Weed Technology 2013 27:682–689

WSSA WEED SCIENCE SOCIETY OF AMERICA

Herbicide Options for Weed Control in Dry-Seeded Aromatic Rice in India

Gulshan Mahajan and Bhagirath S. Chauhan*

The looming water crisis and shortage of labor during rice transplanting in northwest India have led researchers to develop alternative methods to transition away from puddled transplanted rice. In this context, dry-seeded rice (DSR) is emerging as an efficient production technology to replace puddled transplanted rice. Weeds, however, are the main biological constraints to its success. A study comprising 12 treatments was conducted to evaluate the efficacy of PRE (pendimethalin and pyrazosulfuron) and POST herbicides (bispyribac, penoxsulam, and azimsulfuron) applied either alone or in a sequence for weed control in dry-seeded fine rice cv. 'Punjab Mehak 1'. Results indicated that the single application of pendimethalin (750 g ai ha^{-1}) PRE, pyrazosulfuron (15 g ai ha^{-1}) PRE, bispyribac-sodium (25 g ai ha^{-1}) POST, penoxsulam (25 g ai ha^{-1}) POST, and azimsulfuron (20 g ai ha^{-1}) POST reduced total weed biomass by 75, 68, 73, 70, and 72%, respectively, compared with the nontreated control at flowering stage of the crop. Azimsulfuron POST and pyrazosulfuron PRE proved effective against purple nutsedge and crowfootgrass, respectively. Chinese sprangletop, large crabgrass, and junglerice were effectively controlled with pendimethalin PRE. POST application of bispyribac-sodium and penoxsulam provided effective control of rice flatsedge. Compared to the nontreated control, grain yield following the single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST increased by 149, 119, 138, 124, and 144%, respectively. The sequential application of herbicides proved better than single applications. The lowest weed biomass was observed with the sequential application of pendimethalin PRE followed by azimsulfuron POST, and rice yielded 228% more than the nontreated control following this treatment. The results of this study are important for farmers growing DSR in making decisions regarding the application of POST herbicides, according to existing weed flora in the field.

Nomenclature: Azimsulfuron; bispyribac-sodium; pendimethalin; penoxsulam; pyrazosulfuron; Chinese sprangletop, *Leptochloa chinensis* (L.) Nees LEFCH; crowfootgrass, *Dactyloctenium aegyptium* (L.) Willd. DTTAE; junglerice, *Echinichloa colona* (L.) Link ECHCO; large crabgrass, *Digitaria sanguinalis* (L.) Scop., DIGSA; purple nutsedge, *Cyperus rotundus* L. CYPRO; rice flatsedge, *Cyperus iria* L. CYPIR; rice, *Oryza sativa* L.

Key words: Asia, weed control, weed density, weed biomass, yield.

La creciente crisis por escasez de agua y de mano de obra durante el trasplante de arroz en el noroeste de India ha llevado a los investigadores a desarrollar métodos alternativos para cambiar las prácticas de trasplante en lodo. En este contexto, el uso de siembra de arroz en seco (DSR) está surgiendo como una tecnología de producción eficiente para remplazar el trasplante de arroz en lodo. Sin embargo, las malezas son uno de los impedimentos biológicos más importantes para el éxito de esta tecnología. Se realizó un estudio compuesto de 12 tratamientos para evaluar la eficacia de herbicidas PRE (pendimethalin y pyroxasulfuron) y POST (bispyribac, penoxsulam, y azimsulfuron) aplicados ya sea solos o en secuencia para el control de malezas en arroz fino cv. 'Punjab Mehak 1′ sembrado en seco. Los resultados indicaron que una sola aplicación PRE de pendimethalin (750 g ai ha^{-1}), PRE de pyrazosulfuron (15 g ai ha^{-1}), POST de bispyribac-sodium (25 g ai ha^{-1}), POST de penoxsulam (25 g ai ha^{-1}), y POST de azimsulfuron (20 g ai ha^{-1}), redujo la biomasa total de malezas en 75, 68, 73, 70, y 72%, respectivamente, al compararse con el testigo no-tratado en el estado de floración del cultivo. Azimsulfuron POST y pyrazosulfuron PRE probaron ser efectivos contra *Cyperus rotundus* y *Dacyloctenium aegyptium*, respectivamente. *Leptochloa chinensis*, *Digitaria sanguinalis* y *Echinochloa colona* fueron controlados efectivamente con pendimethalin PRE. La aplicación POST de bispyribac-sodium y penoxsulam brindó un control efectivo de *Cyperus iria*. Al compararse con el testigo no-tratado, el rendimiento en grano después de una sola aplicación de pendimenthalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, y azimsulfuron POST aumentó en 149, 119, 138, 124, y 144%, respectivamente. La aplicación secuencial de herbicidas probó ser mejor que las aplicaciones solas. La menor biomasa de malezas se observó con la aplicación secuencial de pendimethalin PRE seguido por azimsulfuron POST, y el arroz rindió 228% más que el testigo no-tratado. Los resultados de este estudio son importantes para los productores usando DSR y que toman decisiones en relación a la aplicación POST de herbicidas, según la flora de malezas existente en el campo.

Rice is a predominant *kharif* crop of northwestern India. In this region, seedling transplanting in puddled soils (wet tillage) with alternative flooding and drying is the most common method of rice crop establishment, and this method requires a large amount of water and labor. Water and labor, however, are becoming increasingly scarce in the region, raising the question of the sustainability of rice production systems. In northwest India, the increasing use of groundwater for rice cultivation has led to a decline in the water table of 0.1 to 1.0 m yr^{-1}, resulting in water scarcity and increased cost for pumping water (Hira 2009; Rodell et al. 2009). The implementation of the Mahatma Gandhi National Rural Employment Guarantee Act, introduced by the Indian

DOI: 10.1614/WT-D-13-00016.1

* Rice Agronomist, Punjab Agricultural University, Ludhiana, Punjab, India, and Weed Scientist, Crop and Environmental Sciences Division, International Rice Research Institute, Los Baños, Philippines. Corresponding author's E-mail: b.chauhan@irri.org

government in 2005 (Government of India [GOI] 2011) and promising 100 d of paid work in people's home villages, has been creating a labor scarcity in northwest India, which is considered the cereal bowl of this region. Rice transplanting in northwest India, particularly in Punjab and Haryana, is dependent on thousands of migrant laborers from eastern Uttar Pradesh and Bihar (Chauhan et al. 2012). The migrant laborers are obtaining employment in their own state and are now not moving to this region. This has resulted in high wages for transplanting in puddled fields. These issues suggest that alternatives to puddled transplanted rice (PTR) are required to save water and increase crop and labor productivity.

