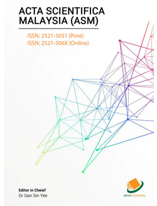
ZIBELINE INTERNATIONAL PUBLISHING

Acta Scientifica Malaysia (ASM)

DOI : http://doi.org/10.26480/asm.01.2018.17.25

ISSN: 2521-5051 (Print)
ISSN: 2521-506X (online)

CODEN : ASMCCQ



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EFFICACY OF HERBICIDES IN NON-PUDDLED TRANSPLANTED RICE UNDER CONSERVATION AGRICULTURE SYSTEMS AND THEIR EFFECT ON ESTABLISHMENT OF THE SUCCEEDING CROPS

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ARTICLE DETAILS

Article History:

Received 12 November 2017
Accepted 12 December 2017
Available online 1 January 2018

ABSTRACT

Transplanting of rice seedlings in non-puddled soil under conservation agriculture systems is a new promising technology for which effective and economic weed control strategies have to develop. Therefore, a study was conducted in wet season rice during 2013 and 2014 with some commonly used pre- and post-emergence rice herbicides (pyrazosulfuron-ethyl, butachlor, orthosulfamuron, acetochlor + bensulfuron methyl, butachlor + propanil and 2,4-D amine) in strip tilled non-puddled field condition at Mymensingh, Bangladesh to evaluate their weed control efficacy singly or in sequences, their cost-effectiveness and residual effect on the succeeding crops like wheat and lentil. Sole application of herbicide was less effective to control all types of weed species than sequentially applied herbicides. Sequential application of pre- and late post-emergence, early post- and late post-emergence or pre-, early and late post-emergence herbicides controlled weeds by 46-98% and 43-95%, respectively in terms of weed density and biomass. Sequential application of pyrazosulfuron-ethyl followed by orthosulfamuron and butachlor + propanil provided the most effective and economic weed control under this new rice establishment practice. Moreover, the study suggested a range of effective herbicides for strip-tilled non-puddled wet season rice, but possible rotation of those herbicides in a sequential application is needed. Additionally, residue of those herbicides did not show any adverse effect on the succeeding crops of rice like wheat and lentil. However, further research is needed with various new molecules of herbicide and their residual effect on the subsequent crop as well as soil environment.

KEYWORDS

Herbicide residue, Herbicide rotation, Sequential herbicide application, Strip tillage and Weed infestation.

1. INTRODUCTION

Traditional puddling of soil prior to transplanting rice (*Oryza sativa*) is tedious, costly, time and energy-consuming [1]. However, this practice helps to suppress weeds during rice establishment. Moreover, puddling changes soil physical properties to the detriment of non-rice crops in a rotation [2,3]. By contrast, non-puddled transplanting is an emerging option to overcome these problems and also reduce cost of rice cultivation [4-6]. Additionally, rice established by non-puddled transplanting gives similar or higher yield than that of puddled transplanted rice, but grain yield may sharply decline if weed management is not done properly [4-9].

In conventional puddled transplanting systems, existing weeds are controlled by burying weed seeds into the saturated and submerged soil that results in less early emergence of weeds [10,11]. By contrast, to achieve a similar low weed competition at crop establishment, pre-planting non-selective herbicides must be used to kill the existing weeds on the non-puddled field and subsequently pre-emergence herbicide also need to apply because of remaining viable weed seeds on the surface of the non-puddled soil still after pre-plant herbicide application [12-15]. The emergence of those viable seeds at the early crop growth period is caused to higher weed infestation in strip tilled non-puddled establishment compared to the conventional puddle system [16-19]. Moreover, adoption of this technique may be limited if heavy weed infestation cannot successfully be controlled [20, 21].

Weeds are traditionally managed in Bangladesh by hand weeding. But, decreased labour availability and high wages, especially during the periods of peak demand, are curtailing the amount of manual weeding on farms [22]. To overcome this situation, farmers are switching to herbicidal weed control as it is quick, effective and low cost weed control method [23-25]. Mazid reported that use of pre-emergence herbicides reduced the weeding cost by 38-46% compared to manual weeding in puddled transplanted rice while provided only partial weed control [26]. Conversely, other reports confirmed that application of pre-emergence and post-emergence herbicides ensured continuous effective control of weed species that emerged in several flushes and provided better yield over manual weeding even under minimum tillage practice [27,28]. But, the repeated use of herbicide with the same mode of action may leads to develop quick herbicide resistance in weeds which will make weed control more difficult [29-32]. Therefore, rotation of herbicides with different modes of action would benefit weed management in the longer term and minimise risks for development of herbicide resistance in weeds.

Tillage has a great influence on weed composition and minimum tillage alters species diversity, but weed composition and their management in wetland rice fields under the non-puddled transplanting system are not yet clearly defined [33,34]. Moreover, efficacy of herbicides especially pre-emergence herbicides might be different in strip-tilled non-puddled transplanting practice from conventional puddled transplanting because of having crop residue retention and less loose sediment on the surface layer of soil or in the standing water. Therefore, the present study was conducted to evaluate the effect of pre- and post-emergence herbicides on weeds of wet season rice established by strip tillage non-puddled transplanting with a view to select effective and economic herbicides for routine application and also to examine the residual effect of those herbicides on the succeeding crop.

2. MATERIAL AND METHODS

2.1 Experimental site and season

The study was conducted at the Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh (24^{0} $75^{/}$ N latitude and 90^{0} $50^{/}$ E longitudes in the south-west part of the old Brahmaputra plain). The experimental field was medium-high land with sandy clay loam type soil texture (50 % sand, 23 % silt, 27 % clay) having pH 7.2. During the study period, the highest temperature was recorded in July during both years (maximum 32.3^{o} C and minimum 26.8^{o} C in 2013 and in 2014, maximum 32.5^{o} C and minimum 26.7^{o} C). Then, temperature declined gradually from July to October, but more sharply decreased in November during both years (maximum 25.1^{o} and minimum 13.6^{o} C in 2013 and maximum 29.9^{o} and minimum 18.1^{o} C in 2014). Sufficient rain water was available in 2013 during the transplanting and early growth of rice due to heavy rainfall in July (339 mm). In 2014, comparetively less rainfall was recorded in the month of July (300 mm) than 2013 but no additional irrigation was required at that period. The highest rainfall of 2014 was recorded in the month of August (569 mm). Soil temperature remained stable in both years of the study (Figure 1). In the month of July, mean soil temperature was 31.4^{o} C in 2013 and 31.7^{o} C in 2014 at 5 cm depth of soil. Soil temperatures gradually declined from July to November and the mean soil temperature of November was 20.7^{o} C in 2013 and 25.2^{o} C in 2014.

