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RESEARCH ARTICLE

Optimizing productivity, energetics and economics in a rice-blackgram cropping system under variable sowing dates, establishment methods and weed management

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Abstract

A field experiment was conducted to evaluate the influence of sowing dates and crop establishment methods of *Kharif* rice followed by weed management methods in *Rabi* blackgram on the productivity, energetics and economics of a rice-blackgram (*Oryza sativa-Vigna mungo*) cropping system. The experiment was laid out in a split-split plot design, with four sowing dates and three establishment methods in rice and three weed management treatments in blackgram. Results of the experiment revealed that sowing rice one week after the onset of the monsoon, combined with non-puddled transplanted rice (NPTR) and post-emergence application of imazethapyr at 0.1 kg ha^{-1} in blackgram, significantly enhanced system rice equivalent yield (7.93 t ha^{-1}), productivity (19.90 kg ha^{-1} day^{-1}), energy use efficiency (5.74) and profitability (₹55750 ha^{-1} net return). Direct-seeded rice (DSR) recorded higher energy productivity of 0.25 kg MJ^{-1}, while NPTR offered a balance between productivity and energy efficiency and recorded the maximum energy efficiency ratio of 2.84. Overall, the combination of NPTR sown one week after the onset of monsoon, followed by imazethapyr-based weed management in blackgram, proved most effective for maximizing productivity, system energetics and profitability. These findings offer valuable insights for optimizing rice-pulse based cropping systems under monsoon-dependent agro-ecosystems of coastal Odisha.

Keywords: blackgram; direct seeded rice; energetics; non-puddled transplanted rice; puddled transplanted; weed management

Introduction

Sustainable crop production practices are important to sustain the expanding world food demand at low environmental cost and efficient natural resource utilization. Rice-based cropping systems form the backbone of agricultural productivity in the tropical and subtropical countries including India. Rice-blackgram (*Oryza sativa* L.-*Vigna mungo* L.) is one such system which is assuming increasing importance, as it is reported to offer potential to enhance soil fertility, resource-use efficiency and farm productivity (1). Blackgram, a short-duration pulse crop, possesses huge potential in biological nitrogen fixation with soil while maintaining soil structure and disrupting pest and disease cycles, whereas rice is a high-input, resource-demanding crop. When adopted appropriately, the rice-blackgram system may provide a synergistic benefit by enhancing system productivity and profitability while minimizing environmental pollution (2).

Literature revealed that the productivity and sustainability of rice-pulse systems are higher than the rice-fallow or rice-rice system (3). Nevertheless, the efficacy and duration of these systems are significantly affected by key agronomic parameters such as seeding time, crop establishment procedure and weed control strategy. Sowing date is a critical factor in determining a crop's exposure to climatic conditions, pest and disease pressures and the overall growing period (4). Similarly, the method of crop establishment, whether through transplanting or direct seeding, has a significant impact on labor, water and crop productivity (5). In addition, weed competition is a major limitation in both rice and blackgram phases, particularly under minimum tillage or direct-seeded situations and resulting in very heavy yield diminution when left uncontrolled (6).

Although rice-pulse rotations are commonly adopted in many regions of South and Southeast Asia, very few integrated studies have examined the influence of various sowing date-establishment techniques - weed control combination effects on productivity, energetics and economics of the system. Deciphering these interactions is crucial in the context of climate change and declining resource availability. Against this backdrop, the present investigation was carried out to assess the influence of various dates of sowing and methods of crop establishment in rice and weed management in blackgram, on the productivity, energy dynamics and economics of the rice-blackgram cropping system. The results are intended to offer evidence-based guidance to improve system performance and sustainable intensification strategies in rice-dominated agro-ecosystems.

Materials and Methods

Experimental site

The field experiment was conducted during 2017-18 and 2018-19 at the Instructional Farm, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar. The farm is situated at 20°15’ N latitude and 85°52’ E longitude, at an elevation of 25.9 m above mean sea level, approximately 64 km from the Bay of Bengal. The station falls under the East and South Eastern Coastal Plains Agro-climatic Zone of Odisha with Moisture Deficit Index (MDI) of -0 to -20 and a length of growing season of 180 to 210 days. The climate of the area is warm and moist with hot humid summers and mild winters. Broadly, the climate falls in the category of moist hot (7).

Treatment and layout

The field experiment was designed as a split-split-plot design with three replications. Four dates of sowing were assigned to the main plots, three crop establishment methods were allocated to the sub-plots and three weed management practices were implemented in the sub-sub-plots. Altogether, there were 108 plots. The same layout was followed during both the years (Table 1).

Rice variety ‘Hiranmayee’ of 132-138 days duration and blackgram variety ‘Prasad’ (B 3-8-8) of 65-70 days duration were taken up as test crops during *Kharif* and *Rabi* respectively.

