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Phytotoxic Residual Effects of Herbicides on Growth and Yield of Mustard (*Brassica juncea* L.) in Pulse-based Cropping Systems in Arid Regions

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Abstract: In this study, the phytotoxic effects of eleven residual herbicide treatments were investigated on growth and yield of mustard (*Brassica juncea* L.). These treatments included various concentrations of imazethapyr, imazethapyr-based mixtures, and clodinafop-propargyl combined with sodium acifluorfen were applied on preceding crop of mung bean. Our aim was to how the influence of residual effect these herbicides was assess on the growth and overall productivity of mustard. Results indicated that imazethapyr-containing treatments (50 to 125 g a.i. ha^{-1}) significantly inhibited mustard growth, with reductions in shoot length (26.0 to 46.2%) at 30 days after sowing (DAS) and up to 63.4% growth inhibition by 45 DAS, along with 59.3 to 67.0% decrease in seed yield. Conversely, post emergence treatments with clodinafop-propargyl + sodium acifluorfen (187.5 to 312.5 g a.i. ha^{-1}) performed statistically at par with control treatment in plant height, dry matter, and seed yield, making it a safer PoE herbicide for kharif pulse-mustard rotations in arid regions.

Key words: Arid cropping, growth inhibition, herbicide residue, imazethapyr, mustard, phytotoxicity

Weed infestation presents a considerable challenge to achieving optimal yields in field crops, particularly in arid and semi-arid tropical regions. Here, pulses often rely on rainfed production systems and exhibit slow initial growth, making them especially susceptible to intense weed competition during the monsoon season. This competition can lead to significant yield losses. Research has shown that weed-related yield reductions in pulses frequently surpass those caused by insects or diseases (Yadav *et al.*, 2017). Specifically, weed infestations can result in yield decline to the tune of 30-50% for mung bean (*Vigna radiata* L.) and 75-80% for moth bean (*V. acontifolia* L.) (Verma *et al.*, 2015; Jat and Singh, 2021a). Consequently, effective weed control emerges as a critical strategy for enhancing the productivity of kharif pulses and other legumes in arid and semi-arid regions.

Traditionally, weed control in the arid parts of India has been a manual task. However, labour shortages and rising labour costs have driven the cost of manual weed management to constitute nearly one-third of the total production costs for field crops (Jat and Singh, 2021b). As a result, the use of herbicides has become indispensable. This shift has led to a sharp increase in herbicide consumption in India rising from 3,575 MT in 2008 to 6,335 MT in 2018, accounting for 11% of the total pesticides produced globally (FAO, 2018).

Earlier, only pre-emergence (PE) herbicides were recommended for controlling weeds in kharif pulses. The application of PE herbicides, such as pendimethalin, has yielded promising results in mung bean (Singh *et al*., 2015) and also in other kharif legumes. However, the narrow time window for application during the rainy season often makes PE herbicides less appealing to farmers. As a result, the use of post-emergence (PoE) herbicides is gaining traction. Among these, imazethapyr and imazamox-selective herbicides from the imidazolinone chemical group-are being increasingly preferred. These herbicides target and inhibit the acetolactate synthase (ALS) enzyme in plants, providing effective broad-spectrum weed control in kharif legumes (Rodrigues and Almeida, 2011). Imazethapyr, for instance, has shown to be very effective in cluster bean (Singh *et al*., 1916), cowpea (Kumar and Singh, 2017), and mung bean (Balyan *et al*., 1916).

Imidazolinone herbicides offer both soil and foliar activity, allowing for flexible application timing. Their growing popularity among farmers can be attributed to several advantages, including excellent crop tolerance, broad-spectrum and prolonged weed control due to soil residual activity, low application rates, and minimal mammalian toxicity (Vencill, 2002). But some studies have shown that some imidazolinones or their metabolites can persist into subsequent growing seasons (Ball *et al.*, 2023). This prolonged persistence poses a risk of damaging sensitive crops, such as lentil, mustard, or sugar beet, that may be grown in rotation (Moyer and Hamman, 2001). The significant residual effects of imazethapyr (at rates of 120 to 160 g a.i. ha^{-1}) on the growth of subsequent mustard crops have also been reported (Radovanov, 2017).