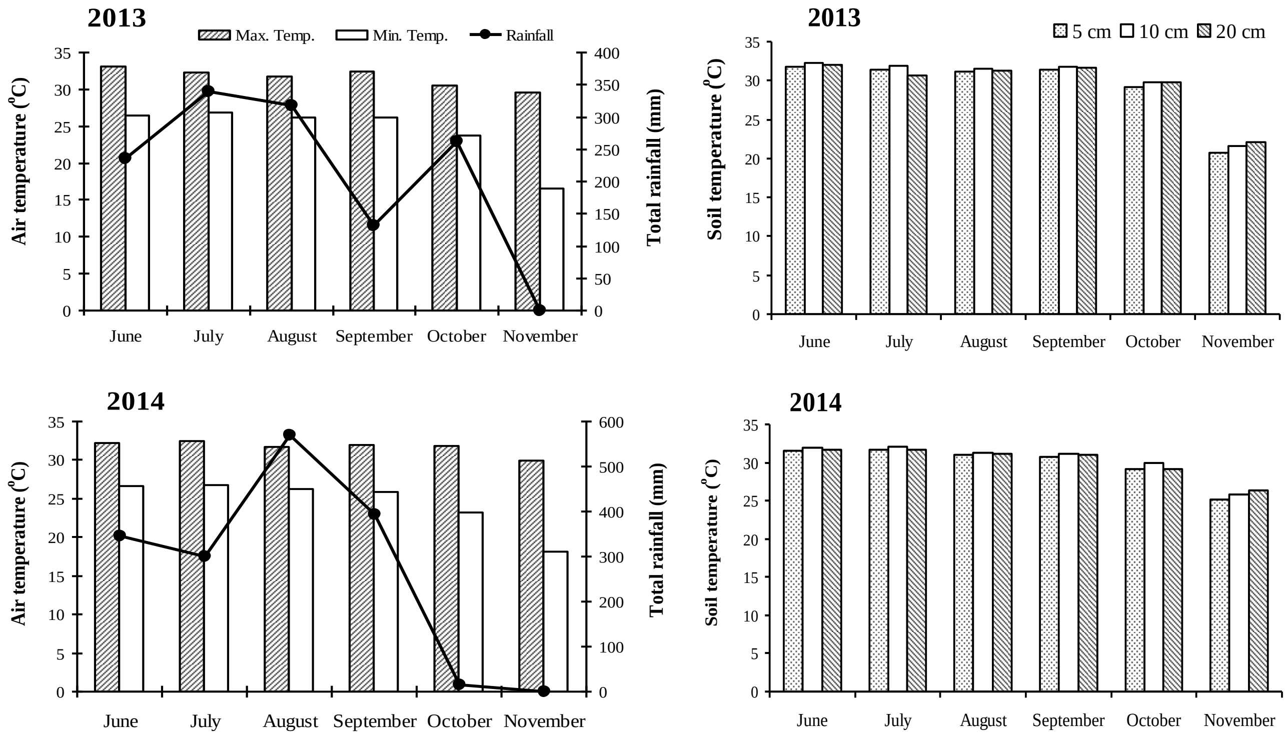

Figure 1: Monthly total rainfall, average maximum and minimum air temperature and soil temperature at 5 cm, 10 cm and 20 cm soil depth of the experimental site from July to November in 2013 and 2014 (Source: Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh, Bangladesh)

2.2 Experimental treatments and design

In 2013, six herbicides or proprietary mixture of herbicides (pyrazosulfuron-ethyl, butachlor, orthosulfamuron, acetochlor + bensulfuron methyl, butachlor + propanil and 2,4-D) were tested in 10 treatment combinations along with unweeded and weed-free (four manual weedings done at 20, 35, 50 and 65 days after transplanting) control while the 2014 study comprised 12 treatments using combinations of five herbicides along with unweeded and weed-free treatments (Table 1). Because of crop toxicity observed in 2013, acetochlor + bensulfuron methyl herbicide was discarded from the experiment in 2014 and therefore rest herbicides were examined in different treatment combinations in the second year. The chemical name, mode of action, time and dose of application of different herbicides are given in Table 2. The experiments were laid out in a randomized complete block design with three replications.

Table 1: Weed control treatments in non-puddled transplanted rice during 2013 and 2014

2013	2014
T_1 = Weedy check	T_1 = No weeding (weedy)
T_2 = Weed-free check	T_2 = Weed free
T_3 = Pyrazosulfuron-ethyl fb HW at 25 DAT	T_3 = Pyrazosulfuron-ethyl
T_4 = Butachlor fb HW at 25 DAT	T_4 = Butachlor
T_5 = Pyrazosulfuron-ethyl fb acetochlor + bensulfuron methyl	T_5 = Pyrazosulfuron-ethyl fb butachlor + propanil
T_6 = Butachlor fb acetochlor + bensulfuron methyl	T_6 = Butachlor fb butachlor + propanil
T_7 = Pyrazosulfuron-ethyl fb orthosulfamuron fb butachlor + propanil	T_7 = Pyrazosulfuron-ethyl fb 2,4-D amine
T_8 = Butachlor fb orthosulfamuron fb butachlor + propanil	T_8 = Butachlor fb 2,4-D amine
T_9 = Pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-Damine	T_9= Pyrazosulfuron-ethyl fb orthosulfamuron fb butachlor + propanil
T_{10} = Butachlor fb orthosulfamuron fb 2,4-D amine	T_{10} = Butachlor fb orthosulfamuron fb butachlor + propanil
	T_{11} = Pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine
	T_{12} = Butachlor fb orthosulfamuron fb 2,4-D amine