One way to reduce the water and labor demand is to grow dry-seeded rice (DSR) instead of PTR (Chauhan 2012; Chauhan et al. 2012; Mahajan et al. 2009, 2012). In DSR systems, dry rice seeds are sown under dry conditions into a prepared seedbed after tillage or without tillage, and the systems aim to use less irrigation water than PTR. Dry seeding of rice with subsequent aerobic soil conditions eliminates the need for puddling, thus reducing overall water demand and providing opportunities for water and labor savings (Bouman 2003; Mahajan et al. 2011; Sharma et al. 2002).

Weeds are a serious problem in DSR because dry tillage and aerobic soil conditions are conducive to the germination and growth of many weeds, which can cause grain yield losses from 50 to 90% (Chauhan and Johnson 2011; Chauhan and Opeña 2012; Chauhan et al. 2011; Prasad 2011). Weed problems are more severe in aromatic rice cultivars that have lower yield potential than nonaromatic cultivars. The demand for special-purpose aromatic rice has increased dramatically over the past two decades globally. Therefore, dry seeding of aromatic rice cultivars with proper weed management may increase the profitability of farmers.

Research has shown that grain yield losses are greater in DSR than in PTR because of limited weed control options (Baltazar and De Datta 1992; Chauhan and Johnson 2010). Weeds are more problematic in DSR than in PTR because of (1) the absence of a head-start advantage over germinated weed seedlings and (2) the absence of standing water that prevents light from reaching weed seeds through a layer of standing water (Baltazar and De Datta 1992; Chauhan 2012; Chauhan and Johnson 2010). Weeds grow more quickly in DSR than in PTR (Akwar et al. 2011; Chauhan and Johnson 2010).

Changes in rice establishment methods as well as water, tillage, and weed management options in DSR lead to changes in weed flora. Weed flora composition can change drastically with a shift from PTR to other alternative tillage and rice establishment methods (Singh et al. 2009). After four seasons of rice cropping, for example, a study reported that barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], spreading dayflower (*Commelina diffusa* Burm. f.), purple nutsedge, rice flatsedge, and Chinese sprangletop were dominant in DSR plots, whereas rice flatsedge, pink node flower (*Caesulia axillaris* Roxb.), and junglerice were dominant in PTR plots (Singh et al. 2005). Direct seeding favors the growth of sedges, such as smallflower umbrella sedge (*Cyperus difformis* L.), rice flatsedge, purple nutsedge, and globe fringerush [*Fimbristylis miliacea* (L.) Vahl] (Azmi and Mashor 1995; Gressel 2002; Mortimer and Hill 1999). These weeds severely affected rice growth and sometimes resulted in complete failure of the crop (Singh 2008). Therefore, it is important that systematic herbicide options be available with the changing scenario of weed composition in DSR systems.

Several PRE herbicides, including butachlor, thiobencarb, pendimethalin, oxadiazon, oxyfluorfen, and nitrofen alone or supplemented with hand weeding, have been reported to provide a fair degree of weed control (Chauhan 2012; Chauhan and Opeña 2013; Estorninos and Moody 1988; Janiya and Moody 1988; Mahajan and Chauhan 2011; Moorthy and Das 1998; Pellerin and Webster 2004). However, some difficulties are associated with PRE herbicides, such as their limited application duration and the requirement of adequate soil moisture at the time of their application. In such situations, POST herbicides may be a better option. Singh et al. (2006) suggested that both PRE and POST herbicides, if properly used, were quite effective in suppressing weeds in DSR. It is necessary to evaluate different PRE and POST herbicides that are formulated from time to time to provide wider options to farmers for weed control in rice. Therefore, a study was designed to evaluate the efficacy of single and sequential application of PRE and POST herbicides for selective and season-long weed control in DSR.

Materials and Methods

Experimental Site. A field study was conducted for 2 yr (wet seasons of 2011 and 2012) at the experimental farm of Punjab Agricultural University, Ludhiana (30.93°N, 75.86°E), India. The climate is semiarid, with an average annual rainfall of 400 to 700 mm (75 to 80% of which is received from July to September), a minimum temperature of 0 to 4 C in January, and a maximum temperature of 41 to 45 C in June. The soil type at the experimental site was Fatehpur Series sandy loam (Entisol, Typic Ustipsament) with 0.3% organic matter with a pH of 7.2. Groundwater depth at the site was below 25 m, and the water was nonsaline.

Experimental Design and Treatments. The experiment in each year was arranged in a randomized complete block design with three replications. Twelve weed control treatments were included to evaluate different herbicide options for weed control in DSR (Table 1). Herbicides included in the study were pendimethalin (Stomp®, BASF India Ltd.), pyrazosulfuron (Saathi®, United Phosphorus Ltd.), bispyribac-sodium (Nominee gold®, PI Industries), azimsulfuron (Segment®, Dupont India Ltd.), and penoxsulam (Grasp®, Dow AgroSciences).

