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WEED MANAGEMENT IN AEROBIC RICE: ROLE OF ESTABLISHMENT METHODS AND HERBICIDES

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SUMMARY

Weed management in rice depends on establishment method and proper selection of herbicide. A field experiment was conducted during dry seasons of 2013 and 2014 to develop a robust strategy for effective weed management in aerobic rice system for tropical rice belts. The efficacy of post-emergent herbicides bispyribac-sodium, azimsulfuron and flucetosulfuron were evaluated under different rice establishment methods (row sowing, spot seeding and broadcasting). Grass weed species constituted 58–68% of the total weed density across the establishment methods in the weedy check treatment. The total weed density and weed biomass were lowest in spot seeding with azimsulfuron (35 g active ingredient (a.i.) ha^{-1}) 30 and 60 days after sowing. Among herbicides, use of azimsulfuron caused the highest grain yield (5.2 Mg ha^{-1}), realizing 72% increase in grain yield over the weedy check. Yields in row sowing and spot seeding were similar and the same was verified when comparing yields in plots treated with bispyribac-sodium and azimsulfuron. Based on our findings and considering both weed presence and grain yield, azimsulfuron in spot seeding can be recommended in aerobic rice.

INTRODUCTION

Rice (*Oryza sativa* L.), the leading cereal crop of the world, is the staple food of more than half of the world population. World's rice demand was projected to increase by 25% from 2001 to 2025 to keep pace with population growth (Maclean *et al.*, 2002). India alone would require 113.3 million tonnes to fulfil its domestic demand by 2021–22 and a supply demand gap is pegged at 8.98 million tonnes (Mittal, 2008). These startling facts reveal that meeting the ever increasing rice demand in a sustainable way would be a great challenge. Eastern India accounts for 58% of the total rice area in India (Adhya *et al.*, 2008) and the crop is mainly grown during wet season. However, the crop productivity is very low (2.46 Mg ha^{-1}) (GOI, 2014) as the crop experiences several abiotic stresses such as drought, submergence and water logging along with cyclonic disturbances in coastal areas during the wet season. A second rice crop can be raised in these areas, as the winter is moderate and bright sunshine

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prevails during the dry season. However, limited availability of good quality irrigation water has restricted the cultivation of dry season rice in many areas (Saha *et al.*, 2011).

One of the approaches to address these issues is cultivation of rice under aerobic systems in dry season. Using rice aridity index map, Mandal *et al.* (2010) reported that most of the eastern and south eastern regions of India are moderate to highly suitable for aerobic rice. These systems can reduce water use up to 44% relative to conventionally transplanted systems by reducing percolation, seepage and evaporative losses, resulting in higher water productivity (Dari *et al.*, 2017; Liu *et al.*, 2015). In spite of their advantages, aerobic rice systems have failed to gain popularity among farmers. The adoption and sustainability of the aerobic rice systems is threatened by heavy weed infestation (Chauhan, 2012) and grain yield losses of 50–91% were reported due to weed infestation (Rao *et al.*, 2007).

For successful adoption of aerobic rice, suitable strategies for effective and economical weed control need to be developed. Manual weeding involves huge costs and therefore, herbicides can be used to replace manual weeding. Control of weeds by applying recommended pre-emergence herbicides is often not successful in aerobic rice due to emergence of late flushes of weeds. The time window for the application is very narrow for pre-emergence herbicides and sometimes, farmers miss the optimum application time (Mahajan and Chauhan, 2015). Mahajan and Chauhan (2013) revealed that sequential applications of pre- and post-emergence herbicides provided better control of early and late flushes of weeds than the sole application in direct-seeded rice. However, there is a need to reduce the herbicide load in the environment. Excessive use of herbicides may have negative effects on the environment and human health (Jurewicz and Hanke, 2008). There are concerns about toxicity of some of the herbicides on soil biota (Briggs, 1992), as it may reduce soil fertility and system productivity in long run. Therefore, application of herbicides at low rate/dose is desirable for cost, safety, health and environmental reasons. Low-dosage high-efficacy post-emergent herbicides with a broad spectrum of weed control are expected to be an intervention to suppress weeds during the critical period of crop–weed competition.

It has already been established that direct seeding rice is subject to much higher weed pressure than transplanted rice (Chauhan *et al.*, 2015). Under aerobic systems (which involves direct seeding as a component), the weed pressure and competition depends greatly on how the crop is established (Singh *et al.*, 2006). The aerobic rice can be established by line sowing, broadcasting and spot seeding. Establishment methods have differential effects on weed occurrence, crop growth and rice yield. However, there is limited knowledge about herbicide efficacy under different crop establishment methods (continuous row sowing, broadcasting and spot seeding) particularly in aerobic rice (Singh *et al.*, 2006). Then, we hypothesized that proper choice of establishment method and herbicide will result in higher weed control efficiency and higher crop yield. Therefore, the present study was conducted to recognize the role of establishment methods and herbicides in suppressing the weeds in aerobic rice.