** 'T' denotes 'Treatment', 'fb' denotes 'followed by', 'HW' denotes hand weeding, 'DAT' denotes days after transplanting*

Table 2: Mode of action, application time and rate of application of herbicides used in the experiment during 2013 and 2014

Herbicides	Time of application	Mode of action	Recommended dose
Pyrazosulfuron-ethyl	3 days after transplanting (DAT)	Inhibitor of acetolactate synthase (ALS)	150 g ha^{-1} (100 g ai kg^{-1})
Butachlor	3 DAT	Inhibitor of microtubule assembly	25 kg ha^{1} (50 g ai kg^{-1})
Orthosulfamuron	13 DAT	Inhibitor of ALS	150 g ha^{-1} (500 g ai kg^{-1})
Acetochlor + bensulfuron methyl (Proprietary mixture)	23 DAT	Inhibitor of cell division and ALS	300 g ac^{-1} (100 g ai kg^{-1})
Butachlor + propanil (Proprietary mixture)	23 DAT	Inhibitor of very long-chain fatty acid synthesis and photosynthesis at photosystem II site A	1 L ha^{-1} (700 mL ai L^{-1})
2,4-D amine	23 DAT	Synthetic auxin	2.25 L ha^{-1} (720 g ai L^{-1})

'ai' means 'active ingredient'

2.3 Crop agronomy

Wet season rice was transplanted in strip-tilled non-puddled soil on 22 July 2013 and in the second year on 20 July 2014. One week before of strip-till the soil, pre-planting non-selective herbicide, Roundup® (glyphosate 41 % SL- IPA salt), was applied @ 75 mL/ 10 L water (2.25 L ha^{-1}). Then the land was strip-tilled at 20 cm apart by a locally made 2WT-driven power tiller named Versatile Multi-Crop Planter (VMP) [4]. The land was fertilized with phosphorus, potassium, sulphur and zinc @ 20, 35, 10 and 1.5 kg ha^{-1} as triple super phosphate, muriate of potash, gypsum and $ZnSO_4$, respectively just before strip tillage. After strip tillage, the land was inundated to 3-5 cm depth of standing water for 48 hours and then 25-day-old rice seedlings of cv. BINA Dhan-7 were transplanted at 15 cm spacing between hills in 20 cm strip-tilled rows allocating three seedlings per hill. Nitrogen was applied @ 70 kg N ha^{-1} as urea in two installments, at 7 and 35 days after transplanting (DAT). Herbicides were applied by hand operated knapsack sprayer fitted with flat-fan nozzle at a spray volume of 300 L ha^{-1}.

After harvest of the first-year non-puddled transplanted rice, strip-tilled wheat and then strip-tilled mungbean were grown in the same field without imposing any herbicide except application of knockdown herbicide (Roundup®) prior to crop sowing, and then again non-puddled rice was transplanted in the second year. At the time of rice and wheat harvest 20 cm residue was retained and in case of mungbean 50% residue was retained by height.

2.4 Data recording and crop harvesting

Weed density and biomass were taken from three randomly selected quadrats of 0.25 m^2 (50 cm x 50 cm) each at 20, 35 and 50 DAT (data at 20 and 50 DAT were not presented as these were less well correlated with grain yield) to evaluate the efficacy of herbicides. The weed density was counted in plants m^{-2} and the weed dry matter was recorded in g m^{-2} after oven drying the samples at 70 ^{0}C for 72 hrs. Plant height, number of tiller m^{-2}, number of panicle m^{-2}, number of grains $panicle^{-1}$, filled grains $panicle^{-1}$ and unfilled grains $panicle^{-1}$ were collected from five randomly selected hills before harvest. The crop was harvested at maturity (when 80% of grain became golden yellow) from the central area (2 m × 3 m) of the plot and the grain and straw yields were recorded. Grain yield was adjusted at 14% grain moisture level. Percent yield increase over control (YOC) was calculated by the following formula [35].

$$\text{YOC (\%)} = \frac{TY - WY}{WY} \times 100$$

TY = Grain yield in weed control treatment
WY = Grain yield in weedy treatment

Economic analysis was carried out to determine the cost-effectiveness of different herbicide treatments following the procedure by a group researcher [36]. Four manual weeding operations were considered sufficient to keep the plots weed-free throughout the growing season. Labour required for one manual weeding and one herbicide spraying per hectare area were 25 and 2-person day^{-1}, respectively. The cost required for one labour was 3.21 US$ day^{-1}. Herbicide requirement was calculated by the amount of commercial product ha^{-1} and the cost of each herbicide was calculated based on their local market price. Price of rice and straw was estimated as per government fixed rate. The net benefit per hectare for each treatment was calculated by deducting the total cost (fixed cost + weed management cost) from the gross return.

2.5 Herbicide residue study

After harvest of rice, the residual effect of applied herbicides in strip-tilled non-puddled rice was tested on the succeeding crops by following bioassay technique. Therefore, two micro-plots of 1m × 1m each were made within each of the main plots of rice experiment to allocate two probable succeeding crops that can be grown after rice like wheat and lentil. Within each of the micro-plots, five shallow lines of 1m length were made with the help of a bamboo stick and within these lines, 100 seeds of the wheat and lentil were separately sown in two separate micro-plots by dibbling. Then, germinations of these succeeding crops were recorded daily up to 15 days after sowing (DAS) from each of the micro-plot. The emergence percentage of seeds was calculated using the following formula:

$$\text{Germination (\%)} = \frac{\text{Number of normal seedlings}}{\text{Number of seeds sown}} \times 100$$

Shoot lengths of wheat and lentil were measured from randomly selected 10 plants within each of the micro-plots and their mean values were analysed. To compare shoot response of wheat and lentil to herbicide treated soil, percent growth inhibition was calculated by using the formula [37]:

$$\text{GI (\%)} = \left(1 - \frac{Lt}{L0}\right) \times 100$$

Where, Lt = shoot length measured in the herbicide treated soil
L0 = shoot length in the untreated soil

Seedling dry weights of wheat and lentil were recorded from oven drying the plants of 50cm × 50cm area and converted into g ha^{-1}.

