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Weed control in conventional soybean with pendimethalin followed by imazethapyr + imazamox/quizalofop-*p*-ethyl

R. Yadav, M.S. Bhullar, S. Kaur, T. Kaur, and A.J. Jhala

Abstract: The objectives of this study were to evaluate the efficacy of pendimethalin applied pre-emergence (PRE) followed by post-emergence (POST) application of imazethapyr + imazamox/quizalofop-*p*-ethyl for weed control and their effect on conventional soybean injury, yield attributes, and yield. Field experiments were conducted in 2013 and 2014 in conventional soybean. Herbicide treatments provided ≥90%, 70%, and 85% control of crowfoot grass, large crabgrass, and goosegrass, respectively, and ≤80% control of false amaranth and horse purslane at 30 d after sowing (DAS). At 60 DAS, pendimethalin applied alone or followed by hand-hoeing/quizalofop-*p*-ethyl/imazethapyr +imazamox provided 100% control of goosegrass and 65%–100% control of crowfoot grass/large crabgrass. Pendimethalin followed by imazethapyr + imazamox/quizalofop-*p*-ethyl as well as quizalofop-*p*-ethyl applied alone resulted in complete control of crowfoot grass, large crabgrass, and goosegrass, but control of broadleaf weeds was variable. Pendimethalin followed by imazethapyr + imazamox at 70 g ha^{-1} at 28 DAS, imazethapyr + imazamox at 60 or 70 g ha^{-1} at 21 DAS followed by quizalofop-*p*-ethyl at 37.5 g ha^{-1} at 42 DAS resulted in soybean branch numbers per plant, number of pods per plant, and soybean seed yield comparable to weed-free control. Control of Benghal dayflower and purple nutsedge was not acceptable.

Key words: herbicide, sequential applications, soybean, weed control, yield loss.

Résumé : Cette étude devait évaluer l'efficacité de l'application de pendiméthaline avant la levée (PRE) puis celle d'imazetapyr et du mélange imazamox/quizalofop-*p*-ethyl après la levée (POST) dans la lutte contre les mauvaises herbes. Les auteurs ont aussi examiné les effets du traitement sur les dommages subis par le soja ordinaire, sur les paramètres du rendement et sur le rendement proprement dit. Dans cette optique, ils ont effectué des expériences sur des parcelles de soja ordinaire, sur le terrain, en 2013 et 2014. Le traitement détruit respectivement ≥90, 70 et 85 % du dactyloténion d'Égypte, de la digitaire sanguine et de l'éleusine de l'Inde, ainsi que ≤ 80 % de *Digera muricata* et du pourpier courant, trente jours après les semis (JAS). Soixante jours après les semis, l'application de pendiméthaline seule ou suivie d'un sarclage et de l'application de quizalofop-*p*-ethyl ainsi que du mélange imazethapyr–imazamox entraîne la destruction complète de l'éleusine de l'Inde, de même que la destruction de 65 % à 100 % du dactyloténion d'Égypte et de la digitaire sanguine. L'application de pendiméthaline suivie par celle d'imazethapyr et du mélange imazamox/quizalofop-*p*-ethyl ainsi que l'application de quizalofop-*p*-ethyl seul assure une destruction totale du dactyloténion d'Égypte, de la digitaire sanguine et de l'éleusine d'Égypte, mais l'efficacité de ce traitement contre les dicotylédones varie. L'application de pendiméthaline puis d'imazethapyr et d'imazamox à raison de 70 g par hectare 28 JAS, d'imazethapyr et d'imazamox à raison de 60 ou de 70 g par hectare 21 JAS puis de quizalofop-*p*-ethyl à raison de 37,5 g par hectare 42 JAS entraîne un nombre de ramifications, un nombre de gousses par plant et un rendement grainier du soja comparables à ceux relevés sur les parcelles désherbées. Ces traitements ne permettent pas une lutte acceptable contre la comméline du Bengale et le souchet rond. [Traduit par la Rédaction]

Mots-clés : herbicide, applications séquentielles, soja, lutte contre les mauvaises herbes, diminution du rendement.

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Introduction

India is the fifth largest producer of soybean [*Glycine max* L. (Merr.)] in the world, contributing about 3.3% of global soybean production [United States Department of Agriculture (USDA) 2014]. Soybean occupies the first place among oilseed crops in terms of area and production in India; it is cultivated on about 12.2 million hectares with an annual production of about 12 million tonnes (Anonymous 2013). Soybean–wheat (*Triticum aestivum* L.) has become an important double-cropping system in the Vertisols of the semi-arid tropical regions of India. Soybean cultivation is being encouraged at the national level as an alternative to rice (*Oryza sativa* L.) due to the numerous problems arising in this system, including nutrient imbalances, shifts in weed flora, the evolution of herbicide-resistant weeds, and depleting ground water in the Indo-Gangetic Plains of India, especially in Punjab and Haryana — the northern states of India (Bhatt et al. 2016; Bhullar et al. 2016).

