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REGULAR ARTICLE

Efficacy and economics of herbicidal weed management in monsoon rice of Bangladesh

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Abstract

Weed management is a challenging task in sustainable rice production. Physical and cultural methods of weed control are laborious and expensive, whereas chemical control is cheaper and less time consuming despite of some detrimental effect on environment with its inappropriate application. Considering these points, an investigation was conducted during July–December 2015 to find out appropriate weed management practices for inbred and hybrid rice. The experiment comprised of four rice varieties (two inbred; BRRI dhan49 and Binadhan-7, and two hybrids; Dhani gold and Agrodhan-12); and eight herbicidal weed control treatments (season-long weedy or weed free, Pretilachlor fb Penoxsolum or 2,4-D dimethyl amine, Pendimethalin fb Penoxsolum or 2,4-D dimethyl amine, Pretilachlor or Pendimethalin fb one-time hand weeding). Eleven weed species belonging to five families were observed in the experimental plots. The highest weed density and dry weight were found in season-long weedy treatment and the lowest one was found in Pretilachlor fb one-time hand weeding. The highest above ground crop biomass (9.7 t ha^{-1}) and harvest index (46.3%) were obtained from the hybrid variety Agrodhan-12 and the lowest biomass (8.3 t ha^{-1}) was obtained from the inbred variety Binadhan-7. Season long weed free condition resulted the highest above ground crop biomass (10.9 t ha^{-1}), harvest index (48.7%), highest yield increase over control (213.8), weed control efficiency (100%) and gross return (BDT 141480 ha^{-1}) and the lowest values for all those parameters were obtained from season-long weedy treatment. Season-long weed free treatment combined with Pretilachlor or Pendimethalin fb one-time hand weeding showed the best performance in reducing weed density and increasing above ground crop biomass, but gross return was higher because of high labor wages in these treatments. The highest BCR (2.5) was observed in Pretilachlor fb Penoxsolum. Therefore, from economic view point Pretilachlor fb Penoxsolum is the best combination. But from sustainability view point Pretilachlor or Pendimethalin along with one-time hand weeding may be recommended for effective weed management in inbred and hybrid rice during monsoon season.

Key words: Weed control; late summer rice; herbicides, BCR

Introduction

Agronomic management practice like, variety, fertilizer management, planting methods, sowing time, seed rate etc. are responsible for increased rice production. Among them, selection variety concerning the regional condition of the cultivated area and

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appropriate weed management are the most important features for maximizing rice yield. The research organizations of those countries are carrying out researches and successfully releasing high yielding inbred and hybrid rice varieties suitable for different growing seasons. Moreover, the new seed policy of many developing countries encouraged the participation of private sector in market. And, the government is supporting the private sector to acquire seeds from abroad as the developing countries lack the system to produce seeds in a sustainable way (Husain et al., 2001). Currently, it is believed that high yielding inbred varieties developed through conventional breeding have reached in yield plateau. Hybrid rice cultivars have a 15-30% yield advantage over modern inbred rice varieties, therefore, hybrid rice technology is considered as the key approach for increasing global rice production (Walker et al., 2008; Chauhan et al., 2011; Haque et al., 2015). It is also reported that even in weedy conditions, the yield of hybrid cultivars is high (Chauhan et al., 2011).

Weeds are considered as major limiting factor for crop production as it produced the highest potential loss (34%) compare to animal pests (18%) and pathogens (16%) (Oerke, 2006). In rice, the average yield losses due to weed competition are estimated to vary between 40 – 60% which may go up to 94 – 96% in season long weedy condition (Chauhan and Johnson, 2011). In addition, season long weedy condition reduced crop yield by up to 57% in paddy rice and 82% in direct seeded rice (Mahajan et al., 2009). However, yield loss owing to weed infestation is high and varying from country to country (Rodenburg and Demont, 2009), and in China, the loss was estimated to 10 million tons (5% of total) (Zhang, 2003). Whereas, in India and Sri Lanka, about 30–40% rice yield losses are caused by weeds (Abeysekera, 2001; Mukherjee, 2004). On the other hand, weeds reduce the grain yield by 68–100% in direct seeded early summer rice, 16-48% in transplanted late summer (monsoon) rice, and 22–36% in irrigated winter rice in Bangladesh (Mamun, 1990; Rashid et al., 2007) and is a major problem. The prevailing climate and edaphic conditions of those countries are highly favorable for luxuriant growth of numerous species of weeds. Manual weeding is common in Asian countries. Manual weeding is practiced once or twice depending on the quantity of weeds.

Controlling the weeds is costly in a sense, the labor charges are higher than profits from rice cultivation (Mahajan et al., 2013; Chauhan and Opeña, 2013), and labour crisis for weed control at the peak period makes it difficult to control weeds timely. This puts more emphasis on use of herbicides for effective weed management. This scenario is especially true in small farm holder countries, where farmers are resorting to chemical weed control in an attempt to sustain crop production for ensuring food security. Consequently, in recent years, China, India, and Bangladesh have become hotbeds of herbicide use (Gianessi, 2013; 2013a). However, use of same herbicide for a continuous period will cause herbicide resistant weed biotypes and shifts in weed flora (Johnson and Mortimer, 2008; Chauhan, 2012; Chauhan and Opeña, 2013). Moreover, for the sustainability point of view integration of herbicide with other weed management strategies is needed (Azmi et al., 2005; Chauhan and Johnson, 2011). The choice of a cultivars (inbred or hybrids) may play a vital role in this area as inbred and hybrids may differ in their weed suppressive ability (Mortensen et al., 1998; Gibson and Fischer, 2004).

The ability of an herbicide to produce a desired effect on the target pest determines its efficacy. However, suitability of an herbicide is not only decided by its efficacy alone, cost-effectiveness also has to be taken into consideration in choosing an herbicide (Wibawa et al., 2010). Besides, application time and proper management of herbicide are also important to take into account before arriving at a decision of selecting herbicide. Therefore, present study was undertaken to assess the weed control efficacy and economics of different herbicidal weed control treatments in different monsoon rice varieties.

Materials and methods

Experimental site and soil

The experimental site is located at 24°75' N latitude and 90°50' E longitude at an elevation of 18 m above the mean sea level. The experimental area was characterized by non-calcareous dark grey floodplain soil belonging to the Sonatola Soil Series under the Old Brahmaputra Floodplain, Agro-Ecological Zone 9 of Bangladesh (FAO and UNDP, 1988; Islam et al., 2011). The soil of the experimental field was more or less neutral in reaction with pH value 6.8, low in organic matter content (1.96%) and bulk density (1.35 g cm^{-3}). The land type was medium high with silty-loam in texture (20% sand, 67% silt and 13% clay). Soil contained 0.11% total N, 50.40 ppm available P, 7.36 ppm available S, 0.16 me % exchangeable K.

The climate of the locality is tropical in nature and is characterized by high temperature and heavy rainfall during *kharif* season (April-September) and scanty of rainfall associated with moderately low temperature during *rabi* season (October-March). During the growing season (July–December, 2015), monthly average maximum temperature, minimum temperature, relative humidity, air pressure, wind speed, solar radiation, dew point, pan evaporation and water temperature were 25.2–32.5 °C, 13.3–26.6 °C, 82.2–87.7%, 998.5–1013.8 mb, 2.33–8.72 km h^{-1}, 269–273 W m^{-2},14.9–26.3 °C, 1.6–3.9 mm and 17.5–28.6°C, respectively, while monthly total rainfall and sunshine hours were 0–387.9 mm and 84.4–205.9 h, respectively. The soil temperature at a depth of 5, 10, 20 and 30 cm were 27.5–31.3, 21.4–31.7, 21.9–31.3 and 21.0–29.5°C, respectively.

Experimental treatments and design

The experiment included two factors. Factor A comprising four rice varieties of which two were inbred types (BRRI dhan49 and Binadhan-7) and two were hybrids (Dhani gold and Agrodhan-12). Factor B comprising six different combinations of herbicides, season-long weed-free check and season-long weedy check (Table 1). A brief description of the herbicides used in this experiment is presented in Table 2. The application rates of different herbicides were followed as per manufacturers' recommendations. All herbicides were applied using 500 L water per hectare with a 2L hand sprayer. Season long weed free plots were maintained through manual weeding. No weeds were allowed to grow in these plots. In weedy checks, no hand weeding or herbicides were used and weeds were allowed to grow till harvest without any disturbance. The experiment was conducted in a randomized complete block design with three replicates.

Table 1. Herbicidal weed control treatments used in the experiment.

Treatment	Application	
	Rate	Time (days after transplanting)
Season-long weedy	–	–
Season-long weed-free	–	–
Pretilachlor fb Penoxsolum	80 g *a.i.* ha^{-1} fb 18 g *a.i.* ha^{-1}	2 fb 21
Pretilachlor fb 2,4-D dimethyl amine	80 g *a.i.* ha^{-1} fb 500 g *a.i.* ha^{-1}	2 fb 21
Pendimethalin fb Penoxsolum	850 g *a.i.* ha^{-1} fb 18 g *a.i.* ha^{-1}	2 fb 21
Pendimethalin fb 2,4-D dimethyl amine	850 g *a.i.* ha^{-1} fb 500 g *a.i.* ha^{-1}	2 fb 21
Pretilachlor fb one-time hand weeding	80 g *a.i.* ha^{-1}	2 fb 35
Pendimethalin fb one-time hand weeding	850 g *a.i.* ha^{-1}	2 fb 35

**a.i.*: active ingredient, fb: followed by.

Table 2. Description of the herbicides used in the experiment.

