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Herbicidal efficacy of oxadiargyl in sequence with penoxsulam plus cyhalofop in controlling weed diversity and augmenting productivity of rice under crop establishment options

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Abstract
Direct seeded rice (DSR) has emerged as a resource conserving alternative to puddled transplanted rice to address emerging scarcity of labour and water and the rising cost of cultivation. However, weeds are biggest biological constraint in DSR significantly reducing the yield and income. The availability of effective weed control options is critical for the success and wide-scale adoption of DSR. A field study was conducted at during the wet seasons of 2020 and 2021, at the Agronomy Research Farm of Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India, to evaluate the efficacy and economics of combination of pre and post-emergence herbicides under resource conserving crop establishment options. The treatments included three establishment methods *viz*., Dry-DSR, Wet-DSR and puddled transplanted rice (PTR) in main plot and six weed management treatments *viz*., hand weeding, oxadiargyl @ 90 g ha^{-1} as pre-emergence (PE) followed by (*fb.*) penoxsulam+cyhalofop @ 135 g ha^{-1} as post-emergence (PoE), oxadiargyl @ 90 g ha^{-1} (PE) *fb.* triafamone+ethoxysulfuron @ 60 g ha^{-1} (PoE), oxadiargyl @ 90 g ha^{-1} (PE) *fb.* bispyribac sodium @ 25 g ha^{-1} +fenoxaprop @ 56 g ha^{-1} (PoE), brown manuring (DSR) / green manuring (PTR) *fb.* 2,4-D at 25 DAS/T and unweeded control in subplot. The results demonstrated that weed competition in the unweeded control treatment recorded maximum yield loss in Dry-DSR (82.2%) compared to that of Wet-DSR (56.7%) and PTR (21.9%). Hand weeding resulted in significant reduction in weed density and dry-biomass, but among herbicides, oxadiargyl (PE) *fb.* penoxsulam+cyhalofop (PoE) significantly reduced the density and Dry weight of weeds with WCE of 94.4%, 93.7% and 91.2% in PTR, Wet-DSR and Dry-DSR, respectively. Though the highest grain yield was recorded with the interaction effect of hand weeding treatment with PTR, Wet-DSR and Dry-DSR with values of 5111, 5064 and 4943 kg ha^{-1}, respectively, the values were at par with Oxadiargyl (PE) *fb.* Penoxsulam + Cyhalofop (PoE) when applied in PTR (5055 kg ha^{-1}), Wet-DSR (4441 kg ha^{-1}) and DDSR (4926 kg ha^{-1}). Interaction effect of establishment methods and weed management on net return of rice was found significant, with oxadiargyl (PE) *fb.* penoxsulam + cyhalofop (PoE), being the most profitable treatment, when applied under Dry-DSR (Rs. 49,342 ha^{-1}).

Keywords: Crop establishment, Oxadiargyl, Penoxsulam plus Cyhalofop-butyl, weed management

Introduction
Rice (*Oryza sativa* L.), a vital member of poaceae family, is relished as staple food by majority of world's population, with Indiabeing the second largest producer (118.87 mt), from an area of 43.66 mha (Anonymous, 2021) [2]. Owing to the evidences of plateauing of the system productivity and declining of total factor productivity of rice based cropping system, due to fatigued natural resource base (Ladha *et al*., 2003) [12], sustained rice production demands the use of resource conservation oriented agricultural techniques, as the conventional transplanting of rice after puddling creates problems of high production cost, low input-use efficiency, decline in groundwater, deterioration of soil health, and environmental pollution (Kamboj *et al*., 2012) [9]. Growing of transplanted rice after puddling requires large amount of water, energy and labour, which are becoming increasingly scarce and expensive. To overcome this, direct seeding of rice (DSR) seems to be an alternative and efficient resource conservation technology to reduce the cost of cultivation, energy consumption and to sustain productivity, thereby increasing the profit margin of farmers (Singh *et al*., 2006) [23].

Weeds are the biggest biological constraint in DSR, causing yield losses ranging from 50 to 90% (Prasad, 2011) [16], because of dry tillage and initial aerobic soil conditions, making weeds conducive for germination and simultaneous emergence of weeds along with rice seedlings. Changes in crop establishment from transplanting to direct seeding also resulted in marked changes in the floristic weed diversity, with increased population of annual grasses such as *Echinochloa crusgalli*, *Echinochloa colona* and *Leptochloa chinensis*, sedge like *Cyperus iria*, *Fimbristylis miliacea* and *Cyperus rotundus* and broad leaved weeds such as *Commelina diffusa*, *Sphenochlea zeylanica*, *Ludwigia parviflora*, *Commelina benghalensis* and *Caesulia axillaris* (Saha, 2009) [20]. In India, an economic loss of USD 11 billion has been found to be inflicted by weeds alone in 10 major crops, out of which the share of rice is 21.4% and 13.8% in direct seeded and transplanted rice, respectively (Gharde *et al*., 2018) [6].

Weed control in India is mainly achieved using herbicides and hand weeding, but the latter is becoming uneconomical because of shortage of rural labour during the peak critical period of crop-weed competition (Mahajan *et al.*, 2013) [13], for which chemical weed control has gained importance for weed management in rice-growing tracts. The economic and environmental benefits of dry seeding in rice can be sustained through appropriate weed management strategies. Bispyribac-sodium is the most widely used pyrimidinylthiobenzoate herbicide in Indian subcontinent, used to suppress key grasses *viz*. *Echinochloa* species and *Ischaemum rugosum*, broadleaf and sedges but not effective on grasses such as *Leptochloa chinensis* (Saha *et al*., 2021) [19]. The present study was undertaken to evaluate the efficacy and economics of combination of pre and post-emergence herbicides under resource conserving crop establishment options.