Weeds are a major limiting factor for optimum soybean production in India. Grass weeds, including crowfoot grass [*Dactyloctenium aegyptium* (L.) Willd.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Acrachne racemosa* (B. Heyne ex Roem. & Schult) Ohwi]; broadleaf weeds such as false amaranth (*Digera muricata* (L.) Mart.), horse purslane (*Trianthema portulacastrum* L.), common waterhemp (*Amaranthus rudis* Sauer); and perennial weeds such as purple nutsedge (*Cyperus rotundus* L.), bermudagrass [*Cynodon dactylon* (L.) Pers.], and johnsongrass [*Sorghum halepense* (L.) Pers.] have been reported as major weeds in soybean production fields (Kalpana and Velayutham 2004; Idapuganti et al. 2005; Tuti and Das 2011). Slow initial growth and wide inter-row spacing in soybean provide an ideal environment for weed growth and development. Weeds emerging early in the season compete the most with soybean plants. For example, horse purslane emerges before or with soybean, grows faster than soybean, and competes from the seedling stage (Senthil et al. 2009). Several weeds, including velvetleaf (*Abutilon theophrasti*) and common ragweed (*Ambrosia artemisiifolia*), grow taller than soybean, intercepting photosynthetically active radiation, and reducing soybean yield (Coble et al. 1981; Begonia et al. 1991).

Despite the suitable climatic and edaphic conditions, the average soybean yield in India is one-third (0.78 t ha^{-1}) of the world average (2.5 t ha^{-1}) (USDA 2014). Yield losses in soybean due to weed interference vary from 30% to 84% in India (Tiwari and Kurchania 1990; Gaikwad and Pawar 2002; Singh et al. 2003, 2004), indicating the need for weed control for optimum soybean production. The critical weed-free period in soybean ranges from 9 to 14 d after emergence (Thurlow and Buchanan 1972; Baysinger and Sims 1991; Van-Acker et al. 1993) to as late as 6 wk after emergence (Fellows and Roeth 1992). Thus, the critical period is not static and is influenced by several factors, including cropping practices, the time of weed emergence relative to the crop, and the density and type of emerging weeds in the field.

Hand-hoeing is a traditional method adopted by soybean growers for weed control in India, though it is laborious and time consuming. Often, hand-hoeing cannot be performed at the correct time due to rain, unfavourable soil conditions, higher labour costs, and the unavailability of labour. Under these situations, herbicide use can be a viable option. Glyphosate-resistant soybean has recently been investigated at public university research trials; however, no herbicide-resistant soybean is currently commercially available in India, therefore, conventional soybean varieties developed by public and (or) private sectors are being planted. Limited preemergence (PRE) herbicides have been registered in soybean in India, including alachlor, chlorimuron ethyl, clomazone, diclosulam, metolachlor, metribuzin, pendimethalin, and pendimethalin + imazethapyr [CIBRC 2015]. However, weed control programs based only on PRE herbicide is not adequate for providing season-long weed control because weeds emerging later in the season compete with soybean and reduce seed yield. Furthermore, if farmers are unable to apply PRE herbicides due to unfavourable weather conditions, postemergence (POST) herbicides are needed for managing weeds. The POST herbicides such as fenoxaprop-*p*-butyl, fluazifop-*p*-butyl, imazamox + imazethapyr, imazethapyr, propaquizafop, and quizalofop-*p*-ethyl have been registered for weed control in soybean (CIBRC 2015). The POST application of imazethapyr at 75 g ha^{-1} has been effective for control of weeds in soybean (Anonymous 2014). A PRE followed by POST herbicide program provided better weed control in soybean compared with a POST-only herbicide program in several studies in the United States (Taylor-Lovell et al. 2002; Jhala et al. 2015).

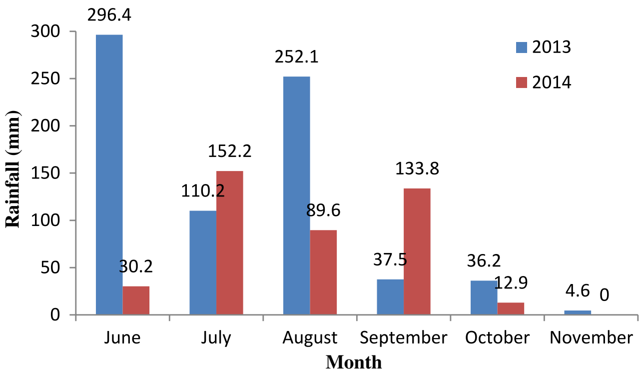
The objectives of this study were to evaluate pendimethalin applied PRE followed by POST application of imazethapyr +imazamox/quizalofop-*p*-ethyl for weed control in conventional soybean and to evaluate their effect on soybean injury, yield, and yield attributes compared with weed-free and untreated controls.

Materials and Methods

Description of the experiment

Field experiments were conducted during the summer of 2013 and 2014 at Punjab Agricultural University, Ludhiana, India. The soil at the experimental site was loamy sand with 83% sand, 10% silt, and 7% clay, a pH of 7.1, 0.27% organic carbon, 182 kg ha^{-1} available nitrogen, 13 kg ha^{-1} available phosphorous, and 145 kg ha^{-1} available potassium. The rainfall received in the 2013 and 2014 cropping seasons was 740 and 420 mm, respectively (Fig. 1). The field was ploughed once with a disc harrow and cultivated twice with a cultivator, followed by

Fig. 1. Total monthly rainfall received during the cropping season in 2013 and 2014 in a field experiment conducted at Punjab Agricultural University, Ludhiana, India. [Colour online.]



planking (tractor-drawn light equipment used to crush the hard clods to smoothen the soil surface and to compact the soil lightly to obtain a fine seed bed). Soybean cultivar SL 744 (140 d maturity) was seeded at 75 kg ha^{-1} on 8 June 2013 and 12 June 2014, with 45 cm spacing between rows. A fertilizer application of 30 kg N ha^{-1} (80 kg urea) and 80 kg P_2O_5 ha^{-1} (500 kg single super phosphate) was applied at the time of soybean seeding.

