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RESEARCH ARTICLE

Sowing dates and establishment methods determine weed dynamics, yield and economics of rainfed lowland rice

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Abstract

The performance of rice cultivation is significantly influenced by agronomic practices, particularly the sowing time and the method of crop establishment. A field experiment was conducted to evaluate the effect of different sowing times and establishment methods on the weed dynamics, yield and economics of rainfed lowland rice (*Oryza sativa* L.) during Kharif 2017 and 2018. Sowing rice one week before the onset of monsoon proved to be the most effective in reducing the weed density and biomass as compared to sowing at the onset of monsoon, one week after the onset and two weeks after the onset of monsoon. However, sowing rice one week after the onset of monsoon recorded the maximum grain yield (5.29 t ha^{-1}), net return (₹42100 ha^{-1}) and return per rupee invested (1.93) and proved significantly superior to all other dates. Among establishment methods, the puddled transplanted rice (PTR) recorded the maximum grain yield (5.12 t ha^{-1}), net return (₹37800 ha^{-1}) and return per rupee invested (1.81), being at par with the non-puddled transplanted rice (NPTR) and significantly superior to direct seeded rice (DSR). The interaction effect revealed that the PTR fetched significantly higher grain yield (5.60 t ha^{-1}) when sown one week after the onset of monsoon and it was found statistically on par with the NPTR sown one week after the onset of monsoon with a grain yield of 5.39 t ha^{-1}.

Keywords: direct-seeded rice; non-puddled transplanted rice; puddled transplanted rice; sowing time; weed dynamics

Introduction

India is the largest rice-growing country in the world in terms of acreage and the second in production, producing 29 % of the nation's calorie requirements, making it the most staple food crop of the country (1). Worldwide, rice feeds ~50 % of the human population and provides 19 % of its global calorie intake (2). With the rising demand for food due to an increasing population and the challenges posed by climate change, improving rice productivity and profitability while ensuring sustainable agricultural practices is more crucial than ever. Among the various agronomic factors influencing rice production, sowing date and establishment method play significant roles in determining crop performance, weed pressure and economic returns.

The sowing date for rice cultivation plays a vital role in improving its growth and increasing the yield. The sowing time of the rice crop is important for three major reasons. Firstly, it ensures that vegetative growth occurs during a period of congenial thermal regime and high levels of solar radiation. Secondly, the optimum sowing time for each cultivar ensures avoiding cold stress. Thirdly, sowing on time guarantees that grain filling occurs when milder autumn temperatures are more likely, hence good grain quality is achieved (3). Similarly, planting techniques not only affect profitability due to the effect on cost of production but also affect the yield and yield components of crops. Similarly, planting techniques affect profitability by influencing production costs and crop yield components. Therefore, by using a suitable method of planting, it is possible to increase production, productivity and profitability of the rice crop. Transplanting puddled soil is the most dominant and traditional method of rice establishment in irrigated lowland. Puddling, the typical pre-planting management practice, is done to reduce water infiltration and to maintain the standing water in the field, which also helps in weed management and facilitates easier transplanting. However, puddling not only consumes much energy and time from the tillage point of view, but also deteriorates soil structure and consumes a large quantity of the total water requirement in rice (4). In the context of looming water scarcity, labour scarcity and deteriorated soil structure due to puddling, there is an urgent need to replace the conventional transplanting method of rice with non-puddled transplanting (NPTR) or direct seeding (DSR).

Weeds are one of the major biotic stresses in rice fields and compete with the crop for nutrients, light, water and space (5). The type and intensity of weed flora are strongly influenced by the sowing date and establishment method. The DSR fields, especially when sown late, tend to have higher and more diverse weed populations, due to pre-germinated or soaked weed seeds and the absence of water stagnation that usually suppresses weed growth in PTR (puddled transplanted rice). The critical period of weed competition varies with the establishment method. For instance, DSR requires more intensive and timely weed management than transplanted rice. Since weed management accounts for a significant proportion of rice production costs, optimising sowing date and establishment method is critical not only for enhancing yield but also for improving economic returns. Thus, with the challenges of climate variability, resource scarcity and labour shortage, the determination of the appropriate sowing times and methods of crop establishment is important to maintain rice productivity and profitability. These factors have been emphasized in previous studies, but information is scanty under certain agro-climatic zones under a changing climate, the eastern coastal plains of India being one of them, where sowing dates are often determined by the variability in the onset of monsoon. Accordingly, the current study was carried out to determine the interaction effects of sowing time and establishment methods on weed dynamics, yield and economics of rice.

Materials and Methods

Experimental site

The field experiment was conducted during the Kharif 2017 and 2018 at the Instructional Farm of the College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, under the East and South Eastern Coastal Plains Agro-climatic Zone of Odisha, India. It is situated at 20°15' N Latitude and 85° 52' E Longitude at an elevation of 25.9 m above mean sea level (MSL). The soil at the site was sandy loam with pH 5.92, organic carbon 0.56 % and available nitrogen 195.7 kg ha^{-1}, available phosphorus 16.2 kg ha^{-1} and available potassium 278.5 kg ha^{-1}.