System indicators

System rice equivalent yield (SREY)

The value of the produce per hectare of each crop was calculated as per the prevailing market price. This value was then divided by the value of rice per kg to get the rice equivalent yield (REY) in kg ha^{-1}. The sum total of the individual crop REYs within a system constituted the overall REY of that system (8).

$$\text{SREY} = \frac{\text{Seed yield of blackgram} \times \text{Unit price of blackgram}}{\text{Unit price of rice}} + \text{Rice Yield} \quad \text{(Eqn. 1)}$$

Table 1. Treatment details of the experiment

***Kharif* rice**	
Main plots	**Date of sowing in rice**
D_1	One week before onset of monsoon
D_2	Onset of monsoon
D_3	One week after onset of monsoon
D_4	Two weeks after onset of monsoon
Sub plots	**Crop establishment methods in rice**
E_1	Puddled Transplanted Rice (PTR)
E_2	Non-puddled Transplanted Rice (NPTR)
E_3	Direct Seeded Rice (DSR) in lines
***Rabi* blackgram**	
Sub-sub plots	**Weed management in conventionally sown blackgram**
W_1	Pendimethalin at 1.0 kg ha^{-1} as Pre emergence
W_2	Imazethapyr at 0.1 kg ha^{-1} at 15-20 Days after sowing
W_3	Weedy check

System productivity

System productivity is expressed as kg ha^{-1} day^{-1}.

$$\text{System productivity} = \frac{\text{Total system yield}}{365} \quad \text{(Eqn. 2)}$$

(Where the system yield indicates the rice equivalent yield).

Energy indices

The energy value of each cropping system was determined based on energy inputs and energy production for the individual crops in the system as studied previously (9, 10). Inputs and outputs were converted from physical to energy unit measures through published conversion coefficients. Energy output of grain and straw was estimated by multiplying the amount of grain and straw/haulm with corresponding equivalent energy.

On the basis of energy input and output, net energy returns, energy use efficiency, energy efficiency ratio, specific energy, energy productivity and energy profitability were calculated using the previously suggested formula (11, 12).

Various energy use indices were computed by using following formula:

$$\text{a) Energy use efficiency} = \frac{\text{Total output energy (MJ.ha}^{-1}\text{)}}{\text{Total input energy (MJ.ha}^{-1}\text{)}} \quad \text{(Eqn. 3)}$$

$$\text{b) Energy efficiency ratio} = \frac{\text{Total output energy in main product(MJ.ha}^{-1}\text{)}}{\text{Total input energy (MJ.ha}^{-1}\text{)}} \quad \text{(Eqn. 4)}$$

$$\text{c) Energy productivity} = \frac{\text{Total main product yield (kg.ha}^{-1}\text{)}}{\text{Total input energy (MJ.ha}^{-1}\text{)}} \quad \text{(Eqn. 5)}$$

$$\text{c) Energy profitability} = \frac{\text{Net energy return (MJ.ha}^{-1}\text{)}}{\text{Total input energy (MJ.ha}^{-1}\text{)}} \quad \text{(Eqn. 6)}$$

Economics

The economics of various treatments was worked out taking into account the existing market rate of various production factors and produce during the course of investigation.

Statistical analysis

The data obtained on various characters were averaged, tabulated and analyzed statistically as per split-split plot design as suggested earlier (13). Data generated on different parameters of rice and blackgram over the course of the study were subjected to pooled analysis following the procedure mentioned previously (13).

Results and Discussion

System rice equivalent yield (SREY)

System yield was expressed as REY which standardizes the yield of different crops in the sequence by converting them into an equivalent rice yield based on prevailing market prices. This allows for a comprehensive evaluation of system yield that incorporates the yields of *Rabi* blackgram and *Kharif* rice and more accurately reflects economic performance than physical yields alone. Date of sowing in *Kharif* rice caused variation in the date of sowing of succeeding blackgram in *Rabi*, which led to a significant difference in system yield. Data presented in Fig. 1 reveal that date of sowing and establishment methods in rice and weed management practices in blackgram, significantly influenced the system yield of rice-blackgram in both years, as well as when data were pooled. The system involving sowing rice one week after onset of monsoon registered the maximum system yield of 7.52 and 7.22 t REY ha^{-1} during 2017-18 and 2018-19, respectively and found at par with sowing rice on the onset of monsoon. Pooled over the seasons, system yield of 7.37 t REY ha^{-1} under the system involving rice sown one week after onset of monsoon was 3.34 %, 8.86 % and 12.01 % higher than rice sown on the onset of monsoon, one week before onset of monsoon and two weeks after onset of monsoon respectively. Timely sowing aligns critical growth stages with optimal weather conditions viz. adequate soil moisture, solar radiation and temperature, enabling efficient vegetative and reproductive growth in both *Kharif* rice and *Rabi* blackgram. Sowing rice too early (D_1) may lead to suboptimal moisture during germination and too late (D_4) may shorten the crop duration of both rice and the succeeding blackgram due to late *Rabi* sowing. Among rice establishment methods, the system involving transplanted rice, both puddled and non-puddled, recorded significantly higher REY of the system than DSR and both methods of transplanting were statistically at par. Pooled over the seasons, the system involving PTR and NPTR based cropping system recorded 8.02 % higher system REY than DSR. Transplanted systems (PTR, NPTR) generally ensure uniform stand establishment, better early weed suppression and longer crop duration, contributing to higher rice yields. Additionally, the better structure and health of the soil in NPTR may benefit the succeeding blackgram crop by improving seedbed conditions and residual fertility. In contrast, DSR often faces challenges like poor crop establishment, higher weed pressure and shorter crop duration, which collectively reduce system productivity. Higher yield of transplanting was reported under the NPTR compared with the DSR due to better weed control under transplanted conditions (14, 15). However, similar grain yield was observed between non-puddled transplanting and puddled transplanting (16). But the experimental results deviate from the findings of other studies that reported similar or higher yield under DSR than PTR (17-19).