MATERIALS AND METHODS

Site description

The field investigation was carried out at the Research Farm of the ICAR-National Rice Research Institute, Cuttack (20.5°N, 86°E and 23.5 m above mean sea-level), India, during the consecutive dry seasons of 2013 and 2014. The soil of the experimental field was Aeric (Endoaquept) with sandy clay loam in texture, slightly acidic to neutral in reaction with pH 6.8 (using 1:2.5, soil: water suspension), total carbon 0.78%, available nitrogen 218 kg ha^{-1}, available P 17.4 kg ha^{-1} and available K 118 kg ha^{-1}. The soil test was based on samples taken from the upper 20 cm of the soil before sowing in 2013.

Experimental design

The experiment was laid out in a split-plot design with three replications. Three establishment methods viz., continuous row sowing in 15 cm apart rows, spot seeding at 15 × 15 cm spacing and broadcasting were assigned to the main plots and five weed management treatments as the sub plots. The post-emergence herbicides used were flucetosulfuron, 1-[3-[(4,6-dimethoxypyrimidin-2-yl)carbamoylsulfamoyl]pyridin-2-yl]-2-fluoropropyl] 2-methoxyacetate (ICH-110 10% SG, Indofil Industries Ltd., Mumbai, India), applied at 25 g a.i. ha^{-1}, bispyribac-sodium, sodium 2,6-bis(4,6-dimethoxypyrimidin-2-yloxy)benzoate (Nominee Gold 10% SC; PI Industries, Gurgaon, India), applied at 30 g a.i. ha^{-1}, and azimsulfuron, 1-(4,6-dimethoxypyrimidin-2-yl)-3-[1-methyl-4-(2-methyl-2H-tetrazol-5-yl)pyrazol-5-ylsulfonyl] urea (Segment 50% DF; E.I. DuPont India Pvt. Ltd., Gurgaon, India), at 35 g a.i. ha^{-1}. In the present experiment, we compared the efficacy of early post-emergence herbicide (flucetosulfuron and bispyribac-sodium) with late post-emergence herbicide (azimsulfuron). Flucetosulfuron is recommended mainly for controlling broadleaf weeds, along with grass weeds and sedges in rice. This herbicide is yet to be registered by Central Insecticides Board and Registration Committee, Department of Agriculture and Cooperation, India. Azimsulfuron is a broad spectrum sulfonylurea herbicide recommended to suppress major grass weeds along with broadleaf weeds and sedges. Bispyribac-sodium is widely used as post-emergence herbicide in Indian subcontinent to suppress grass weeds along with some sedges, which are predominant under aerobic condition.

From earlier study, it was found that late post-emergence herbicide suppressed the weeds effectively in aerobic rice and azimsulfuron applied at 15 days after sowing (DAS) showed very good efficacy (91% weed control efficiency) against complex weed flora, particularly late emergent grass weed *Leptochloa chinensis* (Saha *et al.*, 2015). In recent years, *L. chinensis* has become the major weed in the late vegetative stage of rice crop. To compare the efficacy of early and late post-emergence herbicides, azimsulfuron was applied 15 DAS, about one week after the application of flucetosulfuron (7 DAS) and bispyribac-sodium (8 DAS). Early post-emergence herbicides were applied at 2–3 leaf stage and late post-emergence herbicide was applied at 3–4 leaf stage of weeds. Along with herbicides, weed-free and weedy checks were assigned to the sub-plots. In the weed-free plots, weeds were removed at 15, 30, 45, and 60 DAS to keep the treatment weed-free.

Crop management and herbicide application details

The field was prepared by ploughing thoroughly with disc plough followed by harrowing with rotavator to get a fine tilth for ensuring easy movement of seed drill on dry soil. The gross plot size was 5 m × 6 m and the net plot size used for harvesting was 4 m × 5 m. The pre-soaked seeds of rice variety 'Pyari' (110 days duration, *Indica* type) was sown using a seed rate of 40 kg ha^{-1} on January 14 and 15 during 2013 and 2014, respectively. Continuous sowing at 15 cm apart, rows was done by manual paddy seed drill developed at ICAR-National Rice Research Institute (Formerly Central Rice Research Institute) and spot seeding was done manually using dibbler. For spot seeding, 3–4 seeds were placed in each spot spaced at 15 cm× 15 cm to maintain the seed rate of 40 kg ha^{-1}. First irrigation was given after seeding on the same day. Irrigation was applied at an interval of 5–6 days just after disappearance of water from the field using the alternate wetting and drying method of irrigation (IRRI, 2009). All herbicides were applied at saturated soil moisture using a knapsack sprayer fitted with a flat fan nozzle at a spray volume of 350 L ha^{-1} and spray pressure of about 200 kPa. A full dose of P_2O_5 (50 kg ha^{-1}) and K_2O (50 kg ha^{-1}) were applied before sowing at the final land preparation and N (100 kg ha^{-1}) was applied in three equal splits, at 15, 35 and 55 DAS. All the other recommended agronomic and plant protection measures were adopted to raise the crop.