Experimental design

The experiment was laid out in a split-plot design with three replications. Four dates of sowing in the main plots and three rice establishment methods in the subplots were evaluated in both years. The date of sowing involved D_1- one week before onset of monsoon, D_2- on the onset of monsoon, D_3- one week after onset of monsoon and D_4- two weeks after onset of monsoon and the rice establishment methods involved E_1- PTR, E_2- NPTR and E_3- DSR in line.

Crop management and observations

The rice variety used in this study was 'Hiranmayee' with a growth duration of 132-138 days. The sowing in the nursery under PTR and NPTR coincided with the sowing in DSR in the main field under each date of sowing. Rice seedlings of 25-30 days old were transplanted in the prepared plots under puddled and non-puddled conditions. A uniform dose of 60 kg N, 30 kg P_2O_5 and 30 kg K_2O was applied per one hectare area in the form of urea, diammonium phosphate (DAP) and muriate of potash (MOP) to each treatment. The total phosphorus was applied as basal in the form of DAP (46 % P_2O_5). Potassium was applied in the form of muriate of potash (60 % K_2O/ha) in two equal splits, as basal and at panicle initiation stage. The nitrogen fertilizer was applied in three splits at basal (25 %) as DAP (18 % N), active tillering stage (50 %) and at panicle initiation stage (25 %) as prilled urea (46 % N). In each treatment, Pretilachlor at 1.5 kg active ingredient/ha was applied as a pre-emergence application in order to control weed growth. The rest of the management practices were in accordance with the recommended package of practices.

The species-wise weed population was recorded from each plot by the least-count quadrat method at 60 days after sowing (DAS). Weed population was expressed as individuals per m^2. Dry weight of weeds (excluding roots) was recorded after sun drying, followed by oven drying at 70 °C for 24 hr and was expressed as g m^{-2}. The economic analysis of each treatment was done on the basis of prevailing market prices of the inputs used and outputs obtained under each treatment.

Importance value index (IVI) of weed species

Species-wise weed counts were taken from 20 quadrates at 30 DAS from fallow land adjacent to the experimental site. The phytosociological indices were computed by using the following formulae mentioned previously (6, 7).

$$\text{Density} = \frac{\text{Total number of individuals of a species in all the quadrates}}{\text{Total number of quadrates studied}} \quad \text{(Eqn.1)}$$

$$\text{Dominance /Abundance} = \frac{\text{Total number of individuals of a species in all the quadrates}}{\text{Total number of quadrates in which the species occurred}} \quad \text{(Eqn.2)}$$

$$\text{Frequency (\%)} = \frac{\text{Number of quadrates in which a species occurred}}{\text{Total number of quadrates studied}} \times 100 \quad \text{(Eqn.3)}$$

$$\text{Relative density (RDe)} = \frac{\text{Density of an individual species}}{\text{Total density of all the species}} \times 100 \quad \text{(Eqn.4)}$$

$$\text{Relative dominance (RDo)} = \frac{\text{Dominance of an individual species}}{\text{Total dominance of all the species}} \times 100 \quad \text{(Eqn.5)}$$

$$\text{Relative frequency (RF)} = \frac{\text{Frequency \% of an individual species}}{\text{Total frequency \% of all the species}} \times 100 \quad \text{(Eqn.6)}$$

$$\text{Importance value index (IVI)} = \text{RDe} + \text{RDo} + \text{RF} \quad \text{(Eqn.7)}$$

Statistical analysis

Data was analysed using analysis of variance (ANOVA) to evaluate the differences among treatments as suggested previously (8). The data pertaining to weeds were transformed to a square root scale and analysed. Whenever a significant difference existed, a critical difference was constructed at a five per cent probability level.

Results and Discussion

Importance value index (IVI) of weed species at the experimental site

The importance value index (IVI) quantitatively assesses ecological dominance and prevalence of weed species in the studied area. Importance value index is a composite measure that includes relative frequency, density and abundance, offering insight into relative ecological significance of species in the ecosystem. Rice crop in the experimental site was infested with 16 species of weeds belonging to 7 families (Poaceae, Cyperaceae, Commelinaceae, Onagraceae, Asteraceae, Marsileaceae, Convolvulaceae). The IVI data are presented in Fig. 1. The IVI reflected relative value of each species out of 300.

The IVI analysis revealed that *Echinochloa crusgalli* had the highest IVI value at 32.7, indicating its dominance in the weed flora of the area. This was followed by *Ludwigia parviflora* (29.1), *Cyperus difformis* (27.7) and *Commelina benghalensis* (26.2), suggesting these species are highly competitive and potentially more adaptive to the local agroecological conditions. *Digitaria sanguinalis* and *Marsilea quadrifoliata* also showed considerable presence with IVI values of 25.0 and 20.9, respectively. On the other hand, species such as *Ipomoea aquatica* and *Cyperus compressus* had the lowest IVI values (10.0 each), indicating a relatively minor ecological impact or lower frequency in the surveyed plots. The distribution of IVI values among weed species suggests a moderately heterogeneous weed community. The dominance of a few species like *E. crusgalli* points to the potential need for targeted weed management practices, especially in rice-based or wetland cropping systems where such species may flourish.

