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ORIGINAL ARTICLE / ORIGINALBEITRAG

Evaluation of Economically Viable and Environmental Friendly Weed Control Methods for Wheat (*Triticum aestivum* L.)

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Abstract

During the past few decades, extensive use of herbicides has created ecological and environmental problems such as dominance of minor weeds due to their resistance to herbicides, and human health hazards. Recognising these problems, an experiment was conducted in two consecutive wheat seasons during 2012–2014 in Central Bangladesh to evaluate five weed control methods: (i) control (weedy check), (ii) one hand weeding (one HW) at 25 days after sowing (DAS), (iii) one mechanical weeding by using a BARI dry land weeder (BARI weeder) at 25 DAS, (iv) Mechanical weeding by using a power tiller operated weeder (PTOW) at 25 DAS, and (v) chemical weed control (herbicide) by using carfentrazone + isoproturon (affinity at the rate of 5.75 g a.i. ha^{-1}). Results revealed that one HW at 25 DAS resulted in lowest weed density (numbers m^{-2}) and weed dry biomass (g m^{-2}), but highest weed control efficiency (WCE %), followed by the application of herbicide, using either PTOW or BARI weeder at 25 DAS. Consequently, one HW at 25 DAS produced the highest grain yield of wheat followed by PTOW, herbicide, and BARI weeder, while the weedy check treatment produced the lowest yield. Grain yield increased over weedy check by 28, 24, 18, and 15% in one HW, PTOW, herbicide and BARI weeder, respectively. The weed control treatment PTOW also resulted in the highest benefit-cost ratio (BCR) and marginal benefit-cost ratio (MBCR) (1.5 and 10.4, respectively) followed by the herbicide, hand weeding, and BARI weeder treatments. Considering the negative effect of herbicides on the environment and the labour crisis during the peak period of weed control for manual weeding wheat farmers can use PTOW which would also reduce the weeding costs as well as increase yield and net return. However, manual weeding would still remain an option for the resource-poor farmers with abundant family labour.

Keywords Wheat · Weeds · Power tiller operated weeder · BARI dry land weeder · Herbicide

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Evaluierung von wirtschaftlich tragfähigen und umweltfreundlichen Unkrautbekämpfungsmethoden für Weizen (*Triticum aestivum* L.)

Zusammenfassung

Während der letzten Jahrzehnte hat der extensive Einsatz von Herbiziden zu ökologischen und Umweltproblemen geführt, z. B. zur Dominanz kleinerer Unkräuter aufgrund ihrer Resistenz gegen Herbizide, sowie zur Gefährdung der menschlichen Gesundheit. Um diese Probleme anzugehen, wurde in Zentral-Bangladesch in zwei aufeinanderfolgenden Weizensaisons im Zeitraum 2012–2014 ein Experiment zur Beurteilung von fünf Methoden zur Unkrautbekämpfung durchgeführt: (i) Kontrolle (keine Behandlung), (ii) manuelles Unkrautjäten (*hand weeding*, HW) 25 Tage nach der Aussaat (*days after sowing*, DAS), (iii) mechanische Unkrautbekämpfung (BARI-Unkrautvernichter) 25 DAS, (iv) mechanische Unkrautbekämpfung mit einem mit einer Motorhacke betriebenen Unkrautvernichter (*power tiller operated weeder*, PTOW) 25 DAS und (v) chemische Unkrautbekämpfung (Herbizid) mit Carfentrazon + Isoproturon (Affinität mit einer Rate von 5.75 g a.i. ha^{-1}). Die Ergebnisse zeigten, dass HW zur geringsten Unkrautdichte und Unkrauttrockenmasse führte, und die höchste Unkrautbekämpfungseffizienz (WCE %) zur Folge hatte; gefolgt von der Anwendung des Herbizids, PTOW- und BARI-Unkrautvernichtung. Folglich ergab HW den höchsten Kornertrag, gefolgt von PTOW, Herbizid und BARI, während die Kontrolle den niedrigsten Ertrag erbrachte. Der Kornertrag stieg gegenüber der Kontrolle bei HW, PTOW, Herbizid und BARI um 28, 24, 18 bzw. 15 %. Die PTOW-Methode führte ebenfalls zu dem höchsten Nutzen-Kosten-Verhältnis (BCR) und Grenznutzen-Kosten-Verhältnis (MBCR) (1,5 bzw. 10,4), gefolgt von der Herbizid-, HW- und BARI-Behandlung. In Anbetracht der negativen Auswirkungen der Herbizide auf die Umwelt und der Knappheit der Arbeitskräfte während der Hauptzeit der Unkrautbekämpfung können die Weizenbauern bei der manuellen Unkrautbekämpfung PTOW einsetzen, was ebenfalls die Unkrautbekämpfungskosten senken sowie den Ertrag und den Nettogewinn erhöhen würde. Die manuelle Unkrautbekämpfung bleibt jedoch weiterhin eine Option für ressourcenarme Landwirte mit ausreichend familiären Arbeitskräften.

