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Article

EXPLORING THE HERBICIDAL AND HORMETIC POTENTIAL OF ALLELOPATHIC CROPS AGAINST FENOXAPROP-RESISTANT *Phalaris minor*

Exploração do Potencial Herbicida e Hormético de Culturas Alelopáticas contra ***Phalaris minor*** *Resistente ao Fenoxaprop*

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ABSTRACT - Recent increases in the development of herbicide resistance in *Phalaris minor* worldwide demand alternative non-chemical strategies to control this weed. A series of experiments were conducted under laboratory and greenhouse conditions to explore the herbicidal potential of four allelopathic crops, including maize, rice, sorghum and sunflower, at different concentrations of aqueous extracts (2.5% and 5%), residues (1%, 2% and 4%) and mulches (4, 8, and 12 ton ha^{-1}) against fenoxaprop-resistant *P. minor*. Aqueous extracts, residues and mulches provided 86-100%, 73-100% and 16-40% control of this resistant weed biotype, respectively. The dry biomass reduction due to aqueous extracts, residues and mulches was 48-100%, 48-100% and 20-54%, respectively. Mulches also caused 17-41% reduction in the seed production potential of *P. minor*. Lower concentrations of allelochemicals showed hormesis (positive effect) against some emergence and growth traits of *P. minor*. The phytotoxic chemicals of these four crops have a strong herbicidal potential against herbicide-resistant *P. minor*, and can be used as an organic alternative to control herbicide resistant *P. minor*, thus ensuring a sustainable wheat production.

Keywords: allelopathy, alternative weed management, hormesis, littleseed canarygrass, natural herbicides.

RESUMO - Aumentos recentes no desenvolvimento da resistência a herbicidas em ***Phalaris minor*** *no mundo inteiro exigem estratégias não químicas alternativas para controlar essa planta daninha. Uma série de experimentos foi conduzida em condições laboratoriais e de estufa para explorar o potencial herbicida de quatro culturas alelopáticas, incluindo milho, arroz, sorgo e girassol, em diferentes concentrações de extratos aquosos (2,5% e 5%), resíduos (1%, 2% e 4%) e coberturas (4, 8 e 12 toneladas ha*$^{-1}$*), contra* ***P. minor*** *resistente ao fenoxaprop. Os extratos aquosos, resíduos e coberturas proporcionaram controle de 86-100%, 73-100% e 16-40%, respectivamente, desse biótipo de planta daninha resistente. A redução na biomassa seca devido a extratos aquosos, resíduos e coberturas foi de 48-100%, 48-100% e 20-54%, respectivamente. As coberturas causaram também redução de 17-41% no potencial de produção de sementes de* ***P. minor****. Menores concentrações de aleloquímicos mostraram hormese (efeito positivo) contra algumas características de emergência e crescimento de* ***P. minor****. Os produtos químicos fitotóxicos dessas quatro culturas têm forte potencial herbicida contra* ***P. minor*** *resistente a herbicidas e podem ser usados como uma alternativa orgânica para controlá-la, garantindo uma produção sustentável de trigo.*

Palavras-chave: alelopatia, manejo alternativo de plantas daninhas, hormese, erva-cabecinha, herbicidas naturais.

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INTRODUCTION

Phalaris minor Retz. (littleseed canarygrass) is a self-pollinated, annual winter weed from the Poaceae family. It is a common weed of winter cereals, legumes and several other winter crops in more than 60 countries worldwide. Its morphological and phenotypic similarities to wheat crops, high seed production ability (about 300-460 seeds per plant) and early maturity (about 2 weeks before wheat harvest) has made this weed the most competitive and troublesome one of wheat (Jabran et al., 2010; Yasin and Iqbal, 2011). After the Green Revolution, the introduction of dwarf and fertilizer-responsive wheat varieties increased the problem of *P. minor*, due to the lower competitive ability of the crop. Yield losses in wheat due to solo *P. minor* infestation vary between 25 to 50% (Chhokar and Sharma, 2008), and may cause the complete failure of wheat in case of severe infestation (2,000-3,000 plants m^{-2}) (Chhokar et al*.,* 2006).