Trade name	Common name	Chemical family	Selectivity	Mode of application	Manufacturer
Rifit 500 EC	Pretilachlor	Chloroacetamide	Selective for grass and sedge of rice and wheat	Pre-emergence	Syngenta India Ltd.
Panida 33 EC	Pendimethalin	Dinitroaniline	Selective for weeds of potato, rice and other crops		Auto Crop Care Ltd.
Weed kill 480	2,4-D dimethyl amine	Aryloxyalkanoic acid	Selective for sedge and broadleaf in rice, wheat and maize	Post-emergence	HALEX (M) SDN, BHD, Malaysia
Granite 240 SC	Penoxsolum	Triazolopyrimidine Sulfonamide	Selective for grass, sedge and broadleaf of rice		DAO Agrolicence LLC, USA

Plant materials

The varieties used in the experiment were two inbred namely BRRI dhan49 and Binadhan-7 and two hybrids; Dhani gold and Agrodhan-12. BRRI dhan49 was developed by the Bangladesh Rice Research Institute (BRRI) in 2008. It attains a plant height of 100 cm and gives a grain yield of 5.0–5.5 t ha^{-1}. Binadhan-7 is a short duration high yielding variety with good quality of rice released in 2007 by Bangladesh Institute of Nuclear Agriculture (BINA). The yield ranges between 5.5 to 6.0 t ha^{-1}. Plant height ranges from 95-115 cm. Dhani gold is a hybrid rice variety marketed by Bayer Crop Science Ltd. Agrodhan-12 is a hybrid rice variety marketed by Petrochem Agro Industries Ltd. The plant height is 100-110 cm. The yield ranges between 6.0 to 6.5 t ha^{-1}.

Crop husbandry

The experiment was set up in puddled conditions on 28 July 2015 where rice varieties were fertilized with the recommended dose of fertilizers. Urea was top dressed in three equal splits at 15, 30 and 45 days after transplanting (DAT). In addition, hybrid varieties were top dressed with 10 kg ha^{-1} zinc sulphate at 15 DAT. Seedlings were uprooted carefully from the bed and transplanted in the plots according to the layout at the rate of 3 seedlings hill^{-1} maintaining 25 cm × 15 cm spacing. Rice was grown as a rainfed crop since rainfall was sufficient. Intercultural operations *e.g.* gap filling, and drainage were done as per requirement. As there were no remarkable infestation of disease and insect, hence no plant protection measure was taken.

Data collection and statistical analysis

Weed species grown in the experimental field were identified and weed density and dry weight were measured at harvest. Dominant weed species were identified using the summed dominance ratio (SDR) which was calculated as per Janiya and Moody (1989).

$$\text{SDR of a weed species} = \frac{[\text{Relative density (RD)} + \text{Relative dry weight (RDW)}]}{2}$$

$$\text{RD (\%)} = \frac{\text{Density of a given weed species}}{\text{Total density of weed}} \times 100$$

$$\text{RDW (\%)} = \frac{\text{Dry weight of a given weed species}}{\text{Total weed dry weight}} \times 100$$

Weed control efficiency (on the basis of weed dry weight) was calculated using the following formula developed by Sawant and Jadhav (1995).

$$\text{WCE} = \frac{\text{DWC} - \text{DWT}}{\text{DWC}} \times 100$$

Where, WCE= Weed control efficiency, DWC= Dry weight of weed in weedy check, DWT= Dry weight of weed in treated plot.

Rice grain and straw yield were recorded after harvesting the whole plot. The total above ground crop biomass at harvest was calculated by combining the grain and straw yield in oven dry basis. Relative yield loss (RYL) and yield increase over control (YOC) were calculated using the following formula:

$$\text{RYL (\%)} = \frac{\text{Weed free yield} - \text{Treatment yield}}{\text{Weed free yield}} \times 100$$

$$\text{YOC (\%)} = \frac{\text{Treatment yield} - \text{Weedy yield}}{\text{Weedy yield}} \times 100$$

The cost of individual head of expenditure was recorded and partial budget analysis was done. Analysis of variance was done with the help of computer package MSTAT-C. The mean differences among the treatments were performed by Duncan's Multiple Range Test (Gomez and Gomez, 1984).

Results

Floristic composition of weeds in the experimental field

The weed species found in the weedy plots of the experimental field are shown in Table 3. Eleven weed species comprising four grasses, four sedges and three broad leaves were identified in weedy plots by grouping weeds according to their methods of reproduction. Results showed that grass weeds constituted about 38% of total density and 53% of the total dry weight, followed by sedges (43% and 32% density and total dry weight, respectively) and broadleaves (19% and 15%, respectively) (Figure 1). Based on the summed dominance ratio (SDR) values, grass weed species *Echinochloa crusgalli* (SDR of 30.66) was the predominant species in the experimental plot followed by sedge weed species *Scirpus juncoides* (SDR of 25.79) and broadleaf weed *Monochoria vaginalis* (SDR of 14.24) (Table 3). On the other hand, the least dominant weeds species of the experimental plot was sedge weed *Fimbristylis miliaceae* (SDR of 0.21) followed by broadleaf weed species *Marsilea quadrifolia* (SDR of 0.61) (Table 3).

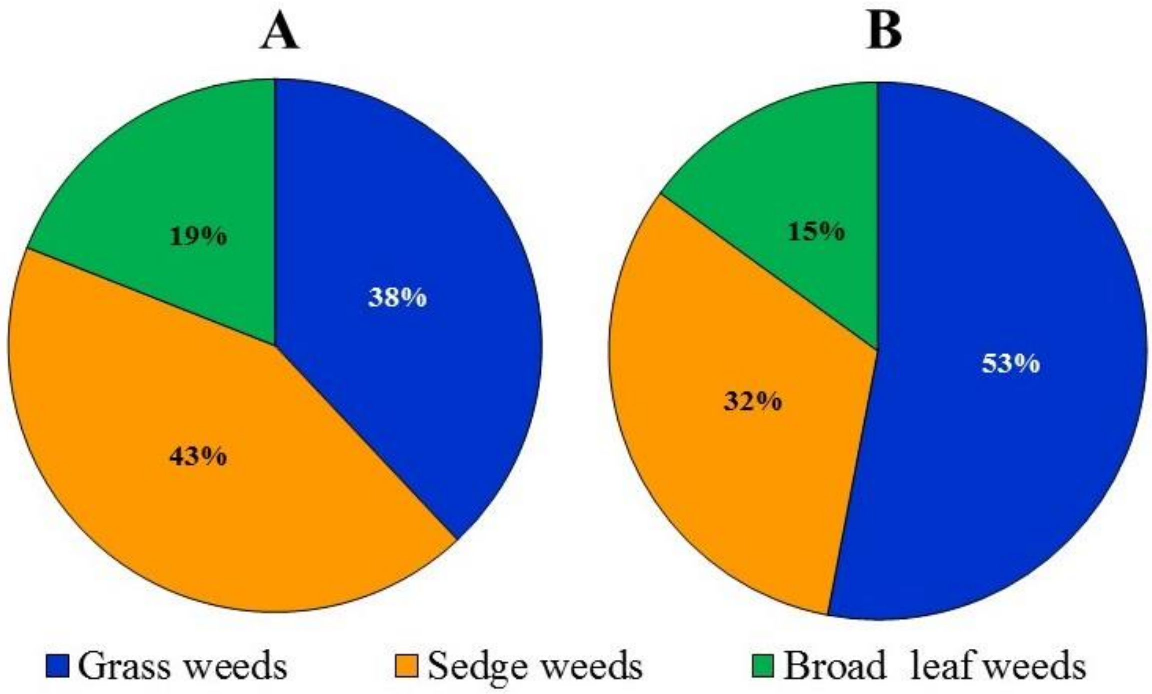

Figure 1. Relative weed density (A) and dry weight (B) of different weed groups.

Weed density

Rice variety, various weed control treatments and their interaction had significant effect on weed density at different crop growth stages (Figure 2, Table 4 and Table 5). It was observed that weed density (no. m^{-2}) gradually decreased in advancement of time. Inbred rice BRRI dhan49 allowed highest number of weeds per square meter at any growth stages compared to other varieties, whereas Agrodhan-12 was most competitive and resulted in lowest weed density (Figure 2). At heading stage, hybrid rice varieties (Dhani gold and Agrodhan-12) allowed fewer weeds per square meter than the inbred rice varieties (BRRI dhan49 and Binadhan-7). The weedy plots showed highest number of weeds at all sampling dates. At heading stage, the highest weed density (44.0 m^{-2}) was found in weedy plots, and the lowest density (10.1 m^{-2}) was found in the Pretilachlor fb one-time hand weeded plots (Table 4). At early tillering stage, the highest number of weeds was observed in the season-long weedy plots of inbred rice varieties (BRRI dhan49 and Binadhan-7) followed by hybrids (Dhani gold and Agrodhan-12) (Table 5). Among the treatments, the lowest number (14.0m^{-2}) of weeds was observed when Pendimethalin fb Penoxsolum was applied in Agrodhan-12. At heading stage, the highest weed density was found in the weedy plot of both inbred (BRRI dhan49 and Binadhan-7) and hybrid rice (Dhani gold and Agrodhan-12) varieties, whereas the lowest density (7.7 m^{-2}) was observed in Pretilachlor fb one-time hand weeded plots of Binadhan-7 and Agrodhan-12 (Table 5).

