Chapter 6
Application of Allelopathy in Crop Production: Success Story from Pakistan

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Abstract Allelopathy is an emerging field with its wider applications in agriculture and allied disciplines. In Pakistan, work on allelopathy was initiated in the early 1970s with screening of local flora for allelopathic potential in laboratory bioassays, while field studies were taken up during the early 1980s. Sorghum was found the most potent allelopathic plant in this regard, which was used as mulch material, intercrop, and plant water extracts for weed management. Application of sorghum plant water extracts proved more effective in controlling weeds than all other strategies. Several other plants including sunflower, canola, eucalyptus, rice, mulberry, etc. were also evaluated. Although each of the allelopathic sources provided some control, mixtures of allelopathic water extracts were more effective than the application of single plant extracts. To achieve effective weed control, allelopathic extracts were applied together with the lower herbicide dose. Mixed application of allelopathic extracts with one-third to half of the standard herbicide dose provided effective weed control as achieved from the standard herbicide dose in several field crops. Application of allelopathic mulches, soil incorporation of allelopathic residues, and intercropping with strong allelopathic crops also provided effective control of several weeds. In recent years, commercialization of allelopathic extracts for weed management is under way. Allelopathy has also been effective in controlling stored grain and field crop pests in addition to several

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pathogens which may also be controlled by allelopathy. Allelopathy is also being evaluated as growth promoter; foliar application of canola, sorghum, sunflower, and moringa extracts has been found effective in this regard. More recently, allelopathic extracts are being evaluated for their potential role in improving resistance against abiotic stresses in cereals.

6.1 Introduction

In the 1970s of the twentieth century, Prof. H. M. Naqvi started investigating allelopathic potential of certain grass species while working at the University of Peshawar in Pakistan. He and his graduate students conducted series of laboratory and greenhouse trials to screen local flora for possible allelopathic potential. Prof. Naqvi moved to the US in 1975 while, his then student but later colleague in the Department of Botany Dr. Farrukh Hussain continued the work and investigated certain other species and found promising results particularly from buffel grass (*Cenchrus ciliaris*); that buffel grass inhibited the germination and shoot growth of cattail millet (*Pennisetum americanum*), foxtail millet (*Setaria italic*), lettuce (*Lactuca sativa*), and mustard (*Brassica campestris*) (Hussain and Anjum 1981). It was the early 1980s when Cheema, initiated his PhD dissertation work at the University of Agriculture, Faisalabad, inspired by an article "killer pants" published in 'The Economist''. The article "killer plants" included the work done by Prof. Putman at University of Michigan, USA, which stated sorghum (*Sorghum bicolor*) as a potent allelopathic crop and he suggested that if fall planted sorghum is killed by frost and left in the field, its residues can kill weeds as common purslane (*Portulaca oleracea*) and smooth crab grass (*Digitaria ischaemum*) (Putnam and DeFrank 1983). With little information about the subject of allelopathy, a PhD dissertation for field application of allelopathy was taken up in 1984 by Cheema under the supervision of Prof Saeed Ahmad (Late).

Sorghum being a common fodder crop in rainfed and irrigated cropping systems of Pakistan and the indication by Putnam was the main reason to start investigations on this crop. The farmers were aware of adverse effects of sorghum on subsequent crops particularly wheat. The yellowing of wheat (*Triticum aestivum*) seedlings during the early growth stages was the common observation which was thought to be due to depletion of soil nutrients by the sorghum crop. Therefore, the findings of Putnam regarding sorghum and suppression of various weeds by its decomposing residues was not merely the physical smothering, rather phytotoxins released from sorghum were also involved. With this background information, the challenge was accepted and it is noteworthy that during the first year, laboratory trials showed prominent inhibitory effects in which fresh sorghum sap was used in petri plates. The sap trials were repeated and the sap exhibited selective inhibitory effects, although it delayed the initiation of germination in wheat and also restricted its seedling growth but the germination and seedling growth of common weeds of

Table 6.1 Effect of sorghum sap on germination of some weeds and wheat

Species	Inhibition in germination (%)
Lambsquarters (*Chenopodium album*)	100
Field bindweed (*Convolvulis arversis*)	100
Littleseed canarygrass (*Phalaris minor*)	100
Wild oat (*Avena fatua*)	77
Wheat (*Triticum aestivum*)	50

Source Cheema (1988)

Control without sorghum   Whole sorghum incorporated at maturity

Fig. 6.1 Allelopathic effects of sorghum under field conditions

wheat as lambsquarters (*Chenopodium album*), field bindweed (*Convolvulus arversis*), little seed canary grass (*Phalaris minor*) and wild oat (*Avena fatua*) was much less than wheat (Table 6.1).

The second-year field experiments (1985) became a landmark in which sorghum (cv. JS 263) was planted and in the same plots its various parts as leaf, stem, roots, or whole plants were incorporated. Visible inhibitory effects on weed flora and the following wheat crop were noticed (Fig. 6.1; Cheema 1988).

Cheema and Saeed continued the work and various other aspects, appropriate fertilizer dose to wheat crop was found to mitigate toxic effects of sorghum while weeds density and biomass was considerably reduced under sorghum treatments. This work was expanded to other crops as pearl millet (*P. glaucum*), maize (*Zea mays*), and sunflower (*Helianthus annuus*) in addition to sorghum. The inhibitory allelopathic effects on weeds were in this order sorghum > pearl millet > maize. Sorghum and pearl millet also inhibited the wheat grain yield while, maize showed some promotive effect on wheat yield. Allelopathic effects of sorghum and pearl millet were modified by fertilizer and conventional tillage (Arshad 1995).

On similar patterns, Naseem (1997) investigated sunflower for its potential against weeds and wheat. His work further strengthened the findings of Cheema and Arshad. In continuation of his laboratory results (Cheema 1988), Cheema et al. (1990) investigated the subsequent inhibitory effects of wheat stubbles on cotton

(*Gossypium arboreum*) under field conditions. It was found that double irrigation before sowing wheat, improved cotton germination due to dilution of wheat allelochemicals. One application of fertilizer decreased inhibitory effects of wheat on cotton germination (unpublished work by Cheema).

A new era began in the history of allelopathy in 1995, when on the suggestion of Ahmad and Cheema, allelopathic water extracts of sorghum and sunflower as foliar spray in a field trial were used. The results were so encouraging that in future, Cheema focused most of his research activities on the use of allelopathic water extracts as natural herbicides. Cheema and his associates have completed two national projects at different locations in Punjab, Pakistan. They concluded that a combination of allelopathic crops extracts (sorghum, sunflower, brassica) can decrease the herbicides usage by 50 to 75 % in field crops such as wheat, maize, rice (*Oryza sativa*), and cotton (Cheema and Irshad 2004; Cheema et al. 2004; Iqbal and Cheema 2007; Jamil et al. 2009).