Weed density and weed biomass

Sowing rice one week before the onset of monsoon was observed to be the most efficient in controlling weeds and recorded the minimum values of grass, sedge and broadleaved weed density at 60 DAS (Table 1). Pooled over years, the treatment recorded the minimum grass, sedge and broadleaved weed density of 32.1, 12.0 and 17.9 m^{-2} reflecting decline of grassy weed density by 24, 35 and 43 %, sedge density by 34, 52 and 64 % and broadleaved weed density by 33, 47 and 62 % compared to sowing at onset of monsoon, one week after onset and two weeks after onset respectively. This may be attributed to the fact that early sowing increases the rate of rice seedling growth under better soil moisture conditions so that the rice seedlings can compete better with the later germinated weeds for light, nutrients and space. These observations agreed with those reported earlier (9), who found that quicker canopy closure of rice with early seeding decreased emergence and biomass of weeds due to better crop-weed competition. On the other hand, delayed sowing coincides with the peak weed germination period, resulting in increased weed density. It is evident from earlier findings that altering sowing dates significantly influences weed dynamics (10).

Among crop establishment methods, the PTR recorded the minimum grass, sedge and broadleaved weed density. It was significantly superior to NPTR and DSR (Table 1). Pooled over seasons, the PTR recorded the minimum grass, sedge and broad-leaved weed density of 32.1, 10.0 and 14.6 m^{-2}, respectively, registering a decline in grassy weed density by 27 and 46 %, sedge density by 54 and 71 % and broad-leaved weed density by 51 and 71 % compared to NPTR and DSR, respectively. The DSR plots exerted the highest weed pressure, corroborating earlier work (11, 12), whereby the absence of standing water during the critical early growth stage stimulated germination of a diverse weed flora. In addition, aerobic conditions, a congenial environment for weed species such as *E. crusgalli* and *C. difformis,* were created in the absence of puddling and incorporation of weeds under DSR.

Weed biomass was highly influenced by differential dates of sowing and different establishment methods in rice (Table 1). Pooled over the seasons, sowing rice one week before onset of

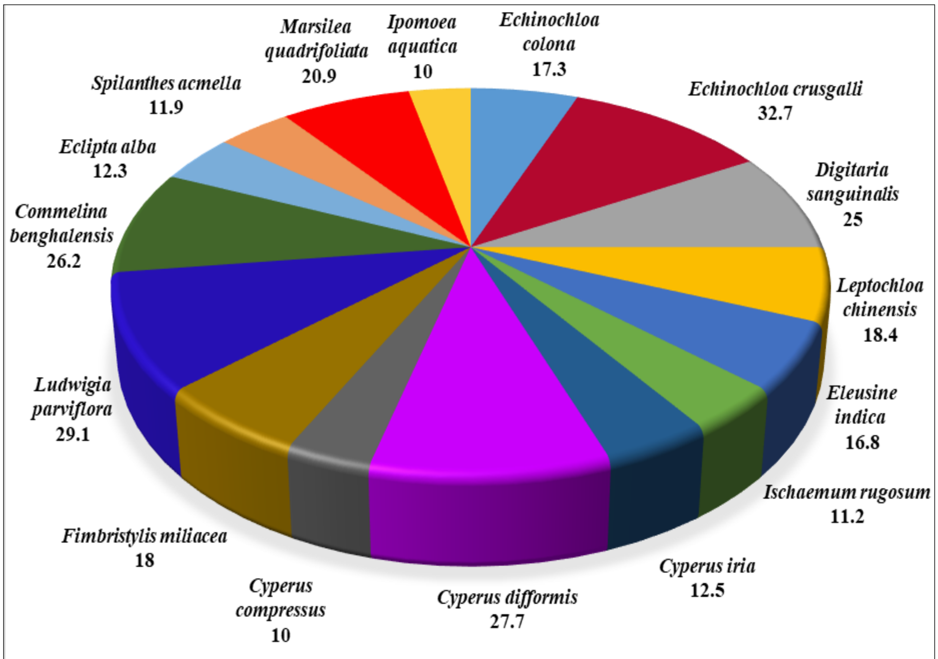

Fig. 1. Importance value index (IVI) of weed species in the experimental site. The value of IVI for each species indicates relative value out of 300.