The experiment was arranged in a randomized complete block design with four blocks and 2 m × 9 m plot size. The experiment consisted of 16 weed control treatments: (*i*) pendimethalin at 450 g ha^{-1} applied PRE alone or (*ii*) pendimethalin at 450 g ha^{-1} applied PRE followed by hand-hoeing at 40 d after sowing (DAS), (*iii*) imazethapyr + imazamox at 60 g ha^{-1} at 21 DAS, (*iv*) imazethapyr + imazamox at 60 g ha^{-1} at 28 DAS, (*v*) imazethapyr + imazamox at 70 g ha^{-1} at 21 DAS, (*vi*) imazethapyr + imazamox at 70 g ha^{-1} at 28 DAS, (*vii*) pendimethalin at 450 g ha^{-1} applied PRE followed by imazethapyr + imazamox at 60 g ha^{-1} at 28 DAS, (*viii*) pendimethalin at 450 g ha^{-1} applied PRE followed by imazethapyr + imazamox at 70 g ha^{-1} at 28 DAS, (*ix*) quizalofop-*p*-ethyl at 37.5 g ha^{-1} at 21 DAS, (*x*) quizalofop-*p*-ethyl at 50 g ha^{-1} at 21 DAS, (*xi*) pendimethalin at 450 g ha^{-1} applied PRE followed by quizalofop-*p*-ethyl at 37.5 g ha^{-1} at 28 DAS, (*xii*) pendimethalin at 450 g ha^{-1} applied PRE followed by quizalofop-*p*-ethyl at 50 g ha^{-1} at 28 DAS, (*xiii*) imazethapyr + imazamox at 60 g ha^{-1} at 21 DAS followed by quizalofop-*p*-ethyl at 37.5 g ha^{-1} at 42 DAS, (*xiv*) imazethapyr + imazamox at 70 g ha^{-1} at 21 DAS followed by quizalofop-*p*-ethyl at 50 g ha^{-1} at 42 DAS, (*xv*) weed-free control, and (*xvi*) untreated control. Pendimethalin was applied on the day of sowing by mixing in 500 L ha^{-1}of water while other herbicides were applied by mixing in 375 L ha^{-1} of water. A knapsack sprayer fitted with a flat fan nozzle was used for herbicide application at a pressure of 280 kPa. The weed-free control plots were kept weed-free by hand-weeding as required, and weeds were not removed in untreated control plots.

Data collection

Weed control was assessed visually at 30 and 60 DAS using a scale of 0%–100%, with 0% meaning no control and 100% meaning complete weed control. Weed densities were recorded at 40 DAS and at soybean harvest by counting the number of weeds by weed category (broadleaves, grasses, or sedges) in two 0.45 m^2 quadrats placed randomly between the centre soybean rows in each plot and are presented as number of plants m^{-2}. At 60 DAS, surviving weeds were cut at the soil surface from two randomly selected 0.45 m^2 quadrats per plot and oven-dried at 65 °C until they reached a constant weight. Data for soybean plant height, number of branches, and number of pods per plant were recorded from five randomly selected representative plants per plot when soybean plants were mature with pods and seed produced. The crop was manually harvested on 29 Oct. 2013 and 11 Nov. 2014. The harvested area for grain yield was 13.5 m^2 and yield was adjusted to 11% moisture content and converted to kg ha^{-1}.

Statistical analyses

Data were subjected to analysis of variance (ANOVA) using the PROC MIXED procedure in SAS version 9.3 (SAS 2011). Years and treatments were considered fixed effects, whereas blocks (nested within year) were considered random effects in the model. Data were tested for normality with the use of PROC UNIVARIATE. Weed density and biomass data were square-root transformed prior to analysis and visual control rating data were arc-sine transformed prior to analysis. Back-transformed means are presented with mean separation based on transformed values. Where the ANOVA indicated significant treatment effects, means were separated with Fisher's protected least significant difference (LSD) test at $P \leq 0.05$.

Results and Discussion

Year × treatment interactions for weed control, weed density and biomass, yield attributes, and soybean yield were significant; therefore, data were analysed and presented separately for both years. This might be due to differences in rainfall received during both years (Fig. 1).

