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Review Article

Wild oat and Canary Grass Weed Management with Allelopathy Techniques: A Review

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Abstract

Allelopathy refers to the direct or indirect effect of plants upon neighboring plants or their associated microflora or microfauna by the production of allelochemicals that interfere with the growth of the plant. The allelochemicals released from the plants act as a defense system against microbial attack, herbivore predation, or competition from other plants. Wild oat (Avena fatua L.) and canary grass (Phalaris minor Ritz.) being the most troublesome grassy weeds in wheat (Triticum aestivum L.) result in yield reduction by about 30%. These weeds not only cause yield reduction but also deteriorate the produce quality by seed mixing with grains and interfere the harvest operations. Although herbicides available in the market may offer effective control of these weeds but environmental damages occur herbicide resistance development among weeds and health concerns due to over and misuse of synthetic herbicides has led the researchers to focus on alternative weed management strategies. The study of allelopathy is a sub-discipline of chemical ecology that focuses on the effects of chemicals produced by plants or microorganisms on the growth and development of other plants in natural or agricultural systems. The effect can be either positive or negative on the growth of the surrounding plants. The word allelopathy is derived from two separate Greek words, allelon meaning of each other or mutual and pathos meaning to suffer or feeling. Even though the term 'allelopathie' was first used by Austrian scientist Hans Molisch in 1937, the chemical interaction between plants has been known for thousands of years. In 300 B.C, the Greek botanist Theophrastus mentioned the negative effects of chickpea on other plants and later Pliny, a Roman scholar noted the inhibitory effect of the walnut tree (Juglans spp.) over nearby crops. The allelochemicals are released from plant parts by leaching from leaves or litter on the ground, root exudation, volatilization from leaves, residue decomposition, and other processes in the natural and agricultural systems. Upon release, the allelochemicals can suppress the germination, growth, and establishment of the surrounding plants or modify the soil properties in the rhizosphere by influencing the microbial community. Since allelopathic substances play an important role in regulating the plant communities, they can also be used as natural biodegradable herbicides. The allelopathic effects of the eucalyptus species have been investigated extensively. Phenolic acids and volatile terpenes are the allelochemicals present in the leaves, bark, and roots of Eucalyptus spp. The foliage of the species also contains a variety of oils and resins that may have a direct or indirect effect on the neighboring plants, seeds, or microbes. Volatile terpenes that act as allelochemicals, such as 1,8-cineol, limonene, α- and β-pinene have been reported present in the species. In a greenhouse study, leachates from fresh leaves of bluegum eucalyptus (Eucalyptus globulus Labill.) at a concentration of 20% (w/v) and 40% (w/v) reduced the resprouting of purple nutsedge (Cyperus rotundus L.) by 57%-68% and Bermuda grass (Cynodon dactylon (L.) Pers.) by 82%-89%. In another study, the essential oils from blue gum eucalyptus reduced the growth of Bermuda grass by 66% at a concentration of 25% (v/v)). Eucalyptus essential oils at a concentration of 0.2% (v/v) and 0.5% (v/v) reduced the germination of Common amaranth (Amaranthus retroflexus L.) and common purslane by 80% and 90% respectively. One of the major allelopathic compounds present in eucalyptus leaf is 1,8-cineol. 1,8-cineol can decrease germination, reduce root growth, and inhibit mitosis.The plant extracts and essential oils from different parts of the plant consist of alkaloids, terpenoids, steroids, flavonoids, phenolic derivatives, and quassinoids. A study comparing the phytotoxicity of different parts of the plant showed that toxic activity was highest in the root bark and lowest in wood. In a container study, the oven-dried root bark of the tree of heaven mixed in the soil was shown to decrease the emergence, biomass, and survival of garden cress (Lepidium sativum L.). A major allelochemical present in the tree of heaven is a quassinoid compound called ailanthone. Fine fescue grasses are known to displace the neighboring plants by releasing allelochemicals through roots into the soil. Several studies have focused on the weed management potential of fine fescue grasses through their toxic root leachates. The major allelochemical released through the root exudates of fine fescue grass is a non-protein amino acid called m-tyrosine. M-tyrosine has been demonstrated to inhibit the germination and growth of large crabgrass (Digitaria sanguinalis (L.) Scop.), white clover (Trifolium repens L.), and common dandelion (Taraxacum officinale. Mtyrosine acts as a natural herbicide that affects the post-germination development and early establishment of the neighboring plants. It has been shown to impact cell division and cell elongation in several higher plant species. Japonica rice cultivar possessed stronger allelopathic potential against root growth of barn yard grass. Many phytotoxic compounds from several chemical classes, such as fatty acids, benzoxazinoids, indoles, phenolic acids, phenylalkanoic acids, and terpenoids have been found in rice extracts. The key allelochemicals found in allelopathic rice cultivars are tricin and momilactone B). These compounds have been shown to inhibit paddy weed growth and increase rice yield.