Field measurements

Weed species were identified within 0.5 m × 0.5 m quadrats placed randomly at two places in each plot. Weed density was measured at 30 and 60 DAS. Weeds were cut at the ground level, washed with tap water and oven dried at 70°C for 48 h, before weighing. Weed control efficiency (%) was computed using the equation given below:

$$WCE = \left[{(x - y)}/{x} \right] \times 100 \tag{1}$$

where x = weed dry weight in weedy check and y = weed dry weight in treated plot.

Grain yield of rice along with other yield components were recorded at harvest at 14% moisture content in seed. Sampling was done from an area of 1 m^2 in each plot to determine above ground total dry weight (total biomass) and yield components. Panicles m^{-2} were counted manually. Filled grains of 10 randomly selected panicles were counted to determine number of grains per panicle. Biomass (sum of straw dry weight and grain dry weight) was calculated using grain and total dry weight of each treatment. Weed index (WI) was computed by using the following equation:

$$WI = \left[{(x - y)}/{x} \right] \times 100 \tag{2}$$

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where x = yield in weed-free plot and y = yield under treatment for which WI is to be calculated.

Statistical analyses

Data for both years (i.e. 2013 and 2014) were presented separately and analysed using analysis of variance (SAS Software packages, SAS EG 4.3). Means of treatments were compared based on least significant difference (LSD) test at $P \leq 0.05$. Weed density and biomass data were subjected to square root transformation and the transformed values were used in analysis. Path analysis was conducted to evaluate direct and indirect effects of panicle numbers m^{-2}, number of grains per panicle, crop biomass, weed dry matter production, weed control efficiency of herbicides and WI on grain yield. The response variable i.e. grain yield and six predictor variables viz., panicle numbers m^{-2}, number of grains per panicle, crop biomass, weed dry matter production, weed control efficiency of herbicides and WI, were used for deriving path coefficient by SAS EG 4.3.

RESULTS

Weed flora

The weed flora was mainly dominated by grass weeds throughout the crop growth period and across the establishment methods. The three grass weeds (*E. colona, L. chinensis, D. sanguinalis*) constituted 65% (103 plants m^{-2}) of total weeds (158 plants m^{-2}) in 2013 (Supplementary Table S1(available online at https://doi.org/10.1017/S0014479717000576)). Similar trend was observed in 2014. The infestation by grass weeds was as 66% (41 plants m^{-2}) and 69% (37 plants m^{-2}), in 2013 and 2014, respectively, in broadcasted rice at 30 DAS (Figure 1 and Table S1). *Echinochloa colona* (L.) link was the predominant grass weed species at this stage. At 60 DAS, the density of grass weed species was 42–43% of total weed density in spot seeding, 53–54% in row sowing and 54–57% in broadcasting (Figure 1). *L. chinensis* (L.) Nees and *D. sanguinalis* (L.) Scop. were the dominant grass weed species at 60 DAS (Tables S1 and S2). Other weeds included sedges viz., *Cyperus difformis* L. and *Fimbristylis miliacea* (L.) Vahl. and broad-leaved weeds viz., *Sphenoclea zeylanica* Gaertn. and *Ludwigia octovalvis* (Jacq.) P. H. Raven. Sporadic and scattered appearance of broad-leaved weeds viz., *Cleome viscosa* L., *Euphorbia hirta* L., *Physalis minima* L., *Eclipta prostrata* L., *Phyllanthus niruri* L. and *Scoparia dulcis* L. were also recorded in the weedy plots at 60 DAS (Table S1).

Among the establishment methods, broadcasted rice recorded highest total weed density at 30 DAS (Figure 1 and Table S1). Owing to inter-row space, row sowing recorded significantly higher total weed density compared to spot seeding at 60 DAS. Among the herbicides, flucetosulfuron-treated plots recorded the maximum number of grass weeds. The interaction effects of rice establishment methods and weed management on total weed density were significant ($P \leq 0.05$). For example, azimsulfuron application recorded 18%, 13% and 11% of weeds in weedy check