Experimental Details and Measurements. In each year, rice (cv. 'Punjab Mehak 1′, a medium-duration aromatic cultivar with a duration of 120 d) was seeded in the last week of June and harvested in October. Fields were prepared by cultivating twice with a disc harrow, followed by leveling with a wooden board. Seeds were sown with a single-row drill at a seeding rate of 30 kg ha^{-1} at 20-cm row spacing. The size of the plots was 5.0 by 2.2 m. The field was surface irrigated immediately after sowing. Nitrogen (60 kg ha^{-1}) was applied in three equal

Table 1. Herbicide treatments used in the study.[a]

Herbicide treatments	Dose	Application time
	g ai ha^{-1}	Days after sowing
Nontreated control	–	–
Pendimethalin	750	3
Pyrazosulfuron	15	3
Bispyribac-sodium	25	20
Penoxsulam	25	20
Azimsulfuron	20	20
Pendimethalin fb bispyribac-sodium	750 fb 25	3 fb 20
Pyrazosulfuron fb bispyribac-sodium	25 fb 25	3 fb 20
Pendimethalin fb penoxsulam	750 fb 25	3 fb 20
Pyrazosulfuron fb penoxsulam	15 fb 25	3 fb 20
Pendimethalin fb azimsulfuron	750 fb 20	3 fb 20
Pyrazosulfuron fb azimsulfuron	25 fb 20	3 fb 20

[a] Abbreviations: fb, followed by.

splits at 20, 40, and 60 d after sowing (DAS). Recommended rates of chlorpyriphos (500 g ai ha^{-1}, Chlorguard®, Gharda Chemical Ltd.) and propiconazole (62.5 g ai ha^{-1}, Tilt®, Syngenta India Ltd.) were used to control insects and diseases. PRE herbicides were applied at 3 DAS and POST herbicides were applied at 20 DAS. Herbicides were applied with the use of a knapsack sprayer with a flat-fan nozzle and water as a carrier at 500 L ha^{-1} for PRE spray and at 375 L ha^{-1} for POST spray. Species-wise density and biomass of weeds were measured at 30 DAS. Weed biomass was measured at 30 and 60 DAS, and at flowering. Weed density was recorded in two quadrats (0.5 by 0.4 m) placed randomly in each plot. Weeds were cut at ground level, washed with tap water, sun-dried, oven-dried at 70 C for 48 h, and then weighed.

Yield variables measured include grain yield, panicles m^{-2}, and grains panicle^{-1}. Grain yield was collected within a 5.6-m^2 area in the center of each plot and expressed in t ha^{-1} at 14% moisture. Panicles m^{-2} were determined with a quadrat (0.5 by 0.4 m) placed randomly in each plot at two locations. At the same time, five plants were randomly selected from each plot to measure grains panicle^{-1}.

Statistical Analyses. ANOVA indicated nonsignificant interaction between years and weed control treatments; therefore, the data were pooled over the 2 yr (a total of six replications) for further analysis (GenStat 8.0., Reference Manual, VSN International, Oxford, UK). Treatment means were separated with the use of the Fisher's Protected LSD test. Weed density and biomass data were transformed with square-root transformation [$\surd(x+1)$] before analyses. Unless indicated otherwise, differences were considered significant only at P $\leq$ 0.05. The nontransformed weed density and biomass data are reported with the interpretation based on transformed data. The relationships between grain yield and weed biomass were assessed with the use of linear correlation.

Results and Discussion

Weed Density and Biomass. The experimental plots contained many weed species: rice flatsedge, purple nutsedge, large crabgrass, Chinese sprangletop, crowfootgrass, junglerice, goosegrass [*Eleusine indica* (L.) Gaertn.], *Digera arvensis* (L.) Mart., longfruited primrose-willow [*Ludwigia octovalvis* (Jacq.) Raven], globe fringerush (*Panicum brevifolium* L.), spurge [*Euphorbia* spp.], Indian love grass [*Eragrostis pilosa* (L.) P. Beauv.], etc. However, species-wise results are presented for the first six weeds only, as they were dominant in the samples.

Rice Flatsedge. All herbicide treatments significantly reduced rice flatsedge density compared with the nontreated control 30 DAS (Table 2). Rice flatsedge density observed following the PRE application of pendimethalin and pyrazosulfuron and POST application of bispyribac-sodium, penoxsulam, and azimsulfuron was 51, 50, 4, 12, and 8 plants m^{-2}, respectively, compared with 70 plants m^{-2} in the nontreated control. The lowest density of rice flatsedge was observed following pendimethalin PRE followed by bispyribac-sodium POST, which provided a 99% reduction in rice flatsedge density compared with the nontreated control. Bispyribac-sodium POST reduced rice flatsedge density similar to pendimethalin PRE followed by penoxsulam or azimsulfuron POST and pyrazosulfuron PRE followed by bispyribac-sodium or azimsulfuron POST (Table 2).

Rice flatsedge biomass collected following the PRE application of pendimethalin and pyrazosulfuron and POST application of bispyribac-sodium, penoxsulam, and azimsulfuron was 6, 5, 0, 1, and 0 g m^{-2}, respectively, compared with 8 g m^{-2} in the nontreated control 30 DAS (Table 3). Pendimethalin PRE followed by bispyribac-sodium POST reduced rice flatsedge biomass greater than all treatments (Table 3). The single application of bispyribac-sodium POST provided similar rice flatsedge biomass reduction as pendimethalin PRE followed by penoxsulam or azimsulfuron POST or pyrazosulfuron PRE followed by bispyribac-sodium or amizsulfuron POST (Table 3). In a recent study in the Philippines, pretilachlor or pendimethalin PRE followed by penoxsulam plus cyhalofop POST provided excellent control of rice flatsedge in DSR (Chauhan and Abugho 2013).

Purple Nutsedge. Azimsulfuron (in both single and sequential applications) reduced purple nutsedge density greater than 95% compared with the nontreated control 30 DAS (Table 2). Purple nutsedge density was reduced following all PRE followed by POST treatments compared to the nontreated control. A similar response was observed for purple nutsedge biomass 30 DAS (Table 3). The single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, and penoxsulam POST did not provide effective control of purple nutsedge. Similarly in a previous study in the Philippines, oxadiazon PRE followed by fenoxaprop plus ethoxysulfuron POST or penoxsulam plus cyhalofop POST did not provide effective control of purple nutsedge in DSR (Chauhan and Opeña 2012).