Further studies (Jamil et al. 2009; Razzaq et al. 2010; Mushtaq et al. 2010a) revealed that water extract of mulberry (*Morus alba*) combined with the sorghum and sunflower significantly inhibited weeds in wheat fields. In a wire house experiment, Haq et al. (2010) found 80 % inhibition of Bermuda grass (*Cynodon dactylon*) seedling and 41 % increase in wheat grain weight with two foliar sprays of mulberry leaf water extract. Perveen et al. (2009) identified allelochemicals as 3, 4-dihydroxy cinnamic acid, caffeic acid, and 4-hydroxybenzaldehyde that retarded the germination of little seed canary grass, with little inhibitory effects on wheat. In other field studies mulberry extract mixed with the previously mentioned extracts suppressed germination and growth of horse purslane (*Trianthema portulacastrum*), up to 76 % (Mushtaq 2007). It is hoped that allelopathic extracts either as water or dried powder, may possibly emerge as natural herbicides in the near future.

Although growth-enhancing effects of allelopathy are mentioned in the literature, very little attention is paid to this very vital aspect; since scanty information is available. Some indication of promotive effects of brassica pollen is available (Grove et al. 1979) and a compound as brassinolide is identified. However, several reports affirm that at lower concentrations the allelopathic extracts stimulate certain growth processes as germination of different test species (Cheema 1988; Randhawa et al. 2002; Anwar et al. 2003). Cheema and his student tested Brassica 2 % extract on wheat as foliar spray under field conditions and found 18 % increase in wheat yield (Cheema and Imran unpublished work). This work has been taken up as a regular feature of research activities by the research team of Cheema. Canola and moringa (*Moringa oleifera*) extracts were used as foliar sprays on maize. It was noted that with two sprays of moringa and canola mixture sprayed at 30 and 40 DAS increased maize grain yield by 83 % (Hussain 2010).

With this brief introduction and history of allelopathy in Pakistan, in this chapter the summary of the salient findings of allelopathic application in crop production in Pakistan has been discussed.

6.2 Allelopathy for Weed Management

Weeds are the aggressive, troublesome, competitive, and undesirable elements of crop lands that pose multidimensional problems in every cropping system, the most important of which is reduction in crop yields due to interference (competition, allelopathy or both). Modern agriculture is productivity oriented and relies predominantly on synthetic inputs to tackle weeds (Sadeghi et al. 2010). Intensive herbicide use over the past few decades for controlling weeds is posing serious ecological and environmental threats to the planet and its inhabitants. Herbicide residues in produce, soil and ground water, shifts in weed populations, evolution of resistant weed biotypes, and associated health hazards have diverted the research attention to discover and establish alternative weed management strategies. There is an ever-increasing thrust for organically produced commodities, the world over (Jamil et al. 2009). Reducing dependence upon traditional practices and synthetic herbicides and finding alternative strategies for weed management is the need of time (Farooq et al. 2011a). During last two decades, there has been a focus on plant-derived materials as an eco-friendly approach which can substitute herbicides for weed control (Cheema et al. 1997, 2001, 2002a–c; Jabran et al. 2010a, b; Farooq et al. 2011a). Allelopathic extracts have been exploited for weed control, and they have shown the potential as important tool for weed management in field crop production (Cheema et al. 1997, 2001, 2002a–c; Farooq et al. 2011a).

Utilization of allelopathic properties of native plant/crop species offers promising opportunities for this purpose. Allelopathic potentiality under field conditions can be utilized in different ways to manage weeds, i.e., surface mulch (Cheema et al. 2000a), incorporation into the soil (Ahmad et al. 1995; Matloob et al. 2010), aqueous extracts (Khaliq et al. 2002; Iqbal and Cheema 2007; Jabran et al. 2008, 2010a, b), combined application with lower herbicide doses (Khaliq et al. 2002; Iqbal and Cheema 2008; Razzaq et al. 2010) or mix cropping/intercropping (Iqbal et al. 2007). In the following lines, application of allelopathy for weed management in field crops has been discussed.

6.2.1 *Aqueous Allelopathic Extracts*

Most of the secondary compounds, possessing inhibitory activity are water soluble and after extraction in water can be used as "nature's own herbicide". In such aqueous extracts, water serves as the carrier and medium to express the allelopathic activity (Farooq et al. 2011a). Although several studies make use of organic solvents for extraction of allelochemicals besides water (Iqbal 2007), the use of aqueous allelopathic plant extracts offers a viable and pragmatic option for sustainable weed management. Aqueous allelopathic water extracts have shown promising results in many studies (Cheema et al. 1997, 2000a, b; Shahid et al. 2007; Iqbal and Cheema 2008; Jamil et al. 2009). In this section herbicidal potential of aqueous extracts of potential allelopathic crops and trees has been discussed.

6.2.1.1 Sorghum

Sorghum is the most extensively studied crop regarding its allelopathic potential (Weston and Duke 2003). Cheema and Khaliq (2000) prepared the aqueous extract after soaking mature sorghum plants in water for 24 h and recorded 35–49 % inhibition of weed density and biomass in wheat under semiarid conditions of Punjab (Table 6.2). Early research work in this context was focused on optimizing frequency, concentration and dose of sorghum water extract for weed management in a number of field crops with diversified weed flora (Cheema et al. 1997, 2000b; Khaliq et al. 1999; Cheema and Khaliq 2000). Simultaneously, susceptibility of various weed species to sorghum water extract was also evaluated in terms of their germination response and seedling growth in various bioassays (Iqbal 1997; Ahmad 1998; Randhawa et al. 2002). Shahid et al. (2006) from bioassay studies concluded that aqueous sorghum extract was inhibitory to germination and seedling growth of wheat and its associated weeds, although wheat was comparatively more tolerant to this extract. Sorghum extract also suppressed the germination of horse purslane (Randhawa et al. 2002) and sprouting of purple nutsedge (*Cyperus rotundus*) tubers (Iqbal 2007). Javaid et al. (2006) showed the susceptibility of parthenium (*Parthenium hysterophorus*) to allelochemicals contained in the shoot and root aqueous extracts of sorghum. Aqueous extract (10 %) of sorghum cultivars exhibited differential allelopathic effects eliciting purple nutsedge as more susceptible test species than horse purslane (Cheema et al. 2007).

In wheat, application of sorghum water extract at various rates and frequencies furnished reductions in weed density and biomass, with a simultaneous increase in grain yield (Cheema et al. 1997; Cheema and Khaliq 2000; Table 6.2). A single spray of 5 % sorghum water extract at 30 days after sowing (DAS) increased wheat yields by 14 % and suppressed weed biomass by 20–40 % (Cheema et al. 1997). In further investigations, Cheema et al. (2002b) showed that one foliar spray of sorghum water extract at 30 DAS or two sprays each at 30 and 60 DAS inhibited the density and biomass of weed species as lambsquarters by 26–32 and 39–48 %, little seed canary grass by 21–34 and 40–49 %, wild oat by 21–27 and 26–35 %, field bindweed by 26–36 and 35–40 %, toothed dock by 27–38 and 35–46 %, respectively. However, exception was observed regarding some species, as density and biomass of sweet clover (*Meliliotus albus*) was either increased or remained unchanged relative to control. Nevertheless, single and multiple applications resulted in similar weed suppression magnitude (Cheema and Khaliq 2000).