Phalaris minor control in wheat totally depends on early post-emergence crop-selective herbicides due to morphological similarities of this weed to wheat crop (Abbas et al., 2017a). A continuous use of herbicides without the integration of non-chemical weed control measures has developed herbicide- resistance in *P. minor* (Gherekhloo et al., 2012; Abbas et al., 2017a). Currently, resistance in *P. minor* against different herbicides, most commonly ACCase and ALS inhibitors, has developed in many parts of the world including India, Iran, Pakistan, Israel, Mexico, South Africa, United States and Australia (Abbas et al., 2016; Heap, 2017). Multiple resistances in *P. minor* against different sites of action (ACCase inhibitors, ALS inhibitors and PS II inhibitors) have also been reported in India and South Africa (Heap, 2017). Thus, herbicide-resistant *P. minor* is a major challenge to the sustainable production of wheat, as it may lead to a complete failure of wheat crops (Chhokar et al*.,* 2006). Therefore, investigations about natural products to control *P. minor* are very crucial to sustain the productivity of wheat, especially in organic production system.

Allelochemicals offer environmentally safe alternatives to herbicides, because they are decomposable, rarely contain halogenated atoms and are quite safer for the environment (Duke et al., 2000; Petroski and Stanley, 2009). In order to identify plant species with biologically active natural products (allelochemicals), the screening of allelopathic plants is a virtuous and commonly used approach (Duke et al., 2000). These compounds would be used for weed management directly, or their chemistry could be used to develop new herbicides. In previous reports, allelopathy is being used for weed management in several crops, including wheat (Cheema and Khaliq, 2000a). In this regard, several potential allelopathic crops, including sorghum (*Sorghum bicolor*), sunflower (*Helianthus annuus*), rice (*Oryza sativa*) and maize (*Zea mays*) have been used to manage weeds in field crops (Cheema et al., 2009; Jamil, 2009; Jabran et al., 2010). The allelochemicals in these crops act as natural herbicides. For instance, Cheema (1988) found several allelochemicals, such as gallic acid, protocateuic acid, syringic acid, vanillic acid, p-hydroxybenzoic acid, p-coumaric acid, benzoic acid, ferulic acid, m-coumaric acid, caffeic acids, dhurrin, p-hydroxybenzaldehyde and sorgoleone in sorghum. Sunflower also contains several allelochemicals, like chlorogenic acid, isochlorogenic acid, scopolin, annuionones and á-naphathol (Macias, 2002; Anjum and Bajwa, 2005). Similarly, rice also possesses several allelochemicals, like azelaic acid, r-coumaric acid, 1*H*-indole-3-carboxaldehyde, 1*H*-indole-3-carboxylic acid; 1*H*-indole-5-carboxylic acid, 1,2-benzenedicarboxylic acid bis (2-ethylhexyl) ester, r-Coumaric acid (Rimando et al., 2001). Benzoxazolinone, 5-chloro-6-methoxy-2-benzoxazolinone and 6-methoxy-2-benzoxazolinone were found in maize and showed strong inhibitory potential (Kato-Noguchi, 2000). These allelochemicals may be used as bio-herbicides to control herbicide-resistant *P. minor.*

Significant literature is available about the allelopathic potential of various crops, but information on the comparative allelopathic potential of maize, rice, sorghum and sunflower against herbicide-resistant *P. minor* has not been recognized yet. It has been observed that wheat crops grown after sorghum, sunflower and maize showed lower *P. minor* infestations. This may be due to the exposure of *P. minor* seeds in soil seed bank to the allelochemicals released by the roots and stubbles of these crops in the cropping system. These series of experiments were, therefore, conducted focusing on *P. minor* in order to investigate the herbicidal potential of aqueous extracts, residues and mulches of four allelopathic crops as organic alternatives to chemical weed control, so as to cope with the change of rapidly increasing herbicide-resistance of *P. minor*.