Weed management in *Rabi* blackgram influenced system REY during both the years. Pooled over the seasons, the application of imazethapyr at 0.1 kg ha^{-1} recorded the maximum system REY of 7.27 t REY ha^{-1}, which was respectively 2.25 % and 11.67 % higher than the application of pendimethalin at 1.0 kg ha^{-1} and weedy check. Legume productivity and nutrient use efficiency are strongly enhanced under herbicide-based weed management, contributing to improved system REY (20).

Interaction effect on system yield (pooled over two years)

The interaction effects of date of sowing with rice establishment methods and weed management in blackgram were significant for system yield of rice-blackgram system (Fig. 2). The system involving sowing rice one week after onset of monsoon with PTR and weed management in *Rabi* blackgram with application of imazethapyr at 0.1 kg ha^{-1} ($D_3E_1W_2$) registered the maximum system REY of 7.93 t ha^{-1}, being at par with sowing rice one week after onset of monsoon with NPTR and weed management in *Rabi* blackgram with application of imazethapyr at 0.1 kg ha^{-1} ($D_3E_2W_2$) or application of pendimethalin at 1.0 kg ha^{-1} ($D_3E_2W_1$) and rice sown on the onset of monsoon with NPTR and weed management in *Rabi* blackgram with application of imazethapyr ($D_2E_1W_2$). The superior performance of these combinations can be attributed to the synergistic effect of timely sowing, which aligns crop phenology with optimal environmental conditions; efficient establishment methods, which ensure better crop stand and resource use; and effective chemical weed management, which reduces early-season crop-weed competition and enhances nutrient availability. These findings are consistent with previous reports, that observed improved productivity under transplanting methods and that demonstrated the benefits of herbicide use in legumes (5, 21, 22). The results underscore the importance of integrating agronomic practices to maximize system productivity in rice-pulse cropping systems, particularly in monsoon-dependent ecologies.

System productivity

Date of sowing in rice-blackgram system influenced system productivity significantly during both years (Fig. 3). Pooled over the seasons, the system involving sowing rice one week after onset of monsoon recorded the maximum system productivity

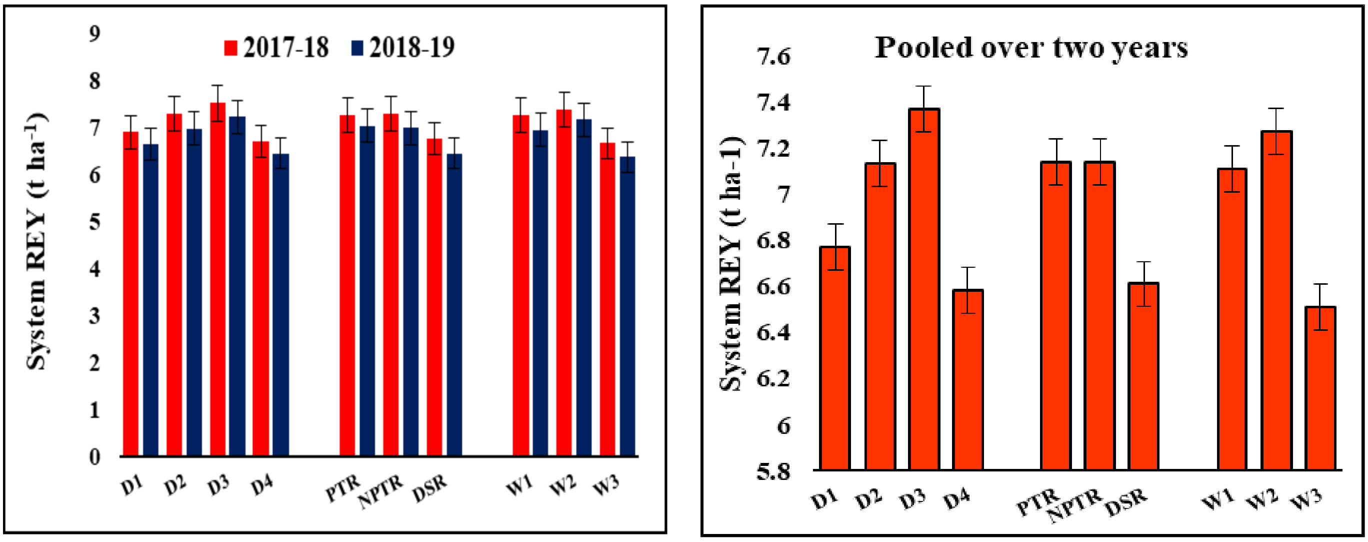

Fig. 1. Effect of date of sowing and establishment methods in rice and weed management in blackgram on system yield of rice-blackgram system.