Weed control and weed density

Crowfoot grass, large crabgrass, and goosegrass were the primary grass weeds, Benghal dayflower was the monocot weed, and false amaranth and horse purslane were the primary broadleaf weeds. Purple nutsedge, a summer perennial sedge, was also found. At 30 DAS, all herbicide treatments provided ≥90%, 70%, and 85% control of crowfoot grass, large crabgrass, and goosegrass, respectively (Table 1). Quizalofop-*p*-ethyl provided 100% control of crowfoot grass, large crabgrass, and goosegrass, but no control of false amaranth, horse purslane, or purple nutsedge. Goosegrass control with imazethapyr + imazamox at 60 or 70 g ha^{-1} was 85% compared with

Table 1. Effect of herbicide treatments on weed control at 30 d after sowing (DAS) in field experiments conducted in soybean at Punjab Agricultural University, India, in 2013 and 2014. This table includes treatments that were applied within 30 DAS.

			Weed control (%)													
			Crowfoot grass		Large crabgrass		Goosegrass		Benghal dayflower		Purple nutsedge		False amaranth		Horse purslane	
Treatment	Timing	Rate (g a.i. ha^{-1})	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
Pendimethalin	PRE	450	90b	90b	90b	100a	95a	100	0c	0b	0b	0c	40b	50b	65b	75a
Imazethapyr + imazamox	21 DAS	60	90b	90b	90b	70b	85b	100	55b	90a	40a	50b	75a	80a	75a	80a
Imazethapyr + imazamox	21 DAS	70	95ab	100a	95ab	70b	85b	100	60a	90a	40a	70a	70a	78a	76a	75a
Quizalofop-*p*-ethyl	21 DAS	37.5	100a	100a	100a	100a	100a	100	0c	0b	0b	0c	0c	0c	0c	0c
Quizalofop-*p*-ethyl	21 DAS	50	100a	100a	100a	100a	100a	100	0c	0b	0b	0c	0c	0c	0c	0c

Note: PRE, pre-emergence. Data were arc-sine transformed before analysis; however, back-transformed actual mean values are presented based on the interpretation from the transformed data. Means followed by different lowercase letters within each column are significantly different according to Fisher's protected LSD test where $P \leq 0.05$.

>95% control with pendimethalin or quizalofop-*p*-ethyl in 2013; however, in 2014, all herbicide treatments were equally effective and achieved 100% control. Imazethapyr + imazamox applied at 21 DAS at 60 or 70 g ha^{-1} provided 70%–80% control of false amaranth and horse purslane (Table 1) and reduced density as low as 10 plants m^{-2} (data not shown). Pendimethalin applied alone reduced density of crowfoot grass, large crabgrass, and goosegrass as low as 0–11 plants m^{-2} (Table 2). Benghal dayflower and purple nutsedge control was ≤60% and ≤40%, respectively, in 2013 at 30 DAS; however, 90% control of Benghal dayflower and 50%–70% control of purple nutsedge was achieved by imazethapyr + imazamox in 2014 (Table 1) and reduced density of Benghal dayflower (≤5 plants m^{-2}) (Table 2). This might be due to the fact that several herbicides are marginally effective for control of Benghal dayflower. In previous research, control of Benghal dayflower by glyphosate was only 53% at 21 d after treatment (Culpepper et al. 2004) and <68% even at the highest glyphosate rate of 2.58 kg a.e. ha^{-1} (Ulloa and Owen 2009). Additionally, it has an aggressive growth habit, along with the ability to creep along the soil and root adventitiously at the nodes, increasing the potential for survival (Kuhns and Harpster 2004). Among all treatments, imazethapyr + imazamox applied at 60 g ha^{-1} at 21 DAS reduced purple nutsedge density to 175 plants m^{-2} in 2013 and 18 plants m^{-2} in 2014 (Table 2). Similarly, Kushwah and Vyas (2006) reported that imazethapyr at 75 g ha^{-1} or imazamox at 60 g ha^{-1} reduced Benghal dayflower and purple nutsedge densities to ≥62% and ≥78%, respectively.

At 60 DAS, pendimethalin applied alone or followed by hand-hoeing/quizalofop-*p*-ethyl/imazethapyr + imazamox provided 100% control of goosegrass and 65%–100% control of crowfoot grass and large crabgrass, depending on the treatment being investigated (Table 3). Control of false amaranth and horse purslane at 60 DAS was similar in 2013 and 2014; therefore, data were combined (Table 3). Several treatments provided 100% control of false amaranth, with the exceptions of pendimethalin or quizalofop-*p*-ethyl applied alone (Table 3). Pendimethalin applied PRE followed by hand-hoeing at 40 DAS provided 100% control of false amaranth in 2013, but declined to 50% control of horse purslane in 2014.

Pendimethalin followed by hand-hoeing or quizalofop-*p*-ethyl and quizalofop-*p*-ethyl applied at 21 DAS provided 100% control of crowfoot grass and large crabgrass in 2013, but resulted in ≤90% control in 2014, with the exception of pendimethalin followed by hand-hoeing (100% control) (Table 3). Pendimethalin followed by imazethapyr + imazamox/quizalofop-*p*-ethyl, as well as quizalofop-*p*-ethyl applied alone, resulted in no density of crowfoot grass, large crabgrass, and goosegrass (Table 2). Kumar et al. (2008) reported complete control of large crabgrass with quizalofop-*p*-ethyl at 50 g ha^{-1}. Pendimethalin followed by quizalofop-*p*-ethyl resulted in no density of grass weeds at 40 DAS; Benghal

Table 2. Effect of herbicide treatments on weed density at 40 d after sowing (DAS) in field experiments conducted for weed control in soybean at Punjab Agricultural University, India, in 2013 and 2014. This table includes treatments that were applied within 40 DAS.