MATERIALS AND METHODS

Effect of aqueous extracts of allelopathic crops on the germination and seedling growth of herbicide-resistant *P. minor.*

For the preparation of aqueous extracts, shade dried plant pieces from the four crops (i.e., maize, rice, sorghum and sunflower) were weighed and placed in distilled water separately, at the ratio of 1:20 (w/v), under room temperature for 24 hours. The whole plant extract was obtained by filtering it through Whatman No.1 filter paper. Leachates were collected in separate bottles and tagged. The extract obtained after filtering was considered as 5% aqueous extract, and was used for study. Twenty fenoxaprop-resistant *P. minor* seeds (Abbas et al., 2017a) were placed in each Petri plate, separately lined with doubled layered filter paper. At the beginning of the experiment, 6 mL of each extract at 2.5% and 5% concentration were applied in each Petri plate, separately. After sowing, Petri plates were sealed with Parafilm® in order to avoid evaporation losses. Petri plates were kept in laboratory. The average minimum and maximum laboratory temperature during the experiment was recorded to be 19 ± 2 ^{o}C and 22 ± 2 ^{o}C, respectively. Petri plates were observed daily and extracts/distilled water were added when needed, according to the treatment, to keep them moist. Germination was recorded daily until constant, and the experiment was observed for 15 days.

Effects of allelopathic crop residues on the emergence and seedling growth of herbicide-resistant *P. minor*

Dried whole plant pieces from the previously mentioned four crops were ground into small pieces with the help of grinder. Crop residues were mixed with soil at the rate of 1%, 2% and 4% before sowing of *P. minor*. Twenty seeds of fenoxaprop-resistant *P. minor* (Abbas et al., 2017a) were spread on the surface of each pot and covered with same soil amount, in order to ensure uniform depth for all seeds. Then, distilled water was applied to avoid the drying out of seedlings throughout the growth period. A completely randomized design with four replications was used to conduct the experiment. Minimum and maximum laboratory temperature was 19 ± 2 ^{o}C and 22 ± 2 ^{o}C, respectively. The experiment was observed for three weeks, followed by the uprooting of seedlings, which were washed under tap water.

Effect of allelopathic crop mulches on the emergence and seedling growth of herbicide-resistant *P. minor*

Studies were conducted in a greenhouse, at the Faculty of Agriculture, University of Agriculture, Faisalabad, Pakistan, from November, 2014 to March, 2015. The greenhouse was located at about 31.25^{o} N latitude, 73.09^{o} E longitude and at an altitude of 184 m. The mean minimum and maximum temperatures in the greenhouse during the experiment were 18 ± 2 ^{o}C and 26 ± 2 ^{o}C, respectively. Relative humidity ranged from 30 to 65%. Soil free from crop residues was collected from research fields near the Department of Agronomy of the University of Agriculture, Faisalabad. Fifteen kilograms (kg) of soil were put in each pot (30 cm diameter and 45 cm depth). Soil was sandy loam, having 1.10% organic matter content and pH of 8.0. Allelopathic crop mulches of maize, rice, sorghum and sunflower at three different rates including 4, 8 and 12 ton ha^{-1} (1.2, 2.4, 3.6 g pot^{-1}) were spread on the surface of each pot after sowing *P. minor*. Twenty seeds of fenoxaprop-resistant *P. minor* (Abbas et al., 2017a) were sown in each pot at a uniform depth. The experiment was laid out in completely randomized design with four replications that were reshuffled each week in order to achieve uniform growth conditions for all plants. Twenty-seven days after sowing, the emergence percentage was counted and five plants from each pot were randomly selected to collect data for growth parameters. Remaining plants were kept growing until maturity. At start, 1.2 liter of water was applied to each pot and then, throughout the experimental period, the pots were kept moistened. At maturity, plant height, dry biomass, spike length and number of seeds per spike were recorded.

At the end of each experiment, seedlings were uprooted and washed under tap water. The length of roots and shoots was measured. Roots and shoots were oven-dried at 70 ^{o}C until a constant weight was obtained, in order to get dry biomass.

