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Boosting Wheat Yield and Profitability: A Study on Various Wheat Varieties in Diverse Cropping Systems under the Arid and Hot Climate of India

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ABSTRACT

Wheat (Triticum aestivum) is one of oldest and most widely cultivated cereal crops, serving as a staple food worldwide. However, climate change significantly threatens its growth and productivity. To improve productivity through varied cropping systems, we evaluated the economic feasibility and profitability of five wheat varieties Raj-765, Raj-4120, HD-3226, DBW-187, and DBW-222 under arid and high-temperature conditions. The study utilized a split-plot design, with cropping systems designated as the main plots and wheat varieties as the sub-plots, each replicated three times. Our findings show that DBW-222 in the cluster bean-wheat system achieved the highest grain and straw yields, net returns (NR), and benefit-cost ratio (BCR) over a two-year analysis. DBW-222, DBW-187, and Raj-4120 also showed superior yields, NR, and BCR across various cropping systems, including fallow-wheat, sesamum-wheat, cluster bean-wheat, green gram-wheat, and moth bean-wheat. Further, Raj-3077 and Raj-3765 performed best in grain and straw yield, net returns (NR), and benefit-cost ratio (BCR) in the groundnut-wheat system, achieving the highest wheat equivalent yield (WEY). In contrast, DBW-222, DBW-187, and Raj-4120 excelled in WEY, WESY, NR, and BCR across the fallow-wheat, sesamum-wheat, cluster bean-wheat, green gram-wheat, and moth bean-wheat systems. However, when grown in the pearl millet-wheat system, Raj-3077 and Raj-3765 recorded significantly lower WEY, WESY, NR, and BCR compared to all other varieties. These findings highlight the significant influence of cropping systems on the performance of wheat varieties, stressing the importance of selecting suitable wheat varieties and cropping systems to boost agricultural productivity and economic returns, particularly in arid and hot climates worldwide.

Keywords: *Cropping system; wheat; net return; profitability; system productivity; agricultural productivity; BC ratio; wheat equivalent yield.*

1. Introduction

The global population is expected to reach around 9 billion by 2050, posing a considerable challenge to food production systems worldwide [1]. As the population expands, the demand for food particularly staple crops will increase substantially [1]. Wheat, the most widely cultivated cereal worldwide, accounts for over 20% of the calories consumed by humans [2, 3]. Although primarily grown for human consumption, wheat also plays a vital role in animal feed. It is a cornerstone of food security, serving as a key ingredient in products such as flour, cereals, pasta, and baked goods [4, 5]. Despite its global importance, wheat yields in India remain significantly below their potential, underscoring the need for improved agricultural practices and technologies. While India is a major producer of wheat, challenges such as suboptimal cultivation practices, limited access to quality seeds, and the impact of biotic and abiotic stresses continue to hinder yield improvements. Addressing these challenges is crucial not only for food security but also for the economic sustainability of agriculture. The economic value of wheat cultivars is determined by their yield, quality, and quantity. High-quality wheat is characterized by key factors such as protein content, gluten quality, sedimentation value, and grain test weight, all of which influence milling and baking performance [6]. Flour quality, which directly impacts baked goods, is influenced by genetic factors, including protein content, gluten strength, and overall baking performance [7]. However, selecting high-performing cultivars alone does not ensure optimal yields or quality. These cultivars must be cultivated under favorable conditions, including proper agronomic practices and crop rotations [7]. Crop rotation, in particular, plays a critical role in ensuring both consistent yields and high grain quality, thereby impacting market value –[8].

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Wheat, which is sensitive to preceding crops, benefits from rotation with crops like *Brassica napus*, which offer soil shade and valuable residues [9]. Other beneficial preceding crops include *Solanum tuberosum* and legumes, which enhance soil fertility and structure [10]. Conversely, sowing wheat after cereal crops can degrade both yield and grain quality due to increased weed competition and heightened susceptibility to diseases, particularly stem diseases [11]. This practice can lead to reductions in volumetric weight, grain uniformity, and wet gluten content, all of which negatively affect flour quality [12]. A comprehensive understanding of the interactions between crop rotation, agronomic practices, and genetic potential is essential for enhancing the sustainability and productivity of wheat farming in India.