			Weed density (plants m^{-2})									
		Rate	Crowfoot grass		Large crabgrass		Goosegrass		Benghal dayflower		Purple nutsedge	
Treatment	Timing	(g a.i. ha^{-1})	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
Pendimethalin	PRE	450	11d	7b	2d	0d	0d	0d	6abc	20b	311a	85a
Imazethapyr + imazamox	21 DAS	60	25c	0d	28b	18c	16b	0d	3de	0e	175de	18e
Imazethapyr + imazamox	28 DAS	60	33b	4c	26b	27b	18a	7c	5bcd	10cd	232abcde	45cd
Imazethapyr + imazamox	21 DAS	70	13d	0d	25b	16c	18a	0d	2e	0e	214cde	5f
Imazethapyr + imazamox	28 DAS	70	10d	3c	14c	24b	14c	10b	4de	8d	303ab	34d
Pendimethalin fb imazethapyr + imazamox	PRE fb 28 DAS	450 fb 60	0e	0d	0e	0d	0d	0d	5bcd	15c	228bcde	46cd
Pendimethalin fb imazethapyr + imazamox	PRE fb 28 DAS	450 fb 70	0e	0d	0e	0d	0d	0d	4bce	14c	253abc	44cd
Quizalofop-*p*-ethyl	21 DAS	37.5	0e	0d	0e	0d	0d	0d	7ab	13c	242abcd	33d
Quizalofop-*p*-ethyl	21 DAS	50	0e	0d	0e	0d	0d	0d	6abc	12cd	235abcde	86a
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 37.5	0e	0d	0e	0d	0d	0d	6abc	34a	178de	59bc
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 50	0e	0d	0e	0d	0d	0d	7ab	25b	169e	69ab
Untreated Control	—	—	55a	62a	51a	39a	14c	37a	8a	13c	253abc	37d

Note: DAS, days after sowing; fb, followed by; PRE, pre-emergence. Data were square-root transformed before analysis; however, back-transformed actual mean values are presented based on the interpretation from the transformed data. Means followed by different lowercase letters within each column are significantly different according to Fisher's protected LSD test where $P \leq 0.05$.

dayflower, however, was the exception, and resulted in a density of 6–13 plants m^{-2}. Younesabadi et al. (2013) reported that a tank mixture of pendimethalin at 500 g ha^{-1} + imazethapyr at 75 g ha^{-1} reduced density and biomass of goosegrass, crowfoot grass, purple nutsedge, and false amaranth to >72% compared with the untreated control.

The PRE application of pendimethalin prevented the germination and establishment of the first cohort of grass weeds; therefore, the plots were relatively clean. It has been reported; however, that the persistence of pendimethalin under hot and moist conditions tends to be limited. Goosegrass control with imazethapyr + imazamox at 60 or 70 g ha^{-1} at both application timings was 0% in 2013 and ≤50% in 2014. Benghal dayflower was the most difficult to control, as ≤40% control was achieved. No herbicide treatment controlled purple nutsedge at 60 DAT (data not shown). Purple nutsedge is a troublesome weed worldwide (Webster and Grey 2014) and it is difficult to control because its reproduction is mainly by rhizomes and tubers, persisting for 3–5 yr (DeFelice 2002).

A premix of imazethapyr and imazamox at 70 g ha^{-1} applied at 21 DAS resulted in 60%–75% control of crowfoot grass and large crabgrass compared with the same premix applied at 28 DAS or at 60 g ha^{-1} at 21 or 28 DAS (Table 3). Weeds were at the 2–3 and 4 to 5 leaf stage at 21 and 28 DAS, respectively; hence, the weed control was relatively higher when herbicides were applied at 21 DAS compared with 28 DAS, indicating that the stage of weeds and timing of herbicide application can affect efficacy. In a similar study, Hong et al. (2009) reported reduced efficacy of imazethapyr from 100% control of Asiatic dayflower (*Commelina communis* L.) when applied at the 1-leaf stage to <90% and <53% control at the 2- and 4-leaf stage, respectively.

For broadleaf weeds, imazethapyr + imazamox applied at 60 or 70 g ha^{-1} at 21 or 28 DAS showed differential efficacy against false amaranth and horse purslane with 100% and 0% control, respectively (Table 2), indicating the herbicide can control the larger plants of sensitive broadleaf weeds even at lower rates. Meena et al. (2011) reported that imazethapyr applied at 50 g ha^{-1} reduced broadleaf weed density and biomass by 50%. In this study, imazethapyr + imazamox resulted in <70% control of Benghal dayflower and purple nutsedge. Kumar et al. (2012) reported 50% control of purple nutsedge with imazethapyr at 75 g ha^{-1} and that at 100 g ha^{-1} it reduced whitemouth dayflower (*Commelina erecta* L.) biomass to ≥83% of the nontreated control (Arregui et al. 2006).

Weed biomass

Herbicide treatments reduced grass/monocot and broadleaf weed biomass compared with the untreated control (Table 4). Pendimethalin followed by hand-hoeing provided the lowest grass weed biomass in 2013,

Table 3. Effect of herbicide treatments on weed control at 60 d after sowing (DAS) in field experiments conducted in soybean at Punjab Agricultural University, India, in 2013 and 2014.