Schoenau *et al.* (2005) emphasized that the extent to which a residual herbicide can persist and damage sensitive succeeding crops is influenced by soil properties and environmental conditions. In hot arid climate of Rajasthan, decomposition of herbicidal residues could be slow due to low soil organic carbon, limited water availability, and reduced soil microbial activity. This highlights the importance of assessing the residual toxicity of kharif-applied herbicides to ensure the safety of subsequent mustard crops. With approximately 3.61 million ha under mung bean and moth bean cultivation in Rajasthan (Anonymous, 2021-22), and assuming mustard follows legumes on 30-50% of this area, the potential impact of residual herbicide toxicity on subsequent mustard crops could be substantial.

However, researchers have paid little attention to the residual effects of herbicides on succeeding crops in the arid regions of India. But with the availability of new herbicides with varying modes of action and comparable weed control efficacy this scenario can be changed. A pre-mix combination of clodinafop-propargyl and sodium acifluorfen or propaquizafop and imazethapyr has shown promise to be a better option against kharif weeds in pulses under arid conditions. The combined PoE of clodinafop-propargyl and sodium acifluorfen at rates of 187 to 300 g ha^{-1} has been reported to be effective in controlling both dicot and monocot weeds in black gram (Lakra, 2017).

Therefore, for developing effective herbicide recommendations, studying the residual effects of herbicides on succeeding crops is essential and also there is limited information on the impact of new ready-mix herbicides available in India on successive crops in kharif legume-based systems. This study aims to determine the persistence and residual phytotoxic effects of varying doses of imazethapyr, alone and with newer herbicide formulations, when applied to kharif moth bean in rotation with mustard.

Materials and Methods

The study was conducted in Experimental Farm of ICAR-Central Arid Zone Research Institute, Jodhpur (24°75′ N latitude and 90°50′ E longitude) under the (Arid Western plains) for three years during 2017-18, 2018-19 and 2019-20 to evaluate to the bio-efficacy of one PE, one PoE and three pre-mix of PoE herbicides on moth bean and their residual effect on the succeeding mustard. The average annual rainfall of the region is about 365 mm, which is mostly received during June to September. The experimental field was well

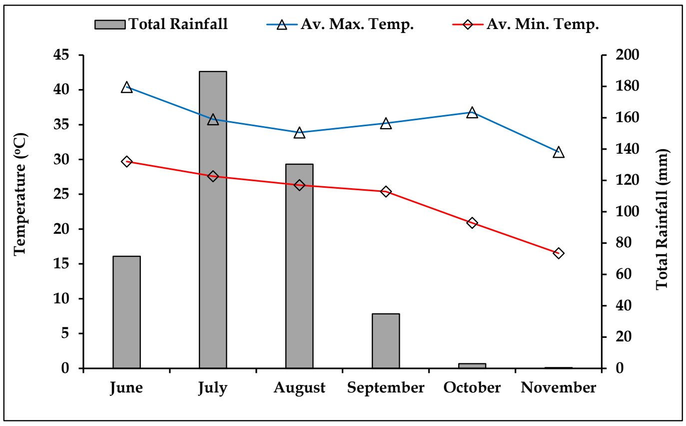

Fig. 1. Monthly weather parameters during the study period (average data of 3 years).

drained with loamy sand textured soil low in organic carbon (0.18%) and available nitrogen (170 kg ha^{-1}), medium in available phosphorous (16.8 kg ha^{-1}) and potassium (277 kg ha^{-1}) with slightly alkaline in reaction (pH 8.3). Weather information regarding average monthly total rainfall and monthly average of maximum and minimum air temperature at the experimental site during the study period is presented in Fig. 1.

Nine treatments comprising of PE and PoE herbicides along with control were applied in moth bean during kharif (Table 1). Among the herbicide treatments, pre-emergence (PE) pendimethalin was applied next day of crop sowing whereas the post-emergence (PoE) herbicides were applied at 20 DAS in respective treatments. The treatments were laid out in randomized block design with three replications keeping the plot size 5 x 3 m. A buffer area of 1.5 m between the plots and 2.0 m between the replications were kept to avoid mixing of soil in field preparation before succeeding mustard sowing. The herbicides were sprayed with knapsack sprayer fitted with flat fan nozzle using water volume of 500 L ha^{-1}. After harvest of moth bean, succeeding crop mustard was sown on the same layout to assess the residual effect of herbicides. Hence, after harvest of moth bean, a pre-sowing irrigation was provided and field preparation was done by two harrowing followed by planking. Mustard was sown in first week of November and harvested in last week of March. Mustard (cv. PM-26) was sown at a seed rate of 4 kg ha^{-1} using a seed drill with a row spacing of 45 cm. The crop was fertilized with 60 kg N, 40 kg P through urea and DAP as per the recommendations of State Department of Agriculture. As per standard practice, half of the N and full dose of P and K were applied as basal while remaining dose of N was applied in two equal splits as top dressing at first and second irrigation. After sowing the mustard was raised with three irrigations. Plots were manually kept weed-free during the crop growing season to assess only the residual effect of herbicides on mustard.