Materials and Methods

Experimental site

The field experiment wasconducted during the wet (*kharif*) seasons of 2020 and 2021, at the Agronomy Research Farm of Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, Eastern India, which lies at 20°15′N latitude and 85°48′E longitude with an altitude of 25.9 m above the mean sea level. The region is characterized by a subtropical climate with average annual rainfall of 1444 mm (Anonymous, 2021) [2]. During rice growing season of 2020, the monthly mean maximum temperature ranged from 31.4 °C in the month of November, 2020 to 34.0 °C in the month of June, 2020, whereas, the monthly mean minimum temperature ranged from 26.7 °C in the month of June, 2020 to 19.6 °C in the month of November, 2020. During rice growing season of 2021, the monthly mean maximum temperature ranged from 34.0 °C in the month of June, 2021 to 30.2 °C, in November, 2021, whereas, the monthly mean minimum temperature ranged from 21.8 °C in the month of November,2021 to 26.3 °C in the month of June, 2021. The crop received 1237 mm of rainfall during 2020 and 1395 mm in 2021. The soil was sandy loam texture (72.6% sand, 12.2% silt and 15.2% clay), with acidic pH (5.42), low available N (213.2 kg ha^{-1}), medium P (21.7 kg ha^{-1}) and K (148.4 kg ha^{-1}).

Experimental design

The experiment was laid out in a split plot design with three replications by taking three establishment methods *viz*. Dry-DSR, Wet-DSR and PTR in the main plot and six weed management practices in rice *viz*., M_1: hand weeding twice at 20 and 40 days after sowing/transplanting (DAS/T), M_2: oxadiargyl @ 90 g ha^{-1} as pre-emergence (PE) followed by (*fb*.) penoxsulam + cyhalofop @ 135 g ha^{-1} as post-emergence (PoE), M_3: oxadiargyl @ 90 g ha^{-1} (PE) *fb*. Triafamone + ethoxysulfuron @ 60 g ha^{-1} (PoE), M_4: oxadiargyl @ 90 g ha^{-1} (PE) *fb*. bispyribac sodium @ 25 g ha^{-1}+fenoxaprop @ 56 g ha^{-1} (PoE), living mulch as brown manuring (DSR) / green manuring (PTR) with 2, 4-D at 25 days after sowing/transplanting (DAS/T) and unweeded control in the sub-plots.

Oxadiargyl is a selective herbicide, the activity of whose lies in binding to the enzyme, protoporphyrinogen oxidase - IX, as an inhibitor and is commonly used to control annual grasses, sedges and broadleaf weeds in a range of crops including rice (EFSA, 2013) [1]. Penoxsulam + cyhalofop is a pre-mix rice herbicide product containing penoxsulam 1.02% w/w + cyhalofop-butyl 5.1% w/w OD, in which penoxsulam is a systemic herbicide, used to control broad spectrum of weeds, whose mode of action lies with the inhibition of acetolactate synthase, whereas, cyhalofop-butyl is a post-emergence, aryloxyphenoxy-propionate herbicide, which is used in controlling grassy weeds in rice fields, whose mode of action involves the inhibition of acetyl-coenzyme-A carboxylase (ACCase) biosynthesis. Triafamone plus ethoxysulfuron is also an acetolactate synthase inhibitor herbicide, recommended in rice to effectively control broad spectrum of weeds.

Field preparation and sowing

The Dry-DSR field was initially dry ploughed with 2 discings and 2 harrowings followed by levelling for sowing. The sowing under Dry-DSR was done with seed drill with a seed rate of 50 kg ha^{-1} at a row-spacing of 20 cm. For preparing the field under Wet-DSR, 2 discings and 2 harrowings were done under aerobic soil conditions and then the land was puddled and levelled. Pre-germinated seeds, prepared by soaking and incubating for 24 h each, were sown on the surface of the drained puddled soil by using a drum seeder. For PTR, 2 discings and 2 harrowings were done under aerobic soil conditions and then soil was puddled with water for easy transplanting of rice seedlings in soft mud of the field.Wet nursery was prepared to raise the seedling for use in main experiment at aseed rate of 40 kg ha^{-1} for puddled transplanting. Rice variety ‘Hasanta’, having maturity duration of 145 days was used for the investigation. For Dry-DSR, dry rice seeds were sown in line on 26th June, 2020 in first year and the same week (26th week) was maintained in second year for sowing and were sown by seed drill on 30th June, 2021. For preparing pre-germinated seeds to be used in Wet-DSR and PTR, dry seeds were soaked in water on the same date of sowing of Dry-DSR of respective years, for 24 h, followed by incubation for 24 h. For Wet-DSR, the pre-germinated seeds were sown by drum seeder on 29th June, 2020, in first year and 3rd July, 2021 in second year, whereas, for PTR, the same pre-germinated seeds were used for nursery raising and 21 days seedlings were used for transplanting.

At the time of final ploughing, FYM @ 5 t ha^{-1} was incorporated into the soil. Inorganic fertilizers @ 80-40-40 kg N-P_2O_5-K_2O ha^{-1} were applied to all the plots irrespective of treatments. Full doses of P_2O_5 and K_2O along with 25% of N were applied as basal, whereas, rest of N was applied in 2:1

ratio at tillering and panicle initiation stage of rice.

Weed management operations were performed as per the treatment specifications.The pre-emergence herbicide was applied two DAS/T in Dry-DSR and PTR, whereas it was applied at four days after drum seeding in Wet-DSR. The post-emergence herbicides were applied at 20 DAS/T. All the herbicides were applied through Knapsack sprayer using 500 L water ha^{-1}.

Field Measurements

Phytotoxic effect of herbicides was scored at 3 days, 5 days, 10 days and 15 days after application in rice by using simple rating scale of 0-10 (equal to 0 to 100%) (Rao, 2000) [18]. The observation of weed density was recorded at 60 DAS/T with the help of quadrate of 1×1 m^2. Weeds were cut at the ground level, washed with tap water, and oven dried at 70º C for 48 h, before weighing, for obtaining the dry-biomass and the data were subjected to square root transformation prior to statistical analysis.

Weed control efficiency (WCE) at 60 DAS/T was worked out taking into consideration of the reduction in weed dry biomass in treated plot over unweeded check. It was estimated by using the following formula suggested by Mani *et al.* (1973) [14] and was expressed in percentage.

$$\text{WCE (\%)} = \frac{x - y}{x} \times 100$$

Where

x=Dry-biomass of weeds in unweeded control plot (g m^{-2}) and y=Dry-biomass of weeds in herbicide treated plots (g m^{-2}).