Schlüsselwörter Weizen · Unkraut · Manuelles Unkrautjäten · Mechanische Unkrautbekämpfung · Herbizid

Introduction

Wheat is an important cereal crop besides rice in Bangladesh and plays an important role in attaining food and nutritional security (Hossain et al. 2019). During 2018–19, 1.15 million tons of wheat were produced from 0.33 million ha that could meet only 20% of the national requirement (Barma et al. 2019). On the other hand, the demand for wheat has been increasing at the rate of 13% per annum due to rapid changes in dietary habit, increase in socio-economic status and per capita income, rapid growth of fast food restaurant, and the growth of branded bakery and biscuit industries, etc. (Barma et al. 2019). Due to the decrease in wheat area by 15% in 2018–19 compared to the previous year, wheat production in Bangladesh also reduced by about 12%. Though there is decrease in wheat area, there has been a significant increase in its average yield per ha (national average: 3.49 t/ha) in Bangladesh due to the use of high yielding, disease-resistant and stress-tolerant varieties (Barma et al. 2019). Wheat production however is also constrained by several management factors of which severe weed infestation and lack of appropriate weed control measures is considered to be the most important one limiting wheat yield (Khaliq et al. 2013b). Fahad et al. (2015) and Jabran et al. (2017) reported that more than 20% yield loss in wheat in Bangladesh is occurred due to weed infestation. The degree of wheat yield losses due to weeds depends on many factors such as the availability of farmers' resources, weed species and density, time of emergence of crop and weeds, crop growth stage, and the duration of weed interference to wheat crop (Estorninos et al. 2005; Hussain et al. 2015).

Farmers in Bangladesh are usually reluctant to control weeds in their wheat field and those who control mostly weed manually. However, manual weeding these day has been impractical due to increasing labour shortage as well as labour wages. The chemical weed control using herbicide is the easiest, cheapest, reliable and a timely measure. However, lack of knowledge in selection of appropriate herbicide, farmers' inadequate skill in its use, and its excessive use have adverse effects on anaimal and human health; such inappropriate practices can harm the environment and develop resistance biotypes supremacy of minor weeds due to their resistance against herbicide (Baghestani et al. 2007; Khaliq *et al.* 2013a; Chauhan et al. 2015; Ahmed et al. 2019). Therefore, to reduce the dependency on herbicides, alternative, low costing and environmentally friendly weed control options need to be explored as the sustainable weed management approach (Khaliq et al. 2013c; Ahmed et al. 2020).

Mechanical weed management options are found to be more economical than manual weeding and more sustainable than chemical methods with herbicides (Subudhi 2004; Cloutier et al. 2007; Jabran et al. 2012; Gongotchame et al. 2014; Narwariya et al. 2016). The tractor/power tiller driven rotary type power weeder (power weeding) are used to control weeds for low-land and upland row crops (other than wheat) in developed countries (Olaoye and Adekanye 2011; Hossain et al. 2011) while power tiller driven shovel type power weeder are used for upland row crops (rice, wheat, maize, etc.) in many developing countries including Bangladesh (Matin et al. 2010; Hoque et al. 2010). Considering the pertinent issues of labor shortage and labour wages for manual weeding and development of herbicide resistance and environmental hazards associated with chemical weeding, Bangladesh Agricultural Research Institute (BARI) developed a two-wheeled power-tiller multi-row weeder which can weed 6 rows at a time in wheat and upland row crops and reduce the weeding cost by reducing the labor requirement (Hossen et al. 2019). However, the performance of multi-row weeder needs to be evaluated for its recommendation for the farmers' fields. In this context, an experiment was undertaken to investigate the effect of different weed control methods in wheat production and find out the most economically viable and environmentally friendly weed control method for sustainable wheat production in Bangladesh. We hypothesized that the multi-row power weeder would be more economically viable and more sustainable than other weed control methods in terms of reducing weeding cost and increasing wheat yield.

Material and Methods

Experimental Duration and Location

The experiment was conducted at the Regional Wheat Research Centre (RWRC; 23° 59′ N, 90° 24′ E; 13.1 m MSL), Bangladesh Agricultural Research Institute, Gazipur-Joydebpur in agro-ecological zone 28 (AEZ–28) (Modhupur Tract) during November to March in consecutive two years (2012–13 and 2013–14).

Soil Characteristics

Soil in the AEZ-28 is weakly acidic, organic matter content is low like others AEZs while total nitrogen (N) and phosphorus (P) are very low. Potassium (K), sulfur (S), boron (B) and zinc (Zn) contents are below critical levels. Overall, with the exception of P, all nutrients were deficient (Jahan et al. 2018; Hossain et al. 2018).

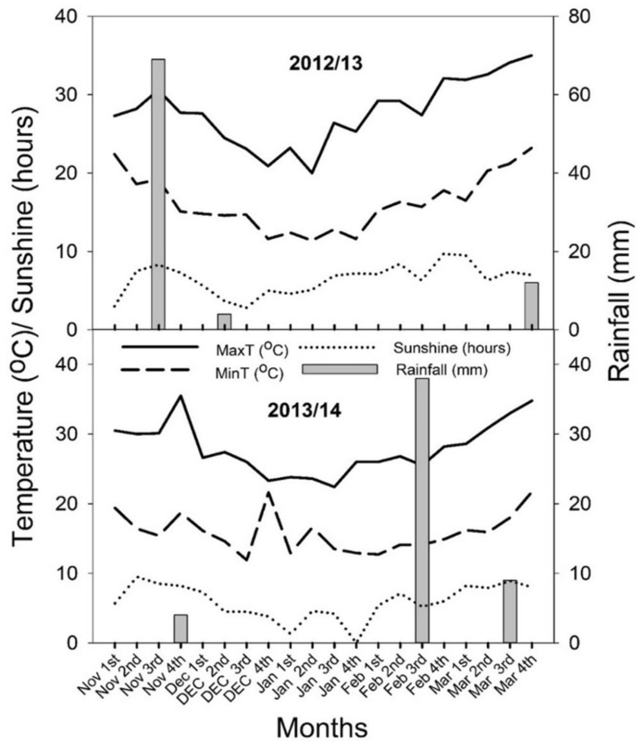

Fig. 1 Meteorological information, particularly maximum (MaxT) and minimum temperature (MinT), sunshine (hours) and total rainfall (mm) during both the growing seasons in the experimental location

Meteorological Information

The climate of the area is subtropical with highly variable rainfall, which during the months of November to May ranges from 4050 mm. The temperature during this period also varies greatly, with maximum daily temperature ranging from 20–35ºC and minimum temperature from 10–15ºC. Weekly maximum (MaxT) and minimum temperature (MinT), sunshine (hours) and total rainfall (mm) during the growing seasons in two years for the experimental location is presented in Fig. 1.