In mustard, plant height was measured at 30 DAS from the base (ground level) of the randomly selected five plants to the tip of the longest leaf. At 45 DAS, plant height was measured from the five randomly selected plants from each plot, as at 30 DAS, and plant population was counted from per meter row length of the crop at the randomly selected spots in the plot. Plant dry weight of mustard was measured from randomly selected 10 plants. The plants were uprooted, cleaned with running tap water and then air-dried samples were oven dried at 70°C for 72 hours and finally their weights were measured by digital weight machine. To evaluate the residual effects of herbicides in the soil, we analyzed plant height data and calculated the percent growth inhibition (GI) using the following formula:

$$GI\ (\%) = 1 - (L_t / L_0) \times 100$$

where, L_t= Plant height at 45 DAS in herbicide treated soil; L_0= Plant height at 45 DAS in the control

The biological yield (kg) of the crop was obtained by weighing the field dried biomass from net plot (2 m x 3 m) and the seed obtained from the net plot biomass was recorded as seed yield after threshing. The yield data then converted in to kg ha^{-1} by a conversion factor.

Table 1. Phytotoxic effect of herbicides on periodic plant height of mustard

Treatment	Plant height 30 DAS (cm)				Plant height 45 DAS (cm)			
	2017-18	2018-19	2019-20	Mean	2017-18	2018-19	2019-20	Mean
Control	19.9^{b}	18.1^{c}	16.0^{c}	18.0^{e}	67.1^{b}	79.6^{b}	74.7^{b}	74.9^{b}
Pendimethalin PE @750 g a.i. ha^{-1}	19.4^{b}	17.8^{c}	15.4^{bc}	17.5^{de}	65.5^{b}	75.7^{b}	71.6^{b}	70.9^{b}
Imazethapyr PoE @ 50 g a.i. ha^{-1}	15.1^{a}	13.4^{abc}	11.5^{a}	13.3^{bc}	32.0^{a}	32.2^{a}	33.9^{a}	32.5^{a}
Imazethapyr + Imazamox PoE @ 60 g a.i. ha^{-1}	12.8^{a}	11.3^{ab}	8.7^{a}	10.9^{ab}	33.3^{a}	31.9^{a}	32.0^{a}	32.2^{a}
Propaquizafop + imazethapyr PoE @ 100 g a.i. ha^{-1}	13.7^{a}	10.0^{a}	8.2^{a}	10.6^{a}	30.8^{a}	28.2^{a}	28.3^{a}	29.1^{a}
Propaquizafop + imazethapyr PoE @ 125 g a.i. ha^{-1}	12.7^{a}	8.7^{a}	7.7^{a}	9.7^{a}	27.1^{a}	25.6^{a}	27.2^{a}	27.0^{a}
Clodinafop-propargyl + sodium acifluorfen PoE @ 187 g a.i. ha^{-1}	18.9^{b}	17.1^{c}	15.3^{bc}	17.1^{de}	68.5^{b}	74.1^{b}	68.8^{b}	70.5^{b}
Clodinafop-propargyl + sodium acifluorfen PoE @ 250 g a.i. ha^{-1}	19.1^{b}	17.5^{c}	14.8^{bc}	17.1^{de}	66.3^{b}	72.3^{b}	67.7^{b}	68.8^{b}
$^{\#}$Clodinafop-propargyl + sodium acifluorfenPoE @ 312.5 g a.i. ha^{-1}	-	16.2^{bc}	14.0^{bc}	15.1^{cd}	-	71.5^{b}	71.6^{b}	71.5^{b}
SEm±	0.74	1.13	0.88	0.54	2.69	3.52	2.93	1.82
CV (%)	7.83	13.52	12.26	11.29	9.53	11.18	9.59	10.31