Table 3. Floristic composition of weeds in untreated weedy plots (average value) of the experimental field with their relative density (RD), relative dry weight (RDW) and summed dominance ratio (SDR).

Sl. No.	Scientific name	Family name	Life cycle	Weed type	RD (%)	RDW (%)	SDR
1.	*Echinochloa crusgalli* (L.) P. Beauv.	Gramineae	Annual	Grass	23.18	38.13	30.66
2.	*Scirpus juncoides* Roxb.	Cyperaceae	Perennial	Sedge	30.23	21.36	25.79
3.	*Monochoria vaginalis* (Burn.F.) C. Presl.	Pontederiaceae	Perennial	Broad leaf	16.16	12.34	14.24
4.	*Cyperus iria* L.	Cyperaceae	Annual	Sedge	7.73	7.72	7.72
5.	*Digitaria sanguinalis*	Gramineae	Annual	Grass	6.82	5.49	6.15
6.	*Leersia hexandra* Swartz.	Gramineae	Annual	Grass	4.09	4.99	4.54
7.	*Panicum repens* L.	Gramineae	Perennial	Grass	4.09	4.04	4.07
8.	*Cyperus difformis* L.	Cyperaceae	Perennial	Sedge	4.55	3.25	3.90
9.	*Nymphaea nouchali*	Nymphaeaceae	Perennial	Broad leaf	2.05	1.68	1.86
10.	*Marsilea quadrifolia*	Marsileaceae	Annual	Broad leaf	0.68	0.54	0.61
11.	*Fimbristylis miliaceae* L.	Cyperaceae	Annual	Sedge	0.05	0.37	0.21

Table 4. Effect of herbicidal weed control treatments on weed density and dry weight at different growth stages of rice.

Weed control treatments	Weed density (no. m^{-2})			Weed dry weight (g m^{-2})		
	Early tillering	Maximum tillering	Heading	Early tillering	Maximum tillering	Heading
Season-long weedy	56.1a	50.6a	44.0a	55.5a	47.95a	37.9a
Season-long weed free	–					
Pretilachlor fb Penoxsolum	19.8c	17.6b	11.5cd	10.1cd	10.6c	10.5bc
Pretilachlor fb 2,4-D dimethyl	21.3bc	18.1b	14.0b	14.0bc	12.5bc	11.1b
Pendimethalin fb Penoxsolum	20.5c	17.3b	12.6c	13.6bc	12.1bc	10.7bc
Pendimethalin fb 2,4-D dimethyl	22.7b	17.3b	13.7b	16.1b	13.6b	12.9b
Pretilachlor fb one-time hand	17.9d	14.8c	10.1d	9.3d	10.0c	8.8c
Pendimethalin fb one-time hand weeding	19.3c	13.8d	11.8cd	11.0c	10.2c	9.2bc
CV (%)	16.2	13.5	12.6	11.5	13.3	10.7
Level of significance	**	**	**	**	**	**

Here, in a column, figures with same letter or without letters do not differ significantly whereas figures with dissimilar letters differ significantly (as per DMRT). **= Significant at 1% level of probability

Table 5. Interaction effect of rice variety and herbicidal weed control treatments on weed density and dry weight at different growth stages of rice.

Interaction		Weed density (no. m^{-2})			Weed dry weight (g m^{-2})		
Variety	Weed control treatments	Early tillering	Maximum tillering	Heading	Early tillering	Maximum tillering	Heading
BRRI dhan49	Season-long weedy	61.0a	55.7a	45.3a	45.8c	43.4b	37.6c
	Season-long weed free	–					
	Pretilachlor fb Penoxsolum	24.0cde	17.3 c-i	10.7 c-h	12.5d-h	11.3c-h	13.8ef
	Pretilachlor fb 2,4-D dimethyl amine	26.3c	23.3c	10.0 d-h	16.0d-g	13.4c-h	12.7e-h
	Pendimethalin fb Penoxsolum	24.7cd	20.3cde	13.3 b-g	12.7d-h	13.3c-h	12.2e-h
	Pendimethalin fb 2,4-D dimethyl amine	22.0c-g	21.3cde	17.3b	18.9d	15.7c-h	15.4e
	Pretilachlor fb one-time hand weeding	18.7c-g	14.0 h-i	13.0b-h	8.1h	8.7e-h	7.2i
	Pendimethalin fb one-time hand weeding	19.0c-g	13.7ghi	12.0b-h	13.4d-h	10.5c-h	8.9f-h
Binadhan-7	Season-long weedy	61.3a	53.3a	45.3a	56.7b	49.1a	49.3b
	Season-long weed free	–					
	Pretilachlor fb Penoxsolum	21.0c-g	20.0ghi	12.0b-h	16.0d-g	14.9cde	15.2e
	Pretilachlor fb 2,4-D dimethyl amine	14.7fg	13.7c-i	10.3d-h	16.7d-g	13.7c-g	12.6e-h
	Pendimethalin fb Penoxsolum	21.7 c-g	17.7 c-i	16.0bc	16.8d-g	12.2c-h	9.0f-i
	Pendimethalin fb 2,4-D dimethyl amine	20.0c-g	16.7 d-i	15.3bcd	17.5de	12.9c-h	12.1e-i
	Pretilachlor fb one-time hand weeding	18.0c-g	17.0 d-i	7.7h	10.6e-h	10.3c-h	10.2f-i
	Pendimethalin fb one-time hand weeding	24.0cde	17.7 c-i	16.0bc	13.3d-h	16.20c	23.9d
Dhani gold	Season-long weedy	50.7b	52.00a	44.3a	55.0b	47.2ab	50.8ab
	Season-long weed free	–					
	Pretilachlor fb Penoxsolum	18.3c-g	17.7 c-i	13.7b-f	13.7d-h	12.2c-h	11.8e-i
	Pretilachlor fb 2,4-D dimethyl amine	21.7c-g	19.3 c-g	12.0b-h	13.4d-h	12.9c-h	11.1e-i
	Pendimethalin fb Penoxsolum	21.7c-g	18.7 c-h	14.3b-e	14.6d-h	14.4c-f	12.9efg
	Pendimethalin fb 2,4-D dimethyl amine	22.0c-g	19.3 c-g	13.7b-f	17.2def	14.9cde	13.8ef
	Pretilachlor fb one-time hand weeding	16.0efg	22.7cd	8.7ghi	8.4h	12.2c-h	9.0f-i
	Pendimethalin fb one-time hand weeding	17.3d-g	12.3hi	10.3 d-h	7.6h	7.1gh	8.7ghi
Agrodhan-12	Season-long weedy	51.3b	42.0b	45.3a	64.6a	52.1a	54.0a
	Season-long weed free	–					
	Pretilachlor fb Penoxsolum	20.0c-g	15.3 e-i	8.0gh	10.3e-h	8.1fgh	9.1f-i
	Pretilachlor fb 2,4-D dimethyl amine	22.7c-f	16.0 e-i	11.0c-h	9.9efg	10.0c-h	7.8hi
	Pendimethalin fb Penoxsolum	14.0g	12.7hi	8.7fgh	10.4e-h	8.2e-h	8.6ghi
	Pendimethalin fb 2,4-D dimethyl amine	14.7fg	13.0ghi	11.7 c-h	10.8e-h	10.8c-h	10.2f-i
	Pretilachlor fb one-time hand weeding	19.0c-g	13.3ghi	7.7h	9.9fgh	9.0d-h	8.8ghi
	Pendimethalin fb one-time hand weeding	16.7d-g	11.3i	9.0e-h	9.7gh	6.8h	7.2i
CV (%)		16.3	13.5	12.6	11.5	13.3	10.7
Level of significance		**	**	**	**	**	**

Other details are same as Table 4.