Treatments and Design

The trial considered five weed control methods such as i) control plot (weedy check), ii) one hand weeding (1 HW) at 25 days after sowing (DAS), iii) mechanical weeding by using a BARI dry-land weeder (BARI weeder) at 25 DAS, iv) mechanical weeding by using power tiller operated weeder (PTOW) at 25 DAS, and v) chemical weed control. Treatment details are presented in Table 1. All treatments were arranged in a randomized block design and repeated three times. Each treatment plot size was 5 m × 2.4 m (12 m²).

Table 1 Treatment details of the trial

Treatment no	Weed control methods	Treatment short form
1	Weeds were allowed to grow during the entire period of the crop life cycle	Weedy check
2	One manual hand weeding was done at 25 days after sowing (DAS)	One HW
3	One mechanical weeding was done by using a BARI dry-land weeder at 25 DAS	BARI weeder
4	One mechanical weeding was done by using a power tiller operated weeder at 25 DAS	PTOW
5	Chemical weed control using a ready-mix formulation of Carfentrazone + Isoproturon, at the rate of 5.75 g ai. ha^{-1}, (trade name Affinity). Affinity (1.5 kg ha^{-1} marketing product) was applied dilution with 350 liter water at 25 DAS using a multi-nozzle booms sprayer	Herbicide

Wheat Variety and Characteristics

The seeds of wheat variety 'BARI Gom 26' were collected from Bangladesh Wheat and Maize Research Institute (BWMRI), Dinajpur, Bangladesh. It is a high-yielding popular variety released in 2010. The yield potential of the variety ranges from 3.5 to 5 t ha^{-1} (Barma et al. 2019). It can tolerate terminal heat stress caused by late sowing andis resistant to *Bipolaris* leaf blight, leaf rust and stem rust race (Ug 99).

Land Preparation and Application of Fertilizers

The experimental field was deep ploughed and cross-ploughed with a two-wheel power tiller to obtain good tilth required for higher crop yield. All weeds and stubble were removed from the experimental field before the seed sowing. The soil was treated with Furadan (Carbofuran) 5G at the rate of 8 kg ha^{-1} (marketed by FMC International S.A. Bangladesh Ltd.) to protect the young plants against insect attack. Fertilizer was applied as recommended by BWMRI: 110-27-40-20–1 kg ha^{-1} of N, P, K, S, and B, respectively, through urea, triple superphosphate, muriate of potash, gypsum and boric acid respectively. Two-thirds of N and full amounts of other fertilizers were applied as basal doses during final land preparation. The remaining (1/3) N was applied immediately after the first irrigation during the crown root initiation stage (17–21 DAS).

Seed Treatment and Seed Sowing

Before sowing, seeds were treated with Provax-200 WP (marketed by Hossain Enterprise CC Bangladesh Ltd., an agrochemical company, in association with Chemtura Corp., USA), which is a carboxin and thiram containing fungicide to control fungi in the soil at the seedling stage (Hossain et al. 2013). In 2012, seeds were sown on 26 November and in 2013 on 28 November. Seeds were sown manually at the rate of 120 kg seeds ha^{-1} with a spacing of 20 cm and depth of 4–5 cm by making specific narrow furrows with an iron rod. After sowing, seeds were covered with soil and slightly pressed by hand. Special care was taken to protect seeds from birds.

Irrigation and Weed Management

The first irrigation was performed at 17–21 DAS, the second at 53–56 DAS during the panicle initiation stage, and the last one at 78–81 DAS at the grain-filling stage. A proper drainage system was developed to drain off excess water. A total of 0.0251 m or 2.51 cm of irrigation water was applied in each season. Weeding was performed as per treatments.

Harvesting and Post-harvest Operation

In both years, crop was harvested at full maturity in the last week of March, when leaves and stems became yellowish in color. The central position of each plot area was harvested for grain and biomass yield and data were converted to t ha^{-1}. The harvested plants were tied into bundles, transferred to a threshing floor, and sun-dried by spreading out evenly on the threshing floor. Seeds were separated from the chaff by a mechanical thresher and then cleaned, dried and weighed.