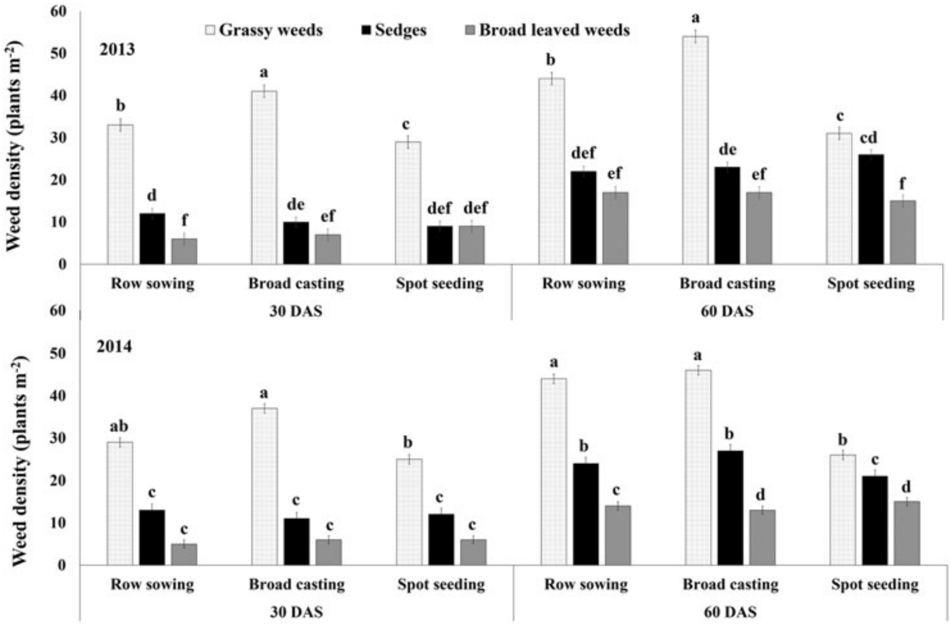

Figure 1. Weed density in weedy check plots grown under different rice establishment methods at 30 and 60 DAS. Vertical bars indicate standard error and bars with at least one letter common are not statistically significant using least significant difference at $P \leq 0.05$.

plots under broadcasting, row sowing and spot seeding at 30 DAS, respectively (Figure 1).

Total dry matter production (biomass) of weeds recorded similar trend as weed density (Figures 1 and 2). Weed dry weight was lowest in spot seeding and highest in broadcasting at 30 DAS and the highest weed dry matter (79.3 and 76.8 g m^{-2} during 2013 and 2014, respectively) was obtained at 60 DAS in the weedy check plots (Figure 2). All the herbicides showed higher weed control efficiency at 30 DAS, being highest in azimsulfuron (93.8%) followed by bispyribac-sodium (86.6%) and flucetosulfuron (84.8%) (Table 1). At 60 DAS, the herbicide treatments recorded a similar trend. Among the establishment methods, row and spot seeding recorded weed control efficiency at par and significantly higher than broadcasting (Table 1). The interaction between the establishment methods and herbicides treatments was found to be significant at 60 DAS. Like weed control efficiency, WI also recorded a significant interaction between the establishment methods and herbicides treatments (Table 1).

Effect on yield parameters

Among the establishment methods, the number of panicles m^{-2} (mean of two years) was significantly higher in spot seeding (241.3) compared to broadcasting (213.1) (Table 2). Azimsulfuron-treated plots recorded about 51% higher panicles compared to weedy plots, which contributed greatly to achieving higher grain yield. Being

Table 1. Effect of establishment methods and weed management treatments on weed control efficiency (%) and weed index at different growth stages of rice. Means are separated by least significant difference (LSD). The LSD value under interaction compares establishment method means at same weed management treatment.

	Weed control efficiency (%)								Weed Index			
	Method of establishment (T)											
	Year 2013											
	30 DAS				60 DAS				At harvest			
Weed management treatments (W)*	Row sowing	Broadcasting	Spot seeding	Mean	Row sowing	Broadcasting	Spot seeding	Mean	Row sowing	Broadcasting	Spot seeding	Mean
BPS	86.1	85.1	87.9	86.3^{b}	82.5	75.3	82.0	79.9^{ab}	14.4	12.85	8.64	11.97^{b}
AZM	92.9	92.9	95.3	93.7^{a}	85.3	79.9	84.7	83.3^{a}	8.24	6.34	2.76	5.78^{c}
FCS	84.6	82.4	85.5	84.1^{b}	78.9	71.9	79.1	76.6^{b}	24.28	20.31	16.94	20.51^{a}
Mean	87.8	86.8	89.6	88.1	82.2^{A}	75.7^{B}	81.9^{A}	80.0	15.64	13.16	9.45	12.75
LSD												
Main plot (T)		NS				3.39				NS		
Sub plot (W)		6.25				4.72				5.21		
T*W		7.78				7.52				6.24		

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Table 1. Continued.