Table 1. Effect of date of sowing and establishment methods on weed density (No. m^{-2}) and total weed biomass (g m^{-2}) of Kharif rice at 60 DAS

Particulars	Weed density (No. m^{-2})			Weed biomass (g m^{-2})			Total weed biomass (g m^{-2})
	Grasses	Sedges	BLW	Grasses	Sedges	BLW	
Sowing dates in rice							
D_1	5.6 (32.1)	3.4 (12.0)	2.86 (8.77)	2.85 (8.25)	2.73 (7.54)	2.86 (8.77)	4.81 (24.56)
D_2	6.4 (42.4)	4.1 (18.3)	3.58 (12.86)	3.68 (13.72)	3.45 (11.76)	3.58 (12.86)	6.16 (38.35)
D_3	7.0 (49.7)	4.9 (25.1)	3.96 (15.75)	3.95 (15.55)	3.74 (14.01)	3.96 (15.75)	6.68 (45.33)
D_4	7.5 (56.9)	5.7 (33.9)	4.22 (17.94)	4.39 (19.40)	3.90 (15.29)	4.22 (17.94)	7.20 (52.64)
SEm±	0.161	0.157	0.117	0.113	0.089	0.117	0.123
CD (p=0.05)	0.50	0.48	0.36	0.35	0.26	0.36	0.35
Establishment methods in rice							
PTR	5.6 (32.1)	3.1 (10.0)	2.93 (8.84)	3.00 (9.10)	2.81 (7.91)	2.93 (8.84)	4.99 (25.85)
NPTR	6.6 (44.4)	4.6 (21.8)	3.62 (13.20)	3.69 (13.45)	3.44 (11.70)	3.62 (13.20)	6.16 (38.36)
DSR	7.7 (59.4)	5.9 (35.2)	4.41 (19.45)	4.47 (20.14)	4.12 (16.84)	4.41 (19.45)	7.48 (56.45)
SEm±	0.148	0.116	0.103	0.105	0.084	0.103	0.116
CD (p=0.05)	0.43	0.33	0.30	0.30	0.26	0.30	0.35

Population data are transformed to and the figure in parentheses indicates the original values. **D_1**= One week before onset of monsoon; **D_2**= On the onset of monsoon; **D_3**= One week after onset of monsoon; **D_4**= Two weeks after onset of monsoon; **PTR**= Puddled transplanted rice; **NPTR**= Non-puddled transplanted rice; **DSR**= Direct seeded rice in line; **SEm±** = Standard error of mean; **CD**= Critical difference.

monsoon proved to be the most effective in reducing the biomass and recorded the minimum grass, sedge and broadleaved weed biomass of 8.25, 7.54 and 8.77 g m^{-2} respectively registering decline of grassy weed biomass by 39, 46 and 57 %, sedge biomass by 35, 46 and 50 % and broad leaved weed biomass by 31, 44 and 51 % compared to sowing at the onset of monsoon, sowing one week after onset of monsoon and sowing two weeks after onset of monsoon, respectively. These results indicated that delayed sowing increased weed density and biomass, which could be due to poor seedling vigour of the crop that favoured germination and growth of a wide array of weed species. These findings were in agreement with earlier studies (13, 14), which concluded that late-sown rice is more susceptible to weed infestation due to longer windows for weed emergence and growing less competitively with the weeds themselves.

Among crop establishment methods, the PTR proved to be the most efficient in reducing the biomass of weeds at 60 DAS and proved superior to other crop establishment methods (Table 1). Pooled over the seasons, the PTR recorded the grass, sedge and broadleaved weed biomass of 9.10, 7.91 and 8.84 g m^{-2}, respectively, registering a decline in grassy weed biomass by 32 and 55 %, sedge biomass by 32 and 53 % and broadleaved weed biomass by 33 and 54 % compared to NPTR and DSR, respectively. Lower weed population under transplanted rice might be due to continuous submergence of the crops, that have effectively suppressed the weed population and weed seed germination. The effectiveness of PTR in suppressing weeds has also been reported by previous research findings (15), who reported that transplanting under puddled conditions renders better weed control in Kharif rice compared to non-puddled and direct-seeded methods. A similar trend was observed in earlier studies (5, 16).

Effective tillers per m^2

The number of effective tillers per unit area is a critical determinant of rice yield and is strongly influenced by the time of sowing. In the present study, sowing one week after the onset of monsoon consistently recorded the maximum number of effective tillers m^{-2}, which remained statistically at par with sowing at the onset of monsoon but significantly superior to delayed sowing by two weeks across both years (Fig. 2). When pooled over seasons, sowing one week after the monsoon onset produced 379 effective tillers m^{-2}, thereby outperforming other sowing dates with 7, 13 and 23 % higher values compared to sowing at the onset of monsoon, two weeks after onset and one week prior to onset, respectively. These findings agree with earlier reports where optimum sowing aligned