Data Collection and Their Procedure

Weed Data

Weed density and biomass were recorded at 20 days after the imposition of treatments. Weed samples were collected from the randomly placed 0.5 m × 0.5 m quadrate from three spots of each plot. After collection, the total weed number was counted, oven-dried at 70 °C for 72 h, and dry weight recorded. Weed control efficiency (WCE %) and weed control index (WCI %) were estimated (Kumar et al. 2015) from total number of weeds and dry weed biomass as per the following equation:

$$\mathrm{WCE}(\%) = \frac{\left(\begin{array}{l}\text{Weed drymatter in weedy plot}-\\ \text{Weed drymatter in treated plot}\end{array}\right)}{\text{Weed drymatter in weedy plot}} \times 100 \qquad (1)$$

Crop Data

For recording yield contributing characters of wheat, plant height (cm), spike length (cm), spikes m^{-2} (no.), grains $spike^{-1}$, and 1000-grain weight (TGW, g) data were collected from the ten randomly selected plants from each plot. Grain and biomass yield were recorded from an area of 8 m^2 (4 m × 2 m) from each plot and grains oven dried. One thousand grains were counted from the yield area of each plot and the grain weight (g) recorded with an electrical balance. Grain yield were converted to 12% moisture content (Hellevang 1995):

$$Y(M_2) = \frac{100 - M_1}{100 - M_2} \times 10^{-6} \times Y(M_1) \quad (2)$$

where, Y (M_2) = grain weight with 12% moisture, Y (M_1) = grain weight with actual moisture %, M_1 = actual moisture %, and M_2 = expected moisture %.

Grain yield (GY) and straw yield (SY) together were regarded as the biological yield of wheat. The biological yield was calculated with the following formula:

$$\text{Biological yield} = GY + SY \quad (3)$$

Harvest index (HI) denotes the ratio of GY to biological yield and was calculated with the following formula (Gardner et al. 1985):

$$HI(\%) = \frac{GY}{\text{Biological yield}} \times 100 \quad (4)$$

Economic Analysis

Economic analysis was performed to determine the efficiency of different weed control methods. For this, only the variable weeding cost was was considered. Other management costs remained same for all treatments and hence were not included in the analysis. The amount of commercial products of herbicides required for one hectare was calculated and the cost was estimated based on their market price. The number of labours for herbicide spraying and mechanical weeding were counted and labor wage was based on an 8-hour work a day. The market price of wheat was determined during the years of the experiment and used for calculating the gross return. Benefit-cost ratio (BCR) and marginal benefit-cost ratio (MBCR) were calculated with the following formula:

$$BCR = \frac{\text{Gross return}}{\text{Total cost}} \quad (5)$$

$$MBCR = \frac{\text{Gross Return}_{(\text{Specific Management})} - \text{Gross Return}_{(\text{Control})}}{\text{Variable Cost}_{(\text{Specific Management})} - \text{Variable Cost}_{(\text{Control})}} \quad (6)$$

Statistical Analysis

Data for both years were analyzed separately using a R package (Core Team R 2013). Since there were significant differencse between years, data were presented year-wise separately. Treatment means were separated using the least significant difference (LSD) at the 5% level of significance. Weed density and biomass data were subjected to square root transformation ($\sqrt{(x}$ plus 0.5) before analyses); but since the relationships did not improve much original data were used for final analysis.

Results and Discussion

Effect of Weed Control Methods on Weed Incidence and Weed Control Efficiency

Major weed species found in the experimental plots were Chapra/Goosegrass (*Eleusine indica* Gaertn.), Shama/Barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), Subuj shiyal-leza/Green foxtail (*Setaria viridis* (L.) P. Beauv.), Mutha/Purple nutsedge (*Cyperus rotundus* L.), Bothua/Lambs quarter (*Chenopodium album* L.), Bon begun/Black night-shade (*Solanum nigrum* L.), Bishkatali/water pepper (*Polygonum hydropiper* L.), Bon mushur/Wild lentil (*Vicia sativa* L.), Shakenotae/Green amaranth (*Amaranthus viridis* L.), and Karpet agacha/Green carpetweed (*Mullugo verticillata* L.). There was higher weed infestation in 2012–13 (first year) than in 2013–14 (second year). Though the most dominant weed species in the second year was *Cyperus rotundus* it was comparatively less in the first year. Weed density (number m^{-2}) at 45 DAS (after 20 days of treatment imposition) was significantly influenced by the weed control method in the first year, but not in the second year (Table S1 and Figs. 2 and 3).

Cyperus rotundus is a persistent, prolific, and the worst weed species in the world. This weed is very difficult to

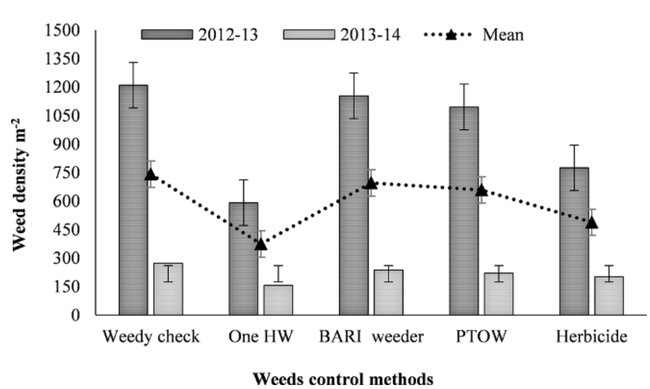

Fig. 2 Weeds m^{-2} of wheat as affected by weed control methods. SD ± in each treatment were calculated from three replications

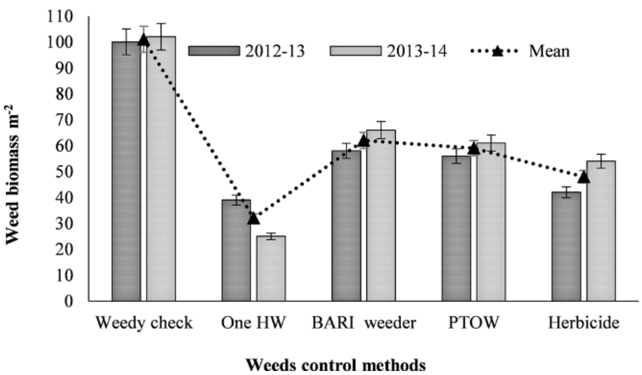

Fig. 3 Weed dry biomass m^{-2} of wheat as affected by weed control methods. SD ± in each treatment were calculated from three replications