Weed index (WI), which is the per cent reduction in crop yield under a particular treatment due to the presence of weeds in comparison to weed free plot (Gill and Kumar, 1969) [7] was determined by the following formula and was expressed in percentage.

$$\text{WI (\%)} = \frac{a - b}{a} \times 100$$

Where

a=Grain yield (kg ha^{-1}) in hand weeded plot; b=Grain yield (kg ha^{-1}) in treated plot.

Herbicide Efficiency Index (HEI), which represents the potential of a particular herbicide in controlling weeds along with their phytotoxic effect on the crop (Krishnamurthy *et. al.*, 1975) [10], was calculated by the following formula.

$$\text{HEI (\%)} = \frac{\frac{b - c}{a} \times 100}{\frac{y}{x} \times 100}$$

Where

b = Grain yield from treated plot, c= Grain yield from weedy check plot, a = Grain yield from hand weeded plot, y = Weed dry-biomass in treated plot and x = Weed dry-biomass in weedy check plot.

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

Economics

All the costs incurred for different field operations along with input costs were computed and summed up to obtain the total cost of cultivation. Sale prices of grain based on minimum support priceand sale price of straw based on prevalent market price were summed up in each treatment to calculate the total revenue received from the sale of produce as gross returns. Net returns for each treatment were calculated by deductingthe cost of cultivation from gross returns. The ratio between gross returns to totalcost of cultivation was taken as benefit-cost ratio (B:C ratio).

Statistical Analysis

The data obtained in both the years in respect of various observations were pooled and statistically analyzed using standard procedures of variance analysis and the significance of different source of variations was tested at 5% level of significance.

Results and Discussion

Floristic composition of weeds

Major weed flora in rice in the experimental site comprised of 16 weed species, comprising five grasses, three sedges and eight broad leaved weeds. Dominant grasses include *Echinochloa colona* (L.) Link., *Echinochloa crusgalli* (L.) Beauv, *Paspalum distichum* (L.), *Leptochloa chinensis* (L.) Nees. and *Digitaria sanguinalis* (L.) Scop., whereas, *Cyperus iria* (L.), *Cyperu sdifformis* (L.) and *Fimbristylis miliacea* (L.) Vahl. were the major sedges in the experimental site. Broad leaved weeds showed wider species diversity than other categories, which include *Alternanthera philoxeroides* (Mart.) Griseb., *Ludwigia parviflora* (L.), *Monochoria vaginalis* (Burm. f.) C. Presl., *Sphenoclea zeylanica* Gaertn., *Eclipta alba* (L.), *Ammannia baccifera* (L.) Hassk, *Spilanthes acmella* (L.) and *Aeschynomene indica* (L.)

Phytotoxic effect of herbicides in rice

Among the herbicides applied in rice field, no phytotoxicity of pre-emergence applied oxadiargyl @ 90 g ha^{-1} was recorded for PTR and Dry-DSR, whereas oxadiargyl @ 90 g ha^{-1} when applied as pre-emergence to Wet-DSR with sprouted seeds resulted in phytotoxicity symptoms, with mortality of some plants. However, the phytotoxicity symptoms declined with the age of the plant after 15 days, but affected the growth of the rice plants significantly. No phytotoxicity symptoms were recorded for any of the post emergence applied herbicides in rice. Similar type of phytotoxicity effect of oxadiargyl in Wet-DSR with sprouted seed was earlier reported by Ahmed and Chauhan (2015) [1] and Gitsopoulos and Froud-williams (2004) [8].

Weed density

Pooled analysis of category wise and total weeds densityat 60 DAS/T revealed lowest density of all categories in PTR, differing significantly with Wet-DSR and Dry-DSR (Table 1). Heavy weed infestation in Dry-DSR than Wet-DSR and PTR might be due to methods of land preparation in Dry-DSR because dry tillage practices and aerobic soil conditions that was conducive for early weed emergence and growth of weeds (Rao *et al.*, 2007) [17] and (Farooq *et al*., 2011) [5].

The interaction effect of planting modules and weed management on category wise weed density at 60 DAS/T was found significant with all categories of weeds and total weed density. Oxadiargyl (PE) *fb.* penoxsulam+cyhalofop (PoE) registered the lowest grass weed density in PTR, which was at par with hand weeding twice and oxadiargyl (PE) *fb.* bispyribac+fenoxaprop (PoE), when applied in PTR. Among the treatment combinations under Wet-DSR, the lowest grass density was recorded with hand weeding twice but was at par with oxadiargyl (PE) @ 90 g ha^{-1} *fb.* penoxsulam+cyhalofop (PoE). With regards to Dry-DSR treatments, oxadiargyl (PE) *fb.* penoxsulam+cyhalofop (PoE) registered lowest grass weed density, being at par with hand weeding twice and oxadiargyl (PE) *fb.* Bispyribac + fenoxaprop (PoE). With regards to the density of sedges, though the lowest weed density was with hand weeding twice under PTR, it was found at par with the same treatment under Wet-DSR, oxadiargyl (PE) *fb.* Penoxsulam + cyhalofop (PoE) under PTR and oxadiargyl (PE) *fb.* Bispyribac + fenoxaprop (PoE) under PTR. Among Dry-DSR treatments, hand weeding twice recorded lowest sedge density, being at par with oxadiargyl (PE) *fb.* penoxsulam + cyhalofop (PoE). Like sedge weed density, the lowest broad leaved weed density at 60 DAS/T was recorded with hand weeding twice under PTR, being at par with oxadiargyl (PE) *fb.* penoxsulam+cyhalofop (PoE) and hand weeding under Wet-DSR. Among the Dry-DSR treatments, though hand weeding recorded lowest sedge density, it was at par with oxadiargyl (PE) *fb.* penoxsulam + cyhalofop (PoE) and brown / green manuring. The highest weed density of grass, sedge and BLWs at 60 DAS/T was recorded under unweeded control treatment under Dry-DSR and among the weed management options, oxadiargyl (PE) *fb.* Penoxsulam + cyhalofop (PoE), when applied in Dry-DSR significantly reduced all categories of weeds at 60 DAS/T. This treatment was followed by oxadiargyl (PE) *fb.* Bispyribac + fenoxaprop (PoE) under Dry-DSR, which also recorded satisfactory reduction of all categories of weeds in Dry-DSR.

