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Article

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Differential Hormetic Response of Fenoxaprop-p-Ethyl Resistant and Susceptible *Phalaris minor* Populations: a Potential Factor in Resistance Evolution

Resposta Hormética Diferencial de Populações de Phalaris Minor Resistentes e Suscetíveis ao Fenoxaprop-P-Ethyl: Fator Potencial na Evolução da Resistência

ABSTRACT - Resistance evolution in weeds against all major herbicide groups demand investigations to identify various factors responsible for resistance development. Herbicide hormesis has not yet been included in the list of factors promoting the evolution of resistance. Studies were conducted to evaluate the degree of hormesis in fenoxaprop-p-ethyl susceptible and resistant *Phalaris minor* to provide a first indication of whether hormesis is a potential factor in the development of resistance. In the first experiment, a wide range of doses up to 160% of the recommended field rate was used to identify potential hormetic doses for resistant and susceptible *P. minor* populations. Doses below 40% have been designated as potential hormetic doses. In the second experiment, ten different doses of fenoxaprop below 40% (0, 2, 4, 8, 12, 16, 20, 24, 28 and 32% of the recommended rate) were sprayed at the 4-5 leaf stage of both resistant and susceptible *P. minor* populations. At fifteen days after spraying, dose range of 2-12% and 2-20% caused a significant increase (up to 22% and 24%) in growth traits of susceptible and resistant populations, respectively. At maturity, dose range of 2-12% for susceptible and 2-24% for resistant populations caused a significant increase (up to 20% and 57%) in growth and seed production potential (13% and 17%), respectively. The upper limit of the hormetic dose range (16 to 24%) for the resistant population was inhibitory for the susceptible populations. These results indicate that fenoxaprop hormesis could play a vital role in the evolution of fenoxaprop resistance in *P. minor*.

Keywords: ACCase hormesis, resistant *Phalaris minor*, resistance avoidance.

RESUMO - A evolução da resistência de plantas daninhas contra todos os principais grupos de herbicidas requer estudos para que sejam identificados os vários fatores responsáveis pelo desenvolvimento dessa resistência. A hormese de herbicidas ainda não foi incluída na lista de fatores que promovem a evolução da resistência. Foram conduzidos estudos para avaliar o grau de hormese em ***Phalaris minor*** *suscetível e resistente ao fenoxaprop-p-ethyl, com o propósito de fornecer uma primeira indicação sobre se a hormese é um fator potencial no desenvolvimento da resistência. No primeiro experimento, uma ampla gama de doses de até 160% da dosagem recomendada foi usada para identificar potenciais doses horméticas para populações de* ***P. minor*** *resistentes e suscetíveis. Doses abaixo de 40% foram designadas como potenciais doses horméticas. No segundo experimento, dez doses diferentes de fenoxaprop abaixo de 40% (0, 2, 4, 8, 12, 16, 20, 24, 28 e 32% da dose*

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*recomendada) foram pulverizadas no estádio de 4-5 folhas de ambas as populações resistentes e suscetíveis de **P. minor**. Aos 15 dias após a pulverização, as variações de dose de 2-12% e 2-20% provocaram aumento significativo (até 22% e 24%) nas características de crescimento das populações suscetíveis e resistentes, respectivamente. Na maturidade, as variações na dose de 2-12% para as populações suscetíveis e 2-24% para as resistentes causou aumento significativo (até 20% e 57%) no crescimento e potencial de produção de sementes (13% e 17%), respectivamente. O limite superior de variação na dose hormética (16% a 24%) para a população resistente causou inibição das populações suscetíveis. Esses resultados indicam que a hormese do fenoxaprop poderia desempenhar papel vital na evolução da resistência de **P. minor** ao fenoxaprop.*

Palavras-chave: hormese da ACCase, *Phalaris minor* resistente, prevenção da resistência.