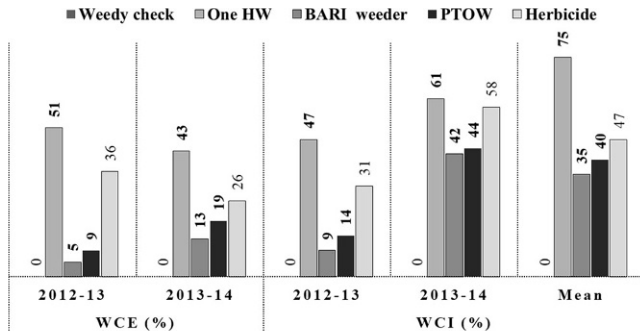

Fig. 4 WCE (%) and WCI (%) in different weed control methods of wheat

control by manual or mechanical weeding or even by application of a pre-emergence herbicide (Ahmed and Chauhan 2014) because it can spread and survive even following the destruction of its aerial parts (Horowitz 1972). This weed can propagate through both tubers and rhizomes. The rhizome and tuber function both as storage and reproductive organs. When rhizomes elongate, they form tubers and ensure the translocation of nutrients and assimilates between above ground and underground parts (Horowitz 1972). In 2012–13, the highest weed density was recorded in weedy check (1209 weeds m^{-2}); all weed control treatments had significantly lower weed density than the weedy check. Among the weed control methods, one hand weeding (HW) had the lowest weed density (51% less than the weedy check) followed by the herbicide treatment (31% less). Weed density may not be the right parameter to measure the weed control efficiency (WCE) because many times a weed control treatment helps retardation of the weed growth but weeds do not fully die or eradicate (Ahmed and Chauhan 2014; Chauhan et al. 2015). In crop-weed competition when weed growth is retarded due to the application of any control measure, the crop may get a growth advantage.

Weed biomass was significantly influenced by the weed control method in both years. In both years, compared to the weedy check treatment, different weed control methods reduced weed biomass by 35–75% (Table 1S and Fig. 3). In both years, the lowest weed biomass was found with one HW which was 61–75% lower than the weedy check. Among the weed control methods, both BARI weeder and PTOW plots had similar weed biomass and WCE (Fig. 4), but the latter was significantly lower than with one HW or with herbicide. In terms of WCE, manual weeding was the best option but currently it is not an economically viable option (Ahmed and Chauhan 2014, 2015). Manual weeding is the non-chemical and ecologically sound weed control method that provides the best clean and thorough weeding but is only good for resource-poor farmers where labour is available at low wages. In Bangladesh, a significant number of farmers still rely on manual weeding due to lack of farmer's knowledge and unavailability of herbicide information, lack of farmer's skill on herbicide application and lack of suitable mechanical weeders, and hence farmers spend a lot of money on manual weeding. In the current study, both types of mechanical weeders performed similarly in terms of WCE but compared with the weedy check they reduced weed biomass by only 35–44%, indicating that significant numbers of weeds were not controlled by the mechanical weeders. No doubt mechanical weeding needs less time and causes less drudgery than the manual weeding, it has some limitations also. To control weeds mechanically using a mechanical weeder, plants must be in straight rows and soil should be moist before weeding. Often, it becomes difficult to remove weeds within crop rows, the cut weeds above root system can re-establish, and the improper use of weeders can damage the crops.

Yield and Yield Contributing Characters of Wheat

Among the yield contributing characters, only the number of spikes m^{-2} in 2012–13 (first year) was significantly affected by the weed control method; other parameters were not influenced significantly in any year (Table S2 and Figs. 5, 6 and 7). The highest number of spikes m^{-2} was obtained from the one HW plot and was statistically different from all other treatments; it could be due to the effect of higher WCE. The lowest spikes m^{-2} was observed in the weedy check due to higher weed infestation and suppressing the growth and development of the growing plants.

Grain yield in both years was influenced significantly by the weed control method with almost similar yield trends (Table 2). The highest grain yield (4.07–4.35 t ha^{-1}) was recorded from one HW which was 25–35% higher than the weedy check and 23–25, 11–25, and 9–20%, higher respectively than the PTOW, herbicide, and BARI dry land weeder. The higher grain yield with one HW was due to sig-

Fig. 5 Plant height (cm) and spike length (cm) of wheat as influenced by different weed control methods

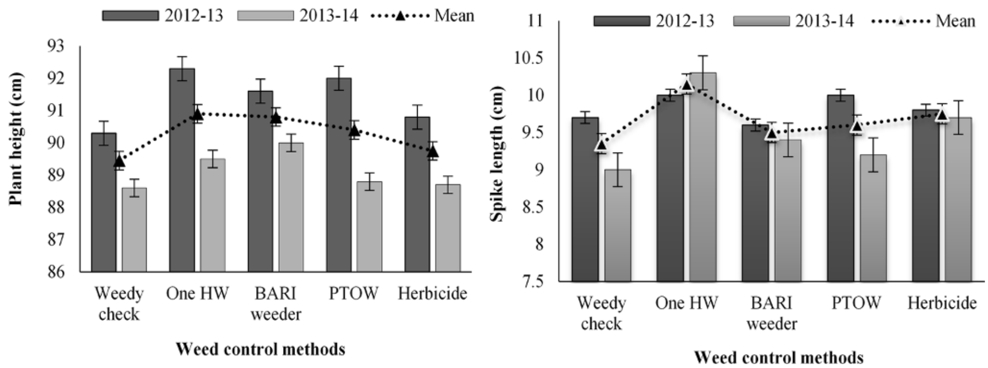

Fig. 6 Spikes m^{-2} and grains spike^{-1} of wheat as influenced by different weed control methods