Means superscripted with different letters are significant at $p<0.05$ as per Tukey's HSD test; a.i.=active ingredient
$^{\#}$Treatment was applied during 2018-19 and 2019-20 only

The collected data for each of the crop parameter were statistically analyzed separately by using SPSS (ver. 25). The significance of treatment difference was determined through Analysis of Variance (ANOVA) using the F-test at the 5% level of significance. Multiple comparisons of treatment means were made using Tukey's Honest Significant Difference Test (HSD). ANOVA of different biological parameters across the years exhibited non-significant variation (p=0.05) between the experimental years, among the year x treatment interactions. Therefore, the mean data of the three experimental years have been reported here. Figures were drawn with the help of GraphPad Prism 10.0.0 software.

Results and Discussion

Plant height

Analysis of three experimental years and mean data demonstrated that the application of four herbicide treatments significantly reduced mustard plant height at 30 days after sowing (DAS) which persisted upto 45 DAS compared to the untreated control (Table 1). Herbicide treatments including imazethapyr (PoE, 50 g a.i. ha^{-1}), imazethapyr + imazamox (PoE, 60 g a.i. ha^{-1}), propaquizafop + imazethapyr (PoE, 100 g a.i. ha^{-1}), and propaquizafop + imazethapyr (PoE, 125 g a.i. ha^{-1}) exhibited equally detrimental effects on plant height. Mean analysis revealed that the treatments involving imazethapyr caused reduction in mustard plant height to the tune of 26.0% to 46.2% at 30 DAS and a 63.9% to 68.7% at 45 DAS relative to the control.

The significantly reduced plant height observed under the effect of imazethapyr suggested that this herbicide persists at phytotoxic levels in the soil during the subsequent growing season. These findings align with those of Moyer and Esau (1996), who documented similar injurious effects of imazethapyr on canola. However, these findings contrast with Yadav and Bhullar (2014), who reported no effects of imazethapyr and imazamox applied in soybean on the plant height and dry matter accumulation of subsequent crops. The treatments involving clodinafop-propargyl + sodium acifluorfen (PoE, 187 g a.i. ha^{-1}), clodinafop-propargyl + sodium acifluorfen (PoE, 250 g a.i. ha^{-1}), clodinafop-propargyl + sodium acifluorfen (PoE, 312.5 g a.i. ha^{-1}), and pendimethalin (PE, 750 g a.i. ha^{-1}) did not exhibit adverse effects on plant height at either 30 or 45 DAS, and these treatments were statistically comparable to the control.

The phytotoxicity of a herbicide on sensitive crops in subsequent seasons depends partly on the herbicide's half-life. Among the tested herbicides, the reported half-lives are as follows: pendimethalin, 54 days; clodinafop-propargyl, 2.35-11.20 days; sodium acifluorfen, 28-40 days; imazamox, 20-30 days; imazethapyr, 60-90 days; and propaquizafop, 25.29-27.63 days (Hazra *et al*., 2016). Following their application in moth bean, the time available for herbicide degradation varied before sowing mustard. Pendimethalin, being a pre-emergence herbicide, had approximately 100 days for dissipation, reducing its likelihood of persisting at toxic levels in the soil. In contrast, post-emergence (PoE) herbicides such as clodinafop-propargyl, sodium acifluorfen, imazamox, and propaquizafop had shorter degradation periods due to their later application. The shorter field half-lives of these herbicides make their residual toxicity less concerning. However, imazethapyr, with a reported field half-life of 60-90 days (Vencill, 2002), demonstrates greater persistence and potential phytotoxicity, even at concentrations as low as 0.5-3 µg kg^{-1} of soil (Bresnahan et al., 2000). This persistence likely accounts for the significant reductions in plant height observed in mustard under treatments involving imazethapyr.