INTRODUCTION

Phalaris minor Retz. (little seed canary grass) is a major and troublesome weed of wheat and other winter crops in more than 60 countries (Travlos, 2012). Control of this weed is generally herbicide dependent because of its mimicry with the wheat crop. Continued use of chemicals has developed resistance in this grass against all key herbicides (Gherekhloo et al., 2012; Heap, 2016). Recently, cross-resistance has been reported in India and South Africa (Heap, 2016). Herbicide resistant *P. minor* is considered as a major challenge to wheat sustainability, as this weed may cause complete failure of wheat crops (Chhokar et al., 2006). The increasing impact of herbicide resistant *P. minor* increasingly disturbed chemical weed control, and delay of resistance development has become the main task for weed scientists. Numerous factors have been reported that cause and increase the evolution of herbicide resistance (Chhokar et al., 2006; Gherekhloo et al., 2012; Heap, 2016). These factors include initial frequency of resistant biotypes, mechanism of resistance, type of herbicide, herbicide rotation and crop rotation (Renton et al., 2011). Based on these factors, different strategies have been introduced to decrease herbicide selection pressure for weed resistance (Beckie, 2006; Norsworthy et al., 2012).

A characteristic of herbicides that has not been included yet in the list of factors promoting the evolution of resistance is the growth promoting potential of herbicides at their ultra-low doses (hormesis). However, the low-dose weed growth-promoting potential of herbicides would be of prime importance in development of herbicide resistance in weeds (Belz et al., 2011). It has been reported that the low-dose growth-promoting potential of glyphosate may cause a significant increase in growth and reproductive potential of different crops and weeds (Abbas et al., 2015; Nadeem et al., 2016). The recommended dose of herbicides may act as a low dose and, therefore, serve as the promotive dose for resistant plants. Consequently, the recommended dose of herbicide spray selects the resistant weed biotypes and, on the other hand, it indirectly enhances the growth of resistant weeds as a result of hormesis. Therefore, hormesis indirectly influences the development of resistance by making hormetically boosted resistant biotypes more competitive as compared to other weeds and crop plants. Additionally, it is more reproductive potential and more resistant to other weed control measures than triggering direct selection pressure (Belz et al., 2011).

A lesser sensitivity to alternative weed control measures resulting from an increase in biomass and induction of the herbicide detoxification process should be unwanted under field conditions as the alternate herbicide is a common practice to control surviving weeds. If hormetically stimulated weed plants show more reproductive potential, hormesis would directly increase the evolution of herbicide resistance under field conditions. For instance, Abbas et al. (2016a) reported that hormesis in *P. minor* after exposure to low doses of fenoxaprop caused a significant increase up to 28% in the reproductive potential of *P. minor*. Furthermore, highly resistant weed biotypes are believed to be more responsive to low dose growth stimulation (Calabrese and Baldwin, 2002). In agroecosystems, greater weed competitiveness leads to unwanted modifications in the composition of weed species towards herbicide resistant weeds as compared to weeds that are inhibited or killed by herbicides (Cedergreen, 2008). Research addressing these issues is yet absent, and reports on such hormetic enhancement of resistant weeds are lacking.

Fenoxaprop-p-ethyl is commonly used narrow leave herbicide. Low concentrations of this herbicide have caused hormesis in narrow-leaf weed like *Phalaris minor* and *wild oat* (Abbas et al., 2016a). It also caused a significant increase in growth and seed production potential of *Phalaris minor* and *wild oat*. At the recommended herbicide doses, ACCase target-site resistant biotypes of *Alopecurus myosuroides* Huds. (Leu1781-Allel) showed a maximum stimulation of shoot biomass (39%) after treatment with fenoxaprop and a maximum stimulation (54%) at reduced cycloxydim doses (Petersen et al., 2008; Belz et al., 2011).