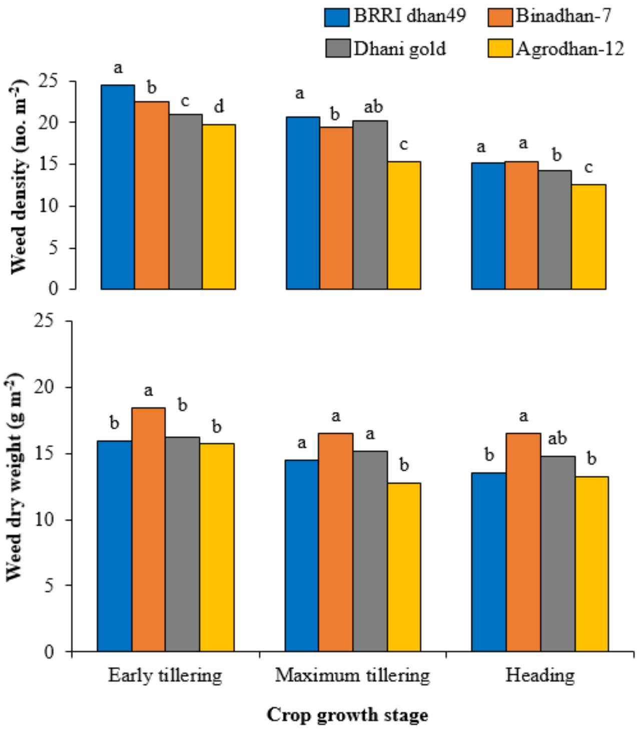

Figure 2. Effect of rice variety on weed density and weed dry weight at different growth stages (Here, in each cluster, figures with same letter(s) do not differ significantly whereas figures with dissimilar letters differ significantly).

Weed dry weight

Weed dry weight was significantly influenced by rice variety, various weed control treatments and their interaction at different crop growth stages (Figure 2, Table 4 and Table 5). Like weed density, weed dry weight (g m^{-2}) also gradually decreased in advancement of time. Inbred rice Binadhan-7 allowed highest weed dry weight per square meter at any sampling, whereas hybrid rice Agrodhan-12 yielded the lowest one (Figure 2). At heading stage, BRRI dhan49 and Agrodhan-12 allowed less weed dry weight per square meter than Binadhan-7 and Dhani gold. On the other hand, at the same stage the highest weed dry weight (37.9 g m^{-2}) was found in weedy plots, and the lowest dry weight (8.8 g m^{-2}) was found in Pretilachlor fb one-time hand weeded plots (Table 4).

Considering the interaction of variety and weed control measurement the weedy plot of Agrodhan-12 had the highest weed dry weight per square meter at any growth stage followed by inbred Binadhan-7. At early tillering stage, the lowest weed dry weight (g m^{-2}) was found in Pendimethalin or Pretilachlor fb one-time hand weeded plots of hybrid Dhani gold. However, the value was statistically identical with Pretilachlor fb one-time hand weeded plots of BRRI dhan49 (Table 5). At heading stage, the lowest weed dry weight (g m^{-2}) was found in both Pretilachlor fb one-time hand weeded plots of inbred BRRI dhan49 and Pendimethalin fb one-time hand weeded plots of hybrid Agrodhan-12 (Table 5).

Relationship of weed density and dry weight with above ground crop biomass

Experimental results revealed that above ground crop biomass (t ha^{-1}) of rice showed negative relationship with weed density at all sampling dates (Figure 3). This means a decrease in weed density will result in the corresponding increase in the biomass of both inbred and hybrid rice. Lowest total biomass (5.9 and 5.0 t ha^{-1} at heading and harvest, respectively) were observed when weed density was highest at heading.

Total above ground biomass of rice also showed negative correlation with weed dry weight (Figure 4), which confirms that decrease in weed dry weight will result in the corresponding increase in the total biomass of inbred and hybrid rice. The lowest total biomass (5.9 and 5.0 t ha^{-1} at heading and harvest, respectively) was observed when weed dry weight was highest at all growth stages.

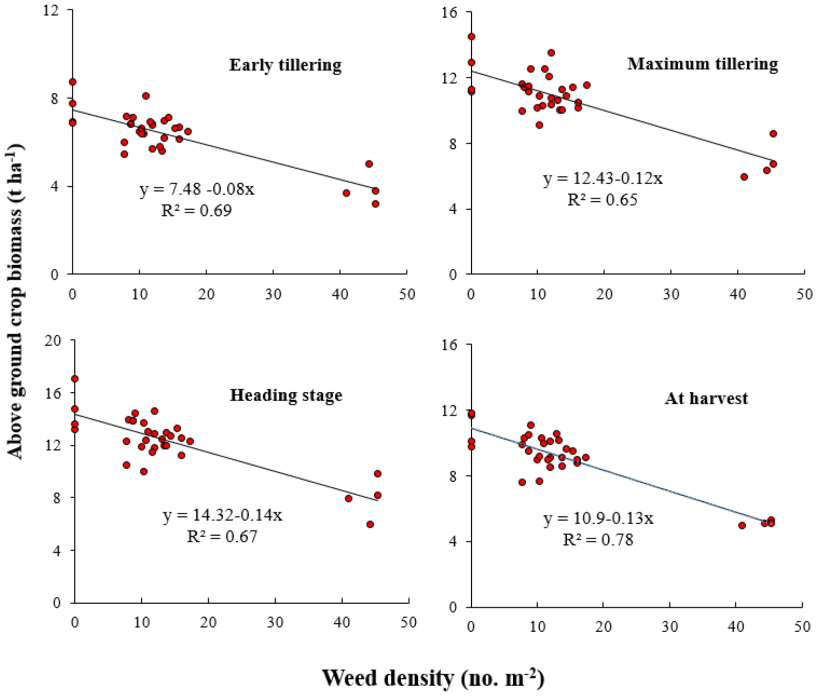

Figure 3. Relationship of above ground crop biomass with weed density at different crop growth stages

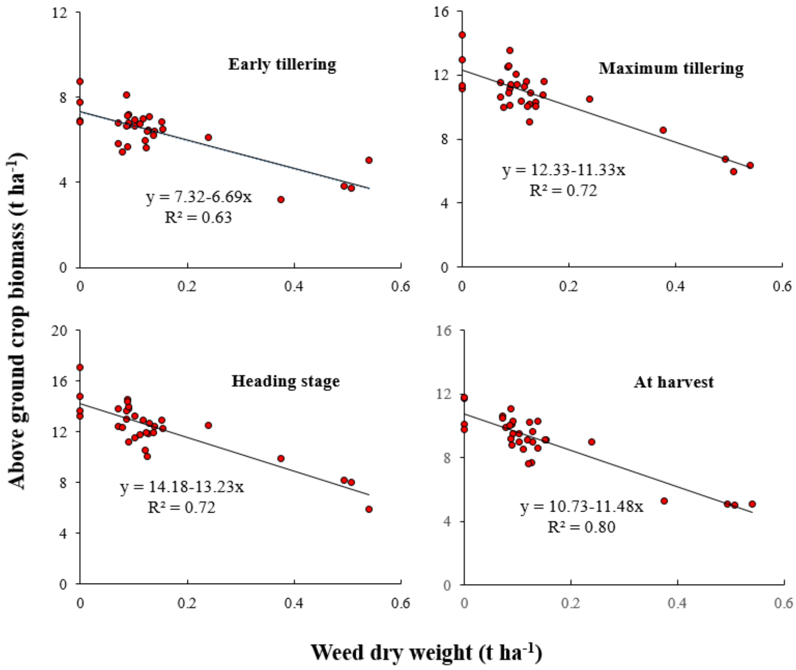

Figure 4. Relationship of above ground crop biomass with dry weight at different crop growth stages.

Weed control efficiency

The weed control efficiency based on the weed dry matter at harvest varied significantly among the herbicide treatments (Table 6). Among the herbicide treatments, application of Pretilachlor at early growth stage followed by one-time hand weeding at mid growth stage provided the highest weed control efficiency (74.4%). Application of Pendimethalin at early growth stage followed by one-time hand weeding at mid growth stage performed very close (72.6%) to the above mentioned treatments. The lowest weed control efficiency (61.2%) was found in the treatment

Pendimethalin fb 2,4-D dimethyl amine. Therefore, application of Pretilachlor or Pendimethalin just after transplanting followed by one hand weeding at mid growth stage provide satisfactory in terms of efficacy.

According to the scale of degrees of weed susceptibility based on weed control efficiency as stated by Mian and Gaffer (1968), weeds were found moderately susceptible to pre– fb post–emergence herbicide treatments. On the other hand, weeds were highly susceptible to the application of Pretilachlor or Pendimethalin just after transplanting followed by one hand weeding at mid growth stage. So, any of those treatments will give better control over weeds than other treatments (except weed-free treatment).

Above ground crop biomass

Total above ground biomass of rice was significantly influenced by rice variety, weed control treatments and their interactions (Figure 5, Figure 6 and Table 7). At harvest, the highest biomass (9.7 t ha^{-1}) was obtained from the hybrid Agrodhan-12 and the lowest one (8.3 t ha^{-1}) was obtained from the inbred variety Binadhan-7 (Figure 5). Among the weed control treatments season-long weed free plots produced the highest biomass (10.9 t ha^{-1}) at harvest followed by Pretilachlor fb one-time hand weeded plots (Figure 6). Whereas, the lowest biomass (5.1 t ha^{-1}) was found from the season-long weedy treatment. Considering the interaction of variety and weed control treatments, season-long weed free plots of hybrid rice Agrodhan-12 resulted in the highest biomass (11.8 t ha^{-1}) which was statistically similar with BRRI dhan49 under same weed management (Table 7). The season-long weedy plots resulted in lowest biomass irrespective of rice varieties.