Large Crabgrass. All treatments, except bispyribac-sodium POST, reduced large crabgrass density compared to the nontreated 30 DAS. Large crabgrass density observed following the PRE application of pendimethalin was 3 plants m^{-2} compared with 29 plants m^{-2} in the nontreated control (Table 2). Compared with the nontreated control, large crabgrass biomass was reduced by 98% with the PRE application of pendimethalin followed by bispyribac-sodium POST 30 DAS (Table 3). Bispyribac-sodium POST did not

Table 2. Effect of herbicide treatments on weed density (number m^{-2}) at 30 d after sowing. Square-root transformed [$\sqrt{(x+1)}$] values were used for analyses, and original weed density is shown in parentheses.[a]

Herbicide treatments	Rice flatsedge	Purple nutsedge	Large crabgrass	Chinese sprangletop	Crowfootgrass	Junglerice	Total weeds
	Transformed values of weed density (original values of weed density)						
	No. m^{-2}						
Nontreated control	8.38 (70)	4.45 (19)	5.37 (29)	4.97 (24)	4.54 (20)	7.09 (50)	15.9 (254)
Pendimethalin	7.17 (51)	4.61 (20)	1.97(3)	2.63 (6)	2.89 (7)	2.52 (5)	10.6 (112)
Pyrazosulfuron	7.10 (50)	4.50 (19)	3.84 (14)	4.16 (16)	2.62 (6)	3.97 (15)	11.3 (127)
Bispyribac-sodium	2.33 (4)	4.22 (17)	5.05 (26)	5.16 (26)	3.90 (14)	4.02 (15)	11.1 (123)
Penoxsulam	3.65 (12)	4.66 (21)	4.35 (19)	4.66 (21)	3.84 (14)	4.54 (20)	11.1 (124)
Azimsulfuron	2.98 (8)	1.41 (1)	4.30 (18)	4.66 (21)	3.96 (15)	4.02 (15)	9.31 (87)
Pendimethalin fb bispyribac-sodium	1.41 (1)	3.15 (9)	1.40 (1)	1.58 (1)	2.80 (7)	1.22 (0)	4.56 (20)
Pyrazosulfuron fb bispyribac-sodium	2.41 (4)	2.79 (8)	2.21 (4)	2.18 (4)	1.39 (1)	2.43(5)	5.28 (29)
Pendimethalin fb penoxsulam	2.63(6)	2.66 (7)	2.42 (5)	1.99 (3)	2.59 (6)	2.79 (7)	6.30 (40)
Pyrazosulfuron fb penoxsulam	3.20 (9)	2.92 (9)	2.87 (7)	2.71 (6)	3.01 (8)	2.32 (4)	7.23 (54)
Pendimethalin fb azimsulfuron	2.19 (4)	1.00 (0)	1.85(2)	1.41 (1)	1.40 (1)	2.79 (7)	4.23 (17)
Pyrazosulfuron fb azimsulfuron	2.50 (5)	1.00 (0)	2.31 (4)	1.99 (3)	2.40 (5)	3.41 (11)	5.73 (33)
LSD (0.05)	0.6	1.0	0.8	0.7	0.6	0.5	0.9

[a] Abbreviations: fb, followed by.

reduce large crabgrass density or biomass compared to the nontreated. In a recent study, bispyribac-sodium provided a poor control (30 to 40%) of southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.] (Chauhan and Abugho 2012).

Chinese Sprangletop. Application of pendimethalin PRE reduced the density and biomass of Chinese sprangletop compared with the nontreated control 30 DAS (Tables 2 and 3). All treatments containing sequential applications reduced Chinese sprangletop biomass compared with the nontreated control 30 DAS (Table 3). The sequential application of pendimethalin PRE followed by bispyribac-sodium POST reduced biomass 94%. Similarly, the sequential application of pendimethalin PRE and azimsulfuron POST reduced Chinese sprangletop crabgrass biomass by more than 96% 30 DAS (Table 3). In a recent study in Sri Lanka, thiobencarb plus propanil followed by MCPA provided 100% control of Chinese sprangletop (Chauhan et al. 2013). However, a single application of bispyribac-sodium controlled Chinese sprangletop 74% (Chauhan and Abugho 2012).

Crowfootgrass. Crowfootgrass density declined following the application of pendimethalin and pyrazosulfuron PRE 30 DAS (Table 2). A similar response was observed for biomass (Table 3). Compared with the nontreated control, all sequential PRE followed by POST treatments reduced crowfootgrass density and biomass 30 DAS. The sequential application of pyrazosulfuron PRE followed by bispyribac-sodium POST and pendimethalin PRE followed by azimsulfuron POST reduced crowfootgrass biomass by more than 95%. In a previous study, bispyribac-sodium POST did not control four- and six-leaf crowfootgrass (Chauhan and Abugho 2012). However, fenoxaprop plus ethoxysulfuron applied to four- and six-leaf crowfootgrass had only 9 and 16% surviving plants, respectively.

Junglerice. All herbicide treatments reduced the density of junglerice compared with the nontreated control 30 DAS (Table 2). Junglerice density following pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST was 5, 15, 15, 20, and 15 plants m^{-2}, respectively, compared with 50 plants m^{-2} in the

Table 3. Effect of herbicide treatments on weed biomass (g m^{-2}) at 30 d after sowing. Square-root transformed [$\sqrt{(x+1)}$] values were used for analyses and original weed biomass is shown in parentheses.[a]