Therefore, the current study was conducted primarily to reveal hormetic growth stimulation in susceptible and resistant *P. minor*. We hypothesized that hormesis may occur at higher doses in resistant populations as compared to hormetic doses for susceptible populations. These were the specific research questions of our study: (1) are resistant biotypes more prone to developing hormesis?; (2) does hormesis promote overall plant fitness?; and (3) would the stimulatory effect be maintained over time and influence the reproductive potential of *P. minor* for direct involvement in resistance evolution? For this purpose, two greenhouse experiments were conducted twice for sensitive and resistant biotypes of *P. minor*.

MATERIALS AND METHODS

Studies were conducted in a greenhouse at University of Agriculture, Faisalabad, Pakistan, during 2014-15 and 2015-16. Fifteen seeds of both susceptible and resistance suspected populations were sown at a uniform depth in each pot separately (12 x 13 x 5 cm). Herbicide-free soil was collected from the area where no herbicide had been sprayed previously. Farmyard manure was incorporated at the ratio of 2:1 w/w. Tap water was regularly applied to keep the posts moist. The experimental site was located at 31.25° N latitude, 73.09° E longitude, and at an altitude of 184 m. A completely randomized design with a factorial arrangement was used and replicated four times. Progeny of previously tested *P. minor* plants having uniform resistant (resistance index 6) to fenoxaprop-P-ethyl (ACCase inhibitor) was used in present study (Abbas et al., 2016b). *Phalaris minor* populations and fenoxaprop doses were factors in the experiment. Pots were randomized to provide uniform conditions for all plots. Fenoxaprop-P-ethyl (Puma Super® 750 EW, Bayer crop science, Pakistan) was sprayed at 3 to 4 leaf stage at post emergence for both resistant and susceptible populations. Fenoxaprop-P-ethyl was applied using a CO_2 pressurized backpack sprayer fitted with TeeJet 8003VS nozzle at 30 psi pressure, which sprayed about 20 gallons of water per acre. All the experiments were repeated. Mortality percentage (0% no plant death; 100% complete plant death) and above ground biomass data for all populations were recorded three weeks after herbicide spray. Dry biomass was determined by oven drying above ground parts at 70 °C to constant weight.

Experiment 1: Investigating potential hormetic dose range of fenoxaprop for *P. minor* susceptible and resistance populations

For identification of potential hormetic dose, a wide range of herbicide doses were used ranging from 0 to 160% of the recommended dose. The experiment included the following herbicidal treatments: 0, 5, 10, 20, 40, 80 and 160% of the recommended field rate. Mean minimum and maximum temperatures in the greenhouse during the experiments were 25 ± 2 °C and 29 ± 2 °C, respectively. Relative humidity ranged from 32-61%. Parameters including mortality (%), shoot length (cm), root length (cm) and dry biomass (mg) were recorded during the course of the study.

Experiment 2: Comparing the hormetic response of susceptible and resistance *P. minor* populations at various hormetic doses of fenoxaprop

In this experiment, fenoxaprop was applied at ten different hormetic doses including 0, 2, 4, 8, 12, 16, 20, 24, 28 and 32% to investigate the comparative response of herbicide resistant and susceptible biotypes. Mean minimum and maximum temperatures in the greenhouse during the experiment were 23 ± 2 °C and 29 ± 2 °C, respectively. Relative humidity ranged from 25-45%.

Parameters including mortality (%), shoot length (cm), root length (cm), dry biomass (mg) were recorded at 21 days after herbicide application and at plant maturity. At maturity, spike length (cm) and number of seeds per spike were also recorded.

Fisher's analysis of variance techniques were carried out to analyze the data, and comparison of treatment means at each dose was made using Tukey's test at 5% probability level (Steel et al., 1997). There was no significant difference between the two experimental runs; therefore, the data were pooled for statistical analysis. Data about mortality percentage was transformed using square root transformation before statistical analysis.