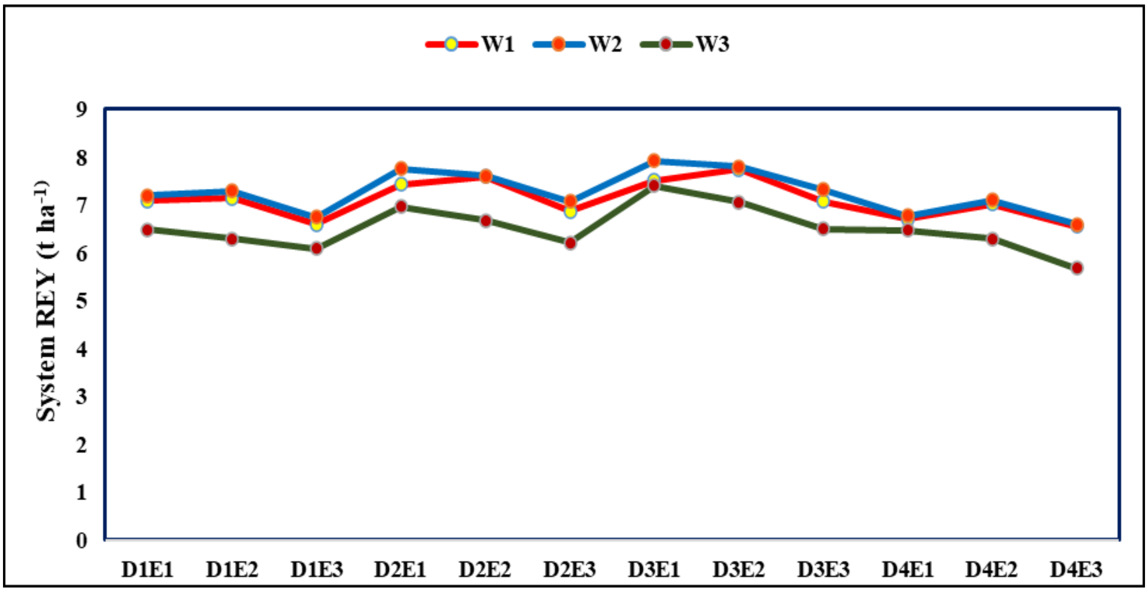

Fig. 2. Interaction effect of date of sowing with rice establishment methods and weed management in blackgram on system yield of rice-blackgram system (pooled over two years).

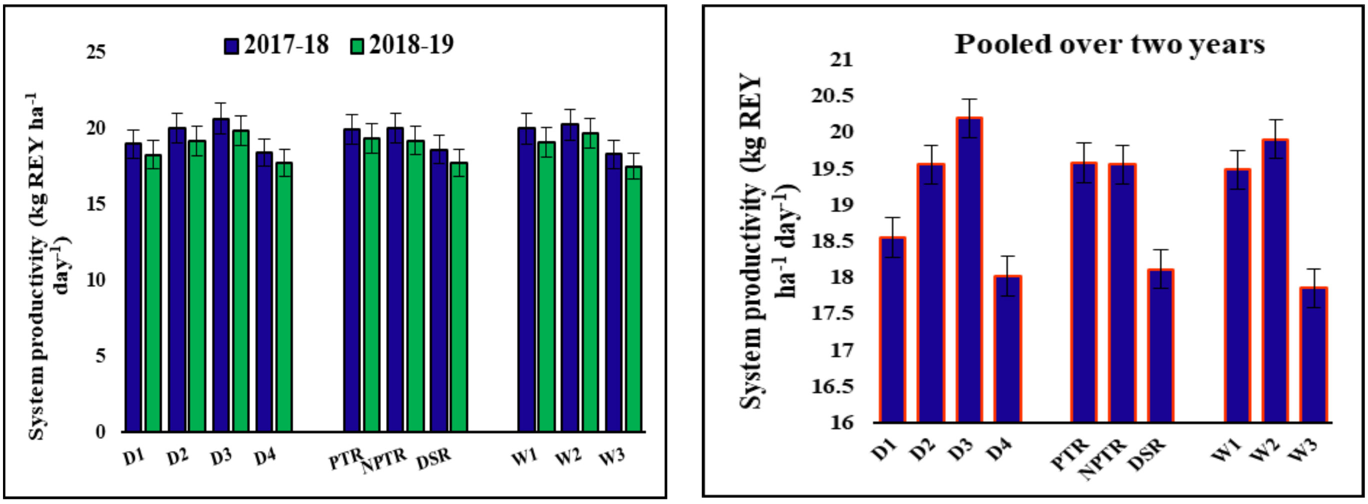

Fig. 3. Effect of date of sowing and establishment methods in rice and weed management in blackgram on system productivity of rice-blackgram system.

of 20.19 kg REY ha^{-1} day^{-1}, being at par with sowing rice on the onset of monsoon, which yielded a system productivity of 19.55 kg REY ha^{-1} day^{-1}. These two timings were followed by sowing rice two weeks after onset of monsoon and sowing rice one week before the onset of monsoon. The crop establishment methods also exerted a significant influence on system productivity during both years. Pooled over the seasons, the system involving PTR recorded the maximum system productivity of 19.57 kg REY ha^{-1} day^{-1}, being at par with NPTR (19.55 kg REY ha^{-1} day^{-1}), which were respectively 8.06 % and 7.95 % higher than DSR.