2.6 Statistical instrument

Data were subjected to analysis of variance (ANOVA) and means were compared by Tukey's Honest Significant Difference (HSD) test at P<0.05 using statistical package program 'Statistical Tool for Agricultural Research (STAR) nebula' developed by International Rice Research Institute (version 2.0.1, January 2014).

3. RESULTS AND DISCUSSION

3.1 Weed species composition and their control by herbicides

Nine weed species were identified in the strip tilled non-puddled transplanted rice field at 35 days after transplanting (DAT) during 2013 whereas seven weed species were found in 2014 (Figure 1). During 2013, three grasses (*Cynodon dactylon*, *Echinochloa colona* and *Leersia hexandra*), three sedges (*Cyperus rotundus*, *Fimbristylis miliacea* and *Cyperus difformis*) and three broad-leaf (*Ludwigia decurrens*, *Cyanotis axillaris* and *Commelina benghalensis*) weeds were emerged. While in 2014, one grass weed (*Leersia hexandra*) and one broad-leaf weed (*Commelina benghalensis*) were completely absent. Some of researcher has reported that tillage practice had a great influence on the availability of weed species and continuous practice of minimum tillage helped to reduce number of weed species after a certain period [38-40].

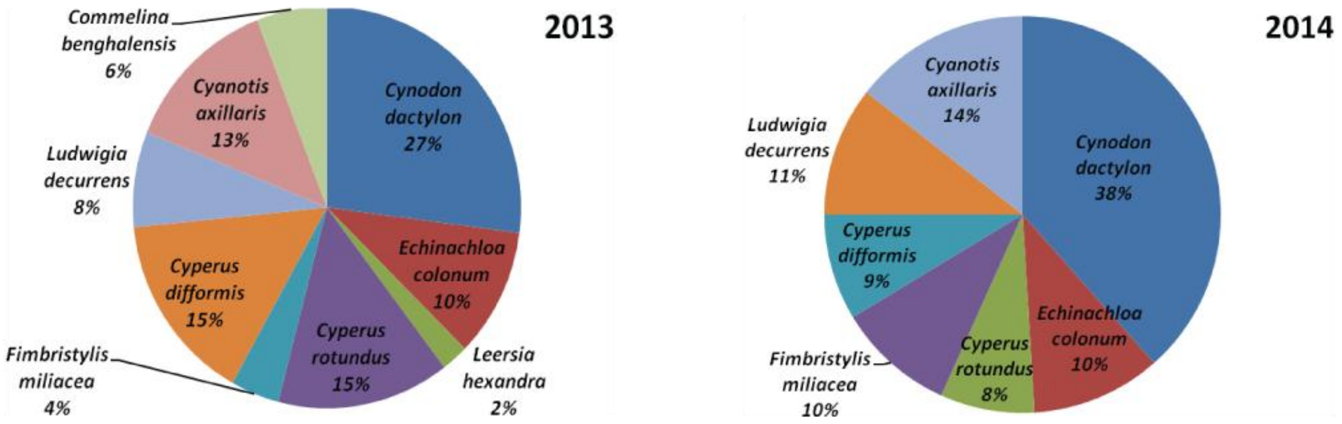

Figure 2: Weed species composition of the weedy plots of strip-tilled non-puddled transplanted wet season rice in 2013 and 2014

The highest densities of all weed species were in the weedy plots and herbicide treated plots had significantly lower densities than that of the weedy plots during both years (Table 3).

Among grass weeds, herbicide treatments controlled *C. dactylon* by 66-83%, *E. colona* by 60-100% and *L. hexandra* by 20-100% in term of density during 2013. During 2014, 23-95% of *C. dactylon* and 45-100% of *E. colona* were controlled by herbicide treatments while *L. hexandra* was completely absent (Table 4). None of the herbicide treatments provided full control on *Cynodon dactylon* in either year perhaps, due to the regenerating capability of this perennial grass weeds from the viable stolon and branched underneath rhizome. However, the best control on this species was obtained from pyrazosulfuron fb orthosulfamuron fb butachlor + propanil in both years whereas butachlor fb acetochlor + bensulfuron methyl gave the lowest control in 2013 and butachlor fb 2,4-D amine gave in 2014. In case of *E. colona*, full control was provided by pyrazosulfuron fb orthosulfamuron fb butachlor + propanil during both years. Pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine and pyrazosulfuron-ethyl fb acetochlor + bensulfuron methyl were also controlled this species fully in 2013. Effective grass weed control by pyrazosulfuron-ethyl was previously reported by a group researcher [41,42].

In case of sedge weeds, treatments having pyrazosulfuron-ethyl followed by one hand weeding/ one late post-emergence herbicide or followed by one early post-emergence herbicide with one late post-emergence herbicide gave full control on *Cyperus rotundus*, *Fimbristylis miliacea* and *C. difformis* (Table 3). Sole application of pyrazosulfuron-ethyl provided full control on *C. rotundus* and *F. miliacea*, however, controlled *C. difformis* only by 56%. On the other hand, treatments having butachlor were less effective on sedge weeds. Previous studies also agreed that butachlor was less effective on sedges, but in dry direct seeded rice [43-45]. Olofintoye and Mabbayad also reported butachlor as a less effective herbicide on sedge weeds in upland rice under minimum tillage system [46]. The reason of less efficiency of butachlor in the present study might be related to the presence of decomposed residue and the less muddy soil on the surface of non-puddled land that might restrict the proper incorporation of butachlor (a powder herbicide) in the surface soil. However, among butachlor treatments, only butachlor followed by (fb) butachlor + propanil gave full control on *C. rotundus* fully. In case of *F. miliacea*, butachlor fb orthosulfamuron fb butachlor + propanil and butachlor fb orthosulfamuron fb 2,4-D amine provided complete control during both years, and in case of *C. difformis*, butachlor fb acetochlor + bensulfuron methyl gave full control.