Besides as a potent natural weed inhibitor in wheat, sorghum water extract was also effective against weed flora of other field crops of both winter and summer seasons including soybean (*Glycine max*; Khaliq et al. 1999), rapeseed (*Brassica napus*; Bhatti et al. 2000), sunflower (Nawaz et al. 2001), cotton (Cheema et al. 2000a), rice (Irshad and Cheema 2004), maize (Cheema et al. 2004) and mungbean (*Vigna radiata*; Cheema et al. 2001). The extent of suppression in weed density and biomass in these crops was 27 and 16 %, 39–62 and 43–85 %, 16–19 and 21–27 %, 54 and 40 %, 0 and 41 %, 12–55 and 26–67 % and 11–32 and 14–44 %, respectively. Sorghum water extract at 12 and 15 L ha^{-1} as pre-emergence spray

Table 6.2 Allelopathic potential of water extracts for weed suppression in field crops

Allelopathic extract	Frequency[a]; time of application	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
Sorghum (*Sorghum bicolor* L.)	Three; 15, 30 and 45 DAS[b]	Cotton	*Trianthema portulacastrum*	Reduction in total weed density (47 %) and dry weight (DW) (29 %)	45	Cheema et al. (2002c)
	One; 30 DAS	Wheat	*Fumaria indica* *Phalaris minor*	Reduction in total weed density (21.6 %) and DW (35.4 %)	11	Cheema and Khaliq (2000)
	Two; 30, 60 DAS		*Rumex dentatus* *Chenopodium album*	Reduction in total weed density (23.1 %) and DW (38.7 %)	15	
	Two; 30, 60 DAS			Reduction in total weed density (44.2 %) and DW (49 %)	20	
	Two; 30, 60 DAS			Reduction in total weed density (39.0 %) and DW (36.0 %)	14	
	One; 30 DAS	Mungbean	*Cyperus rotundus* *Chenopodium album*	Reduction in total weed density (17.54 %) and DW (23.73 %)	8.23	Cheema et al. (2001)
	Two; 30, 60 DAS		*Convolvulus arvensis*	Reduction in total weed density (31.58 %) and DW (44.11 %)	17.75	
	One; 20 DAS	Cotton	*Trianthema portulacastrum* *Convolvulus arvensis*	Reduction in total weed DW (32.6 %)	17.7	Cheema et al. (2000a, 2000b)
	Two; 20, 40 DAS		*Cynodon dactylon* *C. rotundus.*	Reduction in total weed DW (35.2 %)	59.0	
	Three; 20, 40, 60 DAS			Reduction in total weed DW (40.1 %)	23.0	
	One; 20 DAS	Sunflower	*Cyperus rotundus* *Trianthema portulacastrum*	Reduction in total weed density (19.3 %) and DW (27.2 %)	7.7	Nawaz et al. (2001)
	One; 40 DAS			Reduction in total weed density (15.8 %) and DW (19.12 %)	3.6	

(continued)

Table 6.2 (continued)

Allelopathic extract	Frequency[a]; time of application	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
Sorghum	Two, 15, 30 DAS)	Mungbean	*Cyperus rotundus* *Chenopodium album* *Convolvulus arvensis*	Reduction in total weed DW (59.62 %)	4.0	Khaliq et al. (2002)
Sunflower (*Helianthus annuus* L.)	Two, 30, 40 DAS	Wheat	*Phalaris minor* *Avena fatua*	Reduction in total weed density (16.53 %)	1.58	Cheema et al. (2003a)
	Two, 30, 40 DAS		*Melilotus officinalis* *Rumex obtusifolius*	Reduction in total weed density (33.59 %) and DW (2.22 %)	5.50	
Eucalyptus (*Eucalyptus camaldulensis* L.)	Two, 30, 40 DAS			Reduction in total weed density (15.86 %) and DW (22.75 %)	–	
Sorghum + Sunflower + Eucalyptus	One, 30 DAS			Reduction in total weed density (27.53 %) and DW (34.26 %)	3.47	
Sorghum	Two, 30, 40 DAS		*Phalaris minor* *Avena fatua*	DW reduction in *Phalaris minor* (23–41 %) and *Avena fatua* (21–41 %)	39	Jamil et al. (2009)
Sorghum + Eucalyptus	Two, 30, 40 DAS			DW reduction in *Phalaris minor* (13–28 %) and *Avena fatua* (28–32 %)	47.5	
[c]Sorghum + Sunflower	Two, 30, 40 DAS			DW reduction in *Phalaris minor* (30–35 %) and *Avena fatua* (24–39 %)	62	

Table 6.2 (continued)

Allelopathic extract	Frequency[a]; time of application	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
Sorghum + Sesame (*Sesamum indicum* L.)	Two, 30, 40 DAS			DW reduction in *Phalaris minor* (21–24 %) and *Avena fatua* (19–24 %)	44	
Sorghum + tobacco *Nicotiana tobaccum* L.)	Two, 30, 40 DAS			DW reduction in *Phalaris minor* (10–14 %) and *Avena fatua* (14 %)	18.5	
Sorghum + Brassica	Two, 30, 40 DAS			DW reduction in *Phalaris minor* (21–27 %) and *Avena fatua* (18–24 %)	19	
[d]Sorghum + Sunflower	Two, 30, 40 DAS			DW reduction in *Phalaris minor* (36–55 %) and *Avena fatua* (42–62 %)	53.5	
[e]Sorghum + Sunflower + rice (*Oryza sativa* L.)	One, 07 DAT[f]	Rice	*Echinocloa crusgalli* *Cyperus iria* *Dactyloctenum aegyptium*	Density reduction in *Echinocloa crusgalli* (18 %), *Cyperus iria* (10 %), and *Dactyloctenum aegyptium* (17 %)	29	Rehman et al. (2010)
[g]Sorghum	One, 15 DAT	Rice	*Echinocloa crusgalli* *Echinocloa colonum* *Cyperus rotundus* L. *Cyperus iria* *Dactyloctenum aegyptium*	Reduction in total weed DW (40.41 %)	12.52	Wazir et al. (2011)

(continued)

Table 6.2 (continued)

Allelopathic extract	Frequency[a]; time of application	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
Sunflower	One, Pre-emergence	Wheat	*Chenopoduim album* *Coronopus didymus* *Phalaris minor* *Avena fatua* *Convolvulus arvensis*	Reduction in total weed density (25.26 %) and DW (14.60 %)	12.38	Naseem et al. (2010)
	One, 25 DAS			Reduction in total weed density (10.63 %) and DW (11.24 %)	10.71	
	Two, Pre-emergence + 25 DAS			Reduction in total weed density (17.19 %) and DW (35.92 %)	17.38	
	Two, 25, 35 DAS			Reduction in total weed density (7.5 %) and DW (34.72 %)	15.71	
	Three, Pre-emergence + 25, 35 DAS			Reduction in total weed density (20.94 %) and DW (41.0 %)	7.28	
Mulberry	One, Pre-emergence- 25 % (v/v) extract	Wheat	*Cynodon dactylon*	Reduction in DW of weed shoot (29 %)	–	Haq et al. (2010)
	One, Pre-emergence- 50 % (v/v) extract			Reduction in DW of weed shoot (43 %)		
	One, Pre-emergence- 75 % (v/v) extract			Reduction in DW of weed shoot (64 %)		
	One, Pre-emergence- 100 % (v/v) extract			Reduction in DW of weed shoot (80 %)		

[*] Sorghum allelopathic water extract
[a] Number of sprays
[b] Days after sowing
[c] 6 L ha^{-1} each
[d] 12 L ha^{-1} each
[e] 15 L ha^{-1} each
[f] Days after transplanting [g] 15 L ha^{-1}
Extended from Farooq et al. (2011)

in cotton suppressed density of purple nutsedge by 31–56 and 35–52 %, respectively (Iqbal and Cheema 2008).