Among weed management practices in *Rabi* blackgram, the system involving application of imazethapyr at 0.1 kg ha^{-1} recorded the maximum system productivity, achieving 20.20 kg REY ha^{-1} during 2017-18 and 19.61 kg REY ha^{-1} during 2018-19. This was followed by the application of pendimethalin at 1.0 kg ha^{-1} and weedy check. Pooled over the seasons, the application of imazethapyr at 0.1 kg ha^{-1} registered the highest value of system productivity (19.90 kg REY ha^{-1} day^{-1}) reflecting increase of 2.16 % and 11.48 % over application of pendimethalin at 1.0 kg ha^{-1} and weedy check respectively. Blackgram is highly sensitive to early weed competition due to its slow initial growth and shallow rooting. Early-season weed control using post-emergence herbicide (imazethapyr) ensures maximum resource availability (light, nutrients and water) to the crop. Imazethapyr's broad-spectrum weed control and residual activity reduce competition over an extended period, enhancing yield and thereby system productivity.

System energetics

Agriculture both consumes and produces energy. Hence, energy-efficient practices are crucial for sustainable productivity. The agricultural sector requires energy as an essential input to production, enhancing food security, adding value and contributing to rural economic development (23). The use and cost of energy in agriculture have increased tremendously. Hence, it is necessary to make it more energy efficient. Analysis of input-output energy relationship is a key factor to find out energy efficient cropping systems. Data pertaining to energetics viz. energy productivity, energy profitability, energy use efficiency and energy efficiency ratio of rice-blackgram cropping system are presented in Table 2.

Energy productivity

Data presented in Table 2 reveals that all the three factors under study caused significant variation in energy productivity during both years. Pooled over the seasons, the trend for date of sowing in rice was sowing rice one week after onset of monsoon > on the onset of monsoon > one week before onset of monsoon > two

Table 2. Effect of date of sowing and establishment methods in rice and weed management in blackgram on energy productivity and profitability of cropping system

Particulars	Energy productivity (kg REY MJ^{-1})			Energy profitability			Energy use efficiency			Energy efficiency ratio		
	2017-18	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**	**2017-18**	**2018-19**	**Pooled**
Date of sowing in rice												
D_1	0.22	0.21	0.22	4.43	4.50	4.47	5.43	5.50	5.47	2.69	2.66	2.68
D_2	0.23	0.22	0.23	4.67	4.59	4.63	5.67	5.59	5.63	2.86	2.78	2.82
D_3	0.24	0.23	0.24	4.77	4.70	4.74	5.77	5.70	5.74	2.96	2.88	2.92
D_4	0.21	0.21	0.21	4.41	4.38	4.40	5.41	5.38	5.40	2.67	2.62	2.65
SEm±	**0.007**	**0.005**	**0.004**	**0.052**	**0.065**	**0.041**	**0.072**	**0.076**	**0.052**	**0.038**	**0.045**	**0.029**
CD (p=0.05)	**0.02**	**0.02**	**0.01**	**0.18**	**0.22**	**0.14**	**0.25**	**0.26**	**0.18**	**0.13**	**0.15**	**0.10**
Establishment methods in rice												
PTR	0.22	0.21	0.22	4.40	4.40	4.40	5.40	5.40	5.40	2.76	2.71	2.74
NPTR	0.23	0.22	0.23	4.68	4.61	4.65	5.68	5.61	5.65	2.87	2.81	2.84
DSR	0.25	0.24	0.25	4.64	4.64	4.64	5.64	5.64	5.64	2.76	2.69	2.73
SEm±	**0.005**	**0.004**	**0.003**	**0.045**	**0.048**	**0.033**	**0.049**	**0.051**	**0.035**	**0.029**	**0.027**	**0.020**
CD (p=0.05)	**0.01**	**0.01**	**0.01**	**0.13**	**0.14**	**0.10**	**0.15**	**0.15**	**0.11**	**0.09**	**0.08**	**0.06**
Weed management practices in blackgram												
W_1	0.23	0.22	0.23	4.54	4.52	4.53	5.54	5.52	5.53	2.79	2.74	2.77
W_2	0.23	0.23	0.23	4.58	4.60	4.59	5.58	5.60	5.59	2.81	2.79	2.80
W_3	0.22	0.21	0.22	4.59	4.51	4.55	5.59	5.51	5.55	2.78	2.68	2.73
SEm±	**0.003**	**0.003**	**0.002**	**0.037**	**0.029**	**0.023**	**0.037**	**0.040**	**0.027**	**0.020**	**0.021**	**0.015**
CD (p=0.05)	**NS**	**0.01**	**NS**	**NS**	**0.08**	**NS**	**NS**	**NS**	**NS**	**NS**	**0.06**	**0.04**