Application of mulberry extract to both wild oat and canary grass seeds resulted in complete germination inhibition of both weeds, which can be attributed to strong allelopathic potential of the mulberry plant. Allelopathic potential of the mulberry has also been explored previously on pulses and radish, respectively. Inhibitory effects of mulberry leaf extract on pulses including peas, broad beans and lentils and reported suppression of germination and seedling growth. Sorghum has been intensively reported to possess strong allelopathic potential and obstruct the growth processes of other plant species, however, sorghum cultivars vary for their allelopathic potential and this might be a possible reason that sorghum did faintly affect the growth of weed species in this study. Recent allelopathic studies made great improvements with rapid progress in separation and structural elucidation techniques, active compounds can be detected, isolated, and characterized. Allelochemicals are produced by plants as secondary metabolites or by microbes through decomposition. Allelochemicals are classified into 14 categories based on their chemical similarities. The 14 categories are water-soluble organic acids, straight-chain alcohols, aliphatic aldehydes and ketones; simple unsaturated lactones; long-chain fatty acids and polyacetylenes; benzoquinone, anthraquinone and complex quinones; simple phenols, benzoic acid and its derivatives; cinnamic acid and its derivatives; coumarin; flavonoids; tannins; terpenoids and steroids; amino acids and peptides; alkaloids and cyanohydrins; sulfide and glucosinolates; and purines and nucleosides. Plant growth regulators, such as salicylic acid, gibberellic acid, and ethylene are also considered to be allelochemicals. Allelochemicals vary in mode of action, uptake, and effectiveness (Weston and Duke, 2003; Rice, 2012). The mode of action for many of the identified allelochemicals is still unclear. Many allelochemicals have mechanisms that are not used by any of the synthetic herbicides, giving researchers leads to new mode of action (Duke et al., 2002). While the efficacy and specificity of many allelochemicals are unknown or limited (Bhadoria, 2010), they are an appropriate alternative for synthetic herbicides. Many plant species have been listed worldwide for their allelopathic effects, and of these, we have listed a few with great potential for further research. In Pakistan, important broad-leaved weeds in wheat are lamb's quarters, field bindweed, broad-leaved dock, wild cress, wild pea and sweet clover, while narrow-leaved weeds comprise two grasses, viz. wild oat and canary grass. These two grasses are responsible for major yield loss in wheat and it is more cumbersome to control them than all other weeds. Although effective chemical weed control methods are available, nonetheless, continuous use of the same type of herbicide also leads to the development of herbicide-resistant weed bio-types. Several re-ports indicate the resistance of wild oat and canary grass to clodinafop-propargyl,diclofop-methyl, fenoxaprop-p-ethyl, isoproturon, fluazifop-p-butyl, haloxyfop-methyl, sethoxydim and tralkoxydim in various countries across the globe. In addition, herbicides pollute the soil, water and aerial environments and may enhance the disease risks (Ronald, 2000). Hence, concern regarding use of herbicides is growing worldwide.

Demand for organically produced commodities in the world is also increasing. The area under organic crops is more than 24 million hectares distributed in 100 countries, while the global market for organic foods is more than $ 23 billion per annum and is growing rapidly. Scientists are looking for new ecological and natural approaches for weed management. The use of allelopathic plant water extracts for weed suppression offers a viable and pragmatic option. In our previous studies, sorghum water extract was found to be effective for weed suppression in many field crops including wheat, rice, maize and mungbean. The extent of weed control was 35–49, 40, 37–41, 18–50 and 44% in wheat, cotton, rice, maize and mungbean, respectively, which is far less than what is achievable by herbicide use. This necessitates exploring some other means of exploiting allelopathic potential. Many plants other than sorghum, such as sunflower (Helianthus annuus L.), brassica (Brassica campestris L.), eucalyptus (Eucalyptus camaldulensis D.), sesame (Sesamum indicum L.), rice (Oryza sativa L.) and tobacco (Nicotiana tabacum L.), etc., have also been found to possess allelopathic potential. This indicates that efficacy of sorghum water extract can be improved by combining it with water extracts of other allelopathic plants. Hence, we evaluated the possible integration of sorghum with eucalyptus and sunflower water extracts and found that mixed application of sorghum, eucalyptus and sunflower water extracts gave 70% more weed suppression than sorghum water extract alone in wheat. Based on a series of previous studies and availability of plants, the allelopathic plants. Sunflower has allelochemicals, viz. chlorogenic acid, isochlorogenic acid, α-naphthol, scopolin and annuionones. Soil from sunflower fields was rich in phenolics, which reduced the stand establishment, growth and yield of the crop following sunflower.