Harvest index

Harvest index was significantly influenced by rice variety, weed control treatments and their interactions (Figure 7 and Table 7). The highest harvest index (46.3%) was obtained from the variety of Agrodhan-12 which was statistically similar with that (46.1%) of Dhani gold. The lowest harvest index (41.9 %) was obtained from the variety of BRRI dhan49 followed by Binadhan-7 (Figure 7). On the other hand, season-long weed free treatment produced highest harvest index (48.7%) and lowest one (32.9%) was observed from season-long weedy plots (Figure 7). In case of interaction effects, highest harvest index (50.5%) was found in hybrid Agrodhan-12 with season-long weed-free conditions which was statistically identical with hybrid Dhani gold at the same condition, and in both hybrids when Pretilachlor fb Penoxsolum or Pretilachlor fb one-time hand weeding was performed (Table 7). The lowest harvest index (28.0%) was recorded with BRRI dhan49 grown in season-long weedy condition.

Table 6. Weed control efficiency, weed inflicted relative yield loss and yield increase over control, weed grading and weed susceptibility due to different weed control treatments.

Weed control treatments	Weed control efficiency (%)	Relative grain yield loss (%)	Grain yield increase over control (%)	Grade of weed*	Degrees of weed susceptibility*
Season-long weedy	0	68.1	0	No control	–
Season-long weed free	100	0	213.8	Completely control	–
Pretilachlor fb Penoxsolum	66.5	15.0	166.8	Fair control	Moderately susceptible
Pretilachlor fb 2,4-D dimethyl amine	65.7	25.4	134.2	Fair control	Moderately susceptible
Pendimethalin fb Penoxsolum	66.8	19.0	154.1	Fair control	Moderately susceptible
Pendimethalin fb 2,4-D dimethyl amine	61.2	27.6	127.0	Fair control	Moderately susceptible
Pretilachlor fb one-time hand weeding	74.4	8.9	185.7	Good control	Highly susceptible
Pendimethalin fb one-time hand weeding	72.6	14.2	169.4	Good control	Highly susceptible

*as per the scale described by Mian and Gaffer (1968).

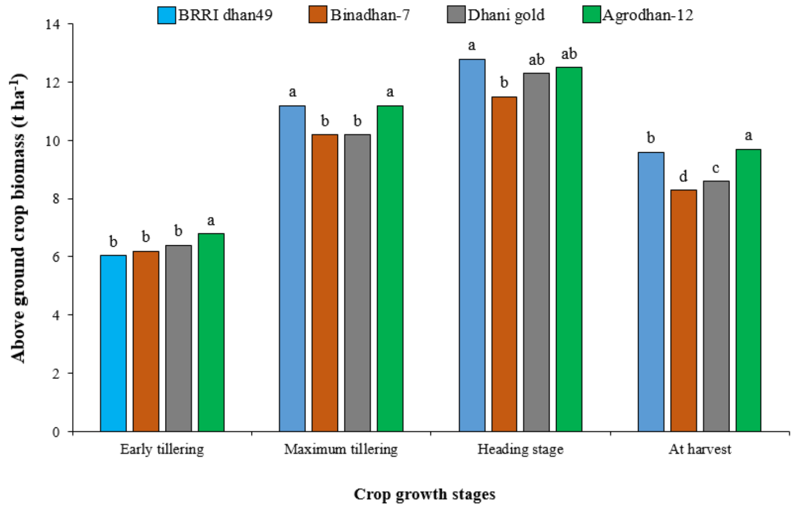

Figure 5. Effect of variety on above ground crop biomass (t ha^{-1}) (Other details are same as Figure 2)

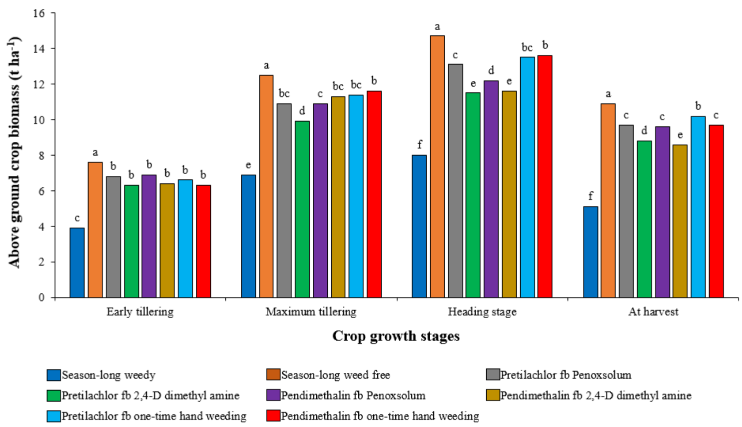

Figure 6. Effect of weed control treatments on above ground crop biomass (Other details are same as Figure 2)

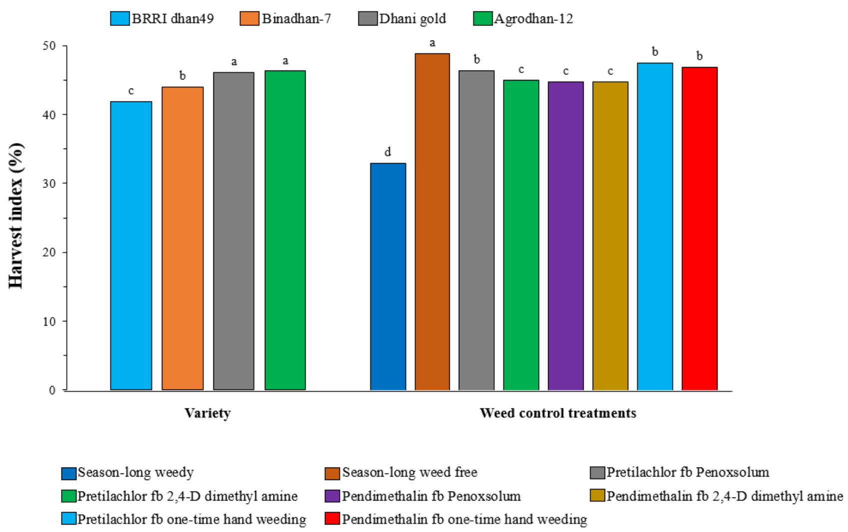

Figure 7. Effect of variety and weed control treatments on harvest index (Other details are same as Figure 2).

Table 7. Interaction effect of variety and herbicidal weed control treatments on above ground crop biomass of rice at different growth stages.

Interaction		Above ground crop biomass (t ha^{-1})				Harvest index (%)
Variety	Weed control treatments	Early tillering	Maximum tillering	Heading stage	At harvest	
BRRI dhan49	Season-long weedy	3.2h	8.6k	9.9m	5.3n	28.0o
	Season-long weed free	8.7a	14.5a	17.0a	11.7a	47.1b-h
	Pretilachlor fb Penoxsolum	6.4c-f	10.3f-j	12.4f-k	10.3cd	44.7h-k
	Pretilachlor fb 2,4-D dimethyl amine	6.5c-f	10.2f-j	11.9ijk	9.0ij	43.0k
	Pendimethalin fb Penoxsolum	5.6def	10.0hij	12.0h-k	10.2cde	40.2l
	Pendimethalin fb 2,4-D dimethyl amine	6.5c-f	11.6c-g	12.3g-k	9.1ghij	40.6l
	Pretilachlor fb one-time hand weeding	5.8def	10.5e-i	12.4f-k	10.6c	45.5g-k
	Pendimethalin fb one-time hand weeding	5.7def	13.5ab	14.6b	10.1de	46.4c-i
Binadhan-7	Season-long weedy	3.8gh	6.8l	8.2n	5.1n	32.8n
	Season-long weed free	6.9b-e	11.2d-i	13.2c-h	10.1de	47.7bg
	Pretilachlor fb Penoxsolum	6.8b-e	10.8e-i	12.9d-i	9.2hij	43.6jk
	Pretilachlor fb 2,4-D dimethyl amine	6.4c-f	9.1jk	10.0m	7.7m	45.9e-j
	Pendimethalin fb Penoxsolum	6.7b-e	10.1f-j	11.2kl	8.8jkl	44.0ijk
	Pendimethalin fb 2,4-D dimethyl amine	6.0def	11.6c-f	10.5m	7.6m	45.5bk
	Pretilachlor fb one-time hand weeding	6.6b-e	11.4d-i	13.3c-h	9.5gh	46.5c-i
	Pendimethalin fb one-time hand weeding	6.1def	10.5f-j	12.5e-k	9.0ijk	46.0d-j
Dhani gold	Season-long weedy	3.7gh	6.0l	8.0n	5.1n	37.8m
	Season-long weed free	6.9b-e	11.3d-i	13.6b-g	9.8ef	49.4ab
	Pretilachlor fb Penoxsolum	7.0b-e	11.3d-i	12.9d-i	9.1g-j	48.3a-f
	Pretilachlor fb 2,4-D dimethyl amine	6.7b-e	10.4f-j	11.8ijk	8.5l	43.0k
	Pendimethalin fb Penoxsolum	7.1bcd	10.9e-i	12.7d-j	9.3ghi	47.5b-g
	Pendimethalin fb 2,4-D dimethyl amine	6.2c-f	10.0g-j	11.9h-k	8.6kl	46.1d-j
	Pretilachlor fb one-time hand weeding	6.8b-e	11.1d-i	13.8b-e	9.5fg	48.9a-f
	Pendimethalin fb one-time hand weeding	6.6b-e	10.9e-i	13.7b-f	9.2ghi	47.5b-j
Agrodhan-12	Season-long weedy	5.0fg	6.4l	5.9o	5.0n	33.2n
	Season-long weed free	7.8abc	12.9bc	14.8b	11.8a	50.5a
	Pretilachlor fb Penoxsolum	7.2bcd	11.4d-i	14.0bcd	10.3cd	48.7a-d
	Pretilachlor fb 2,4-D dimethyl amine	5.5ef	10.0ij	12.3f-k	9.9ef	47.6b-g
	Pendimethalin fb Penoxsolum	8.1ab	12.5bcd	13.0d-i	10.0de	47.3b-h
	Pendimethalin fb 2,4-D dimethyl amine	6.9b-e	12.1cde	11.5jkl	9.0ij	46.7b-h
	Pretilachlor fb one-time hand weeding	7.1bcd	12.5bcd	14.4bc	11.2b	48.7a-e
	Pendimethalin fb one-time hand weeding	6.8b-e	11.5c-h	13.8b-e	10.5c	47.3b-h
CV (%)		15.25	13.25	14.85	2.39	10.9
Level of significance		**	**	**	**	**

Other details are same as Table 3.