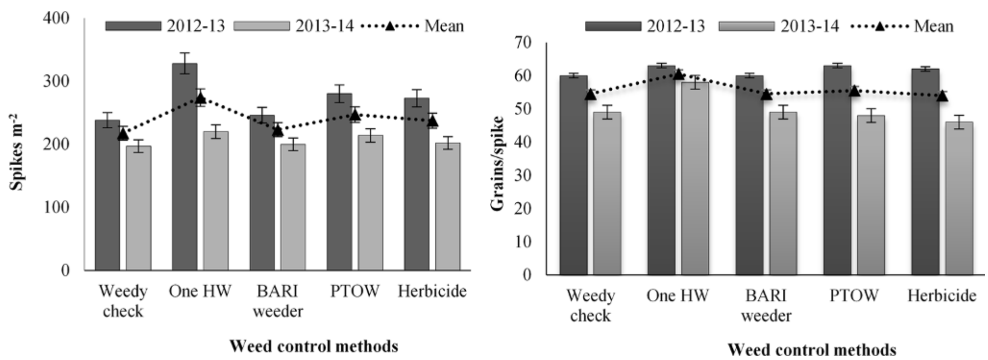

Fig. 7 1000-grain weight and harvest index of wheat as influenced by different weed control methods

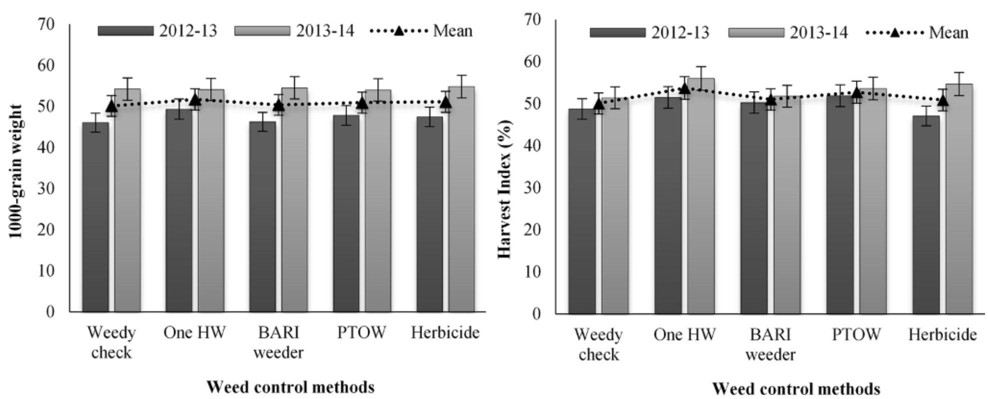

Table 2 Wheat straw biomass and grain yield as influenced by different weed control methods

Treatments	Straw biomass (t/ha)		Grain yield (t/ha)		Mean yield (t/ha)	Grain yield increased over control (%)		Mean
	12–13	13–14	12–13	13–14		12–13	13–14	
Weedy check	7.12	6.07	3.47	3.12	3.30	N/A	N/A	N/A
One HW	8.45	7.27	4.35	4.07	4.21	25	30	28
BARI weeder	7.50	7.20	3.77	3.73	3.75	9	20	15
PTOW	8.23	7.27	4.27	3.90	4.09	23	25	24
Herbicide	8.18	7.13	3.85	3.90	3.88	11	25	18
LSD (0.05)	1.11	0.97	0.39	0.60	N/A	N/A	N/A	N/A

HW hand weeding, *PTOW* power-tiller operated weeder nificantly higher number of spikes m^{-2} and slightly higher grains spike^{-1} (Fig. 6). Compared with weedy check, the BARI dry land weeder had only 15% higher yield indicating that in controlling weeds it did not perform well which was also evident from WCE. In the current study, there was no complete weed-free treatment; however, the highest yield obtaining HW treatment had similar grain yield to the weed-free yield of some previous studies using the same variety (Ahmed et al. 2019, 2020). Grain yield data indicate that one HW around 25 DAS in wheat is enough to obtain a similar yield to weed-free condition yield. In Bangladesh farmers mostly practice one HW and they usually perform that late (30–50 DAS). Grain yield with herbicide data in the current study indicate that if farmers apply only one post-emergence herbicide without any additional hand weeding, they will lose some yield. In situations where farmers would like to control weeds in wheat fields effectively by using only herbicide they will need to apply both pre-and post-emergence herbicides.