Keywords: chlorogenic acid; isochlorogenic acid; α-naphthol; scopolin; annuionone; clodinafop-propargyl; diclofop-methyl; fenoxaprop-p-ethyl; isoproturon; fluazifop-p-butyl; haloxyfop-methyl; sethoxydim and tralkoxydim

Introduction

Wild oat (*Avena fatua* L.) and canary grass (*Phalaris minor* Ritz.) being the most troublesome grassy weeds in wheat (*Triticum aestivum* L.) result in yield reduction by about 30%. These weeds not only cause yield reduction but also deteriorate the produce quality by seed mixing with grains and interfere the harvest operations. Although herbicides available in the market may offer effective control of these weeds but environmental damages occur herbicide resistance development among weeds (Heap 2008) and health concerns due to over and misuse of synthetic herbicides (Kudsk and Streibig

2003) has led the researchers to focus on alternative weed management strategies (Jabran *et al*., 2008). Allelopathy is the process in which secondary metabolites produced by plants, micro-organisms, viruses and fungi influence the growth and development of agricultural and biological systems (excluding animals), this may be stimulatory or inhibitor. Allelopathic potential of sorghum [*Sorghum bicolor* (L.) Moench] has been intensively studied (Hejl and Koster 2004; Jabran *et al*., 2008), nevertheless very little information is avail-able regarding the allelopathic potential of mulberry (*Morus alba* L.), barnyard grass [*Echionoachloa crusgalli* (L.) Beauv.] and winter cherry (*Withania somnifera* L.). Allelopathy refers to the direct or indirect effect of plants upon neighboring plants or their associated microflora or microfauna by the production of allelochemicals that interfere with the growth of the plant (IAS, 2018). The allelochemicals released from the plants act as a defense system against microbial attack, herbivore predation, or competition from other plants (Kong et al., 2019). The study of allelopathy is a sub-discipline of chemical ecology that focuses on the effects of chemicals produced by plants or microorganisms on the growth and development of other plants in natural or agricultural systems. The effect can be either positive or negative on the growth of the surrounding plants. The word allelopathy is derived from two separate Greek words, *allelon* meaning of each other or mutual and *pathos* meaning to suffer or feeling. Even though the term 'allelopathie' was first used by Austrian scientist Hans Molisch in 1937 (Willis, 2007), the chemical interaction between plants has been known for thousands of years. In 300 B.C, the Greek botanist Theophrastus mentioned the negative effects of chickpea on other plants and later Pliny, a Roman scholar (1 A.D.) noted the inhibitory effect of the walnut tree (*Juglans* spp.) over nearby crops. The allelochemicals are released from plant parts by leaching from leaves or litter on the ground, root exudation, volatilization from leaves, residue decomposition, and other processes in the natural and agricultural systems. Upon release, the allelochemicals can suppress the germination, growth, and establishment of the surrounding plants or modify the soil properties in the rhizosphere by influencing the microbial community (Weir *et al*., 2004; Zhou *et al*., 2013). Since allelopathic substances play an important role in regulating the plant communities, they can also be used as natural biodegradable herbicides (Duke *et al*., 2000; Vyvyan, 2002). Since then, numerous studies have reported the allelopathic effects of juglone on various vegetables, field crops, fruit trees, ornamental species, and medicinal plants (Strugstad and Despotovski, 2012). In a greenhouse experiment, Ercisli et al. (2011) reported that 1 mM juglone inhibited the growth of strawberry plants and had a negative impact on plant nutrient uptake. In another study, hydroponically grown corn, and soybean (*Glycine max* [L.] Merr.) seedlings were examined at various concentrations of juglone (10^{-4}, 10^{-5}, 10^{-6} M). Exposure to juglone (>10 μM) has been shown to decrease the cell wall-bound peroxidase activities, root length, and dry mass in the affected plant (Bohm et al., 2006). Black walnut extract (NatureCur®, Redox Chemicals LLC, and Burley, ID, USA) showed the potential to be a PRE and POST emergent bioherbicide against horseweed (*Conyza canadensis* (L.) Cronquist), hairy fleabane (*Conyza bonariensis* (L.) Cronquist), purslane (*Portulaca oleracea* L.), and tall annual morning glory (*Ipomoea purpurea* (L.) Roth) (Shrestha, 2009). This study was conducted in laboratory, greenhouse and in field to test the PRE and POST emergence ability of juglone. The herbicidal activity of juglone was evaluated on the growth of four weed species, wild mustard (*Sinapis arvensis* L.), creeping thistle (*Cirsium arvense* (L.) Scop.), field poppy (*Papaver rhoeas* L.), and henbit (*Lamium amplexicaule* L.). Juglone at a high concentration of 1.15 – 5.74 mM completely controlled the growth of field poppy and significantly reduced the elongation and fresh weight of all the remaining weed species (Topal *et al*., 2007).