Relative yield loss

Weed-inflicted relative yield loss (RYL) varied widely (0–68.1%) among the treatments (Table 6). In season-long weedy check, RYL was very high (68.1%). Among the weed control treatments, Pretilachlor fb one-time hand weeding allowed the least yield penalty (8.9%) followed by Pendimethalin fb one-time hand weeded plots (14.2%). On the other hand, Pendimethalin fb 2,4-D dimethyl amine allowed the maximum RYL (27.6%) followed by Pretilachlor fb 2,4-D dimethyl amine (25.4%).

Yield increase over Control

Yield increase over control (YOC) varied due to herbicide treatments (Table 6). The highest YOC (213.8%) was obtained from season-long weed free treatment. Among herbicide treatments, the maximum YOC (185.7%) was achieved through the application of Pretilachlor fb one-time hand weeding followed by Pendimethalin fb one-time hand weeding (169.4%) and Pretilachlor fb Penoxsolum (166.8%). The lowest YOC (127.0%) was recorded with Pretilachlor fb 2,4-D dimethyl amine.

Economics of different weed control treatments

The economic analysis of weed control treatments under study is worked out in the Table 8 to evaluate the most economic weed control treatment for rice cultivation in the existing situation. Partial budget analysis shows that, the highest gross return (BDT 141480 ha^{-1}) was obtained from the season-long weed free treatment and the lowest one (BDT 54327 ha^{-1}) was calculated from season-long weedy treatment. The highest net income (BDT 74502 ha^{-1}) and benefit-cost ratio (2.5) was obtained from the treatment Pretilachlor fb Penoxsolum. The lowest net income (BDT 7812 ha^{-1}) was found from the season-long weedy plots.

Table 8. Cost effectiveness (partial cost-analysis) of different weed control treatments (BDT ha^{-1}) in rice.

Weed control treatments	Variable cost except herbicide and weeding cost	Herbicide cost	Laborer cost for spraying/ weeding	Total cost	Gross income	Net income	Benefit-cost ratio
Season-long weedy	46517	0	0	46517	54327	7812	1.2
Season-long weed free	46517	0	39000	85517	141480	55963	1.7
Pretilachlor fb Penoxsolum	46517	1338	520	48375	122877	74502	2.5
Pretilachlor fb 2,4-D dimethyl amine	46517	2608	520	49645	109315	59670	2.2
Pendimethalin fb Penoxsolum	46517	2188	520	49225	118900	69675	2.4
Pendimethalin fb 2,4-D dimethyl amine	46517	3458	520	50495	106320	55825	2.1
Pretilachlor fb one-time hand weeding	46517	900	13520	60935	130345	69408	2.1
Pendimethalin fb one-time hand weeding	46517	1750	13520	61787	123493	61706	2.0

Except weed management cost all other variable cost were kept constant.

Herbicide application cost: 2 laborers-1 ha-1 @ 260 BDT day-1

Market price of commercial herbicide: Pendimethalin @ 2.5 L ha-1 (70 BDT 100 mL-1), Pretilachlor @ 1 L ha-1 (90 BDT 100 mL-1), Penoxsolum @ 93.70 mL ha-1 (468 BDT 100 mL-1), 2,4-D dimethyl amine @ 2.24 L ha-1 (70 BDT 100 mL-1). Other details are same as Table 3.

BDT = Bangladeshi taka (1 USD = 80 BDT Approx.)

Discussion

Weeds are the integral part of rice field ecosystem and normally coevolved with rice plant species, and causes severe yield damage. Prolific seed producer, long-term seed dormancy, rapid growth behavior, short seed to seed life duration and ability to grow in disturbed lands are the well-known attributes of weeds, which help them to suppress crop growth. On the other hand, the cultivars that acquire higher initial growth and develop faster canopy, establish themselves rapidly in the composite culture of a crop weed ecosystem and will be less affected by weed competition. In this experiment, inbred rice cultivars allowed highest number of weeds and higher weed dry weight per unit area at any growth stages compare to hybrids. This could be due to higher competitiveness of hybrids against weeds, development of fast and early canopy coverage with higher leaf area index values; higher root growth and crop dry weight (data not shown here). The competitive ability of crops against weeds mainly determine by higher plant height and dry matter accumulation, early canopy closure, enhanced leaf area leading to more light interception and shading over understory plant species, increased nutrient uptake, proliferate root growth, and allelopathic effects (Pavlychenko and Harrington, 1934; Balyan et al., 1991; Cousens et al., 1991; Cudney et al., 1991; Anwar et al., 2010; Bajwa et al., 2017). Early-ripening of improved rice cultivars and hybrids have the ability to acquire larger canopy coverage within a short period of time and can suppress the weed growth to a greater magnitude over traditional, open-pollinated, long-duration cultivars (Zhao, 2006; ICAR, 2007; Sardana et al., 2017; Mahajan and Chauhan, 2013). The significant genotypic differences for weed-competitive abilities of rice, cultivated under moderately weedy and completely weed-free environments have also been documented (Anwar et al., 2010; Mahajan et al., 2014). Due the higher weed suppressive ability, hybrid rice yielded 15–25% more over inbred cultivars (Walker et al., 2008; Dass et al., 2017). Therefore, through selection of weed competitive cultivars, the weed emergence and its subsequent growth can be suppressed and at the same time reduce the cost of weed management (Johnson et al., 1998; Gibson et al., 2002; 2003; Gibson and Fischer, 2004; Zhao et al., 2006; Rao et al., 2007; Mahajan and Chauhan, 2011; Anwar et al., 2013; 2014; Mahajan and Chauhan, 2013; Dass et al., 2017). Whereas, Lemerle et al. (1996) and Mahajan and Chauhan (2013) reported a higher weed control in combination system of herbicides with crop species or genotypes of superior competitiveness.

In this experiment season long weed free condition resulted the highest total crop biomass (10.9 t ha^{-1}), harvest index (48.7%), highest yield increase over control (213.8), weed control efficiency (100%), gross return (BDT 141480 ha^{-1}) and lowest relative yield loss (0.0%). Similar types of findings were also reported by many other researchers around the world (Anwar et al., 2012; Jaya Suria et al., 2013). But in the farmers' fields, it is quite impossible to practice season long weed free condition, as it is most laborious and costly method. On the other hand, traditional method of weed control (2-3 weedings) also become difficult now a days because of labor crisis at the peak period, which results in drastic yield loss due to delaying in weeding (Hasanuzzaman et al., 2009, Rashid et al., 2012). Moreover, mimic nature of grassy weeds like *Echinochloa crusgalli* to rice seedlings (Rao and Moody, 1988), increase difficulty of manual weeding. To overcome this problem, herbicidal weed control has been widely used to manage weeds in some Asian rice-growing countries for example, Philippines (Casimero et al., 1994; Johnson et al., 2010), Malaysia (Karim et al., 2004) and Vietnam (Luat, 2000). It has been widely accepted by researchers that herbicides have the potential to reduce labour inputs (Ahmed et al., 2001). In this situation, the use of herbicides in Bangladesh has seen almost a 78-fold increase in the last three decades; from 52 metric tons (MT) kilolitre^{-1} (kL) in 1984 to 4051 MT kL^{-1} in 2015 (BBS, 2015). The major herbicides registered in rice include 2, 4-D, oxadiazon, oxadiargyl, anilofos, butachlor, cinmethylin, carfentrazone-ethyl, pretilachlor, pyrazosulfuron-ethyl, MCPA-500, ethoxysulfuron, triosulfuron + dicamba, pendimethalin, metribuzin, bensulfuron methyl + mefenacet, orthosulfamuron, triasulfuron, bensulfuron methyl + acetochlor, ethoxysulfuron + iodosulfuron methyl, oryzalin, ethoxysulfuron + anilofos, bensulfuron methyl + pretilachlor, butachlor +

propanil, and penoxsulam (DAE, 2015). Although this looks like an impressive array of herbicides, these represent only 8 modes of action according to the WSSA herbicide classification system (WSSA, 2015). Furthermore, most of these herbicides are sulfonylureas that inhibit the acetolcatate synthase enzyme; globally this chemical group has the greatest number of reported cases of herbicide-resistant weeds (Heap, 2017). Over and indiscriminate use of these herbicides can also result in several adverse effects on the environment (Kortekam, 2011). As the chemical era of weed management has started in Bangladesh, interventions can be made by comparing alternative methods or judicious use of herbicides and by providing an educational program on herbicide use, safety, and consequences.