***Plant stand at 45 DAS*:** A highly significant (p= 0.01) effect of herbicide was observed on the plant population of mustard at 45 DAS in three years of experimentation and mean analysis (Table 2). Data indicates significant plants stand loss under the toxic effect of herbicides. Treatments comprising imazethapyr (PoE 50 g a.i. ha^{-1}); imazethapyr + imazamox (PoE 60 g a.i. ha^{-1}); propaquizafop + imazethapyr (PoE 100 g a.i. ha^{-1}); and propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) recorded significant loss of plant population over control in first and third year of experiment and in mean analysis indicating continuous persistence of herbicide at toxic level up to this stage. The plant stand loss might have been due stunting, withering and dying of roots under the phytotoxic effect of imazethapyr. The plant population under the effects of clodinafop-propargyl + sodium acifluorfen (PoE @ 187 g a.i. ha^{-1}); clodinafop-propargyl + sodium acifluorfen (PoE @ 250 g a.i. ha^{-1}) and clodinafop-propargyl + sodium acifluorfen (PoE @ 312.5 g a.i. ha^{-1}) and pendimethalin (PE 750 g a.i. ha^{-1}) was found at part to control for three years of experimentation and mean analysis. The satisfactory plant stand of mustard these herbicides implied non-significant phytotoxic effect of herbicides growth of roots and shoot. These results are in line with the findings of Maji *et al.* (2020).

***Plant dry matter at 45 DAS*:** Phytotoxic effect of herbicides also caused significant effect on dry weight per plant of mustard at 45 DAS in all three years of experiment and in mean analysis (Table 2). The treatments comprising imazethapyr (PoE 50 g a.i. ha^{-1}); imazethapyr + imazamox (PoE 60 g a.i. ha^{-1}); propaquizafop + imazethapyr (PoE 100 g a.i. ha^{-1}); and propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) resulted in significantly lower plant dry matter than the control and other herbicidal treatments. In control, dry matter of mustard was 21.3 g plant^{-1} (mean mean) while plots treated with imazethapyr containing herbicides had crop dry matter as lesser by 51.2 to 61.0% (mean mean) over control. It was due to initial significantly low shoot growth caused by root stunting under all imazethapyr treatments compared to the control. This indicates that sufficient amounts of imazethapyr may persist beyond the season of application. The reduction in mustard plant dry matter and the significant toxicity lasting 90 to 100 days after applying imazethapyr are attributed to its extended persistence in soil (Kraemer *et al*., 2009). According to Renner *et al*. (1998), the residual effects of imidazolinone herbicides in soil can extend for up to two years, with their phytotoxicity influenced by the susceptibility of subsequent crops and agricultural practices (Ball *et al*., 2003). Furthermore, factors like the applied dosage (Silva *et al*., 1999) and the management techniques used in the area (Añasco *et al*., 2010) can also play a role in prolonging the residual activity of imidazolinone herbicides.

When comparing the imazethapyr (PoE 50 g a.i. ha^{-1}) alone to its other combinations like imazethapyr + imazamox (PoE 60 g a.i. ha^{-1}); propaquizafop + imazethapyr (PoE 100 g a.i. ha^{-1}); propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) it was found that the differences were statistically at par in terms of plant dry matter. This result indicated that imazethapyr found equally effective even at low doses i.e. 35 g a.i. ha^{-1} as found in imazethapyr + imazamox (PoE). Besides, at higher doses of 60 g and 75 g a.i. ha^{-1} in propaquizafop + imazethapyr (PoE 100 g a.i.

Table 2. Phytotoxic effect of herbicides on plant stand and plant dry weight of mustard at 45 DAS.