6.2.1.2 Sunflower

Sunflower (*Helianthus annuus*) is also a potent allelopathic crop (Anjum and Bajwa 2005). Chemical studies of sunflower have revealed its richness in phenolic compounds and terpenoids, particularly sesquiterpene lactones with a wide spectrum of biological activities including allelopathy (Macias et al. 1999, 2002, 2004; Ghafar et al. 2001; Anjum and Bajwa 2005). Higher phenolics content was detected in aqueous sunflower leaf extracts than aqueous stem extract. Five allelochemicals (chlorogenic, caffeic, syringic, vanillic and ferulic acid) in leaves, three in stem (chlorogenic, ferulic and vanillic acids) and only one (ferulic acid) in the roots were tentatively identified (Ghafar et al. 2001). Foliar application of aqueous sunflower extract was found to suppress total weed dry weight by 33–53 % (Cheema et al. 1997).

Anjum and Bajwa (2005) proposed the use of sunflower allelochemicals as a possible alternative for achieving sustainable weed management. Preliminary studies have shown the susceptibility of broad leaf weeds like lambsquarters to sunflower extracts (Anjum 2006). Later, herbicidal potential of aqueous sunflower water extracts was also demonstrated against noxious broad leaf weeds of wheat fields like toothed dock and lambsquarters. Although crude extract failed to score 100 % mortality of these weeds yet higher concentration accounted for substantial reduction in weed biomass and significant yield increase over control, leaf extracts showed greatest allelopathic potential than other plant parts (Anjum and Bajwa 2007a, b). Similarly, Shahid et al. (2006) reported that aqueous sunflower extract was the most-inhibitory to germination, shoot, and root length of wheat and to all species of weeds. Sunflower extract was also phytotoxic to grassy weeds like little seed canary grass (Naseem 1997). Pre-emergence application of sunflower water extract suppressed little seed canary grass density and dry weight by 50 and 65 %. Three foliar sprays of such extract as pre-emergence + 25 + 35 DAS suppressed the total weed biomass by 70 % in wheat fields (Naseem et al. 2010). Sunflower extract was also injurious to noxious invasive weed parthenium (Javaid et al. 2006).

In another study, Anjum and Bajwa (2008) while screening sunflower varieties for their suppressive allelopathic effects against weeds of wheat noticed highly significant interaction between sunflower varieties and tested weed species. Lambsquarters and toothed dock were the most sensitive to various treatments while little seed canary grass was the most resistant. Sunflower genotype Suncross-42 was the most allelopathic against selected weeds. Amelioration in suppression was enhanced with increase in concentration. Kamal and Bano (2008) mentioned the negative effects of aqueous sunflower extracts on germination and seedling growth of wheat. Adding further, Anjum and Bajwa (2010) pointed out that phytochemicals in aqueous extracts of sunflower are inhibitory to wheat, and such an inhibitory potential varied among sunflower genotypes. They proposed the use of sunflower allelochemicals for the management of weeds under field conditions that emerge 3–4 weeks after wheat seedlings.

6.2.1.3 Eucalyptus

Eucalyptus (*Eucalyptus camaldulensis*) is considered to be one of the most important allelopathic trees and possesses a number of allelochemicals. This tree is commonly planted in the command area of several canals as farm forestry in Pakistan. Khan et al. (1999) reported that aqueous extracts of eucalyptus leaves were inhibitory to germination and seedling growth of a number of crops viz. cotton, sorghum, sunflower, mungbean, and moth bean (*V. aconitifolia*). Aqueous extracts of eucalyptus leaves significantly inhibited seed germination, root and shoot length, fresh and dry weight of maize over control (Khan et al. 2004). Similar results were shown by Khan et al. (2007) when maize was grown in different soil series of Dera Ismail Khan, KPK. Marwat and Khan (2006) reported inhibition of wild oat germination and seedling growth by aqueous leaf extract of eucalyptus. Shahid et al. (2006) while evaluating the response of wheat and its associated weeds to aqueous allelopathic extracts showed that eucalyptus was inhibitory to root and shoot elongation as well as biomass accumulation in these parts of test species.

6.2.1.4 Mulberry

Inhibitory effects of mulberry against germination and seedling growth of pulses are known since last decade (Mughal 2000). Inspired from these interesting findings, Jabran et al. (2010b) conducted bioassays to evaluate the phytotoxicity of aqueous mulberry extracts against wild oat and canary grass, two pernicious weeds of wheat fields. Mulberry extract resulted in complete inhibition of germination of both the test species. In another study, Haq et al. (2010) concluded that aqueous mulberry extract suppressed the growth of Bermuda grass that was concentration-dependent, while growth of wheat was promoted. Extract concentrations of 75 and 100 % accounted for 100 % inhibition of the sprouting of Bermuda grass nodes, radicle length, plumule length, and radicle fresh weight as compared with the control.

6.2.1.5 Mixed Application of Allelopathic Aqueous Extracts

Use of allelopathic plant aqueous extracts is one way of employing allelopathy for managing weeds in agro-ecosystems (Cheema and Khaliq 2000; Jamil et al. 2009), and such extracts may be combined to enhance their efficacy. Cheema et al. (2003a) tested this idea with the application of sorghum mixed with sunflower and eucalyptus water extracts. Interestingly, mixed application of sorghum, sunflower, and eucalyptus water extracts gave >70 % weed control in wheat compared with the sole application of sorghum water extract. Adding further, Jamil et al. (2009) in a 2-year field study concluded that combination of sorghum and sunflower aqueous extracts each at 12 L ha^{-1} reduced density and dry matter of wild oat and canary grass by 42 and 62, and 36 and 55 %, respectively (Table 6.2). A combination of sorghum + sunflower + Brassica + mulberry water extracts caused complete failure of germination in horse purslane in laboratory bioassays and drastic reduction (96 %) in dry matter production (Table 6.2). In a recent study, Mahmood et al. (2010) showed 66 % reduction in shoot dry weight of horse purslane by combined application of sorghum and sunflower water extracts.

6.2.1.6 Combined Effect of Crop Water Extracts and Reduced Doses of Herbicides

Substantial scope exists to reduce the herbicide rate if applied together with allelopathic water extracts. For weed control in wheat, for example, when applied in combination with sorghum water extract (12 L ha^{-1}), rate of isoproturon application was decreased by 50–60 % (Table 6.3; Cheema et al. 2003b, c). In studies on weed management in cotton and maize, at sowing half-dose application of atrazine (150 g a.i. ha^{-1}) in combination with sorghum water extract (at 12 L ha^{-1}) controlled weeds paralleling full dose (Table 6.3; Cheema et al. 2003d; Iqbal et al. 2009). These authors further observed that combined application of sorghum water extract (at 12 L ha^{-1}) and pendimethalin at one-third (of the standard) dose produced more seed cotton yield than the full dose, even though weed suppression was relatively lesser. In another study on cotton, pre-emergence application of sorghum water extract (12 and 15 L ha^{-1}) in combination with half and one-third dose of herbicide (S. metolachlor), was more effective in controlling purple nutsedge than the standard dose (Iqbal and Cheema 2008).