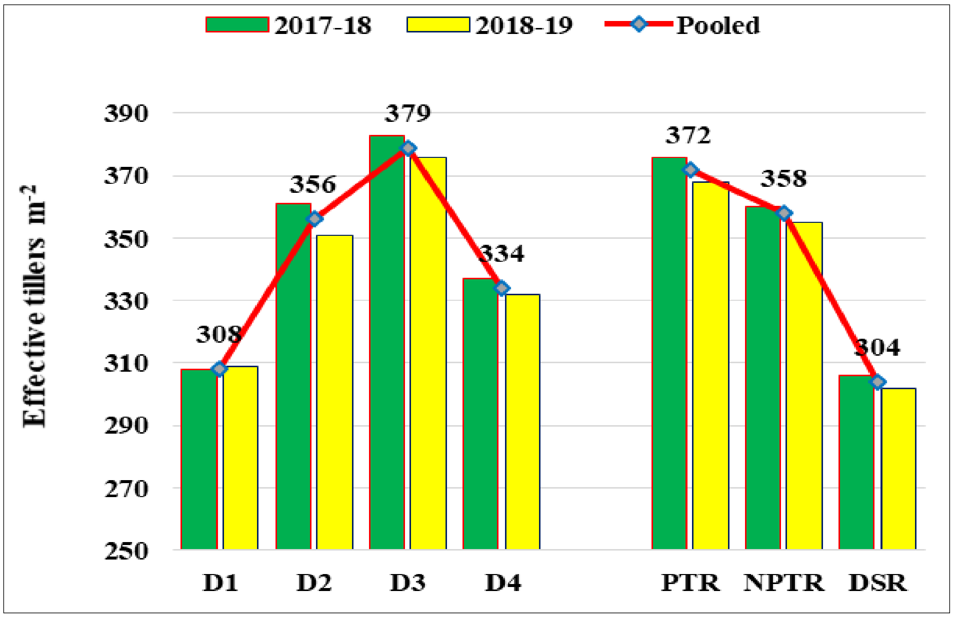

Fig. 2. Effect of date of sowing and establishment methods on the number of effective tillers m^{-2} of Kharif rice.

with favourable rainfall ensured better crop establishment and higher tillering potential (17, 18). Conversely, delayed sowing beyond the optimum window has been reported to reduce tiller formation due to suboptimal soil moisture and shortened vegetative phase (14, 19).

Similarly, the method of crop establishment exerted a significant influence on tiller density. Across both years, PTR produced the maximum number of effective tillers m^{-2}, which remained at par with NPTR but significantly higher than DSR. When data were pooled across seasons, PTR recorded 372 effective tillers m^{-2} and proved superior to the other two establishment methods, registering 4 and 23 % higher effective tiller m^{-2} over NTPR and DSR, respectively. These results corroborate the earlier findings, which reported that transplanting methods, particularly under puddled conditions, favour better crop establishment, uniform plant stand and enhanced tiller development compared to DSR, where early weed competition and uneven crop emergence often restrict tiller production (20).

Filled grains per panicle

Both the date of sowing and the crop establishment methods significantly influenced the number of filled grains $panicle^{-1}$ (Fig. 3). Among the sowing dates, sowing one week after the onset of monsoon produced the maximum number of filled grains $panicle^{-1}$, which was statistically at par with sowing at the onset of monsoon. Pooled over seasons, sowing one week after the onset of monsoon recorded 125 filled grains $panicle^{-1}$ and proved significantly superior to all other dates, registering increases of 12, 23 and 34 % over sowing at onset, two weeks after onset and one week before onset of monsoon, respectively. The higher number of filled grains in this treatment could be attributed to the favourable synchronization between reproductive stages and optimum climatic conditions during flowering and grain filling, which are crucial for spikelet fertility and assimilate partitioning (18, 21).

Among establishment methods, PTR recorded the highest number of filled grains $panicle^{-1}$ during both years, followed closely by NPTR. When data were pooled, PTR registered 116 filled grains $panicle^{-1}$, being statistically at par with NPTR (111 filled grains $panicle^{-1}$). Both PTR and NPTR produced 20 and 15 % higher filled grains $panicle^{-1}$, respectively, over DSR. The superior performance of transplanted systems might be due to better crop stand establishment, uniform tiller development and reduced weed competition, which collectively enhance panicle development and grain filling efficiency (22, 23).

Grain yield

Among dates, sowing rice one week after the onset of monsoon recorded the maximum grain yield in both years and proved significantly superior to all other dates (Table 2). Pooled over seasons, sowing one week after the onset of monsoon gave a grain yield of 5.29 t ha^{-1}, registering 7, 14 and 19 % higher grain yield over sowing at the onset of monsoon, two weeks after and one week before the onset of monsoon, respectively. Significantly higher performances under this sowing window may be attributed to the coincidence of crop phenology with better climate conditions, especially at the crucial reproductive and grain filling phases that led to greater expression of yield-attributing traits, including panicle number, spikelet fertility and test weight. These results are consistent with earlier research findings (24). However, reduced yield under early and late sown crops in the present study was due to exposure to unfavourable environmental conditions. The early sowing is frequently associated with suboptimal soil moisture and erratic distribution of monsoon, affecting tillering and vegetative growth. On the other hand, delayed sowing leads to poor seedling vigour and plant stand (due to high soil moisture and poor germination, reduced bright sunshine hours and disease and insect pest incidence), reduces growing period and exposes crops to stress conditions such as high temperature or moisture stress during grain filling. It is also reported that early or late planting of crops reduced the yield attributing characters and yield significantly (25).