RESULTS AND DISCUSSION

Investigating potential hormetic dose range of fenoxaprop for *P. minor* susceptible and resistance populations

Results exhibited that fenoxaprop application at various doses produced a significant effect on mortality, shoot length and dry biomass of both resistant and susceptible *P. minor* (Table 1). Shoot length of susceptible *P. minor* was increased (21.15%) at 5% dose of herbicide, however, higher doses caused a significant reduction in shoot length of *P. minor*. In resistant *P. minor* herbicide dose range of 5-20% caused an increase in shoot length (4.61 to 20.13% as compared to control). Root length of susceptible *P. minor* was significantly reduced at all herbicide doses; however, in the case of resistant *P. minor* herbicide, doses up to 10% caused 4.57-19.65% increase in root length. Herbicide doses also influenced dry biomass of both susceptible and resistant *P. minor*. Herbicide dose at 5% of the recommended dose caused a 19.35% increase in dry biomass, while doses above 5% caused a reduction in dry biomass. However, in the case of resistant *P. minor,* herbicide at 5 and 10% doses caused an increase by 22.65 and 3.80% in dry biomass, respectively. Doses above 10% caused a significant reduction in dry biomass.

The literature has reported low-dose growth promoting response of various types of toxicants; growth enhancement over control was up to 60% on average and maximum up to 200% (Calabrese and Blain, 2005; Calabrese, 2008; Abbas et al., 2017). In present study, growth enhancement in both susceptible and resistant *P. minor* is in line with the general hormetic enhancement that has been reported in the literature. For example, there was a significant increase (147%) in shoot fresh weight of ACCase resistant black-grass (*Alopecurus myosuroides* Huds.) biotypes as a result of exposure to the herbicide ACCase (Petersen et al., 2008; Belz et al., 2011). A low dose (6 g a.i. ha^{-1}) of fenoxaprop caused significant growth enhancement of *P. minor (*Abbas et al., 2016a). The doses that showed a hermetic response were further tested in another experiment to estimate the hermetic effect on reproductive potential.

Comparing hormetic response of susceptible and resistance *P. minor* populations at different hormetic doses of fenoxaprop twenty-one days after spray

The results showed that low doses of Fenoxaprop caused a significant effect on mortality, shoot length, root length and dry biomass of both resistant and susceptible *P. minor* (Table 2). Significantly less mortality percentage was found in the resistance population as compared to the susceptible population. In the case of susceptible *P. minor* population dose range, 2 to 12% caused an increase by 0.42-22.02% and 3.23-16.90% in shoot length and dry biomass, respectively. Maximum increase in root length (7.19-12.42%) was measured at the 2-4% fenoxaprop-P-ethyl dose. Doses higher than 12% caused a significant reduction in shoot length, root length and dry biomass of fenoxaprop susceptible *P. minor*. The fenoxaprop resistant *P. minor* population showed more hormesis at higher doses than the susceptible population, up to 16% of the recommended field rate. The increase in shoot length, root length, and dry biomass was up to 24.42, 19.14 and 19.64% respectively. Previously, it was hypothesized that resistant individuals might be more responsive to hormesis (Calabrese and Baldwin, 2002; Belz et al., 2014). A slightly higher dose than hormetic dose of herbicide or the recommended field rate of the herbicide can promote resistant individuals. For instance, the dose greater than the hormetic dose may represent a potential hormetic dose to the resistant biotype. In the current study, this hypothesis is proved as hormesis is shown at higher doses (up to 20% of the recommended dose) in the resistant

Table 1 - Investigation of the potential hormetic dose range of fenoxaprop-P-ethyl for susceptible and resistance populations of *P. minor*