Hand weeding twice eliminated weeds during critical period of crop-weed competition, resulting in low weed density that in turn enhanced the yield. Similar type of results were also observed by Sunil *et al*. (2010) [1]. Among the chemical treatments, application of oxadiargyl (PE) *fb.* penoxsulam + cyhalofop (PoE) recorded the lowest weed density, due to early suppression of weeds by oxadiargyl at the time of emergence of weeds and killing of subsequent weed flush by the combination of penoxsulam+cyhalofop, resulting in reducing the crop-weed competition and encouraging the crop growth. Similar results were earlier reported by Yadav *et al.* (2018) [26] and Singh *et al.* (2016) [24].

Weed dry-biomass

Pooled analysis of category wise and total weed dry-biomass at 60 DAS/T revealed lowest dry-biomass of all categories and total weeds in PTR, differing significantly with Wet-DSR and Dry-DSR (Table 2). Dry-DSR registered the highest weed dry-biomass of all categories of weeds among all the establishment methods.

Among the weed management options, the lowest weed dry-biomass of grassy weeds at 60 DAS/T was recorded with hand weeding twice, being at par with oxadiargyl (PE) @ 90 g ha^{-1} *fb.* penoxsulam + cyhalofop (PoE) and oxadiargyl (PE) *fb.* Bispyribac + fenoxaprop (PoE). The interaction effect of establishment methods and weed management on grassweed dry-biomass was found non-significant. With regards to the density of sedges, though the lowest weed dry-biomass was with hand weeding twice; it was at par with oxadiargyl (PE) *fb.* penoxsulam+cyhalofop (PoE) but differed significantly with all other weed management treatments. The interaction effect of treatments on sedge weed dry-biomass was found significant with the lowest sedge weed dry-biomass recorded with oxadiargyl (PE) *fb.* penoxsulam+cyhalofop (PoE), when applied under PTR and was found at par with hand weeding twice under PTR. The lowest broad leaved weed dry-biomass was obtained with hand weeding twice, which differed significantly with all other treatments. The interaction effect of treatments on broad leaved weed dry-biomass at 60 DAS/T revealed the lowest value recorded with hand weeding twice under PTR, being at par with oxadiargyl (PE) *fb.* Penoxsulam + cyhalofop (PoE) and hand weeding under Wet-DSR.

Higher efficacy of the combination of the herbicides was due to the higher efficacy of oxadiargyl as a protoporphyrinogen oxidase inhibitor herbicide, which helped in cell disintegration, wilting, and eventually death of weeds at the time of emergence and penoxsulam+cyhalofop, which inhibited acetolactate synthase and acetyl-coenzyme-A carboxylase, thereby suppressing weeds even at late vegetative stages of rice. Higher efficacy of penoxsulam + cyhalofop was also earlier reported by Sekhar *et al.* (2020) [22].

Weed control efficiency

Among the combination of establishment methods and weed management, the highest WCE was recorded for hand weeding twice with Wet-DSR (96.3%), followed by the same treatment under PTR (95.8%) and Dry-DSR (95.3%) (Fig 1). Among the chemical treatments, the highest WCE was recorded with the combination of oxadiargyl (PE) *fb.* penoxsulam+cyhalofop(PoE) and PTR (94.4%), followed by the same chemical under Wet-DSR (93.7%) and Dry-DSR (91.2%). Patil *et al.* (2014) [15] also reported reduction in weed density, dry-biomass and higher weed control efficiency with the application of penoxsulam+cyhalofop-butyl 6% OD @ 135 g ha^{-1} at 2-4 leaf stage.

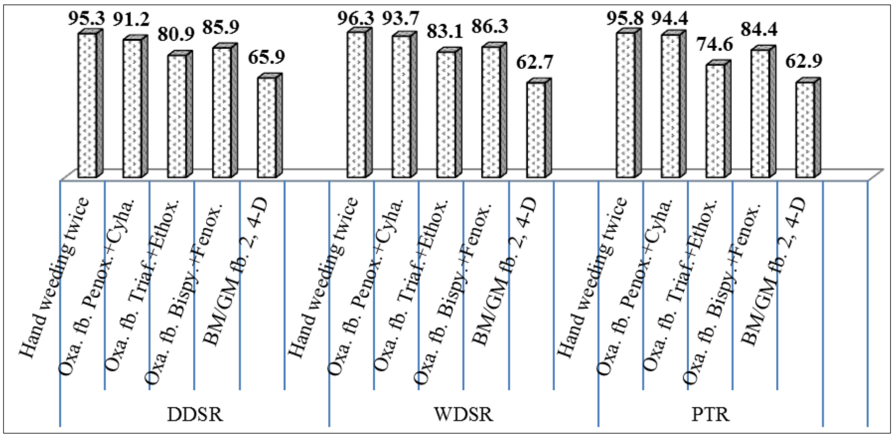

Fig 1: Effect of establishment methods and weed control treatments on weed control efficiency (%) at 60 DAS/T

Yield components

Data pertaining to effective tiller density of rice, recorded at harvest revealed that it was significantly influenced by establishment methods with highest tiller density (287.8 m^{-2}) recorded with Dry-DSR, differing significantly with PTR (247.4 m^{-2}) and Wet-DSR (216.2 m^{-2}) (Table 3). The interaction effect of treatments revealed that the significantly highest effective tiller density (312.2 m^{-2}) was obtained with hand weeding twice under Dry-DSR, being at par with hand weeding twice under Wet-DSR (307.7 m^{-2}), oxadiargyl (PE) *fb*. penoxsulam + cyhalofop (PoE) under Dry-DSR (300.3 m^{-2}), oxadiargyl (PE) *fb*. bispyribac sodium + fenoxaprop (PoE) under Dry-DSR (296.2 m^{-2}) and brown/green manuring under Dry-DSR (283.8 m^{-2}).