Among broad-leaf weeds, pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine and butachlor fb orthosulfamuron fb 2,4-D amine fully controlled all species during both years. Moreover, pyrazosulfuron-ethyl followed by one hand weeding at 25 DAT or followed by acetochlor + bensulfuron methyl/ butachlor + propanil or followed by orthosulfamuron with butachlor + propanil also provided complete control of *Ludwigia decurrens*. But, results revealed that pyrazosulfuron-ethyl/ butachlor fb hand weeding at 25 DAT was less effective on *Cyanotis auxilaris* in 2013, moreover, sole application of butachlor was the worst performed treatment in 2014. In previous study a group researcher also agreed that sequential herbicide treatment including post-emergence herbicide was effective for broadleaf weed control [47].

3.2 Total weed density and biomass

The highest weed density and biomass were in weedy plots during 2013 and 2014; however, the weed density and biomass of 2014 were remarkably lower than the preceeding year by 53% and 36%, respectively (Table 4). This might be happened due to practice of strip tilled non-puddled transplanting in rice and retaining residue of all crops of rice-wheat-mungbean rotation. Weed infestation depends on the abundance of weed seedbank at the top 5 cm of soil. While in strip tilled non-puddled rice field, weed seeds are likely to remain in viable conditions on the soil surface in the first year due to lack of conventional deep puddling resulted higher weed infestation. But in the succeeding year, weed emergence rate decreased possibly because most of the non-dormant weed seeds on the surface soil already emerged in the first year and very few new viable weed seeds could emerge from the sub-soil layers due to the confinement of deep tillage to < 25 % of the soil surface and for the presence of crop residue on the surface soil [48-50]. Mishra and Singh also reported the decrease of weed biomass by three-fold in the second year compared to the first year in DSR under zero tillage system [33].

Table 3: Controlling efficiency of herbicide treatments on different weeds species in strip-tilled non-puddled transplanted rice at 35 days after transplanting during 2013 and 2014

Treatment	*Cynodon dactylon*	*Echinochloa colona*	*Leersia hexandra*	*Cyperus rotundus*	*Fimbristylis miliacea*	*Cyperus difformis*	*Ludwigia decurrens*	*Cyanotis axillaris*	*Commelina benghalensis*
					2013				
Weedy check	0 (60)	0 (23)	0 (5)	0 (32)	0 (9)	0 (34)	0 (17)	0 (29)	0 (13)
Pyrazo fb HW	78 (13)	87 (3)	20 (4)	100 (0)	100 (0)	100 (0)	100 (0)	47 (15)	100 (0)
Buta fb HW	82 (11)	74 (6)	100 (0)	67 (11)	50 (5)	76 (8)	92 (1)	47 (15)	95 (1)
Pyrazo fb aceto+ bensul	66 (20)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	60 (11)	95 (1)
Buta fb aceto+bensul	63 (22)	70 (7)	100 (0)	48 (17)	39 (6)	100 (0)	80 (3)	58 (12)	100 (0)
Pyrazo fb ortho fb buta+prop	83 (10)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	91 (3)	100 (0)
Buta fb ortho fb buta+prop	77 (14)	60 (9)	100 (0)	38 (20)	100 (0)	84 (5)	86 (2)	86 (4)	95 (1)
Pyrazo fb ortho fb 2,4-D amine	77 (14)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)
Buta fb ortho fb 2,4-D amine	72 (17)	86 (3)	100 (0)	60 (13)	100 (0)	78 (7)	100 (0)	100 (0)	100 (0)
					2014				

Weedy check	0 (40)	0 (11)	-	0 (8)	0 (10)	0 (9)	0 (11)	0 (15)	-
Pyrazo	58 (17)	45 (6)	-	100 (0)	100 (0)	56 (4)	55 (5)	60 (6)	-
Buta	45 (22)	45 (6)	-	50 (4)	70 (3)	56 (4)	18 (9)	40 (9)	-
Pyrazo fb buta+prop	88 (5)	64 (4)	-	100 (0)	100 (0)	100 (0)	100 (0)	87 (2)	-
Buta fb buta+prop	85 (6)	55 (5)	-	100 (0)	80 (2)	67 (3)	73 (3)	67 (5)	-
Pyrazo fb 2,4-D amine	40 (24)	55 (5)	-	100 (0)	100 (0)	89 (1)	100 (0)	80 (3)	-
Buta fb 2,4-D amine	23 (31)	45 (6)	-	75 (2)	50 (5)	44 (5)	100 (0)	67 (5)	-
Pyrazo fb ortho fb buta+prop	95 (2)	100 (0)	-	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	-
Buta fb ortho fb buta+prop	93 (3)	82 (2)	-	75 (2)	100 (0)	89 (1)	100 (0)	80 (3)	-
Pyrazo fb ortho fb 2,4-D amine	65 (14)	82 (2)	-	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	-
Buta fb ortho fb 2,4-D amine	50 (20)	73 (3)	-	75 (2)	100 (0)	44 (5)	100 (0)	100 (0)	-

* Absolute densities (plants m^{-2}) of all species are in the parenthesis

Pyrazo = Pyrazosulfuron-ethyl; Buta = Butachlor; HW = hand weeding at 25DAT; aceto+bensul = acetochlor + bensulfuron methyl; ortho = orthosulfamuron; buta+ prop = butachlor + propanil

Table 4: Effect of herbicide treatments on weed density (plants m^{-2}) and biomass (g m^{-2}) along with their percentage of weed control (in the parenthesis) at 35 days after rice transplanting in strip-tilled non-puddled field during 2013 and 2014