All the experiments were repeated twice; however, due to no significant differences, data were pooled through statistical analyses. When the treatment effect was significant at the 5% level, multiple mean comparison treatments were completed and letter groupings were generated using the least significant difference (LSD) at 5% significance level. The validity of normal distribution and constant variance assumptions on the error terms was verified by examining the residuals (Steel et al., 1997).

RESULTS AND DISCUSSION

Effect of allelopathic crop aqueous extracts on the germination and seedling growth of herbicide resistant *P. minor*

Results from the study showed that aqueous extracts of maize, rice, sorghum, and sunflower at 2.5 and 5% concentrations inhibited significantly the germination percentage and seedling growth of *P. minor* (Table 1). At 2.5% concentrations, sorghum and sunflower aqueous extracts caused more inhibition (up to 44.44%) than maize and rice, which caused 30.00% and 33.33% inhibition as compared to the control sample, respectively. A higher aqueous extract concentration (5%) of maize, rice, sorghum, and sunflower caused 85.88, 100, 100 and 100% germination inhibition, respectively, when compared with the control sample. Shoot length, root length and dry biomass of *P. minor* were inhibited in a pattern that was similar to that of the germination percentage. At a 2.5% extract concentration, sorghum showed more inhibition than other extracts. It caused 32.47, 41.47 and 55.69% inhibition of shoot length, root length and dry biomass, respectively. Crops including maize, rice, sorghum and sunflower caused significant inhibition of *P. minor* germination/emergence. Different types of allelochemicals have been identified in these crops (Macias et al., 2002; Anjum and Bajwa, 2005). Allelochemicals released from maize, rice, sorghum and sunflower inhibit the germination/emergence and growth of other plants, including weeds (Cheema et al., 2009; Jamil 2009; Jabran et al., 2010). Differential inhibitory response of *P. minor* against allelopathic crops might be due to varied concentrations and type of allelochemicals in tissues of different crops (Cheema, 1988; Kato-Noguchi, 2000; Rimando et al., 2001; Macias et al., 2002; Anjum and Bajwa, 2005). Allelochemicals released from various aquatic weeds showed different inhibition against wheat germination and growth, depending on type and concentrations (Abbas et al., 2014). Seed germination is a complex sequence of events, which involves different biochemical and physiological changes in a specific sequence (Bewley and Black, 1994). Any interruption in this process due to allelopathic substances leads to failures in the germination and growth of plants (Zohaib et al., 2016). Javaid et al. (2010) revealed that phytotoxic compounds released from *Withania somnifera* caused inhibition of *P. minor* both in germination count and seedling growth. The practical implication of such studies is that allelochemicals caused inhibition in germination and seedling growth; this leads to lower weed

Table 1- Effect of allelopathic crop aqueous extracts on the germination and early seedling growth of herbicide-resistant *P. minor*

Aqueous extract	Germination %		Shoot length (cm)		Root length (cm)		Dry biomass (g per plant)	
	2.5%	5%	2.5%	5%	2.5%	5%	2.5%	5%
Maize	63 b (-30)	12 d (-85.88)	3.27 bc (-23)	1.20 d (-74)	3.52b c (-26)	0.83 e (-81)	0.34 c (-57)	0.43 b (-48)
Rice	60 bc (-33)	0 e (-100)	2.53 cd (-40)	-	3.65 b (-23)	-	0.43 b (-46)	-
Sorghum	50 c (-44)	0 e (-100)	3.63 b (-15)	-	2.96 c (-38)	-	0.41 b (-48)	-
Sunflower	53 c (-41)	0 e (-100)	2.87 c (-32)	-	2.78 cd (-42)	-	0.35 bc (-56)	-
Control	90 a	85 a	4.25 a	4.53 a	4.75 a	4.34 a	0.79 a	0.83 a

Means with the same letter do not differ significantly at 5% confidence level. As for data in parenthesis, negative values represent % inhibition and positive ones represent % stimulation over control.

competitiveness with crop plants and ultimately to lower growth and seed production. Moreover, these allelochemicals may be directly used to control weeds, and might provide bases for new modes of action to develop organic herbicides.