In a field study on wheat, isoproturon application at standard rate provided 94.10 and 78.5 % reduction in total weed density and dry weight, respectively with a yield gain of 34 % over weedy check. However, mixed application of isoproturon at half rate with sorghum water extract provided 94.3 and 64.8 % reduction in total weed density and dry weight, respectively with 32.3 yield gain over weedy check (Table 6.3; Cheema et al. 2003b). Among the weeds, little seed canary grass was the main weed species and was followed by yellow sweet clover, swine cress, while a few plants of other weeds as toothed dock, wild oat, blue pimpernel (*Anagallis arvensis*), lambsquarters and purple nutsedge, wild medic (*Medicago denticulate* Wild) and field bindweed were also present (Cheema et al. 2003b). In a similar study on wheat, combined application of sorghum + sunflower water extracts with half dose of commercial herbicides was more effective in controlling weeds than the standard dose of respective herbicides (Table 6.3; Razzaq et al. 2010). Mushtaq et al. (2010b) proposed that herbicides use can be reduced by 75 % through integration with sorghum + sunflower extracts without

Table 6.3 Combined application of allelopathic water extracts and reduced herbicide doses for weed suppression in field crops

Allelopathic extract	Herbicide	Crop	Weed species	Weed control (%)		Yield increase (%)		Reference
				Standard herbicide	Herbicide (1/2 dose) + allelopathic extract	Standard herbicide	Herbicide (1/2 dose) + allelopathic extract(s)	
Sorghum (10 L ha^{-1})	S. metolachlor (2.3 kg a.i. ha^{-1} Dualgold 960 EC)	Mungbean	*Cyperus rotundus* *Chenopodium album* *Convolvulus arvensis*	Reduction in total weed dry weight (DW; 62.65 %)	Reduction in total weed DW (79.32 %)	25	40.3	Khaliq et al. (2002)
	Pendimethalin (330 g a.i. ha^{-1} Stomp 330 E)			Reduction in total weed DW (44.33 %)	Reduction in total weed DW (75.50 %)	14.00	24.6	
Sorghum + Brassica (15 L ha^{-1} each)	Pendimethalin (1.2 kg a.i.ha^{-1})	Canola	*Trianthema portulacastrum*	100 % reduction in density and DW	Reduction in density (91.3 %) and DW (94.18 %)	35.99	39.99	Jabran et al. (2008, 2010a)
			Cyperus rotundus	Reduction in density (32.2 %) and DW (6.34 %)	Reduction in density (42.82 %) and DW (37.46 %)			
			Chenopodium album	Reduction in density (78.37 %) and DW (83.07 %)	Reduction in density (74.27 %) and DW (62.2 %)			
			Coronopus didymus L.	Reduction in density (39.39 %) and DW (37.25 %)	Reduction in density (66.09 %) and DW (70.45 %)			
Sorghum (12 L ha^{-1})	Isoproturon (1 kg a.i. ha^{-1})	Wheat	*Phalaris minor* *Melilotus parviflora* Desf., *Coronopus didymus*	Reduction in total weed density (94.10 %) and DW (78.52 %)	Reduction in total weed density (94.25 %) and DW (64.82 %)	33.87	32.25	Cheema et al. (2003b)

(continued)

Table 6.3 (continued)

Allelopathic extract	Herbicide	Crop	Weed species	Weed control (%)		Yield increase (%)		Reference
				Standard herbicide	Herbicide (1/2 dose) + allelopathic extract	Standard herbicide	Herbicide (1/2 dose) + allelopathic extract(s)	
Sorghum + Sunflower (15 L ha^{-1} each)	Pendimethalin (825 mL a.i. ha^{-1}; $_{Stomp330E}$)	Sunflower	*Chenopodium album*, *Melitotus indica*	Reduction in total weed density (95 %) and DW (86 %)	Reduction in total weed density (84 %) and DW (67.26 %)	19	16.44	Awan et al. (2009).
Sorghum (12 L ha^{-1})	S. metolachlor (2.15 kg a.i. ha^{-1})	Cotton	*Cyperus rotundus*	Reduction in weed density (82 %) and DW (86 %)	77 % reduction in both weed density and DW	33.85	31.57	Iqbal and Cheema (2008)
Sorghum (10 L ha^{-1})	Pendimethalin (1 kg a.i. ha^{-1})	Cotton	*Cyperus* rotundus	Reduction in weed density (34.78) and DW (50.98 %)	Reduction in weed density (39.13 %) and DW (37.25 %)	19.96	7.97	Iqbal et al. (2009)
			Trianthema portulacastrum	Reduction in weed density (50.54 %) and DW (70.08 %)	Reduction in weed density (51.92 %) and DW (50.31 %)			
	S. metolachlor (2 kg a.i. ha^{-1})		*Cyperus rotundus*	Reduction in weed density (52.17 %) and DW (61.41 %)	Reduction in weed density (47.82 %) and DW (62.82 %)	18.14	3.52	
			Trianthema portulacastrum	Reduction in weed density (53.84 %) and DW (56.91 %)	Reduction in weed density (53.85 %) and DW (56.60 %)			
Sorghum + Sunflower + Rice (15 L ha^{-1} each)	Butachlor (1200 g a.i. ha^{-1})	Rice (*Oryza sativa* L.)	*Echinocloa crusgalli*	Reduction in weed density (80 %) and DW (79 %)	Reduction in weed density (75 %) and DW (66 %)	77	61	Rehman et al. (2010)
			Cyperus iria	Reduction in weed density (79 %) and DW (74 %)	Reduction in weed density (67 %) and DW (71 %)			
			Dactyloctenum aegyptium	Reduction in weed density (76 %) and DW (80 %)	Reduction in weed density (74 %) and DW (76 %)			

(continued)

Table 6.3 (continued)