Herbicide treatments	Rice flatsedge	Purple nutsedge	Large crabgrass	Chinese sprangletop	Crowfootgrass	Junglerice	Total weeds
	Transformed values of weed biomass (original values of weed biomass)						
	g m^{-2}						
Nontreated control	2.94 (8)	1.82 (2)	2.10 (3)	2.10 (4)	1.88 (3)	2.52 (5)	5.56 (30)
Pendimethalin	2.56 (6)	1.83 (2)	1.16 (0)	1.16 (0)	1.35 (1)	1.26 (1)	3.72 (13)
Pyrazosulfuron	2.54 (5)	1.80 (2)	1.64 (2)	1.64 (2)	1.29 (1)	1.62 (2)	3.95 (15)
Bispyribac-sodium	1.22 (0)	1.71 (2)	2.00 (3)	2.00 (3)	1.61 (2)	1.63 (2)	3.95 (15)
Penoxsulam	1.54 (1)	1.84 (2)	1.79 (2)	1.79 (2)	1.59 (2)	1.78 (2)	3.94 (15)
Azimsulfuron	1.37 (0)	1.05 (0)	1.78 (2)	1.78 (2)	1.62 (2)	1.63 (2)	3.34 (10)
Pendimethalin fb bispyribac-sodium	1.05 (0)	1.43 (1)	1.06 (0)	1.06 (0)	1.33 (1)	1.02 (1)	1.81 (2)
Pyrazosulfuron fb bispyribac-sodium	1.22 (0)	1.38 (1)	1.21 (0)	1.21 (0)	1.05 (0)	1.24 (1)	2.05 (3)
Pendimethalin fb penoxsulam	1.29 (1)	1.34 (1)	1.26 (1)	1.26 (0)	1.28 (1)	1.32 (1)	2.35 (5)
Pyrazosulfuron fb penoxsulam	1.42 (1)	1.41 (1)	1.37 (1)	1.37 (1)	1.38 (1)	1.21 (0)	2.66 (6)
Pendimethalin fb azimsulfuron	1.19 (0)	1.00 (0)	1.14 (0)	1.14 (0)	1.05 (0)	1.31 (1)	1.71 (2)
Pyrazosulfuron fb azimsulfuron	1.26 (1)	1.00 (0)	1.24 (1)	1.24 (1)	1.24 (1)	1.47 (1)	2.16 (4)
LSD (0.05)	0.1	0.2	0.2	0.2	0.2	0.2	0.3

[a] Abbreviations: fb, followed by.

nontreated control. The lowest density of junglerice was observed following the sequential application of pendimethalin PRE followed by bispyribac-sodium POST, which reduced junglerice density by more than 99% compared with the nontreated check.

Pendimethalin PRE followed by bispyribac-sodium POST and pyrazosulfuron PRE followed by penoxsulam POST provided similar reduction in junglerice biomass. Junglerice biomass following pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST was 1, 2, 2, 2, and 2 g m^{-2}, respectively, compared with 5 g m^{-2} in the nontreated check 30 DAS (Table 3). The sequential application of pendimethalin PRE followed by bispyribac-sodium POST and pyrazosulfuron PRE followed by penoxsulam POST provided greater biomass reduction than the other treatments. Single application of pendimethalin PRE, and sequential application of pendimethalin PRE followed by bispyribac-sodium POST and pyrazosulfuron PRE followed by penoxsulam POST provided similar reduction in junglerice biomass (Table 3). Similarly, pendimethalin PRE followed by penoxsulam or azimsulfuron POST provided similar reduction in junglerice biomass; however, these herbicide treatments were inferior to pendimethalin PRE followed by bispyribac-sodium POST. Junglerice biomass reduced more with the single application of pendimethalin PRE as compared to the sequential application of pyrazosulfuron PRE followed by azimsulfuron POST. In a previous study in DSR, pendimethalin-treated plots had similar biomass of junglerice to the control plots (Chauhan and Abugho 2013). However, biomass was greatly reduced with pendimethalin PRE followed by penoxsulam plus cyhalofop POST.

Total Weed Density and Biomass at 30 DAS. All herbicide treatments reduced the density of total weeds compared with the nontreated check (Table 2). Total weed density following pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST was 112, 127, 123, 124, and 87 plants m^{-2}, respectively, compared with 254 plants m^{-2} in the nontreated check. The lowest density of weeds was observed with the sequential application of pendimethalin PRE followed by azimsulfuron POST; however, this treatment was similar with the pendimethalin PRE followed by bispyribac-sodium POST. The same response was observed for total weed biomass 30 DAS (Table 3). All sequential herbicide treatments reduced weed biomass more than with the single application of herbicides. The single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST reduced weed biomass by 57, 52, 51, 51, and 66%, respectively, compared with the nontreated control.

Total Weed Biomass at Flowering. All herbicide treatments significantly reduced weed biomass compared with the nontreated check (Table 4). The single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST reduced weed biomass 75, 68, 73, 70, and 72%, respectively, compared with the nontreated check. The lowest weed biomass was produced in the plots treated with the sequential application of pendimethalin PRE followed by azimsufuron POST (20 g m^{-2}); however, the biomass in these plots was similar to the biomass produced in the plots treated with the sequential application of pendimethalin PRE followed by penoxsulam POST (23 g m^{-2}) and pyrazosulfuron PRE followed by azimsulfuron (25 g m^{-2}). Except for the sequential application of pyrazosulfuron PRE followed by penoxsulam POST, all sequential herbicide treatments reduced total weed biomass greater than the single PRE or POST treatments.

Table 4. Effect of treatments on weed biomass (g m^{-2}) at flowering. Square-root transformed [$\sqrt{(x+1)}$] values were used for analyses and original weed biomass values are shown in parentheses.[a]

Herbicide treatments	Transformed values of weed biomass (original values of weed biomass)
	g m^{-2}
Nontreated control	16.77 (285)
Pendimethalin	8.44 (71)
Pyrazosulfuron	9.53 (91)
Bispyribac-sodium	8.67 (75)
Penoxsulam	9.08 (83)
Azimsulfuron	8.83 (78)
Pendimethalin fb bispyribac-sodium	6.95 (48)
Pyrazosulfuron fb bispyribac-sodium	6.53 (42)
Pendimethalin fb penoxsulam	4.83 (23)
Pyrazosulfuron fb penoxsulam	7.78 (60)
Pendimethalin fb azimsulfuron	4.58 (20)
Pyrazosulfuron fb azimsulfuron	5.03 (25)
LSD (0.05)	0.9

[a] Abbreviations: fb, followed by.