Effect of allelopathic crop residues on the emergence and seedling growth of herbicide-resistant *P. minor*

Allelopathic crop residues at 1, 2 and 4% concentrations significantly suppressed the emergence percentage, shoot length, root length and dry biomass of herbicide-resistant *P. minor* (Table 2). However, at 1% concentration, some residues caused shoot length (15.51%), root length (17.60%) and dry biomass (19.55%) stimulation, when compared to the control sample. Emergence percentages were significantly inhibited at all residue concentrations; however, higher inhibition occurred at high concentrations, such as 4%. At this concentration, maize, rice, sorghum, and sunflower caused 72.61, 88.09, 100 and 100% inhibition in emergence percentage, respectively. Shoot length, root length and dry biomass of *P. minor* also showed similar inhibition patterns at different residue concentrations. Sunflower residues caused higher inhibition compared to others; at a 2% concentration it caused 53.85, 56.59 and 49.71% inhibition in shoot length, root length and dry biomass, respectively. Furthermore, at a 4% residue concentration of sorghum and sunflower, 100% inhibition in all growth attributes was recorded. However, maize and rice residues at a 4% concentration caused inhibition in shoot length (69.92 and 60.96%), root length (74.85 and 68.45%) and dry biomass (61.96 and 47.60), respectively. Under field conditions, residues of maize, rice, sorghum and sunflower are incorporated in soil before wheat crop sowing. These residues undergo different chemical reactions within soil; this alters the allelochemicals potential of residues. Therefore, in order to understand the real picture of the allelopathic influence of residues on *P. minor*, crops residues at different concentrations were incorporated in soil, and their effect on *P. minor* were investigated. Inhibitory effects of residues of different crops on the emergence and seedling growth of *P. minor* were due to phytotoxic chemicals released during the decomposition of residues (Javaid et al., 2008; Abbas et al., 2014). Soil-incorporated residues of sorghum and sunflower inhibited weed dry weight up to 56 and 60%, respectively (Cheema and Khaliq, 2000; Khaliq et al., 2010). Javaid et al. (2010) also reported that allelopathic residue incorporation caused significant inhibition of *P. minor*.

Effect of allelopathic crop mulches on the emergence and seedling growth of herbicide-resistant *P. minor*

Results about the effect of allelopathic mulches of maize, rice, sorghum and sunflower showed that different doses (4, 8 and 12 ton ha^{-1}) caused significant inhibition of *P. minor* emergence and seedling growth (Table 3). Increasing the dose of mulch material also increased the inhibition rate, showing that inhibition was proportional to mulch concentration. Mulch dose at 4 ton ha^{-1} caused growth stimulation in some growth traits. However, no consistency in growth stimulation was observed at any dose against any specific trait. Sorghum mulch caused higher inhibition compared to other crops, and was followed by maize and rice mulches. Maximum emergence inhibition (40%) was observed in pots when compared with control samples where sorghum mulch was used at 12 ton ha^{-1}. Shoot length was also significantly inhibited by mulch material; higher inhibition (60%) was observed where sorghum mulches were applied at a dose of 12 ton ha^{-1}. The root length of *P. minor* was less inhibited due to mulch application, compared to other growth traits. Compared to the control sample, highest inhibition in root length (26%) was observed in pots where maize mulch was applied at 12 ton ha^{-1}. It was observed that sunflower mulch, at 4, 8 and 12 ton ha^{-1} doses, caused 14, 7 and 4% increase in *P. minor* root length, respectively. Dry biomass results exposed that allelopathic crop mulches caused a considerable reduction in dry matter. Minimum dry biomass (2.46 g per plant) was observed at higher mulch doses. Residue mulch of maize, rice, sorghum and sunflower at 12 ton ha^{-1} caused 34.96, 53.75, 47.55 and 19.73% reduction in dry biomass, respectively, compared to the control sample. Data recorded at *P. minor* maturity revealed that all allelopathic crop mulches caused significant inhibition in plant height, dry biomass, spike length and number of seeds per plant. Significant inhibition was observed at higher mulch doses (Table 4). Allelopathic mulches at 4 ton ha^{-1} caused no significant inhibition in the measured traits. However, mulches at higher doses (8 and 12 ton ha^{-1}) caused significant