Besides season long weed free condition, application of pre-emergence herbicide; Pretilachlor at early growth stage followed by one-time hand weeding at the mid-growth stage resulted the lowest weed density (10.1 m^{-2}), weed dry weight (8.8 g m^{-2}) and least yield penalty (8.9%), and highest total above ground biomass (10.2 t ha^{-1}), harvest index (47.4%), yield increase over control (185.7%), weed control efficiency (74.4%). Another pre-emergence herbicide, Pendimethalin fb one hand weeding also resulted very close result as like Pretilachlor fb one hand weeding. However, it was evident from present study that Pretilachlor fb Penoxsolum was the most profitable treatment because of the highest net income (BDT 74502 ha^{-1}) and BCR (2.5). Although the maximum gross return was obtained from weed-free treatment, due to high cost involvement (BDT 85517 ha^{-1}) in manual weeding, the net benefit (BDT 55963 ha^{-1}) and BCR was low (1.7). The study revealed that despite high weed control efficiency, manual weeding is not cost-effective, whilst chemical weed controls are highly efficient and economic as well. Though Pretilachlor fb Penoxsolum or Pendimethalin fb Penoxsolum are cost-effective for weed management compared to Pretilachlor or Pendimethalin fb one hand weeding, the latter options are the best in terms of sustainability point of view. Because in the latter options we can at least reduce some amount of herbicide. Moreover, pre-emergence herbicide fb one hand weeding efficiently control weeds and provide higher crop biomass. It has been reported that herbicide combinations or herbicide plus hand weeding provided excellent control of weeds than the single application of herbicides (Sangeetha et al., 2011; Anwar et al., 2012a; Ahmed and Chauhan, 2014; Singh et al., 2008; Shahabuddin et al., 2016).

Conclusion

Weed management is a difficult task in rice production. Researchers around the world are searching to find out a weed management option that is less laborious, less time consuming, cost-effective and not harmful for the environment. However, before making the final choice of weed control method, farmers' available resources such as labour, have to be considered first. Present findings show that the application of one pre-emergence herbicide at early growth stages followed by one hand weeding can yielded higher total crop biomass at harvest. Through this practice at least one post emergence herbicide can be replaced by hand weeding without sacrificing yield. Present findings also showed that the cultivars that have rapid canopy coverage ability (hybrid) can suppress the weed more efficiently than slow canopy coverage inbred varieties. Thus based on the findings of the present study it can be recommended that in order to obtain optimum yield, rice growers can use either pre fb post herbicide or pre emergence herbicide fb one hand weeding to effectively control weeds in their monsoon rice. In addition, weed control efficiency can be improved by growing weed competitive rice genotypes especially hybrid verities.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

Abeysekera, S. K. (2001). Management of *Echinochloa* spp. in rice in Sri Lanka. Paper presented at the FAO workshop on *Echinochloa* spp. control, Beijing, China. p3.

Ahmed, G. J. U., Hassan, M. S., Mridha, A. J., Jabbar, M. A., Riches, C. R., Robinson, E. J. Z., Mortimer, M. (2001). Weed management in intensified lowland rice in Bangladesh. *In:* The BCPC Conference: Weeds, 2001, vols. 1 and 2. Proceedings of the International Conference Held at the Brighton Hilton Metropole Hotel, Brighton, UK, 12–15 November, 2001, p. 205–210.

Ahmed S, Chauhan B S. (2014). Performance of different herbicides in dry-seeded rice in Bangladesh. The Scientific World Journal, 2014: 1–14.

Anwar M P, Juraimi A S, Man A, Puteh A, Selamat A, Begum A. (2010). Weed suppressive ability of rice (*Oryza sativa* L.) germplasm under aerobic soil conditions. Australian Journal of Crop Science, 4: 706–717.

Anwar, M. P., Juraimi, A. S., Samedani, B., Puteh, A., Man, A. (2012). Critical period of weed control in aerobic rice. The Scientific World Journal, 2012: 1–10.

Anwar, M. P., Juraimi, A. S., Puteh, A., Man, A., Rahman, M. M. (2012a). Efficacy, phytotoxicity and economics of different herbicides in aerobic rice. Acta Agriculturae Scandenevica Section B Plant and Soil, 62: 604–615.

Anwar, M. P., Juraimi, A. S., Mohamed, M. T. M., Uddin, M. K., Samedani, B., Puteh, A., Man, A. (2013). Integration of agronomic practices with herbicides for sustainable weed management in aerobic rice. The Scientific World Journal, 2013: 1–12.

Anwar, M. P., Juraimi, A. S., Samedani, B., Mohamed, M. T. M., Uddin, M. K., Hasan, A. K., Hossain, M. D. (2014). Integrating cultural and chemical control methods for higher weed control efficiency and better performance of aerobic rice. Research on Crops, 15 (1): 1–13.

Azmi, M., Chin, D. V., Vongsaroj, P., Johnson, D. E. (2005). Emerging issues in weed management of direct-seeded rice in Malaysia, Vietnam and Thailand. *In:* Toriyama, K., Heong, K. L., Hardy, B. (eds.), Rice is life: scientific perspectives for the 21st century. International Rice Research Institute and Tsukuba, Japan: Japan International Research Center for Agricultural Sciences, Los Baños, Philippines, p. 196–198.

Bajwa, A. A., Walsh, M., Chauhan, B. S. (2017). Weed management using crop competition in Australia. Crop Protection, 95: 8–13.

Balyan, R. S., Malik, R. K., Panwar, R. S., Singh, S. (1991). Competitive ability of winter wheat cultivars with wild oat (*Avena ludoviciana*). Weed Science, 39: 154–158.

BBS (Bangladesh Bureau of Statistics). (2015). Statistical year book of Bangladesh. Statistics and Informatics Division, Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka. Available at: http://www.bbs.gov.bd

Casimero, M. C., Phanyakaew, T., Khotsimuang, S. et al. (1994). Farmers' practices adopting wetdirect seeding in Iloilo province, Philippines. *In:* Proceedings of the 25th PMCP Conference, Pest Management Council of the Philippines, Los Baños, Philippines, p. 14.

Chauhan, B. S., Johnson, D. E. (2011). Competitive interactions between weedy rice and cultivated rice as a function of added nitrogen and the level of competition. Weed Biology and Management, 11: 202–209.

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

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

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

Cousens, R. D., Weaver, S. E., Martin, T. D., Blair, A. M., Wilson, J. (1991). Dynamics of competition between wild oats (*Avena fatua* L.) and winter cereals. Weed Research, 31: 203–210.

Cudney, D. W., Jordan, L. S., Hall, A. E. (1991). Effect of wild oat (*Avena fatua*) infestations on light interception and growth rate of wheat (*Triticum aestivum*). Weed Science, 39: 175–179.

DAE (Dept. of Agric. Extension). (2015). Plant Protection Wing, Dept of Agric Extension, Govt of the People's Republic of Bangladesh. Available at: http://www.dae.gov.bd/

Dass, A., Shekhawat, K., Choudhary, A. K., Sepat, S., Rathore, S. S., Mahajan, G., Chauhan, B. S. (2017). Weed management in rice using crop competition-a review. Crop Protection, 95: 45–52.

FAO-UNDP (Food and Agriculture Organization-United Nations Development Programme). (1988). Land resources appraisal of Bangladesh for agricultural development. Agro-ecological regions of

Bangladesh, BGD/81/035. Technical Report No. 2, FAO, Rome, Italy.

Gianessi, L. P. (2013). The increasing importance of herbicides in worldwide crop protection. *Pest Manag Sci*, 69:1099–1105.

Gianessi, L. P. (2013a). http://deltafarmpress.com/management/china-india-bangladesh-becoming-hotbeds-herbicide-use.

Gibson, K. D., Fischer, A. J., Foin, T. C., Hill, J. E. (2002). Implications of delayed *Echinochloa* spp. germination and duration of competition for integrated weed management in water-seeded rice. Weed Research, 42: 351–358.

Gibson, K. D., Fischer, A. J., Foin, T. C., Hill, J. E. (2003). Crop traits related to weed suppression in water-seeded rice (*Oryza sativa* L.). Weed Science, 51: 87–93.

Gibson, K. D., Fischer, A. J., Foin, T. C. (2004). Compensatory responses of late water grass (*Echinochloa phyllopogon*) and rice to resource limitations. Weed Science, 52: 271–280.

Gibson, K. D., Fischer, A. J. (2004). Competitiveness of rice cultivars as a tool for crop-based weed management. *In*: Inderjit (ed.), Weed Biology and Management. Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 517–537.