The results of our study suggest that the weed control treatments were quite effective in suppressing different weed species by reducing their density and biomass. The single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST reduced total weed biomass by 68 to 75% at the flowering stage compared with the nontreated control. More than a 78% reduction in total weed density over the nontreated control was observed with all the combinations of sequential application of PRE and POST herbicides, indicating their effectiveness against the weed flora present at the experimental site. The results showed that the sequential application of PRE and POST herbicides was able to enhance season-long weed control.

Several studies have concluded that chemical weed control is feasible in DSR systems, as it is quick, easy, and economical (Chauhan 2012; Chauhan and Opeña 2012, 2013; Gitsopoulos and Froud-Williams 2004). The results of recent studies suggested that both PRE and POST herbicides, if used properly, were quite effective in suppressing weeds in DSR (Chauhan and Opeña 2012, 2013). However, contrary to what occurs in other upland cereals, a single application of a particular herbicide seldom furnishes adequate weed control and optimal grain yield in DSR. Appropriate weed control during the first 4 to 6 wk after seeding is crucial because of the slow canopy closure of the rice crop that makes the environment more congenial for weeds; therefore, management of weeds during this period is essential to maximize grain yield. Two herbicide applications are recommended in

Table 5. Effect of herbicide treatments on panicle number, grain number, and grain yield.[a]

Herbicide treatments	Grain yield	Panicle number	Grains panicle^{-1}
	t ha^{-1}	No. m^{-2}	No. panicle^{-1}
Nontreated control	1.48	82	57
Pendimethalin	3.69	178	99
Pyrazosulfuron	3.25	196	85
Bispyribac-sodium	3.52	192	92
Penoxsulam	3.31	199	84
Azimsulfuron	3.61	174	101
Pendimethalin fb bispyribac-sodium	4.99	261	112
Pyrazosulfuron fb bispyribac-sodium	3.96	199	100
Pendimethalin fb penoxsulam	4.63	254	116
Pyrazosulfuron fb penoxsulam	3.81	196	102
Pendimethalin fb azimsulfuron	4.86	253	111
Pyrazosulfuron fb azimsulfuron	4.69	254	109
LSD (0.05)	0.5	34	10

[a] Abbreviations: fb, followed by.

Table 6. Correlation of weed biomass with grain yield.[a]

Weed biomass	*r* value[b]
Biomass of rice flatsedge at 30 DAS	−0.72
Biomass of purple nutsedge at 30 DAS	−0.58
Biomass of large crabgrass at 30 DAS	−0.67
Biomass of Chinese sprangletop at 30 DAS	−0.70
Biomass of crowfootgrassat 30 DAS	−0.70
Biomass of junglerice at 30 DAS	−0.74
Total weed biomass at 30 DAS	−0.86
Total weed biomass at flowering	−0.81

[a] Abbreviations: DAS, days after sowing.

[b] Significant at 5%.

DSR systems—one before or just after sowing and the other at the four- to six-leaf stages of the crop (Kim and Ha 2005). Results from our study inferred that pendimethalin PRE and pyrazosulfuron PRE can control annual grass and broadleaved weed species because of their residual activity in soil. In this regard, pendimethalin PRE and pyrazosulfuron PRE should be used once the rice seed has imbibed water but prior to the emergence of rice and weeds (Jordan et al. 1998). Subsequent weed flushes can then be controlled by a suitable POST herbicide. A grain yield loss of 9 to 60% in DSR systems was observed in the absence of a POST herbicide application (McCauley et al. 2005).

Yield Variables. Rice grain yield following all herbicide treatments ranged from 3.25 to 4.99 t ha^{-1}, and the nontreated plots yielded 1.48 t ha^{-1} (Table 5). Grain yield following the single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST averaged 135% greater than the nontreated control; however, no differences were observed among these herbicides treatments. Pyrazosulfuron PRE proved superior for grain yield only when followed by azimsulfuron POST compared to pyrazosulfuron PRE followed by bispyribac-sodium or penoxsulam POST (Table 5). Grain yield in plots treated with pyrazosulfuron PRE followed by bispyribac-sodium POST and pendimethalin PRE followed by bispyribac-sodium, penoxsulam, or azimsulfuron POST remained similar. The highest grain yield (4.99 t ha^{-1}) was recorded with the sequential application of pendimethalin PRE followed by bispyribac-sodium POST and the lowest in the nontreated control (1.48 t ha^{-1}). Grain yield was similar between the plots treated with bispyribac-sodium POST and penoxsulam POST (both after pyrazosulfuron PRE). The response for the number of grains panicle^{-1} and number of panicles m^{-2} was similar to that observed for grain yield (Table 5). The single application of pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, penoxsulam POST, and azimsulfuron POST increased grains panicle^{-1} by 74, 49, 61, 47, and 77%, respectively, compared with the nontreated check. Pendimethalin PRE followed by penoxsulam POST increased grains panicle^{-1} 103% compared to the nontreated control. Among the sequential treatments, lowest number of grains panicle^{-1} was found with the sequential application of pyrazosulfuron PRE followed by bispyribac-sodium POST. The average number of panicles m^{-2} ranged from 82 to 261. The panicle numbers were lowest in the nontreated check and highest in the plots treated with the sequential application of pendimethalin PRE followed by bispyribac-sodium POST. In sequential treatments, comparatively fewer panicles m^{-2} were found in the plots treated with pyrazosulfuron PRE followed by bispyribac-sodium or penoxsulam POST, resulting in lower yield among the sequential herbicide treatments.