Economic Analysis

The highest weeding cost (107 US$ ha^{-1}) was required for the one HW treatment while lowest (23 US$ ha^{-1}) for the herbicide treatment (Table 3). The mechanical method, PTOW and BARI weeder had similar weeding cost and slightly higher than the herbicide treatment. The fixed cost was similar for all the weed control treatments, therefore, due to higher weeding cost (only variable cost) for the one HW treatment, the total production cost was also higher (Table 3). Although the highest gross return was recorded for one HW due to higher production cost, the highest BCR (1.51) and MBCR (10.44) were recorded for PTOW. The total production cost for the herbicide treatment was slightly lower than the PTOW treatment but due to lower grain yield in the herbicide treatment, the BCR and MBCR were also lower than for the PTOW treatment. One HW treatment had similar BCR to, but lower MBCR, than the herbicide treatment. Many previous studies have reported that the application of herbicide would be the best option to reduce weed control cost and increase farmers' net return in wheat production (Marwat et al. 2006; Safdar et al. 2011; Shehzad et al. 2012). However, the major concerns in using herbicides are environmental pollution and human and animal health hazards, which would discourage the widespread use of herbicides in wheat production in Bangladesh. Mechanical weeding would probably be the best option for farmers as it reduces farmers' weed management cost without environmental and human health hazards but it has limitations too. Integrated weed management approaches with use of mechanical weeder and optimum use of herbicides would be required for best would control, reduce weeding cost and increase farmer's yield and profit by resource-rich farmers with labor constraints but manual weeding would still remain an option for the resource-poor farmers with abundant family labour.

Conclusion

The results of the present study revealed that one hand weeding at 25 DAS was the best in terms of lower weed density (m^{-2}), lower weed biomass (m^{-2}), and higher weed control efficiency (WCE%). Consequently, one hand weeding at 25 DAS also resulted in highest grain yield (increased 28% as compared with control) of wheat followed by the PTOW, herbicide, and BARI weeder treatments, while the lowest grain yield was obtained from the weedy check treatment. The highest BCR and MBCR (1.51 and 10.44 respectively) were found with PTOW followed by herbicide, hand weeding, and BARI weeder. Considering the negative effect of herbicides on the environment and human and animal health hazards and also labour crisis at the peak period of weed control in wheat, farmers can use power tiller operated multi rows weeder to reduce the weeding cost as well as to increase yield with the higher net return. However, manual weeding would still remain an option for the resource-poor farmers with abundant family labour in Bangladesh.

Table 3 Economic analysis (hiring basis) as influenced by different weed control methods

Treatments	Gross return (US$ ha^{-1})	Fixed cost (US$ ha^{-1})	Variable cost (US$ ha^{-1})	Total cost (US$ ha^{-1})	BCR	MBCR (over control)
Weedy check	1179	940	N/A	940	1.25	N/A
One HW	1504	940	107	1047	1.44	3.04
BARI weeder	1339	940	31	971	1.38	5.16
PTOW	1461	940	27	967	1.51	10.44
Herbicide	1386	940	23	963	1.44	9.1

Wheat grain price Tk. 30/kg (0.36 USD/kg)
1 US$ = 84 BDT
HW hand weeding, *PTOW* power-tiller operated weeder, *BCR* benefit cost ratio, *MBCR* marginal benefit cost ratio

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Conflict of interest M.A.H.S. Jahan, A. Hossain, M.A. Hoque, K.K. Saha, K.K. Sarker, S. Ahmed and J. Timsina declare that they have no competing interests.