Among the establishment methods, the PTR recorded the maximum grain yield. In 2017, PTR was at par with NPTR and significantly superior to DSR, while in 2018, it was significantly superior to both (Table 2). Pooled over seasons, the PTR gave the maximum grain yield of 5.12 t ha^{-1} and the NPTR, with a grain yield of 4.97 t ha^{-1}, remained at par. The PTR and the NPTR recorded 17 and 13 % higher grain yield compared to the DSR, respectively. This might be due to the fact that there was optimum space for each hill to express production potential, reduced crop-weed competition and adequate availability of nutrients, water and sunlight for proper expression of tillering behaviour and crop growth. These results are in line with earlier findings (26, 27). Higher grain yield under transplanting methods was also reported in previous studies (28-30).

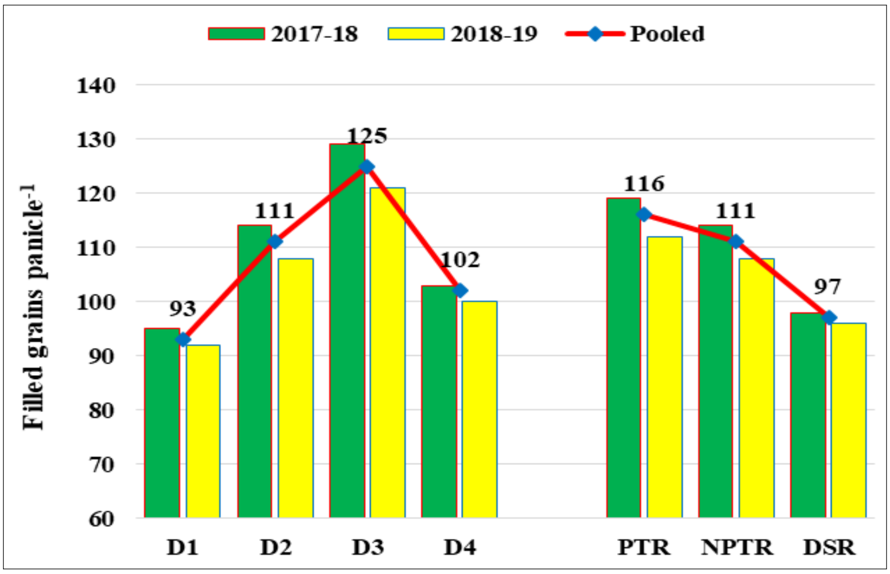

Fig. 3. Effect of date of sowing and establishment methods on the number of filled grains $panicle^{-1}$ of Kharif rice.

Table 2. Effect of date of sowing and establishment methods on yield and harvest index of Kharif rice

Particulars	Grain yield (t ha^{-1})			Straw yield (t ha^{-1})			Harvest index (%)			Net return (₹ '000 ha^{-1})			Return per rupee invested		
	2017	2018	Pooled	2017	2018	Pooled	2017	2018	Pooled	2017	2018	Pooled	2017	2018	Pooled
Sowing dates in rice															
D_1	4.51	4.39	4.45	5.40	5.64	5.52	45.56	44.04	43.75	26.3	30.4	28.4	1.60	1.65	1.63
D_2	5.05	4.84	4.94	5.79	5.74	5.77	46.59	45.73	45.16	34.6	38.3	36.5	1.79	1.82	1.81
D_3	5.40	5.18	5.29	5.88	5.87	5.87	47.92	46.83	46.15	40.1	44.2	42.1	1.92	1.95	1.93
D_4	4.72	4.55	4.63	5.51	5.63	5.57	46.10	44.74	44.42	29.6	33.2	31.4	1.68	1.71	1.70
SEm±	0.097	0.078	0.062	0.147	0.187	0.118	0.540	0.902	0.513	1.513	1.351	1.010	0.036	0.029	0.023
CD (p=0.05)	0.34	0.27	0.22	NS	NS	NS	NS	NS	1.58	5.21	4.74	3.13	0.12	0.10	0.07
Establishment methods in rice															
PTR	5.20	5.04	5.12	5.73	5.82	5.77	47.57	46.61	45.93	35.5	40.0	37.8	1.79	1.83	1.81
NPTR	5.07	4.87	4.97	5.75	5.70	5.72	46.87	46.11	45.49	34.2	38.5	36.4	1.77	1.82	1.80
DSR	4.49	4.30	4.39	5.46	5.64	5.55	45.19	43.28	43.19	28.2	31.0	29.6	1.68	1.70	1.69
SEm±	0.090	0.056	0.052	0.108	0.186	0.104	0.420	0.895	0.494	0.711	0.734	0.512	0.017	0.016	0.011
CD (p=0.05)	0.26	0.16	0.15	NS	NS	NS	1.23	2.61	1.42	2.14	2.09	1.53	0.05	0.05	0.03

D_1= One week before onset of monsoon; **D_2**= On the onset of monsoon; **D_3**= One week after onset of monsoon; **D_4**= Two weeks after onset of monsoon; **PTR**= Puddled transplanted rice; **NPTR**=Non-puddled transplanted rice; **DSR**= Direct seeded rice in line; **BLW**= Broad leaved weed; **SEm±** = Standard error of mean; **CD**= Critical difference.