A negative correlation of weed biomass with grain yield was found at all the stages of crop growth (Table 6), indicating that the weeds had a negative influence on grain yield. In our study, POST application of bispyribac-sodium and azimsulfuron provided effective control of rice flatsedge and purple nutsedge, respectively, and resulted in a 138 and 144% increase, respectively, in grain yield compared to the nontreated check. The relationship of these weeds with grain yield was negative. In addition, total weed biomass at 30 DAS and at rice flowering had a negative relationship with grain yield. The effectiveness of bispyribac-sodium POST and azimsulfuron POST improved when followed pendimethalin PRE and resulted in a 237 and 228% increase, respectively, in yield over the nontreated control. The application of pendimethalin PRE proved effective against junglerice, large crabgrass, and Chinese sprangletop, which increased average yield by 149% compared with the nontreated control. The application of pyrazosulfuron PRE proved effective in reducing the biomass of crowfootgrass, and thus resulted in a 119% increase in yield over the nontreated control. At flowering stage, all the sequential herbicide treatments were effective in reducing the biomass of total weeds. Average grain yield was highest with the sequential application of pendimethalin PRE followed by bispyribac-sodium POST, and this treatment had 237% higher yield than the nontreated control. However, grain yield with pendimethalin PRE followed by bispyribac-sodium, penoxsulam, or azimsulfuron POST and pyrazosulfuron PRE followed by azimsulfurom POST was similar.

The nontreated control negatively affected the number of panicles plant^{-1} and grains panicle^{-1}, and grain yield. All these yield variables improved in the herbicide-treated plots compared with the nontreated plots, which was due to less weed competition with the rice crop. Fewer grains panicle^{-1}

https://doi.org/10.1614/WT-D-13-00016.1 Published online by Cambridge University Press

and panicles plants^{-1} in the nontreated control may be the result of rigorous competition among the crop and weeds for nutrient, space, light, and carbon dioxide (Tindall et al. 2005). In previous studies, improvement in yield variables, including panicles plant^{-1} and grains panicle^{-1}, was reported in the herbicide-treated plots compared with the nontreated plots (Mahajan et al. 2009). The improved yield was attributed to less weed competition as a result of the herbicide treatments. Rice plants in weed-limited environments recorded a higher number of productive tillers than the nontreated control, mainly because of the greater space occupied by the rice plants. Canopy closure might have occurred earlier due to better competitive ability and nutrient-use efficiency in weed-limited environments (Baloch et al. 2005).

In summary, our study found that pendimethalin PRE was the best herbicide for the effective control of junglerice, large crabgrass, and Chinese sprangletop; pyrazosulfuron PRE for crowfootgrass; and bispyribac-sodium POST and penoxsulam POST for rice flatsedge. Our study also demonstrated that the single application of herbicides (pendimethalin PRE, pyrazosulfuron PRE, bispyribac-sodium POST, and penoxsulam POST) provided effective weed control and higher grain yield than the nontreated control. However, depending upon the yield targets and weed spectrum, the PRE application must be followed by a POST herbicide for greater weed control and further improvement in grain yield. This study is particularly important for farmers growing DSR in making decisions regarding the application of POST herbicides, according to existing weed flora in the field.

Acknowledgments

The authors are grateful to Dr. Bill Hardy, International Rice Research Institute, Philippines, for editing the manuscript.

Literature Cited

Akwar, N., K. J. Ehsanullah, and M. A. Ali. 2011. Weed management improves yield and quality of direct seeded rice. Aust. J. Crop Sci. 5:688–694.

Azmi, M. and M. Mashor. 1995. Weed succession from transplanting to direct-seeding method in Kemubu rice area. Malay. J. Biosci. 6:143–154.

Baloch, M. S., G. Hassan, and T. Morimoto. 2005. Weeding techniques in transplanted and wet-seeded rice in Pakistan. Weed Biol. Manage. 5:190–196.

Baltazar, A. M. and S. K. De Datta. 1992. Weed management in rice. Weed Abs. 41:495–597.

Bouman, B.A.M. 2003. Addressing the water shortage problem in rice systems: water saving irrigation technologies. Pages 519–535 *in* T. M. Mew et al., eds. Rice Science: Innovations and Impact for Livelihood. Los Baños, Philippines: International Rice Research Institute and Beijing, China: Chinese Academy of Engineering and Chinese Academy of Agricultural Sciences.

Chauhan, B. S. 2012. Weed ecology and weed management strategies for dry-seeded rice in Asia. Weed Technol. 26:1–13.

Chauhan, B. S., A. S. K. Abeysekera, S. D. Kulatunga, and U. B. Wickrama. 2013. Performance of different herbicides in a dry-seeded rice system in Sri Lanka. Weed Technol. 27:459–462.

Chauhan, B. S. and S. B. Abugho. 2012. Effect of growth stage on the efficacy of postemergence herbicides on four weed species of direct-seeded rice. Sci. World J. 2012. Article ID 123071.

Chauhan, B. S. and S. B. Abugho. 2013. Weed management in mechanized-sown, zero-till dry-seeded rice. Weed Technol. 27:28–33.

Chauhan, B. S. and D. E. Johnson. 2010. The role of seed ecology in improving weed management strategies in the tropics. Adv. Agron. 105:221–262.

Chauhan, B. S. and D. E. Johnson. 2011. Row spacing and weed control timing affect yield of aerobic rice. Field Crops Res. 121:226–231.

Chauhan, B. S., G. Mahajan, V. Sardana, J. Timsina, and M. L. Jat. 2012. Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. Adv. Agron. 117:315–369.

Chauhan, B. S. and J. Opeña. 2012. Effect of tillage systems and herbicides on weed emergence, weed growth, and grain yield in dry-seeded rice systems. Field Crops Res. 137:56–69.

Chauhan, B. S. and J. Opeña. 2013. Weed management and grain yield of rice sown at low seeding rates in mechanized dry-seeded systems. Field Crops Res. 141:9–15.

Chauhan, B. S., V. P. Singh, A. Kumar, and D. E. Johnson. 2011. Relations of rice seeding rates to crop and weed growth in aerobic rice. Field Crops Res. 121:105–115.

Estorninos, L. E., Jr., and K. Moody. 1988. Evaluation of herbicides for weed control in dry-seeded wetland rice (*Oryza sativa*). Philipp. J. Weed Sci. 15:50–58.