weeks after onset of monsoon. Sowing during this optimal window ensures synchronized crop growth with peak resource availability (light, water and temperature), leading to higher yields without proportionally increasing energy inputs, thus improving output-to-input energy ratios. Optimal sowing in pulse-based systems contributes to better dry matter partitioning and harvest index, improving energy return (24). Among establishment methods, the system involving DSR was the most efficient with the maximum energy productivity of 0.25 kg REY MJ^{-1} followed by NPTR and PTR. The system involving PTR registered the least energy productivity of 0.22 kg REY MJ^{-1} and found significantly inferior to other establishment methods. DSR avoids energy-intensive practices such as nursery raising, puddling and manual transplanting. This significantly reduces operational energy input, particularly human and diesel energy, thus improving the energy productivity despite potentially lower yields. PTR, while producing competitive yields, requires greater input of energy, especially for puddling and transplanting, resulting in lower energy productivity. These results align with a previously conducted study, which reported that DSR reduces total energy input by 20 %-30 % compared to PTR, mainly due to savings in labor and irrigation (25). Among weed management practices in blackgram, the system involving application of imazethapyr at 0.1 kg ha^{-1}was more efficient with the maximum energy productivity of 0.23 kg REY MJ^{-1}, which was found at par with application of pendimethalin at 1.0 kg ha^{-1} (0.22 kg REY MJ^{-1}) and both were found superior over weedy check during 2018-19. Effective herbicide-based weed control leads to better yield gains without significant increases in energy input, thereby improving energy productivity. However, weed management practices in blackgram failed to cause significant difference in system energy productivity during 2017-18 as well as when pooled over the years.

Energy profitability

Energy profitability reflects the ratio of energy output (biomass/ yield) to total energy input. It is a crucial indicator for evaluating agricultural system efficiency and sustainability, as higher values reflect greater conversion of resources into useful yield with reduced reliance on non-renewable energy and lower environmental impact. Among the three factors, only date of sowing and establishment methods in rice influenced energy profitability significantly during both the years, whereas weed management in blackgram caused significant variation only during 2018-19. Pooled over the seasons, the system involving rice sown one week after onset of monsoon was the most efficient with the maximum energy profitability of 4.74 and was statistically at par with rice sown on the onset of monsoon (4.63). When sowing is aligned with optimal climatic conditions (as in D_3), both rice and blackgram crops achieve higher physiological efficiency, leading to greater biomass and yield, while input energy remains relatively unchanged. This enhances the net energy returns from the system. The system involving rice sown two weeks after the onset of monsoon was the least efficient with energy profitability of 4.40. The trend exhibited by rice establishment methods for energy profitability was NPTR=DSR>PTR. Although PTR may produce slightly higher yields, its substantially higher energy input requirement lowers its energy profitability to 4.40. The system involving NPTR registered the maximum value of energy profitability (4.65) and was found statistically at par with DSR (4.64). Conservation tillage and non-puddled transplanting improve energy profitability due to reduced machinery use and irrigation (21). Weed management practices in blackgram failed to cause significant difference in system energy profitability.

Energy use efficiency

According to Table 2, date of sowing and rice establishment method significantly influenced system energy use efficiency. Pooled over the seasons, the system involving rice sown one week after onset of monsoon recorded the maximum energy use efficiency of 5.74 and was at par with sowing rice on the onset of monsoon. The system involving rice sown two weeks after onset of monsoon registered the minimum energy use efficiency of 5.40. Delayed sowing shortens the effective growing period and increases susceptibility to terminal drought or suboptimal temperatures, reducing biomass accumulation and yield without proportionately reducing energy input, thereby lowering energy use efficiency (24). Among establishment methods, the system involving NPTR was the most efficient with the maximum energy use efficiency of 5.65 and was statistically at par with DSR (5.64), but PTR was least energy efficient with energy use efficiency of 5.40. Similar findings were reported previously (26, 27).

Energy efficiency ratio

Among all the three factors under study, date of sowing and establishment methods in rice significantly influenced the system energy efficiency ratio, but weed management practices in blackgram caused significant variation only during 2018-19 (Table 2). Pooled over the seasons, the system involving rice sown one week after onset of monsoon was more efficient with the maximum energy efficiency ratio of 2.92, followed by sowing rice on the onset of monsoon (2.82), one week before onset of monsoon (2.68) and two weeks after onset of monsoon (2.65). The trend exhibited by rice establishment methods was NPTR > PTR = DSR. NPTR systems combine the benefits of transplanted rice (good crop stand, weed suppression) with reduced energy inputs (e.g. less diesel use and water pumping due to absence of puddling), improving the energy output:input ratio. While DSR has low input energy, yield instability due to weed competition or uneven germination can reduce total output energy. PTR, despite higher yields in some cases, incurs the highest energy input due to labor- and machinery-intensive operations like puddling and transplanting, thereby reducing its energy efficiency ratio (21). Among weed management practices in blackgram, the system involving application of imazethapyr at 0.1 kg ha^{-1} was more efficient with an energy efficiency ratio of 2.80, while the weedy check was the least efficient with an energy efficiency ratio of 2.73.

Economics

The details of economics including gross returns, net returns and benefit to cost ratio (B:C) of the rice-blackgram system under different treatments are summarized in Fig. 4-6.

Gross return

All the factors under study significantly influenced system gross return during both the years (Fig. 4). Averaged over the seasons, the system involving rice sown one week after onset of monsoon was significantly superior to other dates of sowing with gross return of ₹121460 ha^{-1}. The trend exhibited by the date of sowing for system gross return was sowing rice one week after onset of monsoon > sowing rice on the onset of monsoon > sowing rice one week before onset of monsoon > sowing rice two weeks after onset of monsoon. The system involving PTR accrued the maximum value for gross return (₹117760 ha^{-1}), being statistically comparable to NPTR, but DSR registered the least gross return of ₹108890 ha^{-1}.