Filled grains panicle^{-1} of rice was significantly influenced by establishment methods with highest filled grains panicle^{-1} (115.9) recorded with PTR, being at par with Dry-DSR (101.3), but differed significantly with Wet-DSR (96.8). The interaction effect of treatments revealed that the significantly highest filled grains panicle^{-1} was obtained with hand weeding twice under PTR (125.8), being at par with oxadiargyl (PE) *fb*. penoxsulam + cyhalofop (PoE) under PTR (122.2) and oxadiargyl (PE) *fb*. bispyribac sodium + fenoxaprop (PoE) under PTR (119.0).

The pooled data revealed that the test weight of rice was significantly influenced by establishment methods and weed management options, with highest test weight of rice recorded for PTR (23.62 g), which was found at par with oxadiargyl (PE) *fb*. penoxsulam + cyhalofop (PoE) under PTR (23.41 g) and oxadiargyl (PE) *fb*. bispyribac sodium + fenoxaprop (PoE) under PTR (23.17 g).

Highest number of effective tillers m^{-2} was recorded with Dry-DSR due to higher plant population and higher tiller density in DSR, whereas filled grains panicle^{-1} and test weight of rice was recorded highest in PTR, which may be due to lesser intra-plant competition in PTR, resulting in higher yield attributing characters as earlier reported by Kumar *et al.* (2008) [11].

Grain yield

Grain yield of rice were significantly influenced by establishment methodsand weed management practices in both years (Table 3). The pooled data of both the years revealed significantly highest grain (4731 kg ha^{-1}) with PTR, differing significantly with other establishment methods like Wet-DSR (3890 kg ha^{-1}) and Dry-DSR (3818 kg ha^{-1}). The interaction effect of establishment methods and weed management on grain yield of rice was found significant, with the highest grain yield obtained with hand weeding twice under PTR (5111 kg ha^{-1}), which did not differ significantly with the same under Wet-DSR (5064 kg ha^{-1}), oxadiargyl (PE) *fb*. penoxsulam+cyhalofop (PoE) when applied under PTR (5055 kg ha^{-1}) and oxadiargyl (PE) *fb*. Penoxsulam + cyhalofop (PoE) when applied under Dry-DSR (4926 kg ha^{-1}). Among the chemical weed management treatments, oxadiargyl (PE) *fb*. penoxsulam + cyhalofop (PoE) when applied under PTR, resulted in the highest grain yield being at par with oxadiargyl (PE) *fb*. Bispyribac sodium+fenoxaprop (PoE) when treated under PTR (4935 kg ha^{-1}) and oxadiargyl (PE) *fb*. Penoxsulam + cyhalofop (PoE) when applied under Dry-DSR (4926 kg ha^{-1}). Significantly lowest grain yield of rice (882 kg ha^{-1}) was recorded with unweeded control treatment under Dry-DSR, which was followed by unweeded control treatment under Wet-DSR (2191 kg ha^{-1}).The higher grain yield recorded in PTR was attributed due to lesser intra-plant competition, efficient utilization of natural resources which resulted in higher number spikelet panicle^{-1} (Aslam *et al.*, 2008) [3] than in direct sown densely populated crop. The highest grain yield with oxadiargyl (PE) *fb*. penoxsulam + cyhalofop (PoE) and oxadiargyl (PE) *fb*. bispyribac sodium+fenoxaprop (PoE) was due to inhibition of emergence of weeds by oxadiargyl and subsequent killing of post-emergent weeds by the action of ALS and ACCase inhibitors, during the crop growing period, so that the crop used the available resources effectively during the entire crop growth period and better transfer of photosynthates into the sink resulting in maximum grain yield, as earlier reported by Saphi *et al.* (2018) [21].

Harvest Index (HI)

The pooled data of HI was non-significant with respect to planting modules but influenced significantly with respect to weed management options. The PTR resulted in highest harvest index (44.6%) followed by Wet-DSR (43.9%) and Dry-DSR (43.5%). The interaction effect was found significant, with highest HI value obtained with hand weeding twice under PTR (46.4%), being at par with oxadiargyl (PE) *fb*. penoxsulam + cyhalofop (PoE) under Dry-DSR (45.9%). Significantly lowest HI of rice (37.1%) was recorded with unweeded control treatment under Dry-DSR, followed by the same under Wet-DSR (40.2%).

Weed Index (WI)

The lowest WI was obtained with the combination of oxadiargyl (PE) *fb*. penoxsulam+cyhalofop (PoE) and Dry-

DSR(0.4%), followed by the same treatment under PTR (1.1%) and oxadiargyl (PE) *fb.* bispyribac sodium + fenoxaprop (PoE) under PTR (3.4%) (Fig 2). The highest index (82.2%) was recorded with unweeded control treatment under Dry-DSR, followed by the same under Wet-DSR (56.37%). Sunil *et al.* (2010) [25] had earlier reported yield reduction up to 80% in direct-seeded aerobic rice due to season-long weed competition. Rao *et al.* (2007) [17] also opined yield penalty is as high as 50-91% in direct seeded aerobic rice.

Herbicide efficiency index (HEI)

The HEI of all the herbicide treatments were higher for Dry-DSR followed by Wet-DSR and PTR. Among the treatment combinations, the highest HEI was recorded for oxadiargyl (PE) *fb.* Penoxsulam + cyhalofop (PoE) applied under Dry-DSR (52.3%), followed by and oxadiargyl (PE) *fb.* Bispyribac sodium + fenoxaprop (PoE) (30.4%) and oxadiargyl (PE) *fb.* triafamone + ethoxysulfuron under Dry-DSR (21.1%). The lowest value was recorded with brown/green manuring *fb.* 2, 4-D application (Fig 3).