Allelopathic extract	Herbicide	Crop	Weed species	Weed control (%)		Yield increase (%)		Reference
				Standard herbicide	Herbicide (1/2 dose) + allelopathic extract	Standard herbicide	Herbicide (1/2 dose) + allelopathic extract(s)	
Sorghum + Sunflower + Rice (15 L ha^{-1} each)	Pretilachlor (625 g a.i. ha^{-1})		*Echinocloa crusgalli*	Reduction in weed density (82 %) and DW (73 %)	Reduction in weed density (76 %) and DW (60 %)	74	59	
			Cyperus iria	Reduction in weed density (83 %) and DW (75 %)	Reduction in weed density (66 %) and DW (60 %)			
			Dactyloctenum aegyptium	Reduction in weed density (82 %) and DW (85 %)	Reduction in weed density (74 %) and DW (81 %)			
Sorghum + Sunflower + Rice (15 L ha^{-1} each)	Ethoxysulfuronethyl (30 g a.i. ha^{-1})		*Echinocloa crusgalli*	Reduction in weed density (81 %) and DW (73 %)	Reduction in weed density (72 %) and DW (62 %)	74	41	
			Cyperus iria	Reduction in weed density (79 %) and DW (75 %)	Reduction in weed density (69 %) and DW (64 %)			
			Dactyloctenum aegyptium	Reduction in weed density (85 %) and DW (82 %)	Reduction in weed density (75 %) and DW (69 %)			
Sorghum (15 L ha^{-1})	Penaxolam (30 mL a.i. ha^{-1})	Rice	*Echinocloa crusgalli* *Echinocloa colonum* *Cyperus rotundus* *Cyperus iria* *Dactyloctenum aegyptium*	Reduction in total weeds DW (26 %)	Reduction in total weeds DW (34.75 %)	10.84	4.18	Wazir et al. (2011)
Sorghum + Sunflower (18 L ha^{-1} each)	Bensulfuron + Isoproturon (	Wheat	*Phalaris minor*	Reduction in weed density (84.62 %) and DW (93.37 %)	Reduction in weed density (88.46 %) and DW (94.90 %)	15.24	23.81	Razzaq et al. (2010)
	(1,050 g a.i. ha^{-1} Cleaner 70 WP)		*Coronopus didymus*	Reduction in weed density (81.87 %) and DW (64.29 %)	Reduction in weed density (88.24 %) and DW (87.14 %)			
	Metribuzin (175 g a.i. ha^{-1} Sencor 70 WP)		*Phalaris minor*	Reduction in weed density (92.31 %) and DW (46.43 %)	Reduction in weed density (69.23 %) and DW (82.86 %)	21.43	20.00	

(continued)

Table 6.3 (continued)

Allelopathic extract	Herbicide	Crop	Weed species	Weed control (%)		Yield increase (%)		Reference
				Standard herbicide	Herbicide (1/2 dose) + allelopathic extract	Standard herbicide	Herbicide (1/2 dose) + allelopathic extract(s)	
			Coronopus didymus	Reduction in weed density (90.60 %) and DW (77.14 %)	Reduction in weed density (88.33 %) and DW (97.96 %)			
	Metribuzin + fenoxaprop (190 g a.i. ha^{-1} Bullet 38 SC)		*Phalaris minor*	Reduction in weed density (88.46 %) and DW (92.35 %)	Reduction in weed density (82.31 %) and DW (96.94 %)	17.14	34.29	
			Coronopus didymus	Reduction in weed density (87.25 %) and DW (91.43 %)	Reduction in weed density (87.25 %) and DW (94.29 %)			
	Mesosulfuron + idosulfuron (120 g a.i. ha^{-1} Atlantis 12 EC)		*Phalaris minor*	Reduction in weed density (42.31 %) and DW (85.21 %)	Reduction in weed density (88.46 %) and DW (97.96 %)	13.33	21.90	
			Coronopus didymus	Reduction in weed density (90.60 %) and DW (74.29 %)	Reduction in weed density (87.25 %) and DW (92.86 %)			

Extended from Farooq et al. (2011)

compromising yield and net benefits for cost-effective and eco-friendly management of wild oat and canary grass in wheat.

Likewise in rice, combined application of mixture of allelopathic water extracts with half dose of pre-emergence herbicides butachlor, pretilachlor, and ethoxysulfuron ethyl reduced barnyard grass, flat sedge, and crowfoot grass density by 75, 67, and 74 % and their dry weight by 66, 71, and 76 %, respectively (Table 6.3; Rehman et al. 2010).

Recent field studies evaluated allelopathic suppression of weeds in a canola field using crop water extracts—sorghum, sunflower, Brassica and rice—applied in combination with reduced doses of pendimethalin (one-third and half the recommended dose) (Jabran et al. 2008, 2010a). Crop water extracts at 15 L ha^{-1} each combined with pendimethalin at 400 and 600 g a.i. ha^{-1} were sprayed immediately after sowing, while the standard dose of pendimethalin was taken as control. Application of rice and sorghum water extracts in combination with half dose of pendimethalin suppressed the total weed population the most; by 67.58 and 66.21 % at 40 and 60 DAS, respectively. All treatments reduced total weed dry weight by more than 80 % at 40 DAS, while at 60 DAS reductions ranged from 44.93 to 63.99 %. Plots treated with sorghum and sunflower water extracts + 600 g a.i. ha^{-1} pendimethalin recorded maximum seed yields of 2.6 t ha^{-1}, which was 39.99 % more than the control. The authors concluded that 50–67 % less herbicide combined with allelopathic water extracts may be effective for weed control and increase yields in canola (Jabran et al. 2008, 2010a).

6.2.1.7 Powder Formulation

The powder made by hot air drying of sorghum water extract was investigated by Anwar (2011). The objective was to replace voluminous water extracts with a handy powder. The use of 18 g ha^{-1} of powder was as effective as 18 L ha^{-1} of boiled concentrated extract and 360 L ha^{-1} of water extract obtained after 24 h soaking in water. Sorghum powder reduced the population of two common weeds of wheat as lambsquarters and curly dock by 43 and 52 % respectively with 24.5 % increase in wheat grain yield. This was the first study of its type, which needs further validation. Costs involved in water extracts and powder formulation must be considered.

6.2.2 Mulching and Crop Residues

Mulch is spread over the soil surface to suppress weeds, among other strategies. Mulches obstruct seed germination of weeds and inhibit weed seedling growth through the release of allelochemicals. However, established weeds are difficult to control with mulches.

Residues of certain crops can pose a chemical (allelopathic) as well as a physical effect on the growth and development of subsequent crops and weeds (Matloob et al. 2010). In situ incorporation of whole sorghum plant or its various parts alone or mixed with each other suppressed weed growth in wheat field (Cheema and Khaliq 2000). Cheema et al. (2004) stated that sorghum mulch (10–15 t ha^{-1}) decreased the dry weight of purple nutsedge by 38–41 % compared to control (Table 6.4). Phytotoxicity of dried sorghum, sunflower and Brassica residues against purple nutsedge and horse purslane has been reported by Matloob et al. (2010) and Khaliq et al. (2011). These authors concluded that integration of different crop residues can provide satisfactory weed suppression than sole application of such residues. It was further confirmed by the field studies using maize as a test crop (Khaliq et al. 2010). In a dry seeded rice field, incorporation of sorghum residues at 8 t ha^{-1} scored over 50 % reduction weed density and dry weight (Riaz 2010). Incorporation of wheat straw also suppressed the germination dynamics, early seedling growth and photosynthetic pigments in horse purslane (Aslam 2010).

Soil incorporation of chopped sorghum mulch reduced the total weed dry weight from 26–56 % with yield increase of 6–17 % over weedy check in wheat (Table 6.4; Cheema and Khaliq 2000). In cotton however, application of sorghum surface mulch substantially reduced the weed density with significant yield increase (Table 6.4; Cheema et al. 2000a). In maize, however, 14–23 % mortality of purple nutsedge was observed when sorghum residue was applied at 10–15 t ha^{-1}(Cheema et al. 2001).

6.2.3 Intercropping

Intercropping is growing of two or more crops together. It can be used as an effective weed control strategy. Different plant species growing together enhance weed control by increasing shade and weed-crop competition through closer crop spacing and by releasing allelochemicals. It has high net returns, more biological diversity, less chance of total crop failure, reduced nutrient requirements, better use of resources, and suppressive effects on weeds, insect pests and diseases (Ali et al. 2000).