Fenoxaprop-P-ethyl dose	Susceptible				Resistant			
	Mortality (%)	Shoot length (cm)	Root length (cm)	Dry biomass (g)	Mortality (%)	Shoot length (cm)	Root length (cm)	Dry biomass (g)
0	0.71 c (0)	20.43 b	22.43 a	2.48 b	0.71 d (0)	21.46 b	21.43 b	2.34 b
5	0.71 c (0)	24.75 a (21.15)	18.46 ab (-17.70)	2.96 a (19.35)	0.71 d (0)	24.56 a (14.45)	25.64 a (19.65)	2.87 a (22.65)
10	0.71 c (0)	20.74 b (1. 52)	15.45 b (-31.12)	2.43 b (-2.02)	0.71 d (0)	25.78 a (20.13)	22.41 ab (4.57)	2.43 ab (3.80)
20	8.09 b (65)	13.69 c (-32.99)	7.63 c (-65.98)	1.42 c (-42.74)	3.54 c (12)	22.45 ab (4.61)	19.64 b (-8.330	1.80 c (-23.17)
40	9.77 a (95)	5.61 d (-72.54)	4.73 c (-78.91)	1.06 bc (-57.26)	7.45 b (55)	15.42 bc (-28.15)	14.40 c (-32.80)	1.45 cd (-38.24)
80	10.02 a (100)	0 e (-100)	0 d (-100)	0 c (-100)	6.52 b (42)	7.54 cd (-64.86)	18.01 b (-15.91)	1.09 d (-53.25)
160	10.02 a (100)	0 e (-100)	0 d (-100)	0 c (-100)	9.51 a (90)	4.76 d (-77.82)	9.35 d (-56.34)	0.84 e (-64.04)

The means in the same column marked with the same letter do not differ significantly at the 5% confidence level. Data about mortality % is transformed by using square root transformation before statistical analysis. The values in parenthesis represent the original values for the mortality column and the percent increase for the other growth traits.

Table 2 - Comparison of hormetic response of susceptible and resistance *P. minor* populations at various hormetic doses of fenoxaprop-P-ethyl at twenty-one days after spraying

Fenoxaprop-P-ethyl dose	Susceptible				Resistant			
	Mortality (%)	Shoot length (cm)	Root length (cm)	Dry biomass (g)	Mortality (%)	Shoot length (cm)	Root length (cm)	Dry biomass (g)
0	0.71 c (0)	26.15 b	32.43 b	2.78 b	0.71 c (0)	27.14 b	29.46 b	2.85 b
2	0.71 c (0)	29.75 a (13.76)	36.46 a (12.42)	2.98 ab (7.19)	0.71 c (0)	29.54 ab (2.40)	30.12 b (2.24)	2.98 b (4.56)
4	0.71 c (0)	31.91 a (22.02)	36.21 a (11.65)	3.12 a (12.23)	0.71 c (0)	32.96 a (21.44)	33.28 ab (12.96)	3.31 ab (16.14)
8	0.71 c (0)	29.70 ab (13.57)	33.90 ab (4.53)	3.25 a (16.90)	0.71 c (0)	33.77 a (24.42)	35.10 a (19.14)	3.40 a (19.29)
12	0.71 c (0)	26.26 b (0.42)	31.64 b (-2.43)	2.87 b (3.23)	0.71 c (0)	31.35 ab (15.51)	34.40 a (16.76)	3.41 a (19.64)
16	3.54 bc (12)	21.63 c (-17.23)	27.40 bc (-15.51)	2.59 bc (-6.83)	0.71 c (0)	29.41 ab (8.36)	32.05 ab (8.79)	3.14 ab (10.17)
20	5.34 b (28)	18.27 c (-30.13)	30.74 b (-5.21)	2.52 bc (-9.35)	0.71 c (0)	27.74 b (2.21)	29.65 b (0.38)	2.92 bc (2.45)
24	5.61 b (31)	18.20 cd (30.42)	27.43 bc (-15.41)	2.44 bc (-12.23)	3.08 b (09)	26.26 bc (-3.24)	26.71 c (-9.33)	2.48 c (-12.98)
28	6.82 ab (46)	15.58 d (-40.42)	24.81 c (-23.49)	2.22 c (-20.14)	3.54 b (12)	23.69 c (-12.71)	27.47 c (-6.75)	2.58 c (-9.47)
32	8.22 a (67)	11.24 de (-57.01)	23.41 c (-27.81)	1.96 cd (-29.49)	5.05 a (25)	19.91 d (-26.63)	23.51 (-20.19)	2.39 c (-16.14)