The allelopathic effects of the eucalyptus species have been investigated extensively (Sasikumar *et a*l., 2002; Bajwa and Nazi, 2005; El-Khawas and Shehata, 2005). Phenolic acids and volatile terpenes are the allelochemicals present in the leaves, bark, and roots of *Eucalyptus* spp. The foliage of the species also contains a variety of oils and resins that may have a direct or indirect effect on the neighboring plants, seeds, or microbes (Ruwanza *et al*., 2014). Volatile terpenes that act as allelochemicals, such as 1,8-cineol, limonene, α- and β-pinene have been reported present in the species. In a greenhouse study, Babu and Kandasamy (1997) noted that leachates from fresh leaves of bluegum eucalyptus (*Eucalyptus globulus* Labill.) at a concentration of 20% (w/v) and 40% (w/v) reduced the resprouting of purple nutsedge (*Cyperus rotundus* L.) by 57%-68% and bermudagrass (*Cynodon dactylon* (L.) Pers.) by 82%-89%. In another study, the essential oils from blue gum eucalyptus reduced the growth of Bermuda grass by 66% at a concentration of 25% (v/v) (Daneshmandi and Azizi, 2009). Similar results were observed by Azizi and Fuji (2006) in a petri dish experiment, eucalyptus essential oils at a concentration of 0.2% (v/v) and 0.5% (v/v) reduced the germination of Common amaranth (*Amaranthus retroflexus* L.) and common purslane by 80% and 90% respectively. One of the major allelopathic compounds present in eucalyptus leaf is 1,8-cineol. 1,8-cineol can decrease germination, reduce root growth, and inhibit mitosis (Romagni *et al*., 2000). The plant extracts and essential oils from different parts of the plant consist of alkaloids, terpenoids, steroids, flavonoids, phenolic derivatives, and quassinoids (Albouchi *et al*., 2013; Kim *et al*., 2015; Ni *et al*., 2018). A study comparing the phytotoxicity of different parts of the plant showed that toxic activity was highest in the root bark and lowest in wood. In a container study, the oven-dried root bark of the tree of heaven mixed in the soil was shown to decrease the emergence, biomass, and survival of garden cress (*Lepidium sativum* L.) (Heisey, 1990b). A major allelochemical present in the tree of heaven is a quassinoid compound called ailanthone (Sladonja *et al*., 2015). Fine fescue grasses are known to displace the neighboring plants by releasing allelochemicals through roots into the soil. Several studies have focused on the weed management potential of fine fescue grasses through their toxic root leachates (Bertin *et al*., 2009). The major allelochemical released through the root exudates of fine fescue grass is a non-protein amino acid called m-tyrosine (Bertin et al., 2007). M-tyrosine has been demonstrated to inhibit the germination and growth of large crabgrass (*Digitaria sanguinalis* (L.) Scop.), white clover (*Trifolium repens* L.), and common dandelion (*Taraxacum officinale* F.H. Wigg.) (Bertin *et al*., 2007). M-tyrosine acts as a natural herbicide that affects the post-germination development and early establishment of the neighboring plants. It has been shown to impact cell division and cell elongation in several higher plant species (Bertin *et al*., 2007). Lee et al., 2004 evaluated the allelopathic activities of 749 rice cultivars and reported that japonica rice cultivar possessed stronger allelopathic potential against root growth of barnyard grass. Many phytotoxic compounds from several chemical classes, such as fatty acids, benzoxazinoids, indoles, phenolic acids, phenylalkanoic acids, and terpenoids have been found in rice extracts (Belz, 2007). The key allelochemicals found in allelopathic rice cultivars are tricin and momilactone B (Kato-Noguchi and Ino, 2003). These compounds have been shown to inhibit paddy weed growth and increase rice yield (Xuan *et al.*, 2005). The weed suppressive ability of sorghum is due to the presence of hydrophilic compounds, phenolic acids, and their aldehyde derivatives, as well as hydrophobic substances, such as sorgoleone (Czarnota *et al*., 2003). About 90% of compounds present in the root exudates of sorghum comprises of sorgoleone (Czarnota *et al*., 2003). Sorgoleone is synthesized in the root hair cells of sorghum (Yang *et al*., 2004). Sorgoleone has been characterized as a potent bioherbicide as it can suppress many weed species. It has been shown to have greater activity than that of other allelochemicals such as juglone, and other phenolics and terpenoids (Uddin *et al*., 2013). Sorghum can be applied in various forms to control weeds, such as surface mulch, mixed in the soil, extract spray, or inter-cropping. The incorporation of sorghum roots, stems, and leaves in the soil has been shown to suppress weed biomass by 25-50% Foliar addition of sorghum water extract known as sorgaab reduced the density and dry weight of purple nutsedge by 44 and 67% respectively and increased maize grain yield by 44% (Cheema *et al.*, 2004). A wettable powder formulation with a 4.6% active ingredient (sorgoleone) was prepared by Uddin et al. (2013).Wheat, like rice and sorghum has been comprehensively studied for its allelopathic potential. There have been number of studies on the allelopathic potential of weed residues, straw, seedlings and aqueous extract (Wu *et al.,* 2000). It was reported that the water extract from wheat grass was phytotoxic against ivy leaf morning glory (*Ipomoea hederacea* (L.) Jacq.), velvetleaf (*Abutilon theophrasti* Medic.), and pitted morningglory (*Ipomoea lacunosa* L.) (Steinsiek et al., 1982). Major allelochemical groups present in wheat include polyphenols and hydroxamic acids (Krogh *et al.*, 2006). Burgos and Talbert (2000) reported that DIBOA was seven times more toxic to root growth of weed species than BOA. Wheat shows allelopathic potential due to the presence of various allelochemicals, but more research needs to be focused on understanding the genetic control of wheat allelopathy.Pre- and post-emergent application of parthenin reduced the seedling growth and dry weight of green amaranth (*Amaranthus viridis* L.), coffee senna (*Cassia occidentalis* L.), barnyard grass, and small-seeded canary grass (*Phalaris minor* Retz.) (Batish *et al*., 2007). Other phenolic compounds such as caffeic, vanillic, ferulic, chlorogenic, and anisic acid are also isolated from ragweed parthenium. Common lantana (*Lantana camara* L.) is an obnoxious weed with allelochemicals present in leaves, stems, roots, fruits, and flowers. The allelochemicals present in common lantana include mono and sesquiterpenes, flavonoids, iridoid glycoside, furanonaphoquinones, sthsteroids triterpenes, and diterpenes (Sharma *et al*., 2007). Lantadene A and lantadene B are more potent allelochemicals present in common lantana (Sharma *et al*., 2007). Tricolorin A, a resin glycoside is the major allelopathic compound present in morning glory. Several species of *Artemisia* spp. have shown allelopathic activity in different field settings. The major compounds present in common mugwort (*Artemisia vulgaris* L.) are alpha thujone, a monoterpene, as well as 20 minor components, including numerous sesquiterpenes. Annual wormwood (*Artemisia annua* L.) contains sesquiterpene lactones called arteether and artemisinin, which have shown to be a potent inhibitor of seed germination and plant growth. Giant ragweed (*Ambrosia trifida* L.) contains a carotene type sesquiterpene called 1α-angeloyloxycarotol that acts as a strong allelochemical (Kong et al., 2007). Brazilian pepper (*Schinus terebinthifolia* Raddi) an exotic invasive species contains sequiterpenes that have been shown to inhibit radicle growth of lettuce (*Lactuca sativa* L.) and cucumber (*Cucumis sativus* L.) (Barbosa *et al*., 2007).