	Year 2014											
	30 DAS				60 DAS				At harvest			
Weed management treatments (W)*	Row sowing	Broadcasting	Spot seeding	Mean	Row sowing	Broadcasting	Spot seeding	Mean	Row sowing	Broadcasting	Spot seeding	Mean
BPS	85.9	85.8	88.2	86.6[b]	82.2	75.9	81.7	79.9[b]	11.29	11.17	7.11	9.86[b]
AZM	92.6	93.4	95.5	93.8[a]	85.3	80.7	84.4	83.5[a]	5.22	4.97	1.65	3.95[c]
FCS	85.6	82.7	86.1	84.8[b]	78.4	71.7	78.9	76.3[c]	19.11	13.78	9.58	14.16[a]
Mean	88.1	87.3	89.9	88.4	81.9[A]	76.1[B]	81.7[A]	79.9	11.88	9.97	6.11	9.32
LSD												
Main plot (T)	NS				3.18				NS			
Sub plot (W)	6.90				5.73				2.58			
T*W	7.23				6.84				5.95			

*BPS– Bispyribac Sodium (30 g a.i. ha^{-1}); AZM – Azimsulfuron (35 g a.i. ha^{-1}); FCS – Flucetosulfuron (25 g a.i. ha^{-1}).
Means with at least one letter common (upper case for 'T' and lower case for 'W') are not statistically significant using least significant difference at $P \leq 0.05$.

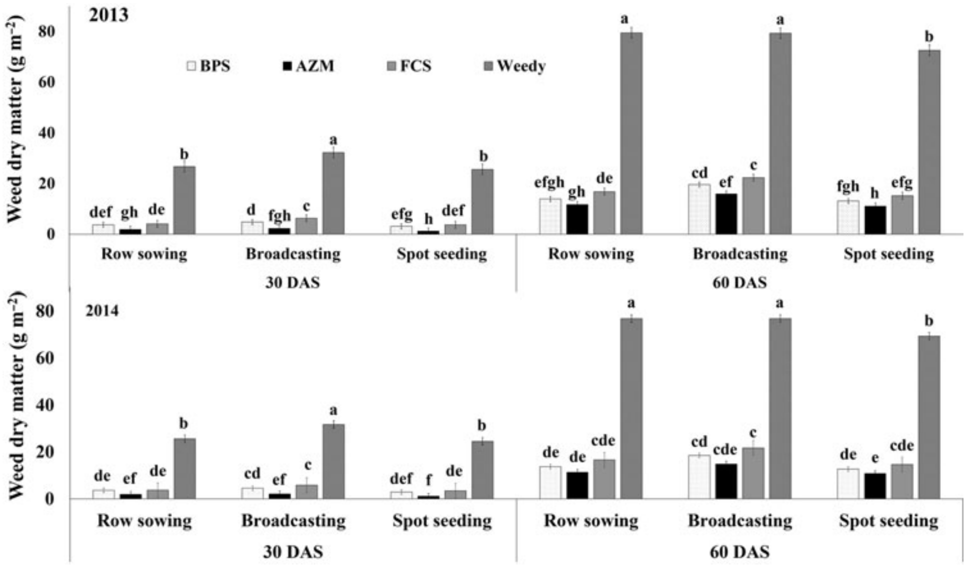

Figure 2. Weed dry matter (g m^{-2}) under different establishment methods and weed management treatment sat 30 and 60 DAS. Vertical bars indicate standard error and bars with at least one letter common are not statistically significant using least significant difference at $P \leq 0.05$.

strictly governed by genetic factors, grains panicle^{-1} did not vary significantly due to establishment methods. However, weedy plot recorded significantly lower grains panicle^{-1} compared to the herbicide treatments in the sub plots. The highest grain yield (5.1 Mg ha^{-1}) was obtained with spot seeding, which was at par with row sowing (4.7 Mg ha^{-1}) and significantly higher than broadcasting (4.2 Mg ha^{-1}). Among the herbicide treatments, the highest grain yield (mean of two years) was obtained with application of azimsulfuron (5.2 Mg ha^{-1}), which was at par with grain yield of 5.5 Mg ha^{-1} recorded under weed-free conditions (Table 2). Yield loss due to weeds in weedy check was 45% compared to weed-free control and there was about 5% yield reduction in azimsulfuron-treated plots compared to weed-free check. Flucetosulfuron was least effective in controlling weeds among the herbicides and there was about 15% yield reduction compared to weed-free check (Table 2).

