorophyll pigment disturbs the health of weed. Another study, described the variation in binding proteins in lettuce on the application of seed extract of cucumber significantly as compared to control (Lee et al., 2015). By the variation of binding proteins total chlorophyll was reduced by 23% and chlorophyll a/b by 27%. Another protein that is very sensitive to environmental factors is oxygen evolving proteins (OEE) attached with PS-II in the

Table 2: Allelochemicals (Essential oils) sources, types, mode of application for different weed management

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<th>Weed species</th>
<th>Allelochemicals</th>
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<tr>
<td>Tagetes minuta L.</td>
<td>Volatile oil</td>
<td>Chenopodium murale L., Ama ranthus viridis L.</td>
<td>Nepetalactone, trans-pulegol, 1,8-cineole, β-bourbonene</td>
<td>(Arora et al., 2015)</td>
</tr>
<tr>
<td>Nepeta mayeri Benth.</td>
<td>Soil application (0.5, 1.0 and 2.0 mg/mL)</td>
<td>Amaranthus retroflexus L., Chenopodium album L., Sinapis arvensis L.</td>
<td></td>
<td>(Kordali et al., 2015)</td>
</tr>
<tr>
<td>Peumus boldus Mol.</td>
<td>Soil application</td>
<td>Portulaca oleracea L.</td>
<td>Ascaridole, p-cymene, 1,8-cineole, Limonene, β-pinene, γ-terpinene</td>
<td>(Blázquez and Carbó, 2015)</td>
</tr>
<tr>
<td>Lemon red thyme, cinnamon</td>
<td>1%, v/v</td>
<td>dandelion</td>
<td>eugenol</td>
<td>(Tworkoski, 2009)</td>
</tr>
<tr>
<td>Thyme (Thymus vulgaris L.) rosemary (Rosmarinus officinalis L.) eucalyptus</td>
<td>Essential oil seed application</td>
<td>Chenopodium album, Echinochloa crus-galli</td>
<td>thymol, Carvacrol, 1,8-cineole</td>
<td>(Angeliní et al., 2003)</td>
</tr>
<tr>
<td></td>
<td>In vitro</td>
<td>Ageratum conyzoides L.</td>
<td>cineole and citronellol</td>
<td>(Singh et al., 2002)</td>
</tr>
</tbody>
</table>
Table 3: Modes of action of different allelochemicals on weeds suppression

<table>
<thead>
<tr>
<th>Mode of Action</th>
<th>Allelochemicals</th>
<th>Assay specie</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ evolution in photosynthesis</td>
<td>Sorgoleone</td>
<td>Solanum tuberosum</td>
<td>(Nimbal et al., 1996a)</td>
</tr>
<tr>
<td>Chlorophyll accumulation</td>
<td>Phenolics</td>
<td>Vigna unguiculata</td>
<td>(Dakshini and Dakshini, 1992)</td>
</tr>
<tr>
<td>Inhibition of electrons between</td>
<td>Sorgoleone, Artemisinin</td>
<td>Lemma minor</td>
<td>(Stiles et al., 1994)</td>
</tr>
<tr>
<td>Qa and Qb</td>
<td>p-coumaric Acids</td>
<td>Spinacia oleracea</td>
<td>(Stiles et al., 1994)</td>
</tr>
<tr>
<td>Depletion plasma membrane</td>
<td>Dehydrozaluzanin</td>
<td>Cucumis sativus</td>
<td>(Galindo et al., 1999)</td>
</tr>
<tr>
<td>Perturbation of water uptake</td>
<td>Juglone</td>
<td>Glycine max</td>
<td>(Hejl and Koster, 2004)</td>
</tr>
<tr>
<td>HPPD</td>
<td>Juglone, Sorgoleone</td>
<td>A. thalian, Arabidopsis thaliana</td>
<td>(Meazza et al., 2002)</td>
</tr>
<tr>
<td>PSII efficiency</td>
<td>Parthenolide, Artemisinin</td>
<td>Algae</td>
<td>(Yang, 1996)</td>
</tr>
</tbody>
</table>

Chloroplast. It’s vital role is to release Oxygen by splitting the water and protects the Magnesium cluster and ionic contents because Mg is the central component of chlorophyll that activates carbon fixation process in chloroplast hence regulates many biochemical reactions within the cell. Any environmental factors that damage the OEE protein actually affect the Mg concentration that reduces the chlorophyll contents. Castro evaluated the role of herbicidal ‘flumioxazin’ on the proteomic variation of Grapevine (Vitis vinifera L.) (Castro et al., 2005). It mainly affected photosynthesis related proteins including OEE and LHCII that interfere with the photosynthesis process. The effect of paraquat was also explored on the mitochondrial proteins and found a clear oxidative modification change in proteomic level by the application of herbicide on Pea (Taylor et al., 2005). It also interacts with photosynthetic machinery and causes extensive production of hydrogen peroxide that disturbs the growth of plant. Allelochemicals also affect the proteomic profile of the plants. These allelochemicals may applied exogenously or approach the plant as volatile organic compounds or scent naturally. Similarly, the effect of floral scent that contains majority of volatile organic compounds including esters, terpenes and aroma alcohols was also studied (Yu et al., 2015). These allelochemicals change the proteomic profile of tobacco leaves. This change in proteomic profile also influenced the photosynthesis, defense response, electron movement and stomata movement regulation.

LIMITATIONS TO ALLELOPATHY AS WEED MANAGEMENT

There are limitation due to plant itself (allelopathic source) and environmental conditions. These allelochemicals do not assure environmental safety. Many potent secondary metabolites such as hemlock and brevetoxins are poisonous in nature. Many biotic and abiotic factors like soil conditions, environmental conditions and plant age influence the phytotoxic level of allelochemicals. Most of the allelochemical studies do not involve soil during experiment rather than artificial substrate, while moving in soil allelochemicals may be toxified or detoxified (Jilani et al., 2008). It is very costly if we desire to synthesize these chemicals due to excellent herbicidal properties like tentoxin (Duke et al., 2000). Auto toxicity is another factor resulted due to shortage of nutrients that harms the plant itself (Yu et al., 2003).

CONCLUSIONS

In view of potential of allelochemicals as a weed management, growth regulator and pest’s control, the use of allelochemicals for better cropping system management is suggested since allelochemicals are natural and eco-friendly in nature. Effect of allelochemicals on yield quality and biochemical interaction with bio-molecules can be studied in future studies. Moreover, the dose of allelochemicals for different crops and vegetable should be optimized to preclude the negative effect of over dose on soil, plants and quality of grains/fruits.

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