Treatment	Plant stand at 45 DAS (per m row length)				Plant dry weight at 45 DAS (g plant^{-1})			
	2017-18	2018-19	2019-20	Mean	2017-18	2018-19	2019-20	Mean
Control	10.7^{cd}	11.4^{bc}	10.3^{d}	10.8^{b}	21.6^{c}	20.7^{b}	21.7^{b}	21.3^{b}
Pendimethalin PE @750 g a.i. ha^{-1}	10.0^{bcd}	10.7^{bc}	9.3^{cd}	10.0^{b}	20.4^{c}	19.4^{b}	20.5^{b}	20.1^{b}
Imazethapyr PoE @ 50 g a.i. ha^{-1}	7.7^{abc}	7.7^{ab}	6.3^{abc}	7.2^{a}	11.7^{ab}	9.4^{a}	10.2^{a}	10.4^{a}
Imazethapyr + Imazamox PoE @ 60 g a.i. ha^{-1}	7.0^{ab}	8.0^{ab}	5.7^{ab}	6.9^{a}	9.8^{a}	8.7^{a}	9.5^{a}	9.3^{a}
Propaquizafop + imazethapyr PoE @ 100 g a.i. ha^{-1}	6.7^{ab}	5.7^{a}	5.3^{ab}	5.9^{a}	9.0^{a}	7.3^{a}	9.4^{a}	8.6^{a}
Propaquizafop + imazethapyr PoE @ 125 g a.i. ha^{-1}	6.3^{a}	6.3^{a}	4.7^{a}	5.8^{a}	8.7^{a}	7.4^{a}	8.7^{a}	8.3^{a}
Clodinafop-propargyl + sodium acifluorfen PoE @ 187 g a.i. ha^{-1}	11.3^{d}	11.3^{bc}	9.7^{cd}	10.8^{b}	19.3^{c}	19.4^{b}	19.3^{b}	19.3^{b}
Clodinafop-propargyl + sodium acifluorfen PoE @ 250 g a.i. ha^{-1}	11.7^{d}	11.7^{c}	8.3^{bcd}	10.6^{b}	18.2^{bc}	18.4^{b}	18.2^{b}	18.2^{b}
Clodinafop-propargyl + sodium acifluorfenPoE @ 312.5 g a.i. ha^{-1}	-	11.0^{bc}	8.0^{abcd}	9.5^{b}	-	18.8^{b}	20.2^{b}	19.5^{b}
SEm±	0.71	0.77	0.71	0.42	1.42	0.99	0.99	0.66
CV (%)	13.87	14.32	16.26	14.72	16.63	11.92	11.24	13.15

Means superscripted with different letters are significant at $p<0.05$ as per Tukey's HSD test; a.i.=active ingredient
[#]Treatment was applied during 2018-19 and 2019-20 only

ha^{-1}) and propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}), respectively it found equally toxic to its sole application at 50 g a.i. ha^{-1} indicating that propaquizafop is not persisting into the next season and not showing any synergistic effect with imazethapyr. However, clodinafop-propargyl + sodium acifluorfen (PoE) even up to 312.5 g a.i. ha^{-1} did not result in a significant difference in plant dry matter over pendimethalin (PE 750 g a.i. ha^{-1}) and control for three years of experiment and mean analysis.

Growth inhibition: The residual effect of herbicides was assessed through plant height at 45 DAS in terms of growth inhibition (GI%) in plant growth. Results indicated that the residual effects of imazethapyr containing herbicides like imazethapyr (PoE 50 g a.i. ha^{-1}); imazethapyr + imazamox (PoE 60 g a.i. ha^{-1}); propaquizafop + imazethapyr (PoE 100 g a.i. ha^{-1}); and propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) caused a significant magnitude ($p=0.01$) of growth inhibition over control in three years of experiment and mean analysis (Fig. 2). Imazethapyr containing herbicides being at par to each other recorded GI in the range of 51.8-60.1% in first year, 59.5-68.1% in second year, 54.2-63.8% in third year and 56.1-63.4% in mean analysis. Different levels of clodinafop-propargyl + sodium acifluorfen (PoE) (4.9-6.7%) and pendimethalin (PE 750 g a.i. ha^{-1}) being at par to each other registered significantly lower GI over imazethapyr containing herbicides (3.7%). Inhibitory effect of imazethapyr on protein synthesis due to adverse effect on acetohydroxy acid synthase activity (Scarponi *et al*., 1997) might have led to severe growth inhibition due disruption of metabolic activities of sensitive plants.

The persistence of the herbicide imazethapyr is influenced by soil properties, environmental factors, and herbicide interactions. The physical and chemical properties of soil, such as organic matter, clay content, and pH, impact herbicide adsorption and desorption. Higher *p*H soils reduce imazethapyr adsorption, yet make the herbicide more resistant to desorption (Bresnahan *et al*., 2000). Environmental factors, especially precipitation and humidity, affect microbial degradation and leaching. Drier conditions, with less rainfall, increase the soil residual half-life due to reduced microbial activity, while wetter conditions encourage herbicide degradation and runoff (Sondhia, 2008). These findings underscore that in the present study the low organic matter content, and high soil pH coupled with limited rainfall between herbicide application in moth bean and mustard planting may have enhanced herbicide persistence, and play a crucial role in the residual activity of imazethapyr in loamy sand soils.