Intercropping is the practice of growing different crops together at the same time in the same field. Intercropping with allelopathic species has great potential to be suppress weed in an environmentally friendly approach. Intercropping involves growing compatible crops together to improve yield, diversify the farm and provides economic benefits. Furthermore, it is also a great way for improving land, water, nutrient and light efficiency. Factors, such as weed-crop competition, release of allelochemical and effect of shade can be used by allelopathic intercrops to control weeds (Baumann et al., 2002). Intercropping cowpea with maize has shown to reduce the growth of jungle rice, purslane., jute mallow (*Chorchorus olitorius* L.), and Egyptian crowfoot grass (*Dactyloctenium aegyptium* (L.) Willd.]) (Saudy, 2015). Intercropping sesame (*Sesamum indicum* L.), soybean and sorghum in cotton (*Gossypium hirsutum* L.) decreased the purple nutsedge density by 70%-96% and dry biomass by 71%-97% (Iqbal et al., 2007). Bulson et al. (1997) reported that intercropping field beans (*Vicia faba* L.) and wheat can reduce growth of weeds and improve yield compared to sole cropping of wheat. Intercropping maize with Spanish tick-clover (*Desmodium uncinatum* [Jacq.] DC.) and green leaf desmodium (*Desmodium intortum* [Mill.] Urb.) decreased the growth and density of giant witchweed (*Striga hermonthica* [Del.]) than the sole maize crop (Khan *et al*., 2002). Intercropping white clover (*Trifolium repens* L.), black medic (*Medicago lupulina* L.), alfalfa, and red clover (*Trifolium pratense* L.) in wheat crop was much effective in controlling various weed species and improve wheat yield (Naeem, 2011). Rad et al., 2020 evaluated intercropping sorghum with different ratios of hairy vetch (*Vicia villosa* Roth) and lathyrus (*Lathyrus sativus* L.) with three different strategies of no weed control, full weed control and hand weeding. The results showed that the highest sorghum yield was obtained with soghum and 33% hairy vetch while lowest in sorghum and 100% lathyrus. Sorghum with 100% lathyrus showed the highest weeding efficiency. In another study, intercropping wheat with white clover along with high N availability resulted in decrease in weed shoot dry matter, increase in cover crop biomass and improved N accumulation with high wheat yield and protein content (Vrignon-Brenas *et al*., 2018). Intercroping wheat with canola (*Bassica napus* L.) was successful in decreasing density and biomass of little seed canary grass, broad-leaved duck (*Rumex obtusifolius* L.), swine cress swine watercress (*Lepidium didymum* L.), and common lambsquarters (*Chenopodium album* L.) (Naeem, 2011). Many of the secondary metabolites with allelopathic potential are water-soluble, and water acts as the carrier and medium for allelopathic activity (Farooq et al., 2011). Water-soluble allelochemical extract from different parts of allelopathic species, such as leaves, stems, roots, and seeds have great potential to be used for controlling weeds. It has been reported that there are about 400,000 compounds in plants with allelopathic potential, and only about 3% of these compounds have been identified for their herbicidal activity. These allelochemicals can control the germination and growth of weeds through various modes of action. For example, sorghum extract releases hydrophilic compounds, phenolic acids, and their aldehyde derivatives, as well as hydrophobic substances, such as sorgoleone (Czarnota *et al*., 2003). The water-soluble compounds in sorghum are phytotoxic to several weed species, such as small seed cannary grass, lambs quaters, toothed dock (*Rumex dentatus* L.), and bindweed (*Convolvulus arvensis* L.). Similarly, different parts of the tree of heaven plant contain alkaloids, terpenoids, steroids, flavonoids, phenolic derivatives, and quassinoids (Albouchi *et al*., 2013; Kim *et al*., 2015; Ni *et al*., 2018). The water extract from fresh leaves of the tree of heaven showed to inhibit alfalfa germination and growth (Tsao *et al*., 2002). The aqueous extract from leaves of eucalyptus inhibited seed germination and decreased root and shoot, fresh and dry weight of maize (Khan et al., 2004). While a single plant water extract may be effective, combining these plant allelopathic water extracts may increase their efficacy. Application of water extract from sorghum, sunflower, and eucalyptus resulted in 70% weed control compared to the sole application of sorghum water extract (Cheema et al., 2003). The combined application of sorghum and sunflower water extract reduced the growth of horse purslane (*Trianthema portulacastrum* L.) by 66% (Azhar *et al*., 2010). Several studies have also shown that the combination of allelopathic water extract applied with herbicide can reduce the herbicide dosage substantially. The mixture of water extracts from sorghum, sunflower, and rice with a lower rate (1/2 of label rate) of pre-emergence herbicides decreased weed growth by 60-70% and reduced the herbicide dosage by 20-67% (Rehman *et al*., 2010). For weed control in cotton and maize, a half dose of atrazine in combination with sorghum water extract, controlled weeds similar to a full dose of atrazine (Iqbal *et al*., 2009). Iqbal and Cheema (2008) reported that pre-emergence application of sorghum water extract in combination with half and one-third dose of S-metolachlor was more successful in controlling purple nutsedge than the standard dose. The use of plant allelochemical water extract solely or in combination with other herbicides can add a new tool for weed management in agriculture.