			Weed control (%)									
			Crowfoot grass		Large crabgrass		Goosegrass		Benghal dayflower		False amaranth	Horse purslane
Treatment	Timing	Rate (g a.i. ha^{-1})	2013	2014	2013	2014	2013	2014	2013	2014	2013–2014[a]	2013–2014[a]
Pendimethalin	PRE	450	70d	70cd	65c	65d	100a	100a	0	0c	0b	30b
Pendimethalin fb hoeing	PRE fb 40 DAS	450	100a	100a	100a	100a	100a	100a	0	0c	100a	50a
Imazethapyr + imazamox	21 DAS	60	70d	60d	75c	60d	0b	50b	0	30b	100a	0c
Imazethapyr + imazamox	28 DAS	60	0f	30e	0e	30e	0b	0c	0	0c	100a	0c
Imazethapyr + imazamox	21 DAS	70	75d	60d	75c	60d	0b	50b	0	40a	100a	0c
Imazethapyr + imazamox	28 DAS	70	60e	30e	50d	30e	0b	0c	0	0c	100a	0c
Pendimethalin fb Imazethapyr + imazamox	PRE fb 28 DAS	450 fb 60	95b	95b	95b	95b	100a	100a	0	0c	100a	30b
Pendimethalin fb Imazethapyr + imazamox	PRE fb 28 DAS	450 fb 70	95b	95b	95b	95b	100a	100a	0	0c	100a	30b
Quizalofop-*p*-ethyl	21 DAS	37.5	100a	60d	100a	60d	100a	100a	0	0c	0b	0c
Quizalofop-*p*-ethyl	21 DAS	50	100a	90b	100a	90b	100a	100a	0	0c	0b	0c
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 37.5	100a	60d	100a	70cd	100a	100a	0	0c	0b	30b
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 50	100a	70cd	100a	80c	100a	100a	0	0c	0b	30b
Imazethapyr + imazamox fb quizalofop-*p*-ethyl	21 DAS fb 42 DAS	60 fb 37.5	90c	80c	90b	80c	100a	50b	0	30b	100a	0c
Imazethapyr + imazamox fb quizalofop-*p*-ethyl	21 DAS fb 42 DAS	70 fb 37.5	95b	80c	95b	80c	100a	50b	0	40a	100a	0c

Note: fb, followed by; PRE, pre-emergence. Data were arc-sine transformed before analysis; however, back-transformed actual mean values are presented based on the interpretation from the transformed data. Means followed by different lowercase letters within each column are significantly different according to Fisher's protected LSD test where $P \leq 0.05$.

[a]Control of false amaranth and horse purslane was similar in 2013 and 2014; therefore, data were combined.

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Table 4. Effect of herbicide treatments on biomass of grass–monocot, broadleaf, and sedge weeds at 60 d after sowing (DAS) in field experiments conducted for weed control in soybean at Punjab Agricultural University, India, in 2013 and 2014.

			Weed biomass (g m^{-2})					
			Grass/ monocot[a]		Broadleaf[a]		Sedge[a]	
Treatment	Application timing	Rate (g a.i. ha^{-1})	2013	2014	2013	2014	2013	2014
Pendimethalin	PRE	450	137b	446b	105c	170b	99a	39abcd
Pendimethalin fb hoeing	PRE fb 40 DAS	450	0h	97g	0d	10d	70bc	47ab
Imazethapyr + imazamox	21 DAS	60	52d	402bc	0d	15d	63bc	45ab
Imazethapyr + imazamox	28 DAS	60	209a	421bc	0d	20d	31f	9f
Imazethapyr + imazamox	21 DAS	70	39d	479b	0d	15d	51cde	15f
Imazethapyr + imazamox	28 DAS	70	80c	405bc	0d	18d	33f	14f
Pendimethalin fb Imazethapyr + imazamox	PRE fb 28 DAS	450 fb 60	4fg	100g	0d	10d	71bc	25e
Pendimethalin fb Imazethapyr + imazamox	PRE fb 28 DAS	450 fb 70	4fg	93g	0d	8d	73bc	31de
Quizalofop-*p*-ethyl	21 DAS	37.5	10ef	312cd	109bc	170b	68bc	42abcd
Quizalofop-*p*-ethyl	21 DAS	50	10ef	218ef	151a	185b	66bc	50a
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 37.5	9efg	266de	110bc	80c	79ab	42abc
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 50	14e	229de	147a	85c	77ab	39abcd
Imazethapyr + imazamox fb quizalofop-*p*-ethyl	21 DAS fb 42 DAS	60 fb 37.5	12e	157fg	0d	10d	57bcd	33cde
Imazethapyr + imazamox fb quizalofop-*p*-ethyl	21 DAS fb 42 DAS	70 fb 37.5	9efg	150fg	0d	79c	36ef	36bcd
Untreated Control	—	—	218a	890a	126b	445a	41def	33cde

Note: DAS, days after sowing; fb, followed by; PRE, pre-emergence. Data were square-root transformed before analysis; however, back-transformed actual mean values are presented based on the interpretation from the transformed data. Means followed by different lowercase letters within each column are significantly different according to Fisher's protected LSD test where $P \leq 0.05$.