Table 2- Effect of allelopathic crop residues on the emergence and early seedling growth of herbicide-resistant *P. minor*

Residues	Emergence %			Shoot length (cm)			Root length (cm)			Dry biomass (g per plant)		
	1%	2%	4%	1%	2%	4%	1%	2%	4%	1%	2%	4%
Maize	75 b (-16)	34 cd (-56)	23 d (-73)	12.27 c (-14)	9.77 d (-36.68)	4.43 g (-70)	14.43 ab (9.98)	10.34 c (-30.41)	3.46 e (-75)	3.52 a (-3)	2.43 d (-32)	1.43 e (-62)
Rice	87 ab (-2)	36 cd (-53)	10 e (-88)	15.42 ab (8)	8.43 e (-45.36)	5.75 g (-61)	15.43 a (17.60)	7.43 d (-50.00)	4.34 e (-69)	4.34 b (20)	2.79 c (-22)	1.97 e (-48)
Sorghum	86 ab (-4)	31 cd (-60)	0 e (-100)	14.43 b (1.33)	9.32 de (-39.59)	-	14.36 ab (9.45)	9.54 bcd (-35.80)	-	3.43 ab (-6)	2.76 c (-22)	-
Sunflower	54 c (-39)	25 d (68)	0 e (-100)	16.45 a (15.51)	7.12 f (-53.85)	-	15.43 a (17.60)	6.45 de (-56.59)	-	2.76 c (-24)	1.79 e (-50)	-
Control	89 a	77 a	84 a	14.24 b	15.43 ab	14.73 b	14.12 ab	14.86 ab	14.76 ab	3.63 ab	3.56 a	3.76 a

Means with the same letter do not differ significantly at 5% confidence level. As for data in parenthesis, negative values represent % inhibition and positive ones represent % stimulation +ve control.

Table 3- Effect of allelopathic mulches of different crops on the emergence and early seedling growth of herbicide-resistant *P. minor*

Mulch (ton ha^{-1})	Emergence %			Shoot length (cm)			Root length (cm)			Dry biomass (g per plant)		
	4	8	12	4	8	12	4	8	12	4	8	12
Maize	76 ab (-5)	87 a (0)	64 b (-16)	13.87 ab (2)	14.50 a (3)	9.45 d (-39)	12.45 d (-10)	10.65 e (-26)	12.46 d (-11)	4.48 b (-6)	4.68 a (0.00)	3.46 cd (-35)
Rice	87 a (9)	76 bc (-13)	64 b (-16)	14.47 a (7)	13.46 b (-5)	7.15 de (-54)	13.47 bc (-2)	12.76 d (-12)	13.14 bc (-6)	3.46 cd (-28)	3.36 cd (-28.20)	2.46 e (-54)
Sorghum	76 b (-5)	79 ab (-9)	46 c (-39)	14.72 a (9)	12.48 c (-12)	6.14 e (-60)	13.45 bc (-2)	13.45 c (-7)	14.54 a (4)	4.87 a (2)	3.77 c (-19.44)	2.79 de (-48)
Sunflower	79 ab (-1)	80 ab (-8)	49 c (-36)	12.68 bc (-6)	11.98 c (-15)	8.55 d (-45)	15.67 a (14)	15.47 a (7)	14.46 a (4)	5.13 a (7)	4.14 bc (-11.54)	3.27 cd (-20)
Control	80 ab	87 a	83 a	14.54 a	14.94 a	15.46 a	13.76 b	14.43 b	13.95 b	4.90 b	4.68 a	5.32 a

Means with the same letter do not differ significantly at 5% confidence level. As for data in parenthesis, negative values represent % inhibition and positive ones represent % stimulation over control.