Seed and biomass yield: Similar to plant height and plant dry weight the seed and dry biomass yield of mustard was also varied significantly in three year of experiment and mean analysis (Table 3). Imazethapyr containing treatments like imazethapyr (PoE 50 g a.i. ha^{-1}); imazethapyr + imazamox (PoE 60 g a.i. ha^{-1}); propaquizafop + imazethapyr (PoE 100 g a.i. ha^{-1}); and propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) recorded significant reduction in both seed and biomass yield of mustard as compared to other treatments. Mean analysis of data reveals that imazethapyr containing treatments registered 59.3% to 67.0% yield reduction in seed yield and 60.0% to 71.3% yield reduction in biomass yield over control. Clodinafop-propargyl + sodium acifluorfen (PoE @ 187 g a.i. ha^{-1}); clodinafop-propargyl + sodium acifluorfen (PoE @ 250 g a.i. ha^{-1}) and clodinafop-propargyl + sodium acifluorfen (PoE @ 312.5 g a.i. ha^{-1}) observed to yield statistically at with control and pendimethalin (PE 750 g a.i. ha^{-1}) (Table 3). Significantly low crop productivity under the toxic effect of imazethapyr treatments was possibly due to reduction in crop growth under these treatments as evident from low plant height, crop dry matter and stand loss (Tables 1 and 2), which persisted long enough to inhibit the yield attributes and finally the yield.

Over three years, imazethapyr treatments (50-125 g a.i. ha^{-1}) consistently caused significant growth inhibition (GI: 51.8-68.1%) compared to controls, whereas clodinafop-propargyl + sodium acifluorfen (4.9-6.7%) and pendimethalin (3.7%) had much lower impacts. The strong inhibitory effect of imazethapyr is linked to its disruption of acetohydroxy acid synthase activity, impairing protein synthesis and plant metabolism (Scarponi *et al.,* 1997). The persistence of herbicide was influenced by soil properties, including high pH, low organic matter, and environmental factors like limited rainfall, which reduced microbial degradation, extending the residual activity of herbicide (Bresnahan *et al.,* 2000; Sondhia, 2008). The low rainfall and loamy sand soil of the experiment site in this study enhanced the persistence of imazethapyr, resulting in significant growth inhibition that eventually led to low yields in mustard. This highlights the importance of soil and environmental factors in determining the residual toxicity of herbicides in arid regions.

Conclusion

This study highlights the persistent residual effects of post-emergence herbicides,