Gomez, M. A., Gomez, A. A. (1984). Statistical procedures for agricultural research. John Wiley and Sons, New York, Chichesten, Brisbane, Toronto. p. 97–215.

Haque, M. M., Pramanik, H. R., Biswas, J. K., Iftekharuddaula, K. M., Hasanuzzaman, M. (2015). Comparative performance of hybrid and elite inbred rice varieties with respect to their source-sink relationship. The Scientific World Journal, 2015: 1–11.

Hasanuzzaman, M., Ali, M. H., Alam, M. M., Akther, M., Alam, K. F. (2009). Evaluation of pre-emergence herbicide and hand weeding on the weed control efficiency and performance of transplanted aus rice. American–Eurasian Journal of Agronomy, 2: 138–143.

Heap, I. (2017). The international survey of herbicide resistant weeds. Online internet. Corvallis (OR): Ian Heap; [cited 2017 May 23]. Available from: www.weedscience.org.

Husain, A. M. M., Hossain, M., Janaiah, A. (2001). Hybrid rice adoption in Bangladesh: a socioeconomic assessment of farmers' experiences. Research Monograph Series No. 18. Research and Evaluation Division, BRAC, Dhaka. p. 45.

ICAR. (2007). Vision 2025. NRCWS Perspective Plan. Indian Council of Agriculture Research, New Delhi, India.

Islam, A. K. M. M., Van Meirvenne, M., Islam, M. M. (2011). Proximal soil sensing system for paddy field variability mapping: the potential of a proximal soil sensor for soil properties mapping. Saarbrücken, Germany: VDM Verlag Dr. Müller, p. 1 – 60.

Janiya, J. D., Moody, K. (1989). Weed populations in transplanted wet-seeded rice as affected by weed control method. Tropical Pest Management, 35: 8–11.

Jaya Suria, A. S. M., Juraimi, A. S., Selamat, A., Man, A., Anwar, M. P., Uddin, M. K. (2013). Critical period of weed control in aerobic rice system. Australian Journal of Crop Science, 7(5): 665-673.

Johnson, D. E., Dingkuhn, M., Jones, M. P., Mahamane, M. C. (1998). The influence of rice plant type on the effect of weed competition on *Oryza sativa* and *Oryza glaberrima*. Weed Research, 38: 207–216.

Johnson, D. E., Mortimer, A. M. (2008). Issues for weed management in direct-seeded rice and the development of decision-support frameworks. *In*: Singh, Y. et al. (eds.), Direct Seeding of Rice and Weed Management in the Irrigated Rice-Wheat Cropping System of the Indo-Gangetic Plains. Los Banõs (Philippines): International Rice Research Institute, and Pantnagar (India). Directorate of Experiment Station, G B. Pant University of Agriculture and Technology, Los Baños, Philippines, p. 223–228.

Johnson, D., Casimero, D., Chauhan, B., Janiya, J. (2010). Lost to the Weeds – Changing Practices Favor an Old Enemy. Technical Innovation Briefs. CGIAR-SP-IPM. No. 2. International Rice Research Institute, Philippines.

Karim, S. M. R., Man, A. B., Sahid, I. B. (2004). Weed problems and their management in rice fields of Malaysia: an overview. Weed Biology and Management, 4: 177–186.

Kortekam, A. (ed). 2011. Herbicides and environment. Intech Publ. 760 p.

Lemerle, D., Verbeek, B., Cousens, R. D., Coombes, N. E. (1996). The potential for selecting wheat varieties strongly competitive against weeds. Weed Research, 36(6): 505–513.

Luat, N. V. (2000). Integrated weed management and control of weeds and weedy rice in Vietnam. In: Baki, B. B. et al. (eds.), Wild and Weedy Rice in Rice Ecosystems in Asia: A Review. Limited Proceedings No. 2. International Rice Research Institute, Los Baños, Philippines, p. 1–3.

Mahajan, G., Chauhan, B. S., Gill, M. S. (2013). Dry-seeded rice culture in Punjab State of India: lessons learned from farmers. Field Crops Research, 144: 89–99.

Mahajan, G., Chauhan, B. S. (2011). Effects of planting pattern and cultivar on weed and crop growth in aerobic rice system. Weed Technology, 25 (4): 521–525.

Mahajan G, Chauhan B S. 2013. The role of cultivars in managing weeds in dry seeded rice production systems. Crop Protection, 49: 52–57.

Mahajan, G., Chauhan, B. S., Johnson, D. E. (2009). Weed management in aerobic rice in northwestern Indo-Gangetic Plains. Journal of Crop Improvement, 23: 366–382.

Mahajan, G., Poonia, V., Chauhan, B. S. (2014). Integrated weed management using planting pattern, cultivar, and herbicide in dry-seeded rice in northwest India. Weed Science, 62: 350–359.

Mamun, A. A. (1990). Weeds and their control: A review of weed research in Bangladesh. Agricultural and Rural Development in Bangladesh. Japan Intl. Co-operation Agency, Dhaka, Bangladesh. JSARD. 19: 45–72.

Mian, A. L., Gaffar, M. A. (1968). Tok granular (2,4- dichloroplenyl 4-nitrophenyl ether) as weedicide in transplanted aman rice in East Pakistan. Journal of Scientific Research, 20(3): 119–124.

Mortensen, D. A., Dieleman, J. A., Johnson, G. A. (1998). Weed spatial variation and weed management. *In:* Hatfield, J. L. et al. (eds.), Integrated Weed and Soil Management. Ann Arbor Press, Chelsea, MI, p. 293–310.

Mukherjee, D. (2004). Weed management in rice. Agriculture Today, 11:26–27.

Oerke, E. C. (2006). Centenary review: crop losses to pests. Journal of Agricultural Science, 144: 31–43.

Pavlychenko, T. K., Harrington, J. B. (1934). Competitive efficiency of weeds and cereal crops. Canadian Journal of Research, 10: 77–94.

Rao, A. N., Johnson, D. E., Sivaprasad, B., Ladha, J. K., Mortimer, A. M. (2007). Weed management in direct-seeded rice. Advances in Agronomy, 93: 153–255.

Rao, A. N., Moody, K. (1988). Weed control in rice seedling nurseries. Crop Protection, 7: 202–206.

Rashid, M. H., Alam, M. M., Rao, A. N., Ladha, J. K. (2012). Comparative efficacy of Pretilachlor and hand weeding in managing weeds and improving the productivity and net income of wet-seeded rice in Bangladesh. Field Crops Research, 128: 17–26.

Rashid, M. H., Uddin, M. H., Islam, A. K. M. M., Alam, A. H. M. J., Anwar, M. P. 2007. Efficiencies and economics of some weed control methods in transplant aman rice cv. BRRI dhan32. Bangladesh Journal of Crop Science, 18(2): 259–264.

Rodenburg, J., Demont, M. (2009). Potential of herbicide resistant rice technologies for sub-Saharan Africa. *AgBioForum*, 12(3 & 4): 313–325.

Sangeetha, S. P., Balakrishnan, A., Priya, R. S., Maheswari, J. (2011). Nutrient depletion by weeds, yield and economics of drum seeded rice influenced by weed management. Indian Journal of Weed Science, 43: 233–235.

Sardana V, Mahajan G, Jabran K, Chauhan B S. (2017). Role of competition in managing weeds: An introduction to the special issue. Crop Protection, 95: 1-7.

Sawant, A. C., Jadhav, S. N. (1995). Efficiency of different herbicides for weed control in transplanted rice in Konkan. Indian Journal of Weed Science, 17(3): 35–39.

Shahabuddin, M., Hossain, M. M., Salim, M., Begum, M. (2016). Efficacy aof Pretilachlor and oxadiazon on weed control and yield performance of transplant Aman rice. Progressive Agriculture, 27 (2): 119–127.

Singh, S., Ladha, J. K., Gupta, R. K., Bhushan, L., Rao, A. N. (2008). Weed management in aerobic rice systems under varying establishment methods. Crop Protection, 27 (3-5): 660–671.

Walker, T. W., Bond, J. A., Ottis, B. V., Gerard, P. D., Harrell, D. L. (2008). Hybrid rice response to nitrogen fertilization for mid-southern United States rice production. Agronomy Journal, 100: 381–386.

Wibawa, W., Mohayidin, K. G., Mohamad, R. B., Juraimi, A. S., Omar, D. (2010).

Efficacy and cost-effectiveness of three broad-spectrum herbicides to control weeds in immature oil palm plantation. Pertanika Journal of Tropical Agricultural Science, 33(2): 233–241.

WSSA (Weed Science Society of America). (2015). http://wssa.net/wp-content/uploads/WSSA-Mechanism-of-Action.pdf

Zhang Z P. (2003). Development of chemical weed control and integrated weed management in China. Weed Biology and Management, 3:197–203.

Zhao, D. L., Atlin, G. N., Bastiaans, L., Spiertz, J. H. J. (2006). Developing selection protocols for weed competitiveness in aerobic rice. Field Crops Research, 97: 272–285.

Zhao, D. (2006). Weed competitiveness and yielding ability of aerobic rice genotypes. PhD thesis. Wageningen University, The Netherlands.