Mesotrione was derived from a natural compound called leptospermone from the roots of bottle brush plant (*Callistemon citrinus* (Curtis) Skeels) (Mitchell et al., 2001). The triketone herbicides are derivatives of phytotoxin leptospermone. Leptospermone is also a major component present in the essential oil of the tea tree (*Leptospermum scoparium* J.R.Forst. & G.Forst.) (van Klink *et al*., 1999). Sulcotrione and mesotrione are post-emergent broadleaf herbicides that are based on the leptospermone structure template. Another example is cinmethylin, the first-ever commercial allelopathic herbicide that was derived from monoterpene 1,8-cineole. Monoterpene 1,8-cineole is present in essential oils of several plant species. Many other herbicides, such as AAL toxin, artemisinin, biolaphes, glufosinate, and dicamba have been developed from plant allelochemicals (Motmainna *et al*., 2021). Allelochemicals may not only provide us clues to new herbicide chemistry but also the natural compounds themselves that can be modified into active, selective, and persistent products. It was also reported that there were 13 natural herbicides registered globally, nine of which were derived from fungi, three from bacteria, and only one from plant extract (Cordeau *et al*., 2016). Since then, six commercial natural herbicides derived from essential oils and/or their compounds were registered and available in the USA by 2020 (Verdeguer *et al*., 2020).The six commercial herbicides derived from essential oil are GreenMatch (55% d-limonene), Matratec (50% clove oil), WeedZap (45% clove oil + 45% cinnamon oil), GreenMatch EX (50% lemongrass oil), AvengerWeed Killer (70% d-limonene), and Weed Slayer (6% eugenol)(Verdeguer *et al*., 2020). Ailanthone is a quassinoid lactone, a major allelochemical present in the tree of heaven (Sladonja *et al*., 2015). It has the potential to be used as a post-emergence herbicide, but it degrades rapidly in the field, losing its effect after several days. Sorgoleone, an allelochemical secreted from sorghum is a great example of a natural herbicide (Tibugari *et al*., 2020). Sorgoleone affects photosynthesis by disturbing the minerals and water uptake, especially in lower plants (Ashraf *et al*., 2017). The efficacy of sorgoleone as an herbicide has been compared to synthetic herbicides for commercial use (Jesudas *et al*., 2014). Sorgoleone has been shown to directly influence plant growth in laboratory, greenhouse, and field studies (Uddin *et al*., 2013). Juglone is another allelochemical that is a strong candidate for developing a natural herbicide. Juglone is a quinoid compound that is released from trees in the walnut family (Juglandaceae) including black walnut and English walnut (*Juglans regia* L.). NatureCur® (Redox Chemicals LLC, Burley, ID, USA) a botanical extract of the leaves, fruits, and branches of black walnut is available for commercial use (Shrestha, 2009). In recent years, tricin has received a great deal of attention for an allelochemical-based herbicide discovery (Kong *et al*., 2010). An isomer of tricin has been synthesized called aurone, which has shown much stronger herbicidal activity than tricin itself, guiding research towards a useful molecule for new herbicide discoveries. A series of aurone-derived compounds, including substituted aurones and benzothiazine derivatives, have been synthesized and several of these derivatives have shown great pre-emergent activity against weeds (Kong *et al*., 2010). Many allelochemicals are firstly very expensive to isolate and synthesize, regardless of having excellent herbicidal properties. One example is the cyclic tetrapeptide tentoxin, a good herbicide, but is very expensive to synthesize (Duke *et al*., 2002). Secondly, there is a misconception in the public that everything in nature is probably healthy. Several of the most toxic compounds known to humans, such as aflatoxin, fumonisins, and ricin are natural. AAL toxin and fumonisin are toxic to mammalian cells (Duke *et al*., 2000), while sorgoleone is reported to cause dermatitis (Inderjeet and Bhowmik, 2002). However, from an environmental toxicology perspective, the relatively short half-life of most allelochemicals in the field is desirable, but an herbicide must persist longer in the environment to get desired results (Ferguson *et al*., 2013).