Among weed management practices in blackgram the system involving application of imazethapyr at 0.1 kg ha^{-1} registered the maximum gross return of ₹119770 ha^{-1} reflecting increase of 2.23 % over application of pendimethalin at 1.0 kg ha^{-1} and 11.59 % over weedy check.

Net return

All the three factors significantly influenced system net return during both the years (Fig. 5). Averaged over the seasons, the system involving rice sown one week after the onset of monsoon registered the maximum net return of ₹55750 ha^{-1}. This represented an increase of 7.54 %, 21.51 % and 30.62 % over sowing rice on the onset of monsoon, one week before the onset of monsoon and two weeks after the onset of monsoon respectively. Sowing one week after the monsoon provided maximum net return, driven by superior yields without a corresponding increase in input costs. Earlier or later sowings either reduced yields or increased crop management efforts (e.g. irrigation or replanting), thus reducing profitability. The decreasing trend of rice establishment methods for system net return was NPTR=PTR>DSR. NPTR matched PTR in returns but reduced input costs, especially labor, water and energy, thereby maximizing net return. DSR, while having the lowest gross return, offset some of the losses by lower cultivation costs, especially in terms of labor and irrigation, hence achieving net return comparable to PTR (28). However, its lower productivity limits its economic viability compared to NPTR. The system involving the application of imazethapyr at 0.1 kg ha^{-1} fetched the maximum net return of ₹53570 ha^{-1}, followed by the application of pendimethalin at 1.0 kg ha^{-1} (₹51360 ha^{-1}) and weedy check (₹42190 ha^{-1}).

Benefit to cost ratio (B:C)

All the factors under study significantly influenced system return per rupee invested during both the years of investigation. Averaged over the seasons, the system involving rice sown one week after the onset of monsoon fetched the maximum return per rupee invested of ₹1.85 and was found superior to other rice sowing dates (Fig. 6). Sowing rice two weeks after the onset of monsoon recorded the least return per rupee invested of ₹1.65. Delayed sowing resulted in reduced crop duration and productivity, leading to a reduced B:C. Similar findings were reported previously (4). Among rice establishment methods, the system involving NPTR accrued the maximum value for return per rupee invested of ₹1.77 due to reduced cost of cultivation under NPTR. This was in close

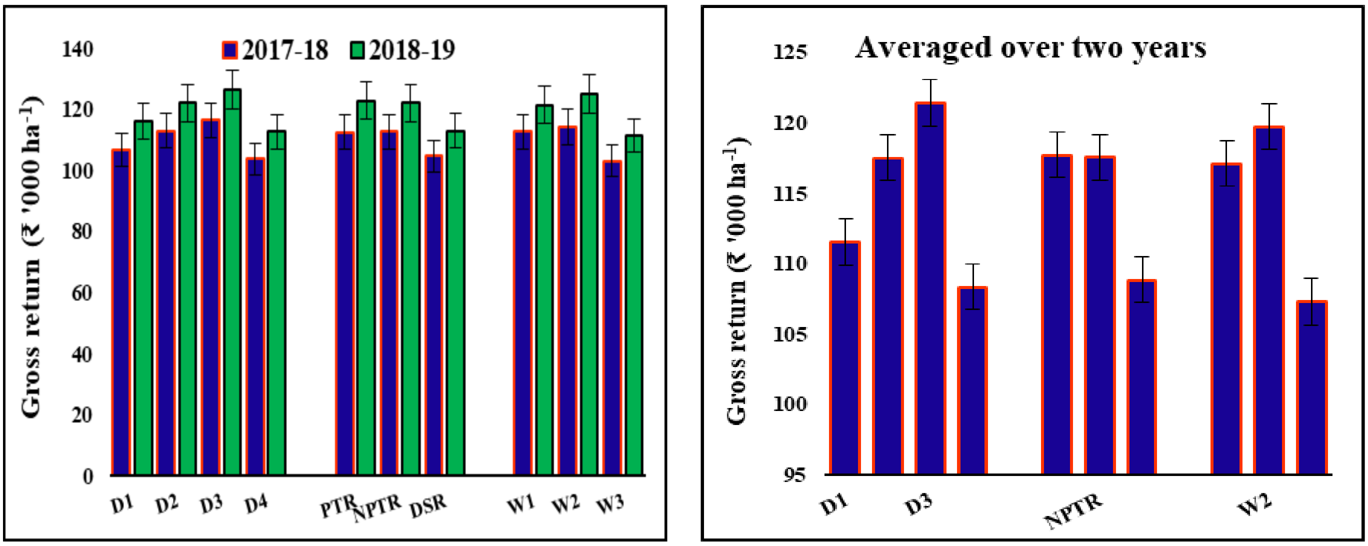

Fig. 4. Effect of date of sowing and establishment methods in rice and weed management in blackgram on gross return of the system.