Interaction effect of date of sowing and establishment methods on grain yield

The interaction effects of date of sowing and establishment methods on rice grain yield were significant and the pooled data are presented in Fig. 4. The PTR fetched significantly higher grain yield (5.60 t ha^{-1}) when sown one week after onset of monsoon and it was found statistically on a par with the NPTR sown one week after onset of monsoon with grain yield of 5.39 t ha^{-1}. This indicates that planting right after the onset of the monsoon creates the best environmental conditions for crops to get established and grow well. Meanwhile, whether the rice seedlings are transplanted into puddled or non-puddled soil, both systems help the crop compete better against weeds and improve the availability of nutrients and water. However, the DSR recorded lower grain yield than the PTR and NPTR and it was the minimum (4.06 t ha^{-1}) when sown one week before the onset of monsoon. This suggests that sowing too early, when the soil moisture is sub-optimal, combined with the greater weed pressure typical under DSR, led to poor crop establishment and ultimately low yield. These results align with previous findings (31).

Straw yield

In the present experiment, neither sowing date nor establishment method significantly affected straw yield, though numerical differences were noted (Table 2). Among the dates, sowing one week after the onset of monsoon gave the highest mean straw yield of 5.87 t ha^{-1}, while among establishment methods, puddled transplanted rice (PTR) gave the mean maximum straw yield of 5.77 t ha^{-1}. The relatively consistent straw yield across treatments indicates that vegetative biomass production in rice is less responsive to manipulation of sowing window and establishment methods when compared with grain yield. This ability may owe itself to the crop's ability to sustain tiller production and vegetative growth through a wide range of conditions, unlike grain yield components, which are particularly sensitive to changes in migration of assimilates from source (leaf and stem) to sink, effective tillers and filled grains per panicle. Similar trends have been reported in earlier studies (32).

Harvest index (HI)

Sowing dates failed to cause any significant variation in HI during both years in 2017 and 2018, although some numerical differences were observed between the years (Table 2). When pooled over years, the maximum HI of 46.15 % was attained when sowing was done one week after the onset of monsoon and was found statistically like sowing done at the onset of monsoon, while earlier and later sowings were recorded with a significantly lower HI. This indicates that, if the optimum sowing time is adapted, better synchronization between vegetative and reproductive growth is achieved, thereby allowing for a greater partition of assimilates towards grain than towards biomass. These results aligned with earlier findings, which reported that rice sown at appropriate times experiences favourable

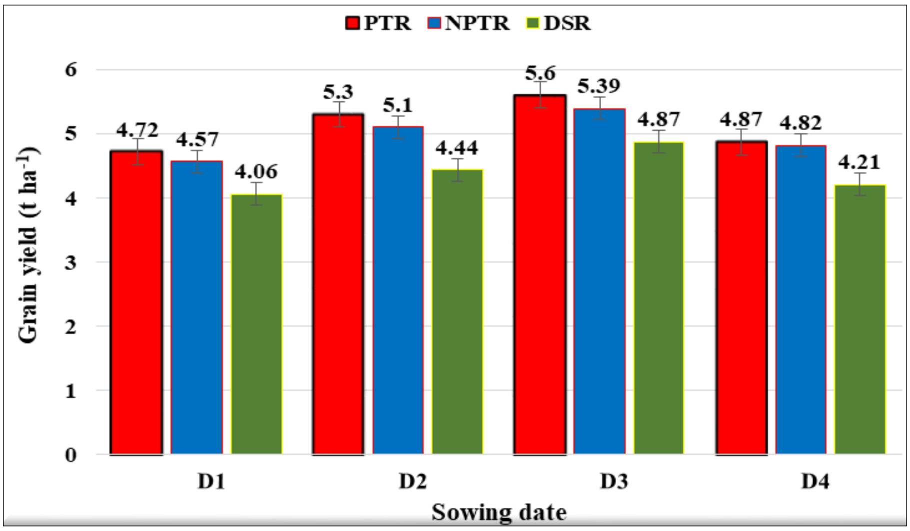

Fig. 4. Interaction effect of date of sowing and establishment methods on grain yield (t ha^{-1}) of Kharif rice.

environmental conditions during grain filling, allowing a greater share of assimilates to be allocated to grains, thereby increasing HI (3).