Application of mulberry extract to both wild oat and canary grass seeds resulted in complete germination inhibition of both weeds, which can be attributed to strong allelopathic potential of the mulberry plant. Allelopathic potential of the mulberry has also been explored previously by Mughal (2000) and Hong et al. (2003) on pulses and radish, respectively. Mughal (2000) evaluated inhibitory effects of mulberry leaf extract on pulses including peas, broad beans and lentils and reported suppression of germination and seedling growth. Sorghum has been intensively reported to possess strong allelopathic potential and obstruct the growth processes of other plant species (Hejl and Koster, 2004; Jabran *et al*., 2008), however, sorghum cultivars vary for their allelopathic potential (Alsaadawi *et al*., 2005) and this might be a possible reason that sorghum did faintly affect the growth of weed species in this study. Recent allelopathic studies made great improvements with rapid progress in separation and structural elucidation techniques, active compounds can be detected, isolated, and characterized (Mallik, 2000; Scavo *et al*., 2019). Allelochemicals are produced by plants as secondary metabolites or by microbes through decomposition. Allelochemicals are classified into 14 categories based on their chemical similarities. The 14 categories are water-soluble organic acids, straight-chain alcohols, aliphatic aldehydes and ketones; simple unsaturated lactones; long-chain fatty acids and polyacetylenes; benzoquinone, anthraquinone and complex quinones; simple phenols, benzoic acid and its derivatives; cinnamic acid and its derivatives; coumarin; flavonoids; tannins; terpenoids and steroids; amino acids and peptides; alkaloids and cyanohydrins; sulfide and glucosinolates; and purines and nucleosides (Cheng and Cheng, 2015). Plant growth regulators, such as salicylic acid, gibberellic acid, and ethylene are also considered to be allelochemicals. Allelochemicals vary in mode of action, uptake, and effectiveness (Weston and Duke, 2003; Rice, 2012). The mode of action for many of the identified allelochemicals is still unclear. Many allelochemicals have mechanisms that are not used by any of the synthetic herbicides, giving researchers leads to new mode of action (Duke *et al*., 2002). While the efficacy and specificity of many allelochemicals are unknown or limited (Bhadoria, 2010), they are an appropriate alternative for synthetic herbicides. Many plant species have been listed worldwide for their allelopathic effects, and of these, we have listed a few with great potential for further research.