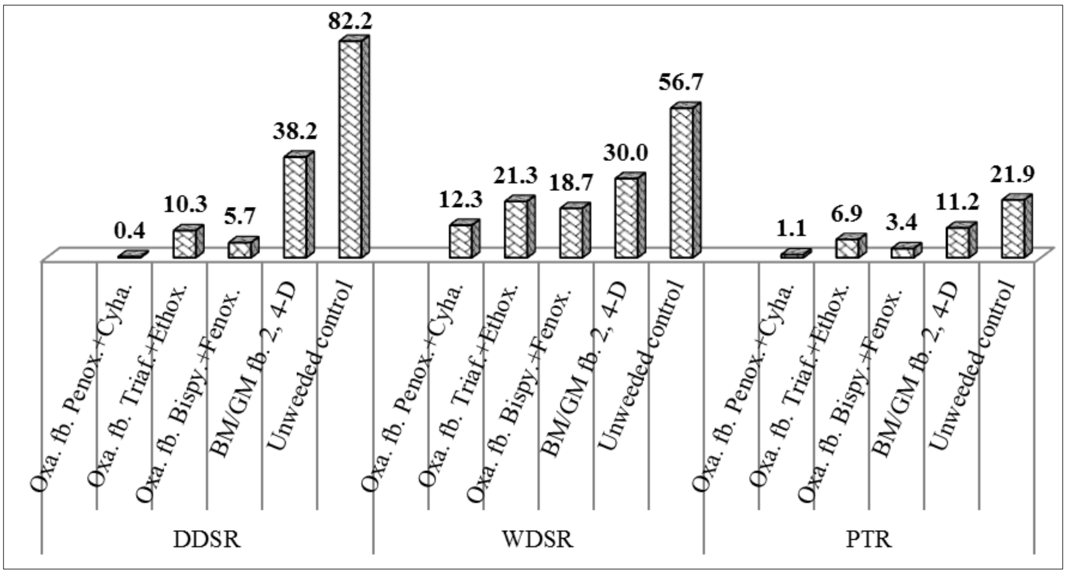

Fig 2: Effect of establishment methods and weed control treatments on weed index (%) at 60 DAS/T

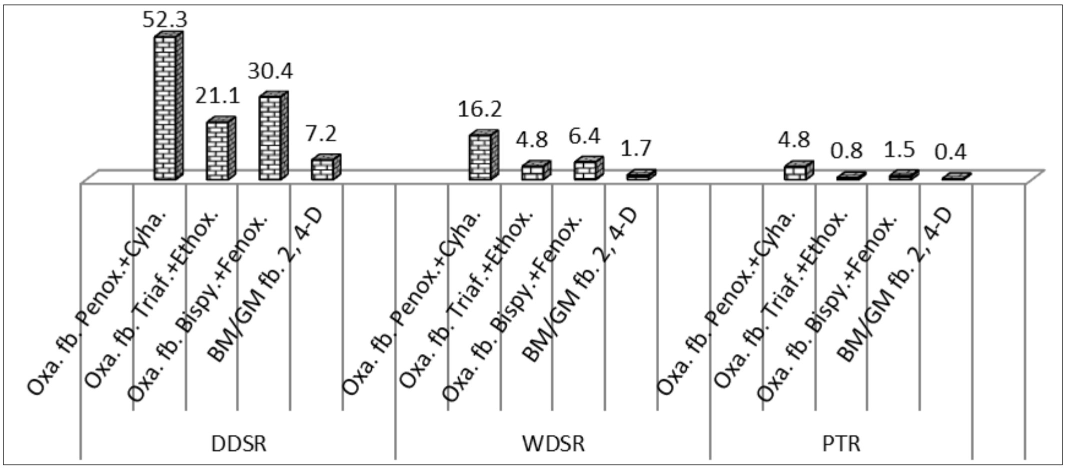

Fig 3: Effect of establishment methods and weed control treatments on herbicide efficiency index (%) at 60 DAS/T
N.B.: DDSR: Dry-DSR, WDSR: Wet-DSR, PTR: Puddled Transplanted rice

Economics

Net return of rice calculated on the basis of pooled data was significantly influenced by establishment methods, weed management practices and their interaction effects (Table 4). The interaction effect of establishment methods and weed management on net return of rice was found significant, with the highest value obtained with oxadiargyl (PE) *fb.* penoxsulam + cyhalofop (PoE) when applied under Dry-DSR(Rs. 49,342 ha^{-1}), which did not differ significantly with the hand weeding twice under Wet-DSR (Rs. 43,842 ha^{-1}) and oxadiargyl (PE) *fb.* bispyribac sodium + fenoxaprop (PoE) when treated under Dry-DSR (Rs. 43,401 ha^{-1}). Significantly lowest and negative net return of rice (Rs. -27,214 ha^{-1}) was recorded with unweeded control treatment under Dry-DSR, which was followed by unweeded control treatment under Wet-DSR (Rs. -2,273 ha^{-1}).

B:C ratio of rice was significantly influenced by establishment methods, weed management practices and their interaction effects. The interaction effect revealed the highest B:C ratio with oxadiargyl (PE) *fb.* penoxsulam+ cyhalofop (PoE), when applied under Dry-DSR (1.99), which did not differ significantly with oxadiargyl (PE) *fb.* bispyribac sodium + fenoxaprop (PoE) under Dry-DSR (1.86) and oxadiargyl *fb.* triafamone+ ethoxysulfuron when treated under Dry-DSR(1.78). Significantly lowest B:C ratio (0.40) was recorded with unweeded control treatment under Dry-DSR, which was followed by unweeded control treatment under Wet-DSR (0.95).

Conclusion

Unweeded growth of rice in Dry-DSR resulted in significant loss of grain yield and economics. Selection of proper crop establishment method along with application of suitable herbicide module have a remarkable influence on weed control and grain yield of rice. Establishment of the rice crop by puddled transplanting followed by hand weeding was effective in attaining higher rice grain yield, but was at par with direct seeding under dry and wet conditions when weeds are suppressed by hand weeding. However, economic advantage from rice cultivation can be obtained with establishment method Dry-DSR in combination with pre-emergence application of oxadiargyl followed by post-emergence application of penoxsulam+cyhalofop. The information generated from this study will encourage the farmers to grow Dry-DSR and realize higher profitability by controlling weeds through herbicides.