The path analysis suggested panicles m^{-2}, grains panicle^{-1}, crop biomass and weed control efficiency had a positive combined direct and indirect effect on yield during both the years of experiment (Table S3 and Figure S1). On the other hand, weed dry matter and WI had significant effect on grain yield (–0.6185 and –0.6925, for weed dry matter and weed index, respectively) at $P < 0.0001$ indicating a very strong negative correlation with yield. The path analysis revealed that the highest combined direct and indirect contribution to seed yield was made by crop biomass. Path coefficients of weed dry matter, weed control efficiency and WI revealed the negative direct effect on grain yield. The weakest direct effect (mean of two years) was from panicles m^{-2} (0.0566). The highest combined indirect effect (mean of two years) on yield was from weed dry matter via weed control efficiency (0.6355), while

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Table 2. Effect of establishment methods and weed management treatments on yield attributes and grain yield of rice. Means are separated by least significant difference (LSD). The LSD value under interaction compares establishment method means at same weed management treatment.

	Panicle m^{-2}				Grains $panicle^{-1}$				Grain yield (Mg ha^{-1})			
	Method of establishment (T)											
Weed management treatments (W)*	Row seeding	Broadcasting	Spot seeding	Mean	Row seeding	Broadcasting	Spot seeding	Mean	Row seeding	Broadcasting	Spot seeding	Mean
	Year 2013											
BPS	234	218	246	232.6^{bc}	84	78	89	83.7^{ab}	4.8	4.3	5.4	4.8^{ab}
AZM	241	231	255	242.3^{ab}	88	83	91	87.3^{ab}	5.1	4.6	5.6	5.1^{a}
FCS	217	204	232	217.7^{c}	80	76	85	80.3^{b}	4.3	4.0	5.0	4.4^{b}
Weed-free	263	245	274	260.7^{a}	90	81	94	88.3^{a}	5.4	4.9	5.8	5.4^{a}
Weedy	157	141	173	157.0^{d}	56	51	63	56.7^{c}	2.9	2.5	3.3	2.9^{c}
Mean	222.4^{AB}	207.8^{B}	236^{A}	222.1	79.6^{AB}	73.8^{B}	84.4^{A}	79.4	4.5^{A}	4.1^{AB}	5.0^{A}	4.6
LSD												
Main plot (T)		15.31				7.99				0.51		
Sub plot (W)		20.63				7.99				0.64		
T*W		38.61				11.12				0.91		

Table 2. Continued.

	Year 2014											
Weed management treatments (W)*	Row seeding	Broadcasting	Spot seeding	Mean	Row seeding	Broadcasting	Spot seeding	Mean	Row seeding	Broadcasting	Spot seeding	Mean
BPS	243	226	254	241.0^{bc}	88	81	90	86.3^{ab}	5.1	4.6	5.6	5.1^{ab}
AZM	249	238	267	251.3^{ab}	90	80	94	88.0^{ab}	5.4	4.9	5.7	5.3^{a}
FCS	231	216	244	230.3^{c}	82	78	87	82.3^{b}	4.7	4.5	5.4	4.9^{b}
Weed-free	271	258	282	270.3^{a}	93	85	96	91.3^{a}	5.7	5.2	5.9	5.6^{a}
Weedy	169	154	186	169.7^{d}	65	61	71	65.7^{c}	3.2	2.7	3.5	3.1^{c}
Mean	232.6^{AB}	218.4^{B}	246.6^{A}	232.5	83.6^{AB}	77^{B}	87.6^{A}	82.7	4.8^{A}	4.4^{AB}	5.2^{A}	4.8
LSD												
Main plot (T)		20.21				6.94				0.61		
Sub plot (W)		19.23				7.14				0.45		
T*W		28.98				11.23				0.86		

*BPS– Bispyribac Sodium (30 g a.i. ha^{-1}); AZM – Azimsulfuron (35 g a.i. ha^{-1}); FCS – Flucetosulfuron (25 g a.i. ha^{-1}).
Means with at least one letter common (upper case for 'T' and lower case for 'w') are not statistically significant using least significant difference at $P \leq 0.05$.

the effect of weed control efficiency via crop biomass (–0.4375) made the weakest contribution (Table S3).

DISCUSSION

Effect on weeds

Across the establishment methods and herbicide treatments, *E. colona was* the most dominant species in the early vegetative stage and *L. chinensis* in late vegetative stage (Table S1). Dominance of *E. colona* was documented to occur in dry-seeded rice and aerobic rice systems in 24 rice growing countries (Rao *et al.*, 2007). *L. chinensis* is emerging as a new weed due to lack of continuous submergence in rice crop and rice grown in light or medium textured soils is severely infested with this weed. The dominance of *L. chinensis,* an annual grass of aquatic and semi-aquatic environment (Manidool, 1992) in aerobic rice indicated its morpho-physiological plasticity to adapt to diverse environments in rice–rice cropping sequence. However, the variation in density of *L. chinensis* and *E. colona* under different establishment methods in aerobic rice system has not been reported elsewhere. *Digitaria sanguinalis* was reported as a predominant species during flowering stage of the rice crop (Mahajan and Chauhan, 2011) as recorded in our study (Table S2).