Treatments	Weed density	Weed biomass
	2013	
Weedy check	222 (0)	37.4 (0)
Pyrazosulfuron-ethyl fb HW	36 (84)	4.6 (88)
Pyrazosulfuron-ethyl fb acetochlor+bensulfuron methyl	32 (85)	10.5 (72)
Pyrazosulfuron-ethyl fb orthosulfamuron fb butachlor+propanil	13 (94)	2.2 (94)
Pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine	14 (94)	2.5 (93)
Butachlor fb HW	56 (75)	5.2 (86)
Butachlor fb acetochlor+bensulfuron methyl	66 (70)	16.6 (56)
Butachlor fb orthosulfamuron fb butachlor+propanil	56 (75)	6.3 (83)
Butachlor fb orthosulfamuron fb 2,4-D amine	40 (82)	6.6 (82)
$LSD_{0.05}$	8.08	1.41
Level of significance	***	***
	2014	
Weedy check	105 (0)	23.8 (0)
Pyrazosulfuron-ethyl	37 (65)	10.1 (58)
Pyrazosulfuron-ethyl fb butachlor+propanil	11 (90)	4.2 (82)
Pyrazosulfuron-ethyl fb 2,4-D amine	33 (69)	6.4 (73)
Pyrazosulfuron-ethyl fb orthosulfamuron fb butachlor+propanil	2 (98)	1.2 (95)
Pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine	16 (85)	3.3 (86)
Butachlor	57 (46)	13.6 (43)
Butachlor fb butachlor+propanil	25 (76)	6.1 (74)
Butachlor fb 2,4-D amine	54 (49)	8.1 (66)
Butachlor fb orthosulfamuron fb butachlor+propanil	11 (90)	3.6 (85)
Butachlor fb orthosulfamuron fb 2,4-D amine	31 (71)	4.9 (79)
$LSD_{0.05}$	3.72	1.38
Level of significance	***	***

'HW' denotes 'one hand weeding at 25 days after transplanting', 'fb' denotes 'followed by', *** denotes p<0.001

Relative to the high density and biomass of weedy plots at 35 DAT, herbicide treated plots had 70-94% and 56-94% reduction in 2013 and 46-89% and 43-95% reduction in 2014, respectively.

In 2013, treatments having pre-emergence spray of pyrazosulfuron-ethyl with the post-emergence spray of orthosulfamuron fb 2,4-D amine or orthosulfamuron fb butachlor + propanil had lower weed density and biomass than other herbicide treatments. On the contrary, treatment having butachlor with acetochlor + bensulfuron methyl as post-emergence herbicide had higher weed density and biomass than the other herbicide treatments.

In 2014, butachlor treatments also had significantly higher weed density and biomass than pyrazosulfuron-ethyl treatments. This lower weed control efficiency of butachlor might be related to the less control of *Echinochloa colona* and *Cyperus rotundus* (Table 4). Another study, accounted that pyrazosulfuron-ethyl @ 15g a.i ha^{-1} reduced weed density and biomass more than butachlor @ 750g a.i ha^{-1} when both herbicides were applied at 4 days after transplanting of rice; however, the study was in puddled field condition [51]. Moreover, all treatments having pre-emergence followed by post-emergent (early post- with late post- or only late post) spray had lower weed density and biomass than the treatments with pre-emergent having no post-emergent spray or followed by one hand weeding at 25 DAT. Generally, weeds emerge in several flushes that could not be properly managed by one hand weeding. Additionally, removal of weeds by the traditional hand weeding method may not be feasible due to lack of labour availability at the critical period [52, 53]. Mishra and Singh stated that integration of one hand weeding with recommended herbicide did not cause significant reduction in weed population over sequential application of herbicide [33]. Similar finding was also observed in the present study that pyrazosulfuron-ethyl fb orthosulfamuron fb butachlor + propanil, butachlor fb orthosulfamuron fb butachlor + propanil, pyrazosulfuron-ethyl fb butachlor + propanil and pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine treatments provided higher control on weed density and biomass while the worst herbicide treatments were butachlor, butachlor fb 2,4-D amine and pyrazosulfuron-ethyl. There some researcher also agreed the present finding that sequential application of herbicides is more effective than sole pre-emergent spray to get season-long weed control [54,55]. But, in sequential application of herbicides, rotational choice of herbicides with different modes of action is advisable to avoid herbicide resistance development in weeds [29, 30].

3.3 Plant height of rice

In 2013, plant heights of strip-tilled non-puddled transplanted rice were significantly differed with herbicide treatments. The highest plant height was recorded from butachlor followed by one hand weeding treatment whereas the lowest plant height was in butachlor followed by acetochlor + bensulfuron methyl treatment and similar result was also found in pyrazosulfuron-ethyl followed by acetochlor + bensulfuron methyl treatment. Usually acetochlor + bensulfuron methyl is recommended for puddled transplanted rice and in our study this chemical was applied as per the recommendation rate. But it was observed that this post-emergence herbicide stunted the height of transplanted rice remarkably. Therefore, present study agrees with the finding of the earlier studies that selection of post-emergence herbicide is one of the most critical factors to reduce crop plant injury [56]. The present study also demonstrated that rice plant heights varied non-significantly with herbicide treatments during 2014. This might be related to the discarding of acetochlor + bensulfuron methyl from the herbicide treatments of 2014 as this late post-emergence herbicide had phytotoxic effect on rice plant height during the first year.

3.4 Rice grain yield

In 2013, the highest grain yield was obtained from weed-free check and similar yield was also recorded from the treatments having pyrazosulfuron-ethyl/ butachlor followed by (fb) orthosulfamuron fb butachlor + propanil (Table 5). Moreover, pyrazosulfuron-ethyl fb orthosulfamuron fb 2,4-D amine and butachlor fb orthosulfamuron fb butachlor + propanil treatments also gave higher yield than other treatments. Results also showed that treatments having pyrazosulfuron-ethyl had higher grain yield than butachlor treatments. Additionally, all herbicide treatments had higher grain yield by 11-75% over weedy control during 2013. In 2014, treatments with pyrazosulfuron-ethyl also had higher grain yield than butachlor treatments and pyrazosulfuron-ethyl with orthosulfamuron fb butachlor + propanil treatment gave the highest grain yield which was even 0.83% higher than the yield of weed-free control. All herbicide treatments provided 20-119% higher grain yield than weedy treatment (Table 6). This happened because better weed control leads to reduced crop-weed competition and facilitates the uptake of more nutrients that results in healthier rice plants with more tillers, panicles and biomass production [54,55].