Table 1: Category-wise weed density (m^{-2}) at 60 DAS/T (Pooled data of 2 years)

Treatments	W_1: Hand weeding twice	W_2: Oxadiargyl *fb.* Penoxsulam + Cyhalofop	W_3: Oxadiargyl *fb.* Triafamone + Ethoxysulfuron	W_4: Oxadiargyl *fb.* Bispyribac + Fenoxaprop	W_5: Brown/ Green manuring *fb.* 2,4-D	W_6: Unweeded control	Mean	Analysis of variance: Treatments	S.Em (±)	CD (P=0.05)
Grass										
M_1: Dry-DSR	1.82 (3.0)	1.77 (2.7)	2.73 (7.0)	2.16 (4.2)	4.99 (24.8)	6.19 (38.3)	3.28 (13.3)	M	0.08	0.26
M_2: Wet-DSR	1.64 (2.5)	1.68 (2.3)	2.34 (5.0)	2.01 (3.7)	5.01 (24.8)	5.90 (34.7)	3.10 (12.2)	W	0.09	0.26
M_3: PTR	1.17 (1.0)	1.08 (0.8)	1.65 (2.3)	1.39 (1.5)	3.07 (9.0)	3.83 (14.3)	2.03 (4.8)	M within W	0.14	0.39
Mean	1.54 (2.2)	1.51 (1.9)	2.24 (4.8)	1.86 (3.1)	4.36 (19.6)	5.31 (29.1)		W within M	0.13	0.37
Sedge										
M_1: Dry-DSR	1.46 (1.3)	2.03 (3.0)	2.67 (5.3)	2.41 (4.0)	4.05 (13.5)	6.06 (28.2)	3.11 (9.2)	M	0.12	0.47
M_2: Wet-DSR	0.88 (0.3)	1.22 (1.0)	1.64 (2.3)	1.52 (1.7)	2.96 (6.5)	4.08 (14.3)	2.05 (4.4)	W	0.09	0.25
M_3: PTR	0.88 (0.3)	1.00 (0.5)	1.34 (1.3)	1.17 (0.8)	2.39 (4.2)	2.99 (7.7)	1.63 (2.5)	M within W	0.18	0.60
Mean	0.70 (1.07)	1.42 (1.5)	1.88 (3.0)	1.70 (2.2)	3.13 (8.1)	4.38 (16.7)		W within M	0.15	0.45
Broad leaved weeds										
M_1: Dry-DSR	1.64 (2.5)	2.54 (6.2)	3.60 (12.8)	3.21 (10.0)	2.63 (6.5)	7.47 (55.5)	3.52 (15.6)	M	0.10	0.33
M_2: Wet-DSR	1.39 (1.7)	1.71 (2.7)	2.96 (8.5)	2.48 (5.8)	2.02 (3.7)	5.75 (32.8)	2.72 (9.2)	W	0.11	0.31
M_3: PTR	1.13 (1.0)	1.29 (1.3)	2.34 (5.2)	1.87 (3.2)	1.45 (1.8)	4.23 (17.7)	2.05 (5.0)	M within W	0.17	0.48
Mean	1.39 (1.7)	1.85 (3.4)	2.97 (8.8)	2.52 (6.3)	2.04 (4.0)	5.81 (35.3)		W within M	0.16	0.44
Total weed										
M_1: Dry-DSR	2.63 (6.8)	3.47 (11.8)	5.02 (25.2)	4.29 (18.2)	6.70 (44.8)	11.03 (122.0)	5.52 (38.1)	M	0.10	0.32
M_2: Wet-DSR	2.18 (4.5)	2.53 (6.0)	4.01 (15.8)	3.36 (11.2)	5.94 (35.0)	9.04 (81.8)	4.51 (25.7)	W	0.09	0.25
M_3: PTR	1.63 (2.3)	1.74 (2.7)	3.02 (8.8)	2.41 (5.5)	3.91 (15.0)	6.32 (39.7)	3.17 (12.3)	M within W	0.14	0.41
Mean	2.15 (4.6)	2.58 (6.8)	4.02 (16.6)	3.36 (11.6)	5.51 (31.6)	8.80 (81.2)		W within M	0.12	0.35

Table 2: Category-wise weed dry-biomass (g m^{-2}) at 60 DAS/T (Pooled data of 2 years)

Treatments	W_1: Hand weeding twice	W_2: Oxadiargyl *fb.* Penoxsulam+ Cyhalofop	W_3: Oxadiargyl *fb.* Triafamone+ Ethoxysulfuron	W_4: Oxadiargyl *fb.* Bispyribac+ Fenoxaprop	W_5: Brown/ Green manuring *fb.* 2, 4-D	W_6: Unweeded control	Mean	Analysis of variance: Treatments	S.Em (±)	CD (P=0.05)
Grass										
M_1: Dry-DSR	2.11 (3.98)	2.37 (5.17)	3.08 (9.03)	2.82 (7.46)	5.52 (30.25)	7.08 (51.12)	3.83 (17.84)	M	0.16	0.61
M_2: Wet-DSR	1.73 (2.80)	1.75 (2.58)	2.66 (6.72)	2.34 (5.08)	5.09 (25.52)	6.52 (42.12)	3.35 (14.14)	W	0.18	0.53
M_3: PTR	1.31 (1.44)	1.23 (1.18)	1.81 (3.07)	1.52 (1.89)	3.45 (11.49)	4.15 (16.91)	2.25 (6.00)	M within W	0.33	NS
Mean	1.71 (2.74)	1.78 (2.98)	2.52 (6.27)	2.23 (4.81)	4.69 (22.42)	5.92 (36.72)		W within M	0.32	NS
Sedge										
M_1: Dry-DSR	1.77 (2.11)	1.99 (3.07)	3.17 (7.33)	2.71 (4.84)	4.90 (19.13)	6.95 (38.14)	3.58 (12.44)	M	0.15	0.61
M_2: Wet-DSR	0.96 (0.27)	1.34 (0.65)	2.02 (3.24)	1.79 (2.55)	3.61 (9.61)	4.94 (18.05)	2.44 (5.73)	W	0.15	0.44