The highest total weed densities were observed in the broadcasting while the lowest densities occurred in the spot seeding (Figure 1 and Table S1). The uneven stand and poor crop establishment in broadcasted crop resulted in severe weed pressure at the early stage resulting higher crop-weed competition in comparison to spot seeding and row seeding (Ichikawa, 2000). The congenial micro environment of rhizosphere in spot seeding resulted in early emergence and fast growth, which offered competition in favour of the crop and ultimately helped in smothering the grass weed flora in aerobic rice (Singh *et al.*, 2011).

Significant reductions in total weed biomass were recorded with azimsulfuron regardless of establishment methods (Figure 2), with higher weed control efficacy of azimsulfuron being found under spot seeding. The variable response of weeds to the application of the same herbicide provided insights into how the establishment methods of rice can influence the efficacy of herbicides. Mahajan and Chauhan (2015) reported higher efficacy of azimsulfuron in row-seeded aerobic rice when compared to other herbicides such as pendimethalin, bispyribac-sodium and fenoxaprop. Bispyribac-sodium, the most widely used herbicide for control of grass weeds in rice, was less effective in controlling late emergent *L. chinensis* because it emerged after application of herbicide. Bispyribac-sodium has minimal translocation and a large amount is retained in the treated area (plant leaves) (Martini *et al.*, 2015), indicating that the residue left in the soil only gets absorbed by weed roots if weeds have extensive roots. This could be one reason for relatively poor efficacy of bispyribac-sodium in controlling *L. chinensis* (Table S2). Abeysekera and Wickrama (2005) reported the lowest efficacy of bispyribac-sodium as compared to cyhalofop butyl, propanil, fentrazmide+propanil and quinclorac against *L. chinensis*. Weed density was significantly higher in the flucetosulfuron-treated plots due to poor control of grass weed species (Table 3). At 60 DAS, the grass weed density was as high as 79% of the total weed population in the flucetosulfuron-treated plots in spot seeding (Table 3 and Table S1). Poor control of weeds and poor herbicidal efficacy of flucetosulfuron without adjuvants was already reported by Kim *et al.* (2013).

Higher efficacy of azimsulfuron compared to bispyribac-sodium and flucetosulfuron in different establishment methods ensured that the herbicide was effective to suppress the weeds at late vegetative stages in aerobic rice fields (Table 1). Gradual and persistent degradation of azimsulfuron in soil might have helped in suppressing the weeds for longer period of time. The slow degradation of azimsulfuron was aided by neutral pH (pH 6.8) of the experimental soil (Boschin *et al.*, 2007). Accordingly, Pinna *et al.* (2007) reported faster degradation of azimsulfuron in acid soils compared to neutral and slightly alkaline soil. Again, in aerobic (unflooded) soils, azimsulfuron was characterized as exhibiting moderate to high persistence (EFSA, 2010a), which also indicates prolonged availability of azimsulfuron in soil. Bispyribac-sodium is low to moderately persistent in aerobic rice field, whereas it is moderately to highly persistent in anaerobic flooded paddy soils (EFSA, 2010b). As the residual effect is generally associated with higher persistence, bispyribac-sodium is more likely to control weeds for longer periods in transplanted rice than in aerobic rice. High weed control efficiency of azimsulfuron in spot seeding indicated that the efficacy of herbicide was further influenced by crop establishment techniques (Table 1). Bispyribac-sodium was applied as early as 8 DAS when the crop was too small to cover the space between the plants, which led to its rapid photo-transformation and photo-degradation enabling the weeds to emerge in the second flush. Suppression of grass weeds (weed control efficiency 98.5%) along with complete control of sedges and broad-leaved weeds in the plots treated with azimsulfuron at 60 DAS was also reported by Saha *et al.* (2011). Suppression of late flushes of weeds resulted in higher efficacy of azimsulfuron (Tables 2 and S2).

Effect on yield parameters

Crop established by broadcasting showed reduction in panicle numbers m^{-2} and reduction in grains per panicle was also recorded in broadcasted crop under weed-free conditions, compared to spot-seeded crop (Table 2). This finding indicates that rice plants faced severe competition from weeds due to uneven crop establishment in broadcasted crop. There was highly significant and negative correlation between weed dry matter with panicles numbers m^{-2} ($r = -0.78$, $P < 0.0001$) and grains per panicle ($r = -0.76$, $P < 0.0001$). A negative effect of weed growth on development of yield attributes in rice plants has been reported earlier (Labrada, 1996). There was 45% reduction in yield due to weed competition in weedy plots over weed-free plots (Table 2). Mahajan and Chauhan (2013) reported increased rice yield (228% more than the weedy check) following a sequential application of pendimethalin (pre-emergence) and azimsulfuron. An increase in yield to such a great extent has not been reported by any previous study with single spray of azimsulfuron. Spot seeding recorded higher yields compared to other establishment methods, but

Table 3. Effect of establishment methods and weed management treatments on dominant grassy weed (*E. colona, L. chinensis* and *D. sanguinalis*) density (plants m^{-2}) at 30 and 60 days after sowing (DAS). Means are separated by least significant difference (LSD). The LSD value under interaction compares establishment method means at same weed management treatment.