In Pakistan, important broad-leaved weeds in wheat are lambs quarters, field bindweed, broad-leaved dock, wild cress, wild pea and sweet clover, while narrow-leaved weeds comprise two grasses, viz. wild oat and canary grass (Tanveer and Ali, 2003). These two grasses are responsible for major yield loss in wheat and it is more cumbersome to control them than all other weeds.

Although effective chemical weed control methods are available, nonetheless, continuous use of the same type of herbicide also leads to the development of herbicide-resistant weed bio-types (Bhowmik and Inderjit, 2003). Several re-ports indicate the resistance of wild oat and canary grass to clodinafop-propargyl,diclofop-methyl, fenoxaprop-p-ethyl, isoproturon, fluazifop-p-butyl, haloxyfop-methyl, sethoxydim and tralkoxydim in various countries across the globe (Heap, 2007). In addition, herbicides pollute the soil, water and aerial environments and may enhance the disease risks (Ronald, 2000). Hence, concern regarding use of herbicides is growing worldwide. Demand for organically produced commodities in the world is also increasing. The area under organic crops is more than 24 million hectares distributed in 100 countries, while the global market for organic foods is more than $ 23 billion per annum and is growing rapidly (Roseboro, 2006). Scientists are looking for new ecological and natural approaches for weed management. The use of allelopathic plant water extracts for weed suppression offers a viable and pragmatic option. In our previous studies, sorghum water extract was found to be effective for weed suppression in many field crops including wheat (Cheema *et al*., 2000a), cotton (Cheema *et al*., 2000b), rice (Irshad and Cheema, 2004), maize (Cheema *et al*., 2004)and mungbean (Cheema *et al*., 2001). The extent of weed control was 35–49, 40, 37–41, 18–50 and 44% in wheat, cotton, rice, maize and mungbean, respectively, which is far less than what is achievable by herbicide use. This necessitates exploring some other means of exploiting allelopathic potential. Many plants other than sorghum, such as sunflower (*Helianthus annuus* L.), brassica (*Brassica campestris* L.), eucalyptus (*Eucalyptus camaldulensis* D.), sesame (*Sesamum indicum* L.), rice (*Oryza sativa* L.) and tobacco (*Nicotiana tabacum* L.), etc., have also been found to possess allelopathic potential (Weston and Duke, 2003; Farooq *et al*., 2008). This indicates that efficacy of sorghum water extract can be improved by combining it with water extracts of other allelopathic plants. Hence, we evaluated the possible integration of sorghum with eucalyptus and sunflower water extracts and found that mixed application of sorghum, eucalyptus and sunflower water extracts gave 70% more weed suppression than sorghum water extract alone in wheat (Cheema *et al*., 2003). Based on a series of previous studies (Cheema *et al*., 2003; Turk and Tawaha, 2003; Cheema *et al*., 2007) and availability of plants, the allelopathic plants. Sunflower has allelochemicals, viz. chlorogenic acid, isochlorogenic acid, α-naphthol, scopolin and annuionones (Macias *et al*., 2002; Anjum and Bajwa, 2005). Batish et al. (2002) reported that soil from sunflower fields was rich in phenolics, which reducedthe stand establishment, growth and yield of the crop following sunflower.

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