Among the methods of establishment, PTR recorded the maximum HI of 54.93 %, which was closely followed by NPTR- (45.49 %), while DSR had a significantly lower HI value of 43.19 % (Table 2). The superiority of PTR and NPTR may be attributed to adequate crop establishment, lesser weed competition and a more favourable source-sink relationship, which collectively facilitate higher assimilate partitioning toward grain. The lower HI in DSR could be due to greater weed competition and less-than-optimal moisture conditions during the critical growth stages that promote the quantification of grain against total biomass. Similar observations were reported previously (5, 30), stating that transplanted rice had higher HI than DSR due to better weed control and resource utilisation.

Through these findings, it remains to be established that while sowing time has a slight influence on HI, establishment method, on the other hand, appears to have a very large influence, with systems of PTR and NPTR favouring higher levels of HI through enhancement of grain yield relative to straw production. This has important implications for productivity and resource-use efficiency, as higher HI indicates greater economic returns from the same biomass investment.

Net return

Date of sowing was found to have a significant influence on the net returns of rice cultivation in this study (Table 2). Rice sown one week after the monsoon was found to be the most economically beneficial over both years analysed, with an average net return of ₹42,100 ha^{-1}. This corresponds to an increase of 15, 34 and 48 % over sowing at the onset of monsoon, two weeks after and one week before the onset of monsoon. The higher profitability with this sowing window is because of the very high grain yield observed, which ultimately translated into more monetary returns, given that input costs remained similar. The findings of this study corroborate earlier results (10), which stated that timely sowing in direct-seeded rice enhanced productivity and profitability by synchronizing crop phenology with favourable climatic conditions. In turn, it is emphasized that optimising sowing date would improve yield and economic returns at the farm level under differing agro-climatic conditions (33).

Puddled transplanted rice (PTR) recorded the maximum net returns among the establishment methods, which were statistically at par with NPTR, both being significantly superior to the DSR (Table 2). The pooled net return for PTR and NPTR was ₹37,800 ha^{-1}and ₹36,400 ha^{-1}, respectively, against just ₹2600 ha^{-1}under DSR. This marked 28 and 23 % higher returns in PTR and NPTR, respectively, over DSR. PTR and NPTR were favoured due to their higher grain yields and stable performance even under variable monsoon conditions, while DSR faced greater weed pressure and yield penalties that hindered profitability. Similar findings were observed previously (15), reporting higher profitability of PTR and NPTR over DSR in Kharif rice systems due to enhanced weed suppression and yield stability. Higher net returns were also reported under PTR as compared to DSR in coastal saline ecosystems of eastern India (34).

Return per rupee invested

Among dates, sowing one week after the onset of monsoon recorded the maximum return per rupee invested and was significantly superior to all other dates (Table 2). Pooled over season, sowing one week after the onset of monsoon recorded the maximum return per rupee invested of ₹1.93 and proved significantly superior to all other dates. This advantage can be attributed to the higher grain yield achieved under this sowing window, which increased gross returns while input costs remained nearly constant across treatments. These findings are in agreement with earlier findings (10), which reported that sowing time plays a decisive role in profitability in direct-seeded rice, with optimal sowing windows ensuring higher returns due to better resource use efficiency and reduced yield losses.

Among the three establishment methods, the PTR recorded the maximum return per rupee invested and NPTR remained statistically at par with it, while DSR recorded significantly less value (Table 2). Pooled over seasons, the PTR recorded a return per rupee invested of ₹ 1.81 and the NPTR with ₹ 1.80 remained at par, while DSR gave the minimum value and proved significantly inferior to both the PTR and NPTR. This pattern highlights that although DSR has lower operational costs, the yield penalties caused by higher weed pressure and variable crop establishment reduce its profitability compared to PTR and NPTR. It aligns with earlier findings (35, 36), who reported that, despite lower input costs, profit from DSR was less than that from PTR as yield performance was inconsistent.

Conclusion

The findings of the present research revealed that both sowing time and establishment method significantly affected the weed dynamics, productivity and profitability of Kharif rice. Among all the treatment combinations, PTR sown one week after monsoon onset recorded the highest grain yields and accrued the best economic return; yet NPTR under the same sowing window was equally productive and remunerative. The latter, with reduced soil disturbance and water usage, was found to be an eco-friendly alternative to puddled transplanted rice. In contrast, DSR was prone to weed pressure and yield penalties under adverse conditions. Overall, sowing rice one week after monsoon onset was considered the most suitable window and NPTR offers an opportunity for enhanced productivity, profitability and long-term sustainability of rice-based systems. Future research should focus on evaluating the long-term sustainability, soil health and climate resilience of NPTR across diverse agro-ecological zones. Additionally, studies on integrated weed management, resource-use efficiency and varietal adaptation could further enhance the productivity and environmental benefits of this system.

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Authors' contributions

SP planned and executed the experiment, collected data, performed statistical analysis and drafted the manuscript. BB and BKM guided the experimental design, supervised field experimentation. AB, RKN, RB, AM, IK, ST and MR contributed to data analysis and critically reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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