References

Ahmed S, Chauhan BS (2014) Performance of different herbicides in dry-seeded rice in Bangladesh. Sci World J. https://doi.org/10.1155/2014/729418
Ahmed S, Chauhan BS (2015) Efficacy and phytotoxicity of different rates of oxadiargyl and Pendimethalin in dry-seeded rice (Oryza sativa L.) in Bangladesh. Crop Prot 72:169–174
Ahmed S, Alam MJ, Awan TH, Islam AKMM (2019) Herbicidal weed control in drill sown spring wheat under Bangladesh condition. Fund App Agril 4(2):839–848
Ahmed S, Alam MJ, Awan TH, Chauhan BS (2020) Effect of application timings and tank mixture of herbicides on weed suppression, crop growth and yield of wheat. J Res Weed Sci 3(2):214–229
Baghestani MA, Zand E, Soufizadeh S, Mirvakili M, Jaafarzadeh N (2007) Response of winter wheat (Triticum aestivum L.) and weeds to tank mixtures of 2, 4-D plus MCPA with clodinafop propargyl. Weed Biol Manag 7(4):209–218. https://doi.org/10.1111/j.1445-6664.2007.00258.x
Barma NC, Hossain A, Hakim MA, Mottaleb KA, Alam MA, Reza MM, Rohman MM (2019) Progress and challenges of wheat production in the era of climate change: a Bangladesh perspective. In: Hasanuzzaman M, Nahar K, Hossain M (eds) Wheat production in changing environments. Springer, Singapore, pp 615–679 https://doi.org/10.1007/978-981-13-6883-7_24
Chauhan BS, Ahmed A, Awan TH, Jabran K, Manalil S (2015) Integrated weed management approach to improve weed control efficiencies for sustainable rice production in dry-seeded systems. Crop Prot 71:19–24
Cloutier DC, Van der Weide RY, Peruzzi A, Leblanc ML (2007) Mechanical weed management. Non-chemical weed management. CAB International, Oxfordshire, pp 111–134
Core Team R (2013) A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna (http://www.R-project.org/)
Estorninos JLE, Gealy DR, Gbur EE, Talbert RE, Mc-Clleland MR (2005) Rice and red rice interference. II. Rice response to population densities of three red rice (Oryza sativa) ecotypes. Weed Sci 53:683–689
Fahad S, Hussain S, Chauhan BS, Saud S, Wu C, Hassan S, Tanveer M, Jan A, Huang J (2015) Weed growth and crop yield loss in wheat as influenced by row spacing and weed emergence times. Crop Prot 71:101–108
Gardner FP, Pearce RB, Mitchell RL (1985) Physiology of Crop Plants. IowaState University Press, Ames, pp 98–131
Gongotchame S, Dieng I, Ahouanton K, Johnson JM, Alognon AD, Tanaka A, Atta S, Saito K (2014) Participatory evaluation of mechanical weeders in lowland rice production systems in Benin. Crop Prot 61:32–37
Hellevang KJ (1995) Grain moisture content effects and management. Department of Agricultural and Biosystems Engineering, North Dakota State University. http://www.ag.ndsu.edu/pubs/plantsci/crops/ae905w.htm. Accessed on 10 December 2020
Hoque MA, Matin MA, Wahab MA, Hossain MA, Ahmed S (2010) Design and development of a power weeder for row crop. J Agric Eng 38(2):93–101
Horowitz M (1972) Growth, tuber formation and spread of Cyperus rótundus L. from single tubers. Weed Res 12:348–363
Hossain A, Farhad M, Jahan MAHS, Mahboob MG, Timsina J, Teixeira da Silva JA (2018) Biplot yield analysis of heat-tolerant spring wheat genotypes (Triticum aestivum L.) in multiple growing environments. Open Agric 3(1):404–413
Hossain A, Mottaleb KA, Farhad M, Barma NCD (2019) Mitigating the twin problems of malnutrition and wheat blast by one wheat variety, 'BARI Gom 33', in Bangladesh. Acta Agrobot 72(2):1775. https://doi.org/10.5586/aa.1775
Hossain A, Sarker MAZ, Saifuzzaman M, Teixeira da Silva JA, Lozovskaya MV, Akhter MM (2013) Evaluation of growth, yield, relative performance and heat susceptibility of eight wheat (Triticum aestivum L.) genotypes grown under heat stress. Int J Plant Prod 7(3):615–636
Hossain MA, Islam MS, Huda MD, Zami MA, Bhuyan MGK, Nath BC (2011) Design and development of a weeder for both lowland and upland conditions. Agricultural mechanization in Asia, Arica and Latin America. Farm Mach Ind Res Corp 42(2):56–62
Hossen MA, Alam MA, Paul S, Hossain MA (2019) Modification and evaluation of a power weeder for Bangladesh condition. Eco-friendly Agric J 8(3):37–46
Hussain S, Khaliq A, Matloob A, Fahad S, Tanveer A (2015) Interference and economic threshold level of little seed canary grass in wheat under different sowing times. Environ Sci Poll Res 22:441–449. https://doi.org/10.1007/s11356-014-3304-y
Jabran K, Ali A, Sattar A, Ali Z, Yasin M, Hussain M (2012) Cultural, mechanical and chemical weed control in wheat. Crop Environ 3:50–53
Jabran K, Mahmood K, Melander B, Bajwa AA, Kudsk P (2017) Weed dynamics and management in wheat. Adv Agron 145:97–166
Jahan MAHS, Hossain A, Timsina J, da Silva JAT (2018) Evaluation of tolerance of six irrigated spring wheat (Triticum aestivum L.) genotypes to heat stress using stress tolerance indices and correlation analysis. Int J Agric Res 13:39–52. https://doi.org/10.3923/ijar.2018.39.52
Khaliq A, Gondal MR, Matloob A, Ullah E, Hussain S, Murtaza G (2013a) Chemical weed control in wheat under different rice residue management options. Pak J Weed Sci Res 19:1–14
Khaliq A, Hussain S, Matloob A, Wahid A, Aslam F (2013b) Aqeous swine cress (Coronopus didymus) extracts inhibit wheat germination and early seedling growth. Int J Agric Biol 15:743–748
Khaliq A, Shakeel M, Matloob A, Hussain S, Tanveer A, Murtaza G (2013c) Influence of tillage and weed control practices on growth and yield of wheat. Philip J Crop Sci 38:54–62
Kumar N, Hazra KK, Yadav SL, Singh SS (2015) Weed management using post-emergence herbicides in chickpea (Cicer arietinum)+ mustard (Brassica juncea) intercropping system. Indian J Agric Sci 85(8):1074–1079
Marwat KB, Saeed M, Gul B, Hussain Z (2006) Performance of different herbicides in wheat (Triticum aestivum L.) under rainfed conditions of kohat, Pakistan. Pak J Weed Sci Res 12:163–168
Matin MA, Desbiolles JMA, Jahan MAHS (2010) Technology and Innovation for Sustainable Development International Conference. Faculty of Engineering, Khon Kaen University, Thalind, pp 1–8
Narwariya BS, Tiwari KB, Shrivastava P (2016) Performance evaluation of different manual operated weeding equipment for Paddy crop in vertisols. Eco Env Cons 22:357–363
Olaoye JO, Adekanye TA (2011) Analysis of the motion of weeding tools and development of a rotary power weeder. J Agril Engin Technol 19(2):9–25
Safdar ME, Asif M, Ali A, Aziz A, Yasin M, Aziz M, Afzal M, Ali A (2011) Comparative efficacy of different weed management strategies in wheat. Chilean J Agric Res 71(2):195–203
Shehzad MA, Maqsood M, Anwar-ul-Haq M, Niaz A (2012) Efficacy of various herbicides against weeds in wheat (Triticum aestivum L.). Afr J Biotechnol 11:791–799

Subudhi ECR (2004) Evaluation of weeding devices for upland rice in the eastern Ghat of Orissa, India. Int Rice Res Not 29(1):79–81

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