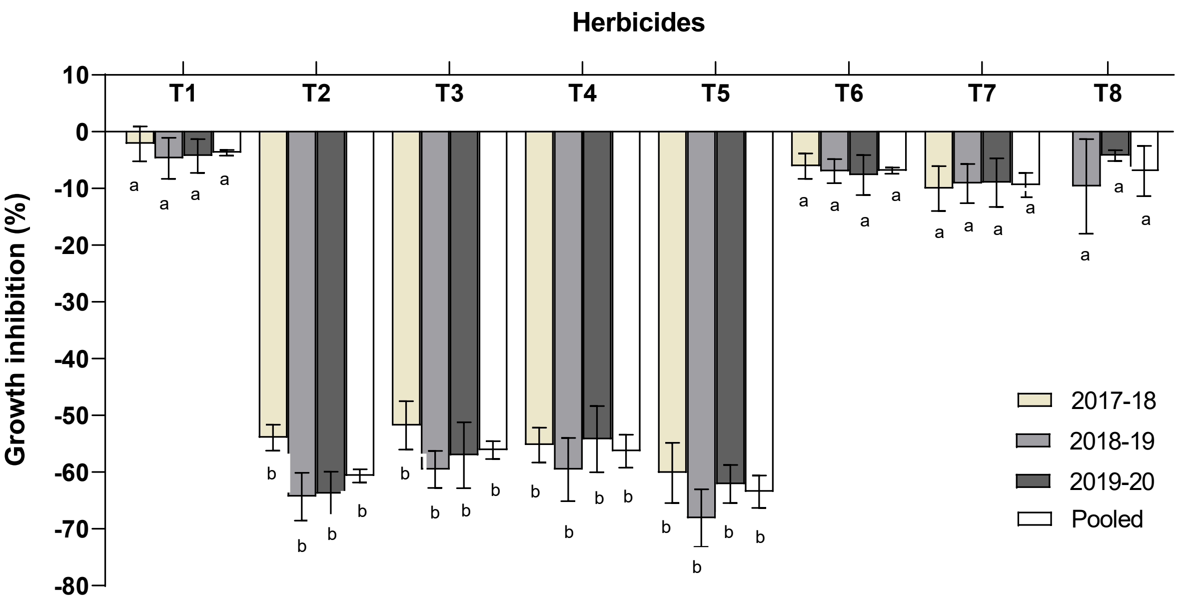

Fig. 2. Growth inhibition (%) of mustard assessed through plant height at 45 DAS under the phytotoxic effects of herbicides applied to previous season. Bars (mean with standard error) with different letters are significantly different at p<0.05 as per Tukey's HSD test.

(T_1 - Pendimethalin PE @ 750 g a.i. ha^{-1}; T_2 - Imazethapyr PoE @ 50 g a.i. ha^{-1}; T_3 - Imazethapyr + Imazamox PoE @ 60 g a.i. ha^{-1}; T_4- Propaquizafop + imazethapyr PoE @ 100 g a.i. ha^{-1}; T_5- Propaquizafop + imazethapyr PoE @ 125 g a.i. ha^{-1}; T_6- Clodinafop-propargyl + sodium acifluorfen PoE @ 187 g a.i. ha^{-1}; T_7- Clodinafop-propargyl + sodium acifluorfen PoE @ 250 g a.i. ha^{-1}; T_8- Clodinafop-propargyl + sodium acifluorfenPoE @ 312.5 g a.i. ha^{-1})

Table 3. Seed and biomass yield (kg ha^{-1}) of mustard under the residual effect of herbicides

Treatment	Seed yield				Biomass yield			
	2017-18	2018-19	2019-20	Mean	2017-18	2018-19	2019-20	Mean
Control	1959^{b}	2007^{b}	2203^{b}	2056^{b}	7196^{b}	6894^{b}	7385^{b}	7158^{b}
Pendimethalin PE @750 g a.i. ha^{-1}	1924^{b}	1947^{b}	2163^{b}	2011^{b}	6991^{b}	6519^{b}	7339^{b}	6949^{b}
Imazethapyr PoE @ 50 g a.i. ha^{-1}	813^{a}	710^{a}	977^{a}	833^{a}	3002^{a}	2508^{a}	3077^{a}	2862^{a}
Imazethapyr + Imazamox PoE @ 60 g a.i ha^{-1}	872^{a}	723^{a}	914^{a}	836^{a}	2845^{a}	2277^{a}	2709^{a}	2611^{a}
Propaquizafop + imazethapyr PoE @ 100 g a.i. ha^{-1}	677^{a}	677^{a}	807^{a}	720^{a}	2194^{a}	2247^{a}	2475^{a}	2305^{a}
Propaquizafop + imazethapyr PoE @ 125 g a.i. ha^{-1}	640^{a}	628^{a}	767^{a}	678^{a}	1909^{a}	2129^{a}	2125^{a}	2054^{a}
Clodinafop-propargyl + sodium acifluorfen PoE @ 187 g a.i. ha^{-1}	1933^{b}	1903^{b}	2170^{b}	2002^{b}	6648^{b}	6588^{b}	7099^{b}	6778^{b}
Clodinafop-propargyl + sodium acifluorfen PoE @ 250 g a.i. ha^{-1}	1893^{b}	1923^{b}	2017^{b}	1944^{b}	6487^{b}	6415^{b}	6928^{b}	6610^{b}
Clodinafop-propargyl + sodium acifluorfenPoE @ 312.5 g a.i. ha^{-1}	-	1907^{b}	2083^{b}	1995^{b}	-	6609^{b}	6751^{b}	6680^{b}
SEm±	101	96	122	62	398	349	385	218
CV (%)	13.0	12.1	13.5	12.8	14.8	12.9	13.1	13.3

particularly imazethapyr, on mustard growth and yield in pulse-based cropping systems. Imazethapyr residues significantly inhibited mustard seedling growth, plant height, and biomass, with seed yield. Conversely, another post-emergence herbicide clodinafop-propargyl + sodium acifluorfen showed no significant residual toxic impact, suggesting it as safer options for rotational cropping with mustard. These findings underscore the need for cautious selection of herbicides in arid cropping systems, considering their potential long-term effects on succeeding crops.

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