	Method of establishment (T)							
	30 DAS				60 DAS			
Weed management treatments (W)*	Row sowing	Broadcasting	Spot seeding	Mean	Row sowing	Broadcasting	Spot seeding	Mean
	Year 2013							
BPS	8	12	6	8.7^{c}	21	26	17	21.3^{c}
AZM	3	5	2	3.3^{d}	13	14	10	12.3^{d}
FCS	14	19	10	14.3^{b}	29	32	24	28.3^{b}
Weed-free†	–	–	–	–	–	–	–	–
Weedy	33	41	29	34.3^{a}	44	54	31	43^{a}
Mean	14.5^{B}	19.3^{A}	11.8^{B}	15.2	26.8^{B}	31.5^{A}	20.5^{B}	26.3
	LSD††				LSD			
Main plot (T)	0.36				0.22			
Sub plot (W)	0.37				0.39			
T*W	0.62				0.56			
	Year 2014							
	30 DAS				60 DAS			
Weed management treatments (W)*	Row sowing	Broadcasting	Spot seeding	Mean	Row sowing	Broadcasting	Spot seeding	Mean
BPS	6	9	6	7.0^{c}	19	21	14	18.0^{c}
AZM	3	5	3	3.7^{d}	10	13	8	10.3^{d}
FCS	12	16	8	12.0^{b}	26	29	21	25.3^{b}
Weed-free†	–	–	–	–	–	–	–	–
Weedy	29	37	25	30.3^{a}	44	46	26	38.7^{a}
Mean	12.5^{B}	16.8^{A}	10.5^{B}	13.2	24.8^{A}	27.3^{A}	17.3^{B}	23.1
	LSD				LSD			
Main plot (T)	0.57				0.37			
Sub plot (W)	0.49				0.34			
T*W	0.86				0.63			

*BPS– Bispyribac Sodium (30 g a.i. ha^{-1}); AZM – Azimsulfuron (35 g a.i. ha^{-1}); FCS – Flucetosulfuron (25 g a.i. ha^{-1})

†Weed-free – No weed count was recorded since weed removed manually at 15, 30, 45 and 60 days after sowing (DAS).

††Calculated using square root transformed values.

Means with at least one letter common (upper case for 'T' and lower case for 'W') are not statistically significant using least significant difference at $P \leq 0.05$.

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increase in yield with azimsulfuron application was only 68% over the weedy check (Table 2). In our study, the maximum yield increase over the weedy check was obtained in azimsulfuron-treated plots with broadcast seeding. This indicated that crop establishment by spot seeding helped in enhancing the rice crop growth even in the weedy check plots that suppressed the weed considerably. It further implies that broadcasting and row sowing encourage weed growth and would require more intensive care to produce equivalent yields as that of spot seeding. The correlation of weed dry matter production with panicle numbers m^{-2} ($r = –0.78$, $P < 0.0001$), number of grains per panicle ($r = –0.76$, $P < 0.0001$), total biomass ($r = –0.87$, $P < 0.0001$) and grain yield ($r = –0.76$, $P < 0.0001$) of rice was highly significant and negative (Table S3). The path analysis revealed that the highest combined direct and indirect contribution to grain yield was made by crop biomass (Figure S1). Mahmood *et al.* (2015) reported similarly that crop biomass had maximum contribution to grain yield of rice. The combined direct and indirect effect of weed dry matter on yield was negative and the negative direct and indirect effect of weeds through weed dry weight is attributed to the impact of excessive weed growth hampering the overall development of rice crop.

CONCLUSION

Both row seeding (spot or continuous) combined with azimsulfuron application was effective in achieving good yield compared to broadcast seeded aerobic system. Although azimsulfuron was more effective in weed suppression than bispyribac-sodium, its effect was not reflected in grain yield. On the other hand, weed seed production in bispyribac–sodium-treated plots would be increased and make weed control difficult in successive years. It may be concluded from the present study that yields in row sowing and spot seeding were similar and the same was confirmed when comparing yields in plots treated with bispyribac-sodium and azimsulfuron. Considering the prevalence of weeds and grain yield of rice, azimsulfuron in spot seeding can be recommended for achieving higher grain yield in aerobic rice.

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SUPPLEMENTARY MATERIAL

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