[a]Primary grass weeds included crowfootgrass, large crabgrass, and goosegrass; monocot weed was Benghal dayflower; broadleaf weed included false amaranth and horse purslane; and purple nutsedge was the sedge species.

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but in 2014 this treatment was comparable with some other treatments. Pendimethalin followd by imazethapyr +imazamox, or imazethapyr + imazamox followed by quizalofop-*p*-ethyl reduced grass weed biomass ≥94% and ≥82% in 2013 and 2014, respectively. Imazethapyr + imazamox resulted in complete control of broadleaf weeds and no biomass was recorded in 2013. Taylor-Lovell et al. (2002) reported ≥80% control of many grass and broadleaf weeds with imazethapyr at 71 g ha^{-1} or imazamox at 36 g ha^{-1} in soybean and similar levels of reduction in weed biomass. Herbicide treatments had no effect on sedge biomass in 2013; however, in 2014, imazethapyr + imazamox applied at 60 g ha^{-1} 30 DAS reduced 70% sedge weed biomass (Table 4).

Quizalofop-*p*-ethyl maintained control of crowfoot grass and large crabgrass and recorded lower biomass of most grass weeds; however, it did not control Benghal dayflower. The infestation of Benghal dayflower is increasing, especially in areas where corn is a crop in rotation, as atrazine commonly used for weed control in maize does not provide satisfactory control (M.S. Bhullar, personal observation). Quizalofop-*p*-ethyl controls several grass weeds in soybean and can be tank-mixed with other broadleaf herbicide(s) to provide broad-spectrum weed control (Peterson et al. 2001). Hand-hoeing was accomplished at 40 DAS, after weed density data collection; however, weed biomass data reported a significant reduction (<100 g m^{-2}) when pendimethalin was followed by hand-hoeing compared with pendimethalin applied alone. Chhokar and Balyan (1999) reported 61 plants m^{-2} of junglerice [*Echinochloa colona* (L.) Link] in plots treated with pendimethalin at 1 kg ha^{-1} compared with <5.0 plants m^{-2} when pendimethalin was integrated with one instance of hand-weeding later in the season. Poor control of Benghal dayflower and broadleaf and sedges in this treatment combination resulted in higher weed biomass. Hence, PRE followed by POST application of grass herbicides may work well in fields dominated by grass weeds, excluding Benghal dayflower. Similarly, it was reported that pendimethalin had no effect on Benghal dayflower, and due to elimination of competition of other grass weeds by this herbicide, Benghal dayflower plants attained maximum vigour and biomass.

Soybean yield and yield attributes

Herbicides applied PRE showed no adverse effects on the germination and (or) emergence of soybean seedlings, and all POST herbicides were also safe on soybean plants in both years (data not shown). In 2013, soybean plants were taller and produced a higher number of branches, number of pods per plant, and seed yield compared with the 2014 growing season (Table 5). This might be due to higher rainfall and distribution over the cropping period (Fig. 1), resulting in higher soybean yield and yield attributes in 2013. Soybean yield attributes and seed yields were greatly reduced in the untreated control where full-season weed interference occurred. Soybean plants in the weed-free treatment produced the highest number of branches compared with other treatments in 2013. Similarly, plants in the weed-free treatment had the highest plant height and number of branches compared with all other treatments; however, in 2014 several herbicide treatments were comparable with the weed-free treatment (Table 5). In 2013, all herbicide treatments, except pendimethalin or imazethapyr + imazamox at 60 g ha^{-1} applied at 30 DAS, produced a number of pods comparable with the weed-free treatment. In 2014; however, relatively fewer treatments were comparable with the weed-free treatment.

The weed-free control treatment had the highest soybean yield (Table 5). The season-long weed infestation in the untreated control reduced soybean seed yield by 37%–54% compared with the weed-free control (Table 5). Pendimethalin applied alone resulted in a soybean yield of <1730 kg ha^{-1} due to the higher weed density and biomass accumulation of grass weeds (Tables 3 and 4). This indicated that pendimethalin applied alone could not provide weed control sufficient to maintain optimum soybean yields even in fields dominated by grass weeds, and needs to be integrated with other weed control practices at later stages. For example, pendimethalin followed by hand-hoeing resulted in soybean yields of 1900 and 1433 kg ha^{-1} in 2013 and 2014, respectively. Chhokar and Balyan (1999) reported that pendimethalin applied at 1 kg ha^{-1} provided 32% lower soybean yield compared with the weed-free control; whereas, pendimethalin followed by hand-weeding provided soybean yield similar to the weed-free control. In contrast, Rajput and Kushwah (2004) reported that pendimethalin applied at 1.5 kg ha^{-1} produced a soybean seed yield similar to the weed-free treatment; however, at 1 kg ha^{-1} it needed to be integrated with hand-weeding. Additionally, pendimethalin followed by quizalofop-*p*-ethyl was unable to prevent soybean yield loss due to the high weed density (Table 3) and biomass (Table 4) of broadleaf and sedge weeds in the absence of competition from grass weeds.