Gitsopoulos, T. K. and R. J. Froud-Williams. 2004. Effect of oxadiargyl on direct-seeded rice and *Echinochloa crus-galli* under aerobic and anaerobic conditions. Weed Res. 44:329–334.

[GOI] Government of India. 2011. The Mahatma Gandhi National Rural Employment Guarantee Act 2005. Ministry of Rural Development, Government of India. http://nrega.nic.in/netnrega/home.aspx.

Gressel, J. 2002. Preventing, delaying and mitigating gene flow from crops—rice as an example. Proceedings of the Seventh International Symposium on the Biosafety of Genetically Modified Organisms, Beijing, China.

Hira, G. S. 2009. Water management in northern states and the food security of India. J. Crop Improve. 23:136–157.

Janiya, J. D. and K. Moody. 1988. Effect of time of planting, crop establishment method, and weed control method on weed growth and rice yield. Philipp. J. Weed Sci. 15:6–17.

Jordan, D. L., D. K. Miller, and S. H. Crawford. 1998. Barnyardgrass (*Echinochloa crus-galli*) control in dry-seeded rice (*Oryza sativa*) with soil applied and post emergence herbicide programs Weed Technol. 12:69–73.

Kim, S. C. and W. G. Ha. 2005. Direct seeding and weed management in Korea. Pages 181–184 *in* K. Toriyama et al., eds. Rice Is Life: Scientific Perspectives for the 21st Century. Los Banõs, Philippines: International Rice Research Institute, and Tsukuba, Japan: Japan International Research Center for Agricultural Sciences.

Mahajan, G. and B. S. Chauhan. 2011. Effects of planting pattern and cultivar on weed and crop growth in aerobic rice system. Weed Technol. 25:521–525.

Mahajan, G., B. S. Chauhan, and D. E. Johnson. 2009. Weed management in aerobic rice in Northwestern Indo-Gangetic Plains. J. Crop Improve. 23:366–382.

Mahajan, G., B. S. Chauhan, J. Timsina, P. P. Singh, and K. Singh. 2012. Crop performance and water- and nitrogen-use efficiencies in dry-seeded rice in response to irrigation and fertilizer amounts in northwest India. Field Crops Res. 134:59–70.

Mahajan, G., J. Timsina, and K. Singh. 2011. Performance and water use efficiency of rice relative to establishment methods in northwestern Indo-Gangetic Plains. J. Crop Improve. 25:597–617.

McCauley, G. N., J. H. O'Barr, and J. M. Chandler. 2005. Evaluating the efficacy and economics of weed management systems using current commercial herbicides in early and late season treatments alone and in all combinations. *In* Water Management and Weed Science Research in Rice. Research Report. Beaumont, TX: Rice Research Foundation.

Moorthy, B.T.S. and T. K. Das. 1998. Threshold level of weed umbrella sedge (*Cyperus iria*) in upland rice (*O. sativa*) under rainfed direct-seeded condition. Ind. J. Agric. Sci. 68:7–8.

Mortimer, A. M. and J. E. Hill. 1999. Weed species shifts in response to broad-spectrum herbicides in sub-tropical and tropical crops. Brighton Crop Prot. Conf. 2:425–437.

Pellerin, K. J. and E. P. Webster. 2004. Imazethapyr at different rates and timings in drill and water seeded imidazolinone-tolerant rice. Weed Technol. 18:223–227.

Prasad, R. 2011. Aerobic rice systems. Adv. Agron. 111:207–247.

Rodell, M., I. Velicigna, and J. S. Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India. Nature (London) 460:999–1002.

Sharma, P. K., L. Bhushan, J. K. Ladha, R. K. Naresh, R. K. Gupta, B. V. Balasubramanian, and B.A.M. Bouman. 2002. Crop–water relations in rice–wheat cropping under different tillage systems and water-management practices in a marginally sodic, medium-textured soil. Pages 223–235 *in* B.A.M. Bouman et al., eds. Water-Wise Rice Production. Proceedings of the International Workshop on Water-Wise Rice Production. Los Banõs, Philippines: International Rice Research Institute.

Singh, G. 2008. Integrated weed management in direct-seeded rice. Pages 161–175 *in* Y. Singh et al., eds. Direct Seeding of Rice and Weed Management in the Irrigated Rice–Wheat Cropping System of the Indo-Gangetic Plains. Pantnagar, India: G.B. Pant University of Agriculture and Technology, and Los Baños, Philippines: International Rice Research Institute/Directorate of Experiment Station.

Singh, S., L. Bhusan, J. K. Ladha, R. K. Gupta, A. N. Rao, and B. Sivaprasad. 2006. Weed management in dry-seeded rice (*Oryza sativa*) cultivated in the furrow-irrigated raised-bed planting system. Crop Prot. 25:487–495.

Singh, S., R. S. Chhokar, R. Gopal, J. K. Ladha, R. K. Gupta, V. Kumar, and M. Singh. 2009. Integrated weed management: a key to success for direct-seeded rice in the Indo-Gangetic Plains. Pages 261–277 *in* J. K. Ladha et al., eds. Integrated Crop and Resource Management in the Rice–Wheat System of South Asia. Los Baños, Philippines: International Rice Research Institute/ Directorate of Experiment Station.

Singh, Y., G. Singh, D. Johnson, and M. Mortimer. 2005. Changing from transplanted rice to direct seeding in the rice–wheat cropping system in India. Pages 198–201 *in* K. Toriyama et al., eds. Rice Is Life: Scientific Perspectives for the 21st Century. Los Baños, Philippines: International Rice Research Institute, and Tsukuba, Japan: Japan International Research Center for Agricultural Sciences,.

Tindall, K. V., B. J. Williams, M. J. Stout, J. P. Geaghan, B. R. Leonard, and E. P. Webster. 2005. Yield components and quality of rice in response to graminaceous weed, weed, density and rice stink bug population. Crop Prot. 24:991–998.

Received January 23, 2013, and approved July 9, 2013.