The means in the same column marked with the same letter do not differ significantly at the 5% confidence level. Data about mortality % is transformed by using square root transformation before statistical analysis. The values in parenthesis represent the original values for the mortality column and the percent increase for the other growth traits.

populations and at comparatively lower doses (up to 8% of the recommended dose) in the susceptible populations. Therefore, this study is in line with the assumption that resistant individuals are responsive to hormesis at higher doses, which act as lethal doses for susceptible individuals. Thus, herbicide hormesis may indirectly influence the evolution of herbicide resistance by hormetically enhancing the growth of resistant weeds to make them more competitive to susceptible weeds and crop plants, as well as more reproductive and resistant to other weed control practices (Belz et al., 2011).

Comparing hormetic response of susceptible and resistance *P. minor* populations at various hormetic doses of fenoxaprop at maturity

At maturity, *P. minor* showed a significant growth stimulatory response at low doses both in susceptible and resistant populations (Table 3). However, the response of the resistant population was different than in the susceptible one regarding their stimulatory response. In the *P. minor* susceptible population, the fenoxaprop dose range 2 to 12% caused hormesis. They caused an increase by 0.94-15.35%, 3.34-10.04%, 0.26-20.37% in shoot length, root length, and dry biomass, respectively. Fenoxaprop doses above 12% of the recommended field rate caused inhibition in growth traits. The response of fenoxaprop resistant *P. minor* showed that herbicide doses up to 24% of the recommended field rate produced hormesis. There was an increase by 3.77-12.48%, 2.40-20.77% and 8.49-56.55% in shoot length, root length and dry biomass of *P. minor*, respectively. Doses above 24% caused inhibition in growth traits. However, this inhibition was lower than the

Table 3 - Comparing hormetic response of susceptible and resistance *P. minor* populations at various hormetic doses of fenoxaprop-P-ethyl at *P. minor* maturity