The critical period for weed control is relatively long and varies with the time of emergence, density, and type of weed present (Fellows and Roeth 1992; Van-Acker et al. 1993). Some herbicide programs tested in this study provided soybean seed yields similar to the weed-free control. For example, pendimethalin followed by imazethapyr +imazamox at 70 g ha^{-1} applied at 30 DAS; imazethapyr +imazamox at 70 g ha^{-1} applied at 21 DAS followed by quizalofop-*p*-ethyl applied at 42 DAS provided a soybean seed yield similar to the weed-free control ($P \leq 0.05$), probably due to reduced crop–weed competition during the critical period. Aichele and Penner (2005) reported the half-lives of imazamox and imazethapyr to be 1.4 and 16 wk, respectively. Younesabadi et al. (2013) reported that tank-mixing pendimethalin at 500 g ha^{-1} with imazethapyr at 75 g ha^{-1} resulted in a soybean seed

Table 5. Effect of herbicide treatments on yield attributes and yield of soybean in field experiments conducted for weed control in soybean at Punjab Agricultural University, India, in 2013 and 2014.

			Plant height (cm)		Branches (no. plant^{-1})		Pods (no. plant^{-1})		Seed yield (kg ha^{-1})	
Treatment	Application timing	Rate (g a.i. ha^{-1})	2013	2014	2013	2014	2013	2014	2013	2014
Pendimethalin	PRE	450	100b	73e	7.3b	5.3fg	132bc	61gh	1728c	923hi
Pendimethalin fb hoeing	PRE fb 40 DAS	450	95cd	80bcde	6.6c	5.375fg	154a	80abcd	1901abc	1433def
Imazethapyr + imazamox	21 DAS	60	100b	80bcde	7.4b	7.15bcd	150a	76cdefg	1981ab	1486cde
Imazethapyr + imazamox	28 DAS	60	94d	75de	6.5c	5.9ef	128c	80bcde	1688c	1168g
Imazethapyr + imazamox	21 DAS	70	100b	89a	7.6b	8.45a	151a	96a	1853abc	1557bcd
Imazethapyr + imazamox	28 DAS	70	102b	76de	7.5b	5.45fg	150ab	64efgh	1868abc	1127g
Pendimethalin fb Imazethapyr + imazamox	PRE fb 28 DAS	450 fb 60	95cd	87ab	7.5b	8.1ab	150ab	91abc	1793abc	1547bcd
Pendimethalin fb Imazethapyr + imazamox	PRE fb 28 DAS	450 fb 70	94d	84abc	7.4b	7.9abc	153a	93ab	1983ab	1680ab
Quizalofop-*p*-ethyl	21 DAS	37.5	101b	77cde	7.5b	4.7g	145abc	61gh	1875abc	930hi
Quizalofop-*p*-ethyl	21 DAS	50	100b	75e	7.3b	6.65de	146abc	70defgh	1820abc	1325f
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 37.5	99bcd	73e	7.4b	5.35fg	142abc	59h	1787bc	949h
Pendimethalin fb quizalofop-*p*-ethyl	PRE fb 28 DAS	450 fb 50	99bcd	83abcd	7.4b	6.95cde	140abc	77bcdef	1781bc	1358d
Imazethapyr + imazamox fb quizalofop-*p*-ethyl	21 DAS fb 42 DAS	60 fb 37.5	101b	88a	7.5b	7.35a-d	152a	86abcd	1991ab	1601abc
Imazethapyr + imazamox fb quizalofop-*p*-ethyl	21 DAS fb 42 DAS	70 fb 37.5	101b	90a	7.3b	8.2ab	154a	90abc	2005ab	1662ab
Weed-free Control	—	—	106a	90a	8.4a	8.3a	152a	91abc	2025a	1740a
Untreated Control	—	—	85e	73e	5.8d	5.5fg	105d	63fgh	1275d	802i

Note: DAS, days after sowing; fb, followed by; PRE, pre-emergence. Means followed by different lowercase letters within each column are significantly different according to Fisher's protected LSD test where $P \leq 0.05$.

yield similar to the weed-free control. The reduced weed pressure under these treatments over a longer period (>60 d) is reflected in the taller soybean plants with a higher number of branches, higher number of pods, and increased seed yield (Table 5). The results indicated that PRE application of pendimethalin followed by imazethapyr + imazamox or quizalofop-*p*-ethyl can be adopted for control of weeds in conventional soybean with no carry-over concern on crops grown in rotation with soybean in Punjab (Yadav and Bhullar 2014).

No herbicide program tested in this study provided control of all weed species; therefore, selection of herbicide program should be based on weed species present in the production field. Additionally, Benghal dayflower and purple nutsedge were difficult weeds to control in this study and more research is needed. Herbicide-tolerant soybean cultivars, specifically glyphosate-tolerant cultivars, have been recently tested at certain public universities in India; however, their approval and commercial cultivation is uncertain. Therefore, under the current situation, use of registered herbicides is one of the best options to achieve acceptable weed control and secure higher yield in soybean. Additionally, several herbicides, including flumioxazin, pyroxasulfone, and sulfentrazone have not yet been tested or registered for weed control in soybean in India. There is a need to evaluate the efficacy and crop safety of new herbicide tank mix partners so that guidelines can be developed for use of herbicides with multiple modes of action to avoid selection pressure and the evolution of herbicide-resistant weeds.

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