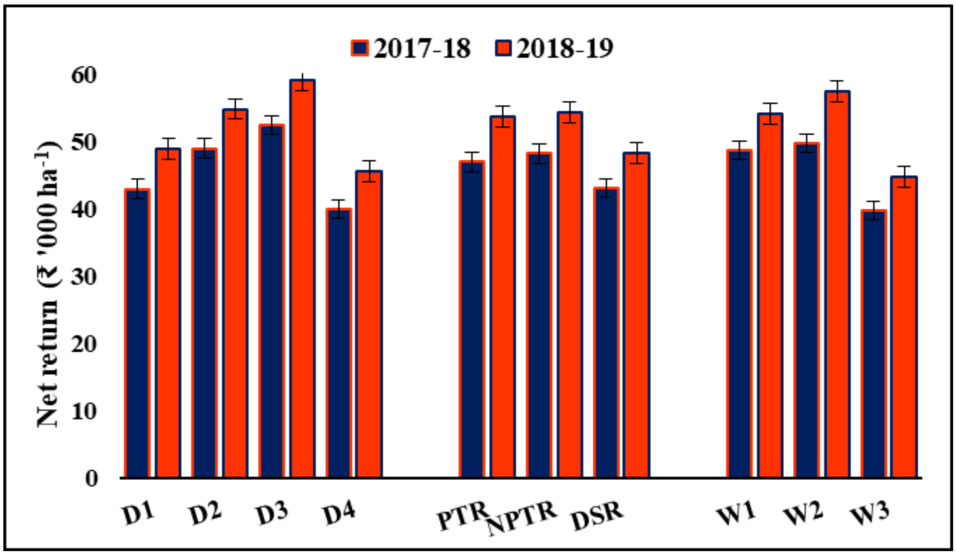

Fig. 5. Effect of date of sowing and establishment methods in rice and weed management in blackgram on net return of the system.

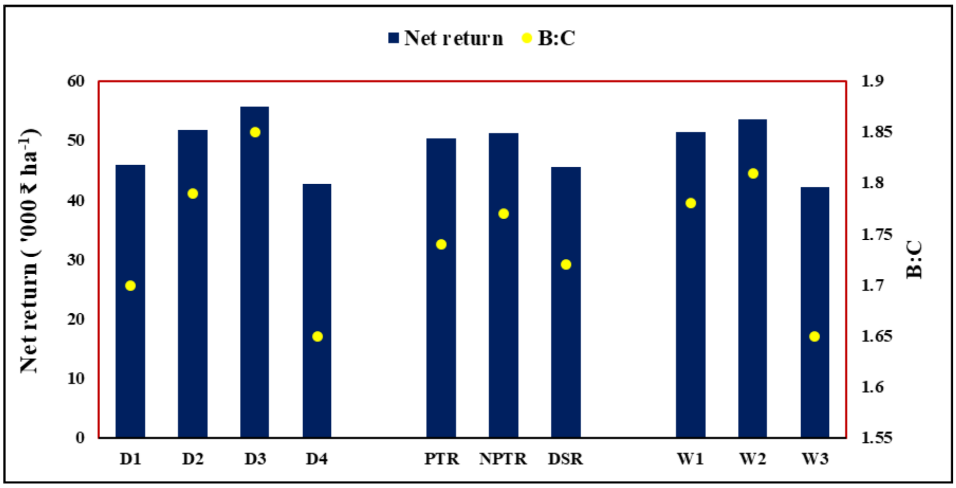

Fig. 6. Effect of date of sowing and establishment methods in rice and weed management in blackgram on production economics of the system (averaged over two years).

conformity with findings that suggested transplanting into non-puddled soil is a labour and cost-saving option (29). The DSR-based system registered the least return per rupee invested of ₹1.72, but it was found on a par with the PTR-based system. This might be due to the PTR involved in higher cost of cultivation as compared to DSR. This authenticated earlier findings, who reported that the net return of DSR was higher than PTR due to lower cost of cultivation which was due to substantial reduction in machinery use (41.34 %), irrigation (22.45 %) and human labour (6.62 %) (30). However, this result is in contrast with previous findings who found that net returns and B:C were higher under DSR as compared to NPTR (31). The trend exhibited by weed management practices in blackgram for system B:C was application of imazethapyr at 0.1 kg ha^{-1}> application of pendimethalin at 1.0 kg ha^{-1}> weedy check. The economic superiority of sowing rice one week after monsoon, using NPTR and managing blackgram weeds with imazethapyr stems from the synergy between optimized agronomic conditions, cost-efficient practices and improved resource use efficiency. These combinations ensure higher productivity and profitability while keeping the cost of cultivation in check, which are key drivers of economic sustainability in rice-based cropping systems.

Conclusion

The present study demonstrated that agronomic management strategies, particularly the date of sowing, method of rice establishment and weed control practices in blackgram, significantly influence the productivity, resource-use efficiency and economic viability of the rice-blackgram cropping system. Among the evaluated treatments, sowing rice one week after the onset of monsoon, coupled with NPTR and chemical weed management using imazethapyr at 0.1 kg ha^{-1} in blackgram, consistently outperformed other combinations across key system indicators.

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Authors' contributions

SP and BB designed and implemented the research plan. SP, BB, BKM, AB, RKN, RB, AM, IK and ST participated in interpretation of the result and writing the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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