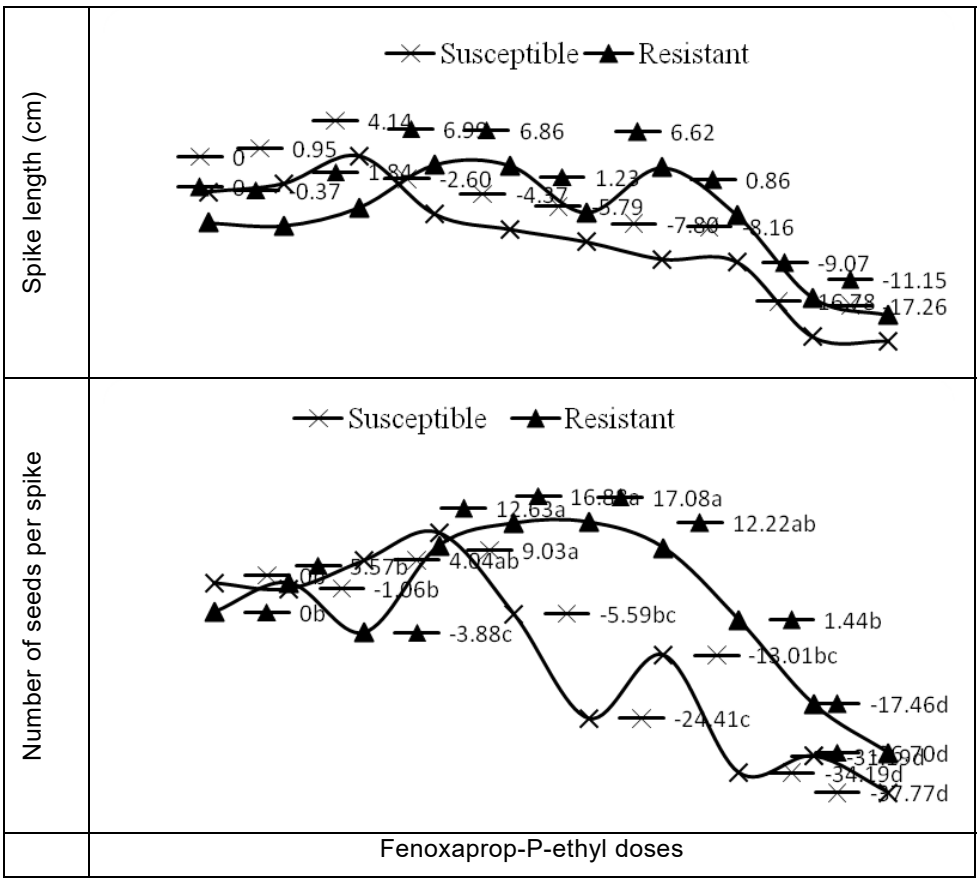
Fenoxaprop-P-ethyl dose	Susceptible			Resistant		
	Shoot length (cm)	Root length (cm)	Dry biomass (g)	Shoot length (cm)	Root length (cm)	Dry biomass (g)
0	65.14 b	46.41 b	3.78 a	71.46 b	54.16 b	4.12 cd
2	65.75 b (0.94)	45.79 b (-1.34)	3.79 a (0.26)	74.16 ab (3.77)	55.46 b (2.40)	4.47 c (8.49)
4	70.86 ab (8.78)	47.47 ab (2.28)	4.23 a (11.90)	78.73 a (10.17)	65.41 a (20.77)	5.91 a (43.44)
8	75.14 a (15.35)	51.07 a (10.04)	4.55 a (20.37)	80.38 a (12.48)	65.10 a (20.19)	5.70 ab (38.34)
12	70.24 ab (7.82)	47.96 ab (3.34)	3.98 a (5.29)	78.23 a (9.47)	60.91 ab(12.46)	6.45 a (56.55)
16	59.05 bc (-9.35)	41.88 b (-9.76)	3.46 ab (-8.47)	78.63 a (10.03)	57.49 b (6.15)	5.64 ab (36.89)
20	56.89 c (-12.67)	39.94 bc (-13.94)	3.02 abc (-20.11)	75.72 ab (5.96)	57.50 b (6.16)	5.30 b (28.64)
24	59.03 bc (-9.38)	42.98 bc (-7.39)	3.19 abc (-15.61)	72.14 b (0.95)	55.76 b (2.95)	4.59 c (11.40)
28	44.88 d (-31.10)	31.88 c (-31.31)	2.42 bc (-35.98)	64.59 bc (-9.61)	43.41 c (-19.85)	3.40 d (-17.48)
32	40.06 d (-38.50)	29.43 c (-36.59)	2.10 c (-44.44)	57.87 c (-19.02)	37.81 d (-30.19)	3.06 de (-25.73)

The means in the same column marked with the same letter do not differ significantly at the 5% confidence level. Values in parenthesis represent the percent increase in the control. ^{ns} = non-significant.