M_3: PTR	0.96 (0.27)	0.94 (0.25)	1.71 (2.10)	1.35 (1.23)	2.69 (5.12)	3.55 (9.77)	1.87 (3.12)	M within W	0.29	0.91
Mean	1.23 (0.88)	1.43 (1.32)	2.30 (4.22)	1.95 (2.87)	3.73 (11.29)	5.15 (21.99)		W within M	0.26	0.76
Broad leaved weeds										
M_1: Dry-DSR	1.49 (1.87)	2.47 (5.92)	3.66 (13.05)	3.12 (9.55)	2.45 (5.56)	8.17 (66.65)	3.56 (17.10)	M	0.09	0.30
M_2: Wet-DSR	1.18 (0.95)	1.74 (2.79)	2.72 (6.99)	2.48 (5.83)	1.91 (3.20)	6.30 (39.67)	2.72 (9.90)	W	0.13	0.36
M_3: PTR	1.05 (0.67)	1.31 (1.32)	2.73 (7.17)	2.20 (4.49)	1.40 (1.49)	4.72 (22.08)	2.24 (6.20)	M within W	0.18	0.52
Mean	1.24 (1.16)	1.84 (3.34)	3.04 (9.07)	2.60 (6.62)	1.92 (3.42)	6.40 (42.80)		W within M	0.18	0.52
Total weed										
M_1: Dry-DSR	2.66 (6.97)	3.63 (13.08)	5.35 (28.56)	4.61 (21.06)	7.13 (50.87)	12.19 (149.26)	5.93 (44.97)	M	0.09	0.28
M_2: Wet-DSR	1.94 (3.57)	2.52 (6.07)	4.06 (16.20)	3.65 (13.09)	5.99 (35.72)	9.76 (95.67)	4.65 (28.38)	W	0.18	0.51
M_3: PTR	1.53 (2.00)	1.74 (2.62)	3.50 (11.98)	2.77 (7.37)	4.23 (17.48)	6.87 (47.14)	3.44 (14.76)	M within W	0.24	0.67
Mean	2.04 (4.18)	2.63 (7.26)	4.30 (18.91)	3.68 (13.84)	5.78 (34.69)	9.61 (97.36)		W within M	0.26	0.72

Table 3: Interaction effects of planting modules and weed management on yield attributes of rice (Pooled data of 2 years)

Treatments	W_1: Hand weeding twice	W_2: Oxadiargyl *fb.* Penoxsulam+ Cyhalofop	W_3: Oxadiargyl *fb.* Triafamone + Ethoxysulfuron	W_4: Oxadiargyl *fb.* Bispyribac+ Fenoxaprop	W_5: Brown/ Green manuring *fb.* 2,4-D	W_6: Unweeded control	Mean	Analysis of variance		
								Treatments	SEm (±)	CD (P=0.05)
Panicles m^{-2}										
M_1: Dry-DSR	312.2	300.3	283.5	296.2	283.8	250.7	287.8	M	5.19	16.91
M_2: Wet-DSR	307.7	185.2	176.2	181.9	271.7	174.8	216.2	W	8.16	23.09
M_3: PTR	284.7	274.0	256.0	270.2	252.3	147.0	247.4	M within W	11.26	31.86
Mean	301.5	253.2	238.6	249.4	269.3	190.8		W within M	11.55	32.66
Filled grains panicle^{-1}										
M_1: Dry-DSR	111.5	107.7	104.0	106.0	101.5	77.2	101.3	M	1.90	6.18
M_2: Wet-DSR	113.8	96.5	89.0	96.0	101.8	83.5	96.8	W	1.09	3.09
M_3: PTR	125.8	122.2	112.3	119.0	116.8	99.2	115.9	M within W	2.32	6.56
Mean	117.1	108.8	101.8	107.0	106.7	86.6		W within M	1.54	4.37
Test wt (g)										
M_1: Dry-DSR	22.97	22.80	22.59	22.69	22.40	22.15	22.6	M	0.16	0.51
M_2: Wet-DSR	23.01	22.00	21.91	22.00	22.41	22.17	22.2	W	0.07	0.21
M_3: PTR	23.62	23.41	23.14	23.17	23.38	22.35	23.2	M within W	0.18	0.51
Mean	23.20	22.73	22.55	22.62	22.73	22.22		W within M	0.10	0.29
Grain yield (kg ha^{-1})										
M_1: Dry-DSR	4943	4926	4436	4662	3056	882	3818	M	76.8	250.3
M_2: Wet-DSR	5064	4441	3983	4118	3543	2191	3890	W	145.9	412.6
M_3: PTR	5111	5055	4759	4935	4536	3992	4731	M within W	194.5	549.9
Mean	5039	4807	4393	4572	3712	2355		W within M	206.3	583.5
HI (%)										
M_1: Dry-DSR	45.84	45.88	43.60	44.62	44.24	37.09	43.54	M	0.79	NS
M_2: Wet-DSR	46.28	44.96	43.62	44.37	43.71	40.23	43.86	W	0.29	0.82
M_3: PTR	46.37	45.61	44.63	45.09	43.29	42.70	44.62	M within W	0.87	2.45
Mean	46.16	45.48	43.95	44.69	43.75	40.01		W within M	0.41	1.16

Table 4: Interaction effect of establishment methods and weed management on economics of rice (Pooled data of 2 years)

Treatments	W_1: Hand weeding twice	W_2: Oxadiargyl *fb.* Penoxsulam + Cyhalofop	W_3: Oxadiargyl *fb.* Triafamone + Ethoxysulfuron	W_4: Oxadiargyl *fb.* Bispyribac + Fenoxaprop	W_5: Brown/ Green manuring *fb.* 2,4-D	W_6: Unweeded control	Mean	Analysis of variance		
								Treatments	S.Em (±)	CD (P=0.05)
NMR (Rs ha^{-1})										
M_1: Dry-DSR	39967	49342	39349	43401	14050	-27214	26483	M	1482	4833.6
M_2: Wet-DSR	43842	38164	28569	30890	22416	-2273	26935	W	2872	8123.4
M_3: PTR	39423	41947	35580	38765	34061	25399	35863	M within W	3817	10794.9
Mean	41077	43151	34500	37686	23509	-1363		W within M	4062	11488.2
B:C Ratio										
M_1: Dry-DSR	1.67	1.99	1.78	1.86	1.29	0.40	1.50	M	0.028	0.090
M_2: Wet-DSR	1.76	1.74	1.55	1.59	1.46	0.95	1.51	W	0.062	0.176
M_3: PTR	1.69	1.77	1.65	1.71	1.66	1.52	1.67	M within W	0.081	0.230
Mean	1.70	1.84	1.66	1.72	1.47	0.96		W within M	0.088	0.249

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