Table 4 - Effect of allelopathic mulches of different crops on the growth and reproductive potential of herbicide-resistant *P. minor*

Mulch (ton ha^{-1})	Plant height (cm)			Dry biomass (g per plant)			Spike length (cm)			Number of seeds per plant		
	4	8	12	4	8	12	4	8	12	4	8	12
Maize	70.49 ab (-7)	67.67 b (-8)	59.48 c (-22)	6.92 a (7)	6.79 a (-1)	4.98 de (-23)	5.14 bc (-11)	5.42 b (-1)	4.89 c (-16)	187 a (6)	179 b (-4)	165 b (-17)
Rice	79.45 a (5)	66.16 b (-10)	47.45 d (-38)	6.48 b (0)	6.67 ab (-3)	5.16 d (-20)	5.81 a (0)	5.49 b (0)	4.46 cd (-23)	179 (1)	198 a (6)	145 b (-27)
Sorghum	68.49 b (-9)	64.15 bc (-13)	58.19 c (-24)	6.89 a (7)	6.48 (-6)	5.12 d (-21)	5.47 b (-5)	5.46 b (0)	4.12 d (-29)	165 b (-18)	189 a (2)	116 c (-41)
Sunflower	76.45 a (1)	67.26 b (-8)	60.45 c (-21)	6.05 c (-6)	6.54 b (-5)	4.76 e (-25)	5.49 b (-5)	5.09 bc (-7)	5.15 bc (-11)	197 a (-11)	149 bc (-20)	145 bc (-27)
Control	75.46 a	73.49 ab	76.19 a	6.76 a	6.87 a	6.79 a	5.78 a	5.89 a	5.81 a	187 a	186 a	198 a

Means with the same letter do not differ significantly at 5% confidence level. As for data in parenthesis, negative values represent % inhibition and positive ones represent % stimulation over control.

inhibition. Allelopathic crop mulches at 12 ton ha^{-1} caused up to 37.72, 25.11, 29.08 and 41.41% inhibition in plant height, dry biomass, spike length and number of seeds per plant, respectively. Sorghum mulch caused comparatively more inhibition than maize, rice and sunflower. Plant mulches inhibit *P. minor* in several ways, as mulches reduce light interception, alter soil temperature, physically hinder emergence through the release of phytotoxic chemicals (Batish et al., 2007). Cheema et al. (2000) reported that sorghum mulch can be successfully used to control weeds in cotton, with 96.60% reduction in weed dry weight. The reduced seed production potential of *P. minor* can be attributed to reduced vegetative growth and reduced size of spikes. In addition to sustainable weed control, plant mulches are also important to be used, compared to other inorganic mulches, because they improve soil structure, prevent water losses and become part of soil after their decomposition.

In this study, it was also observed that lower doses of aqueous extracts, residues and mulches of allelopathic crops caused growth stimulation in some traits of *P. minor*. Growth promotory effect (hormesis) of allelochemicals can be justified by previous studies which revealed that different toxicants, including allelochemicals, produced hormesis at low doses in all groups of organisms, including higher plants (Duke et al., 2006; Abbas et al., 2015; Nadeem et al., 2016; Abbas et al., 2017b). It has been reported that different allelochemicals, including chlorogenic acid, caffeic acid, ferulic acid and phenolics, caused hormesis at lower doses (Farooq et al., 2013; Abbas et al., 2017b). Abbas et al. (2016) revealed that *P. minor* showed hormetic response to lower doses of toxicants. Hormesis in *P. minor* to lower doses of allelochemicals released by crops in the cropping sequence before wheat might boost germination and growth of this weed to enhance its competitive ability with wheat crop. Very rare literature is available on the hormesis (growth stimulatory aspect) of allelochemicals. However, it is important to study this aspect, because in field conditions allelochemicals exist in very low concentrations, due to their dilution and different chemical reactions in the soil (Abbas et al., 2017a).

Based on these findings, it is possible to conclude that crops including maize, rice, sorghum and sunflower have herbicidal potential against herbicide-resistant *P. minor*. Therefore, these allelopathic crops can be directly used as residue incorporation or surface mulch to manage *P. minor*, or might provide a basis to develop natural herbicides to control herbicide-resistant *P. minor*. However, lower doses of these allelochemicals might promote the growth of *P. minor*.

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