3.5 Economic analysis

Partial economic analysis of herbicide treatments resulted in a wide variation in economic return from strip-tilled non-puddled transplanting rice production (Table 8). In both years, the lowest gross income and net benefit were calculated from the weedy check. In 2013, the weed-free treatment had gross income of 1327 US$ and net benefit of 485 US$ whereas all herbicide treatments gave 5-51% higher net benefit over weed-free treatment except pyrazosulfuron-ethyl followed by acetochlor + bensulfuron methyl and butachlor followed by acetochlor + bensulfuron methyl that had lower net benefit than weed-free control but still had higher net benefit than weedy check.

In 2014, the weed-free treatment had gross income of 1427 US$ with net benefit of 585 US$ whereas all pyrazosulfuron-ethyl treatments gave 11-49 % higher net benefit over weed-free treatment except pyrazosulfuron-ethyl and pyrazosulfuron-ethyl followed by 2,4-D amine that offered lower economic return than weed-free treatment but much higher return than the weedy check. In case of butachlor treatments, higher net benefit over weed-free treatment was calculated from those treatments where early post- and late post-emergence herbicides were in the sequence. Several previous researches also mentioned weed-free control as economically non-profitable treatment due to high weeding cost involvement [36, 57].

Table 5: Plant height and grain yield of non-puddled transplanted rice along with the cost effectiveness of herbicide treatments under strip tillage system during 2013 and 2014

Treatments	Plant height (cm)	Grain yield (t ha^{-1})	US Dollar (US$) ha^{-1}			
			Weed management cost	Total cost	Gross income	Net benefit
			2013			
Weedy check	103.8	3.10	0	521	769	248
Weed-free check	104.5	5.51	321	842	1327	485
Pyrazo fb HW	105.7	4.76	92	613	1153	540
Pyrazo fb aceto+ bensul	95.9	3.83	49	570	1300	730
Pyrazo fb ortho fb buta+prop	104.5	5.42	107	628	1135	507
Pyrazo fb ortho fb 2,4-D amine	103.1	5.25	64	585	1205	620
Buta fb HW	109.5	4.68	28	549	937	388
Buta fb aceto+bensul	95.3	3.44	58	579	1260	681
Buta fb ortho fb buta+prop	103.8	5.02	43	564	850	286
Buta fb ortho fb 2,4-D amine	102.0	4.98	73	594	1197	603
$LSD_{0.05}$	1.76	0.31				
Level of significance	***	***				
			2014			
Weedy check	107.0	2.76	0	521	683	162
Weed-free check	107.7	5.99	321	842	1427	585
Pyrazo	110.3	3.97	11	532	971	439
Pyrazo fb buta+prop	108.9	5.02	38	559	1136	577
Pyrazo fb 2,4-D amine	108.7	4.75	58	579	1322	743
Pyrazo fb ortho fb buta+prop	107.5	6.04	45	566	1062	496
Pyrazo fb ortho fb 2,4-D amine	106.1	5.68	64	585	1277	692
Buta	110.6	3.30	30	551	1203	652
Buta fb buta+prop	107.4	4.42	49	570	1441	871
Buta fb 2,4-D amine	108.3	4.12	26	547	811	264
Buta fb ortho fb buta+prop	106.6	5.35	53	574	997	423
Buta fb ortho fb 2,4-D amine	108.1	4.95	73	594	1182	588
$LSD_{0.05}$	2.24	0.27				
Level of significance	ns	***				

‘ns’ denotes ‘non-significant’, *** denotes significant at 0.1% level of significance

- Details of the fixed cost calculation have not been shown and it was same for all treatment (521 US$).

[‘fb’ = followed by, ‘Pyrazo’ = pyrazosulfuron-ethyl, ‘Buta’ = butachlor, ‘ortho’ = orthosulfamuron, ‘aceto + bensul’ = acetochlor + bensulfuron methyl, ‘buta + prop’ = butachlor + propanil and ‘2,4-D’ = 2,4-D amine]
1 US$ = 78 Bangladeshi Taka (BDT) (approx.)

Market price of commercial herbicides: Pyrazosulfuron-ethyl = 5.0 US$ ha^{-1}, Butachlor = 19.87 US$ ha^{-1}, Orthosulfamuron = 13.46 US$ ha^{-1}, Acetochlor+ bensulfuron methyl = 9.69 US$ ha^{-1}, Butachlor+ propanil = 11.67 US$ ha^{-1} and 2,4-D amine = 20.19 US$ ha^{-1}.

Manual weeding cost: 100 labours ha^{-1} for 4 weeding (season-long weed free) @ 3.21 US$ labour^{-1} day^{-1}, Herbicide application cost: 2 labours ha^{-1} round^{-1} @ 3.21 US$ labour^{-1} day^{-1}, Market price of grain: 217.95 US$ ton^{-1}, Market price of straw: 19.23 US$ ton^{-1}, Gross income = {grain yield (t ha^{-1}) × market price (US$ t^{-1})} + {straw yield (t ha^{-1}) × market price (US$ t^{-1})}, Net benefit = Gross income – Total cost.