Allelopathy can be especially important for intercropping systems. Allelopathy is an intercropping benefit that can be exploited for managing weeds in agro-ecosystems. It is possible to utilize allelopathic interactions in farming as a cost effective alternative of synthetic chemical inputs for controlling weeds, thus contributing toward sustainable agriculture. In a study on cotton intercropping with single or double rows of sorghum, soybean and sesame (*Sesamum indicum*), all the intercropping systems significantly inhibited purple nutsedge density and dry matter production relative to control. However, cotton intercropping with two rows of sorghum and soybean were the most effective in controlling purple nutsedge (Iqbal et al. 2007; Table 6.5). In another study, sorghum intercropped with maize

Table 6.4 Effect of allelopathic mulches and crop residues on weed suppression in field crops

Allelopathic source	Application mode and rate	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
Sorghum	Soil incorporation (2 t ha^{-1})	Wheat	*Fumaria indica* Hauskn.,	Reduction in total weeds DW (26 %)	6	Cheema and Khaliq (2000)
	Soil incorporation (4 t ha^{-1})		*Phalaris minor* Retz., *Rumex dentatus* L.,	Reduction in total weeds DW (48 %)	16	
	Soil incorporation (6 t ha^{-1})		*Chenopodium album* L.	Reduction in total weeds DW (56 %)	17	
Sorghum	Surface mulch (3.5 t ha^{-1})	Cotton	*Trianthema portulacastrum* L.	Reduction in total weeds DW (53.2 %)	69.2	Cheema et al. (2000a)
			Convolvulus arvensis L.	Reduction in total weeds DW (80.9 %)		
			Cynodon dactylon (L.) Pers.	Reduction in total weeds DW (5 %)		
			Cyperus rotundus L.	Reduction in total weeds DW (16.5 %)		
	Surface mulch (7.0 t ha^{-1})		*Trianthema portulacastrum* L.	Reduction in total weeds DW (39.7 %)	53.3	
			Convolvulus arvensis L.	Reduction in total weeds DW (92.1 %)		
			Cynodon dactylon (L.) Pers.	Reduction in total weeds DW (63.6 %)		
			Cyperus rotundus L.	Reduction in total weeds DW (60.76 %)		
	Surface mulch (10.5 t ha^{-1})		*Trianthema portulacastrum* L.	Reduction in total weeds DW (49.8 %)	119.3	
			Convolvulus arvensis L.	Reduction in total weeds DW (96.6 %)		
			Cynodon dactylon (L.) Pers.	Reduction in total weeds DW (79.7 %)		
			Cyperus rotundus L.	Reduction in total weeds DW (35.4 %)		

(continued)

Table 6.4 (continued)

Allelopathic source	Application mode and rate	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
Sorghum	Surface mulch (10 t ha^{-1})	Mungbean	*Trianthema portulacastrum*	Reduction in weed density (14 %) and DW (35.2 %)	7.2	Cheema et al. (2000b)
	Surface mulch (15 t ha^{-1})			Reduction in weed density (19.7 %) and DW (44.8 %)	12	
Sorghum + Sunflower + Rice	Soil incorporation (5 t ha^{-1} each)	Maize	*Trianthema portulacastrum*	Reduction in weed density (76.47 %) and DW (67.86 %)	47	Khaliq et al. (2010)
			Cyperus rotundus	Reduction in weed density (47.78 %) and DW (61.89 %)		
	Soil incorporation (7.5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (68.17 %) and DW (65.45 %)	45	
			Cyperus rotundus	Reduction in weed density (43.47 %) and DW (79.66 %)		
Sorghum + Rice + Brassica	Soil incorporation (5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (68.17 %) and DW (65.45 %)	35	
			Cyperus rotundus	Reduction in weed density (61.65 %) and DW (62.67 %)		
	Soil incorporation (7.5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (69.57 %) and DW (68.53 %)	47	
			Cyperus rotundus	Reduction in weed density (86.94 %) and DW (97.03 %)		
Sunflower + Rice + Brassica	Soil incorporation (5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (60.53 %) and DW (60.14 %)	41	
			Cyperus rotundus	Reduction in weed density (78.32 %) and DW (91.80 %)		
	Soil incorporation (7.5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (72.31 %) and DW (70.05 %)	38	

(continued)

Table 6.4 (continued)

Allelopathic source	Application mode and rate	Crop	Weed species	Weed control (%)	Yield increase (%)	Reference
			Cyperus rotundus	Reduction in weed density (60.83 %) and DW (76.70 %)		
Sorghum + Sunflower + Brassica	Soil incorporation (5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (72.82 %) and DW (83.16 %)	39	
			Cyperus rotundus	Reduction in weed density (65.27 %) and DW (88.15 %)		
	Soil incorporation (7.5 t ha^{-1} each)		*Trianthema portulacastrum*	Reduction in weed density (79.91 %) and DW (88.83 %)	54	
			Cyperus rotundus	Reduction in weed density (86.94 %) and DW (97.21 %)		
Sorghum	Surface mulch (10 t ha^{-1})	–	*Cyperus rotundus*	Reduction in weed density (35.71 %) and DW (48.81 %)	–	Mahmood and Cheema (2004)
	Surface mulch (15 t ha^{-1})			Reduction in weed density (51.01 %) and DW (62.41 %)		
	Soil incorporation (10 t ha^{-1})			Reduction in weed density (30.31 %) and DW (47.16 %)		
	Soil incorporation (15 t ha^{-1})			Reduction in weed density (46.07 %) and DW (57.48 %)		

Table 6.5 Effect of allelopathic intercropping on weed dry weight and crop yields

Treatments	Reduction in weed dry weight (%)	Average yield of intercrops (kg ha^{-1})	Average seed cotton yield (kg ha^{-1})
Control (weedy check)	–		1,485
Cotton 75 cm apart rows (two hoeing)	90		1,970
Cotton 75 cm apart rows + single row of sorghum	89	721	1,211
Cotton 75 cm apart rows + two rows of sorghum	92	958	1,157
Cotton 75 cm apart rows + single row of soybean	83	274	1,367
Cotton 75 cm apart rows + two rows of soybean	92	348	1,202
Cotton 75 cm apart rows + single row of sesame	80	348	1,199
Cotton 75 cm apart rows + two rows of sesame	87	669	1,141

Data from Iqbal et al. (2007)

suppressed density and biomass of purple nutsedge, field bindweed and horse purslane compared with other treatments comprising of sunflower and mungbean (Khalil et al. 2010).