inhibition caused by these doses in susceptible *P. minor*. Hormetic growth stimulation was found in all fields and for various types of toxicants; this enhancement average ranges between 30-60% of the control and can be increased up to 200% compared to the control (Calabrese and Blain, 2005; Calabrese, 2008; Abbas et al., 2017). Growth enhancement in both susceptible and resistant *P. minor* is in line with the general hormetic enhancement that has been reported in the literature. For instance, an increase in shoot fresh weight up to 147% of the control was observed in ACCase-target-site-resistant black-grass (*Alopecurus myosuroides* Huds.) biotypes after their exposure to ACCase-inhibiting herbicides doses equal to the recommended lethal field rates of these herbicides (Petersen et al., 2008; Belz et al., 2011). Abbas et al. (2016a) also reported that low doses of fenoxaprop-P-ethyl up to 6 g a.i. ha^{-1} caused significant hormesis in shoot length, root length and dry biomass of *P. minor*. The results of our study also showed that hormetic growth enhancement was sustained over time and ultimately makes the resistant population more productive as compared to the susceptible population. Thus, an increase in reproductive potential may trigger the development of resistance by increasing the number of resistant individuals in the weed seed bank. Additionally, under field conditions, hormetically enhanced resistant individuals may become more competitive as compared to the susceptible weed individuals that are less affected or adversely affected by herbicide application, which may lead to the evolution of resistance. Less sensitivity to second weed control practice resulting from gain in biomass is also unwanted and may trigger the evolution of resistance. Additionally, lesser sensitivity may be epigenetically inherited without fitness consequences; the combination of hormetic growth enhancement with detoxification gene induction can further contribute to the resistance evolution process (Guedes and Cutler, 2014). Growth and reproductive enhancement of the herbicide-resistant population of *P. minor* at higher doses than the susceptible one are clearly undesirable and must be considered as a potential factor in resistance evolution. One of the research questions of our study was whether resistant biotypes are more prone to developing hormesis, and this hypothesis was confirmed. In our study, hormesis was shown in almost all measured growth traits and growth promotion was sustained over time and influenced the reproductive potential of *P. minor* for direct involvement in resistance evolution.

Comparing hormetic response of susceptible and resistance *P. minor* populations at various hormetic doses of fenoxaprop regarding reproductive potential of *P. minor*

Spike length of both susceptible and resistant *P. minor* was not significantly ($p \leq 0.05$) effected after their exposure to different doses (up to 32% of recommended field rate) of fenoxaprop (Figure 1). However, fenoxaprop at 4% caused an increase by 4.14% in spike length of susceptible *P. minor* and an increase by 4-24% (0.86-6.99%) in spike length of resistant *P. minor*. Number of seeds per spike was significantly ($p \leq 0.05$) influenced by different doses of fenoxaprop. In the susceptible *P. minor* population, fenoxaprop at the 4% and 8% doses caused an increase by 4.04 and 9.03% in



Values in data labels represent the percent increase in the control. The values marked with the same letter do not differ significantly at the 5% confidence level.

Figure 1 **-** Comparison of the hormetic response of susceptible and resistant *P. minor* populations at various hormetic doses of fenoxaprop-P-ethyl regarding the reproductive potential of *P. minor*.

number of seeds per spike (Figure 1). Doses above 8% caused a reduction in the seed production potential of susceptible *P. minor*. However, in the case of resistant *P. minor*, a fenoxaprop dose range of 2-24% caused an increase from 5.57 to 17.08% in the number of seeds per spike. Doses above 24% caused a reduction in the number of seeds per spike. The literature showed that hormesis occurs in a single endpoint (Mushak, 2013; Belz, 2014) and it seldom leads toward general plant fitness (Parson, 2003). The current findings are contradictory to those in the previous literature and indicate that hormesis was found in almost all recorded traits. Early growth enhancement was led to overall plant fitness and sustained over time until maturity to increase the reproductive potential of both susceptible and resistant *P. minor* populations. These results are in line with those of Nadeem et al. (2016) and Abbas et al. (2017), who reported that glyphosate hormesis caused overall plant fitness in different broad-leaved weeds. These findings are also reinforced by those of Abbas et al. (2016a). They assessed the increase in growth and reproductive potential of susceptible *P. minor* populations after exposure to low doses of fenoxaprop.

Based on the current findings, we conclude that fenoxaprop at low concentrations (up to 8% of recommended dose in susceptible and up to 20% of the recommended dose in the resistant population) caused hormesis in *P. minor*. Hormesis was shown both in the growth and reproductive potential of *P. minor*. The upper limit of hormetic dose range (16 to 20%) for the resistant population was inhibitory for the susceptible population. Therefore, it is indicated that the hormetic potential of fenoxaprop may trigger the evolution of fenoxaprop resistant *P. minor*. Further research is required to explain the interaction of herbicide hormesis and herbicide resistance evolution in weeds. However, for a complete understanding of herbicide weed management, hormesis should be deliberate.

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