The two-year economic analysis clearly revealed that despite of having higher gross income, weed-free treatment had lower net benefit than the treatments with sequential pre-, early post- and late post-emergence herbicides or with pre- and late post-emergence herbicides

Table 6: Residual effect of rice herbicides on germination (%), shoot length (cm) and percentage of growth inhibition compared to weed-free control (GI_{wf}) within the parenthesis, and dry matter (g m^{-2}) of wheat and lentil at 25 days after sowing during 2013 and 2014

Treatments	Wheat			Lentil		
	Germination	Shoot length	Seedling dry matter	Germination	Shoot length	Seedling dry matter
	2013					
Weedy check	87.0	28.1	10.40	71.3	6.4	2.76
Weed-free check	90.3	24.4 (0)	11.47	72.7	5.5 (0)	2.78
Pyrazo fb HW	89.7	29.7 (-6.3)	12.15	76.0	6.4 (-15.7)	3.28
Buta fb HW	93.0	25.9 (-1.8)	11.33	70.0	6.3 (-13.7)	2.78
Pyrazo fb aceto+bensul	89.0	25.5 (-1.3)	11.36	76.7	6.0 (-8.5)	2.77
Buta fb aceto+bensul	91.7	27.9 (-4.2)	10.67	74.3	6.3 (-14.4)	3.19
Pyrazo fb ortho fb buta+prop	90.7	30.5 (-7.2)	11.12	75.3	6.3 (-13.7)	3.32
Buta fb ortho fb buta+prop	88.7	31.0 (-7.8)	11.00	71.7	6.2 (-12.3)	2.94
Pyrazo fb ortho fb 2,4-D	91.0	31.4 (-8.3)	11.93	74.0	6.0 (-7.4)	2.65
Buta fb ortho fb 2,4-D	92.7	28.9 (-5.3)	11.75	71.0	5.2 (+5.6)	2.77
Level of significance	NS	NS	NS	NS	NS	NS
S.E.D.	2.78	1.78	0.99	4.03	0.57	0.34
	2014					
Weedy check	86.0	26.6	8.84	86.0	7.6	4.13
Weed-free check	87.7	24.8 (0)	10.80	82.7	8.3 (0)	4.03
Pyrazo	87.7	26.0 (-4.8)	12.20	82.0	8.8 (-5.4)	5.10
Buta	88.3	26.4 (-6.5)	9.34	89.0	9.3 (-11.9)	4.80
Pyrazo fb buta+prop	89.0	28.7 (-15.7)	10.97	87.7	8.5 (-2.0)	5.07
Buta fb buta+prop	87.7	25.8 (-4.0)	9.73	84.3	8.5 (-2.0)	5.10
Pyrazo fb 2,4-D	84.0	24.3 (+2.0)	9.33	84.0	7.7 (+7.3)	4.67
Buta fb 2,4-D	84.0	27.6 (-11.3)	11.77	88.3	8.3 (+0.5)	5.07
Pyrazo fb ortho fb buta+prop	89.7	27.4 (-10.5)	10.33	81.0	8.0 (+3.9)	4.77
Buta fb ortho fb buta+prop	84.0	23.1 (+6.9)	10.63	83.3	9.57 (-15.0)	4.27
Pyrazo fb ortho fb 2,4-D	84.3	25.4 (-2.4)	11.83	88.0	8.24 (+1.0)	4.13
Buta fb ortho fb 2,4-D	87.3	25.9 (-4.4)	10.77	85.7	7.83 (+5.9)	4.67
Level of significance	NS	NS	NS	NS	NS	NS
S.E.D.	2.67	1.85	1.45	3.43	0.65	0.46

S.E.D. = standard error of mean difference, NS = non-significant
Pyrazo = pyrazosulfuron-ethyl, buta = butachlor, aceto+bensul = acetochlor + bensulfuron methyl, ortho = orthosulfamuron, buta + prop = butachlor + propanil and 2,4-D = 2,4-D amine

3.6 Residual effect of herbicides on the succeeding crops

Residue of herbicides applied in strip-tilled non-puddled rice did not show any adverse effect on germination, shoot length and seedling dry matter of wheat and lentil in 2013 and 2014 (Table 6) and even shoot growth of wheat and lentil was not inhibited by the residue of those herbicides. The reason might be related to the half-life and rate of degradation of herbicides in soil. Several studies are in agreement with the present study that herbicides like pyrazosulfuron-ethyl, butachlor, etc. had no residual phytotoxic effect on the succeeding crops like cucumber, groundnut, green gram, maize and ladies finger [58,59]. However, some earlier studies reported that herbicides had residual effect on biomass and yield of the succeeding crop like wheat after lentil while some other studies found less sensitivity of herbicide residue on the succeeding crops like wheat, sunflower, grain sorghum and maize [60,61].

4. CONCLUSION

Sole application of pre-emergence herbicide was not effective for controlling weeds in non-puddled transplanted (NPT) wet season rice. Sequential application of pyrazosulfuron-ethyl with orthosulfamuron followed by butachlor + propanil or 2,4-D amine was the most effective for this new rice establishment technique that offered optimum grain yield with higher economic return over weed-free check. The performance of pyrazosulfuron-ethyl as pre-emergence herbicide was superior to butachlor in all sequential treatment combinations. Nevertheless, butachlor with orthosulfamuron followed by butachlor + propanil or 2,4-D amine were also found effective and economic to control weeds under this NPT practice. Moreover, considering the environmental fact, use of pyrazosulfuron-ethyl followed by butachlor + propanil/2,4-D amine or orthosulfamuron fb butachlor + propanil were suggested for effectual and economic weed control of strip-till non-puddled transplanted wet season rice.

In addition, farmers can easily grow wheat or lentil in a cropping pattern as a subsequent crop of rice because the study ensure that tested herbicides did not show any adverse residual effect on the establishment of these succeeding crops. However, continuous use of same herbicide or different herbicides with same mode of action in the same land year after year is strictly prohibited. This study necessitates to conducted long term study on effectiveness of new rice herbicide molecules under conservation agriculture systems and to examine the residual effect of herbicides on soil microbs and other soil elements that may help to develop a strong and sustainable weed management strategy for this novel system.

ACKNOWLEDGEMENTS
This study was the part of the PhD research of the principal author who acknowledges ACIAR (Project LWR/2010/080 for funding the research project and providing a scholarship).

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