6.3 Allelopathy for Insect-Pest Control

Although fewer reports are available, allelopathy has also a potential in managing insect pests. Neem (*Azadirachta indica*) and its extracts are being used since decades for managing stored grain and other insect pests. Several other indigenous plants of Pakistan have also been evaluated in this regard (Jilani and Haq 1984; Jilani et al. 1989, 1991, 1993). For instance, Saljoqi et al. (2006) evaluated leaves and drupes of bakain (*Melia azdarach*), leaves of habulas (*Myrtus communis*) and mint (*Mentha longifolia*), shoots and seeds of harmal (*Pegnum harmala*) and lemon grass (*Cymbopogon citrates*) roots against rice weevil (*Sitophilus oryzae*) Maximum control was achieved from bakain drupes with 61.2 % mortality followed by habulas (48.40 %), mint (47.40 %) and bakain leaves (46.80 %). In a study, Zia et al. (2011) evaluated water extracts of olive (*Olea europea*), tea (*Thea chinensis*), *Canabis sativa*, elephanta (*Elephantia* sp.), neem, *Jacaranda mimosifolia*, garlic (*Allium sativum*), *Syzygium aromaticum* L., black pepper (*Piper nigrum*) and red chillies

(*Capsicum annum*) against stored chickpea beetle (*Callosobruchus chinensis*). Aqueous extract of black pepper was the most effective in this regard followed by cloves, neem and garlic.

Like stored grain pests, allelopathic plants may also be used for suppressing insect pests in field and horticultural crops. In this regard, Ahmad et al. (2011) reported that application of neem based insecticide, for example Neemosal, may effectively control the initial or low mealybug infestation. For controlling wheat aphids, extracts of orange peel *(Citrus sinensis*); bitter gourd (*Momordica dioica*); garlic (*Allium vineale*); hot pepper (*Capsicum frutescens*) and tobacco (*Nicotiana tabacum*) were evaluated in a field study. Application of orange peel extract was the most effective in this regard with 65.69 % aphid mortality followed by garlic (57.91 %), and tobacco (57.90 %) extracts (Iqbal et al. 2011).

Extractants are also very important in determining the efficacy of an allelopathic source, for example Iqbal et al. (2010) evaluated the petroleum ether, acetone and ethanol extracts of sweet flag (*Acorus calamus*), neem and turmeric (*Curcuma longa*) for growth inhibition of *Sitotroga cerealella*. Petroleum ether extract of sweet flag at application rates of 1,000, 500 and 250 μg g^{-1} and its acetone extract at 1,000 and 500 μg g^{-1} completely inhibited emergence of adults.

6.4 Allelopathy for Disease Management

Aqueous extract of many allelopathic plants are known to exhibit antifungal properties. Hassan et al. (1992) reported that leaf extracts of jimson weed (*Datura stramonium*) reduced the development of rust pustules on the leaves of wheat. Mughal et al. (1996) observed that aqueous leaf extracts of garlic, jimson weed and ashwagandha (*Withania somnifera*) inhibited the growth of *Alternaria alternate*, *A. brassicola* and *Myrothecium roridum*. According to Khan et al. (1998) aqueous extract of onion (*Allium cepa*) exhibited antifungal activity against *Helminthosporium turcicum* and *Ascochyta rabiei* and that of *Calotropis procera* against *A. redicina* Bajwa et al. (2004) evaluated the allelopathic potential of parthenium against three pathogenic fungal species viz. *Drechslera hawaiiensis*, *A. alternata* and *Fusarium monilifrome*. They concluded growth suppression of pathogenic species with lower concentrations (10–50 %) of the parthenium extracts. Nonetheless, higher concentrations (60 and 70 %) of parthenium extracts stimulated the biomass production of test fungal species.

Bajwa et al. (2006) investigated the allelopathic potential of aerial parts of chickpea (*Cicer arietinum*) against *D. tetramera* Subram. & Jain, and *D. hawaiiensis*. Chickpea was found to contain antimicrobial compound(s) for the control of plant pathogenic fungi. In another study, Shaukat et al. (2003) evaluated the impact of root leachates of spanish flag (*Lantana camara*), a tropical weed, against *Meloidogyne javanica* Treub., the root-knot nematode. Concentrated and diluted root leachate caused substantial mortality of *M. javanica* juveniles. Significant suppression of the nematode was achieved when soil was treated with a full-strength concentration of the leachate. While this high concentration retarded plant height and shoot fresh weight, more diluted concentrations actually enhanced plant growth. To establish whether this inhibition of plant growth from the leachate was the result of depleted nitrogen levels in the soil due to the leachate, soil treated with such leachates was given urea as an additional nitrogen source. Urea not only enhanced nematode suppressive activity of the root leachates but also increased seedling emergence and growth of mungbean. Application of *L. camara* root leachates in combination with *Pseudomonas aeruginosa*, a plant growth-promoting rhizobacterium, significantly reduced nematode population densities in roots and subsequent root-knot infection, and enhanced plant growth.

6.5 Allelopathy for Growth Enhancement

The promotion of plant growth by allelopathy is another aspect. Allelochemicals activate various enzymes, enhance cell division, increase ion uptake that ultimately increase plant growth and development. There are reports that lower concentrations of allelopathic extracts promote plant growth. In a field study on maize, two foliar sprays of 3 % moringa, 3 % sorghum, and 3 % Brassica water extract increased maize yield by 52, 42 and 42 % respectively over control (Jahangeer 2011). In another field study on canola, three foliar sprays of 2 % moringa + 2 % Brassica increased canola yield by 35 % over control (Iqbal 2011). In another field study on wheat, three foliar sprays of 2 % sorghum, sunflower, brassica, rice, and moringa water extracts improved the wheat grain yield by 22, 17, 18, 28 and 37 %, respectively (Cheema and Afzal unpublished work). The use of allelopathic water extracts in lower concentrations was highly economical and environmentally safe. This approach has a tremendous scope for use in organic agriculture for improving crop yield.

6.6 Allelopathy for Resistance Against Abiotic Stresses

More recently, the phenomenon of allelopathy has been evaluated for its potential in improving resistance against abiotic stresses in cereals. In this regard, Farooq et al. (2011b) soaked seeds of two rice cultivars Super Basmati and Shaheen Basmati in allelopathic extract of sunflower for 48 h. Seed soaking in sunflower water extracts significantly improved the germination and early seedling growth of both rice cultivars at 50 and 100 mM NaCl salinity levels. In another study, exogenous application of 0 % sorghum allelopathic aqueous extract substantially improved the stand establishment, morphology, allometry, leaf elongation, plant biomass, water relations, water use efficiency and total soluble phenolics under moderate and severe drought stress. Application of sorghum allelopathic extract also reduced the stomatal frequency and conductance in order to check water loss

(Munir 2011). In a similar study, exogenous application of sorghum extract (5 and 10 % aqueous extracts) at anthesis substantially improved the plant biomass, grain yield and yield related traits, water relations, membrane stability and total soluble phenolics in wheat plants subjected to heat stress (Munir 2011).

6.7 Conclusion

Allelopathy has great potential in improving the productivity of cropping systems, if used wisely. This phenomenon may be employed in organic agriculture for improving crop yields and for organic management of weeds, insect pests, and diseases to protect the environment from the hazards of agrochemicals. Development of crop cultivars with strong allelopathic potential may be strong enough to combat biotic (weeds, insect pests, and diseases) and abiotic (drought, salinity, heat, etc.) stresses. Inclusion of allelopathic crops in the rotations may also be helpful in minimizing the pest pressure. Utilization of allelopathic crop water extracts combined with reduced doses of herbicides could be the promising strategy for sustainable weed management. Focused interdisciplinary long-term research efforts should be initiated to boost the yield of crop plants by minimizing the vagaries of biotic and abiotic stresses.

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