Monoculture, particularly the cereal-cereal cropping system, has become increasingly susceptible to pest and disease outbreaks due to the lack of crop diversity. This reduced diversity can significantly diminish agricultural productivity over time. While cereal-based systems are vital for food security, their sustainability is compromised by these vulnerabilities [13]. In contrast, crop rotation where different crops are planted in a specified sequence has been proven to improve both yield and overall system health. Studies have shown that crop rotation enhances yield variability, driven by the rotation effect [14-16]. Integrating legumes into cereal-based cropping systems has long been recognized as beneficial [11]. Pulse crops such as *Pisum sativum*, *Cicer arietinum*, and *Lens culinaris* help diversify these systems and reduce the need for nitrogen fertilizers in subsequent cereal crops, thus improving sustainability [17]. For instance, rotating with field pea and lentil can significantly increase wheat yields while cutting nitrogen fertilizer use by more than 50% compared to traditional systems [18]. Beyond soil fertility, pulse crops also help manage disease pressures. The continuous cultivation of a single crop typically exacerbates disease severity, whereas rotation with pulses disrupts pest and disease cycles, leading to healthier crops and improved yields [19]. Research indicates that even a one-year break from cereals through rotation with pulses can effectively reduce pathogen accumulation in the soil [20]. This practice also reduces the need for pesticides, as increased crop diversity subjects pests and weeds to a variety of stresses, limiting their establishment and growth [20, 21]. However, careful management of pulse cropping frequency is essential, as excessive pulse cultivation can lead to the buildup of soil pathogens, such as those responsible for Aphanomyces root rot, which can threaten crop viability [22]. A balanced approach to pulse integration into crop rotations is crucial for maximizing the benefits while minimizing risks. Incorporating pulses into crop rotations plays a crucial role in improving soil quality, enhancing soil health, water retention, and nitrogen availability [23, 24]. Pulses contribute to higher soil nitrogen levels through biological nitrogen fixation, which in turn boosts the yields of subsequent cereal crops. Research shows that rotations incorporating pulses can significantly increase grain yields in both durum and common wheat [25]. Crops such as field pea have also been found to improve grain yield and protein content in cereals, and higher canola yields have been observed when preceded by field pea rather than barley [26]. Overall, cropping systems that include pulses not only enhance economic returns but also reduce production risks and contribute to long-term sustainability [27]. Despite the increasing recognition of pulses benefit, comprehensive data on their combined agronomic and economic advantages in crop rotations especially for long-term sustainability remains limited. As the role of pulse crops continues to grow, it is essential to explore new methodologies for assessing the lasting impacts of various cropping frequencies and sequences. This multi-site study aims to evaluate the effects of rotating cereal crops with different pulse crops in varied sequences and frequencies, with a focus on annual economic returns and associated risks in a semiarid environment. Notably, the legume-wheat cropping system has attracted significant attention for its potential to enhance soil health and boost crop yields. Planting wheat after legumes is especially beneficial, as it incorporates organic matter from legume leaves and weed residues into the soil, improving soil structure, moisture retention, and nutrient cycling key factors for achieving sustainable agricultural practices [28]. Choosing the right crop combinations is crucial for optimizing agricultural productivity. In legume-wheat rotations, legumes enhance organic matter, nutrient availability, and reduce weed pressure, which benefits subsequent wheat crops. Selecting compatible wheat varieties within these systems can further improve economic efficiency by influencing yield, grain quality, and profitability [29]. Genetic diversity among wheat varieties impacts agronomic traits like yield, disease resistance, and environmental adaptability [30]. Modern breeding techniques, including marker-assisted and genomic selection, enhance the development of wheat varieties resistant to biotic and abiotic stresses [31, 32]. Integrating legumes into rotations improves soil fertility and boosts wheat yields [26, 28]. In this study, we evaluated the economic efficiency of different wheat varieties across various cropping systems, providing valuable insights for optimizing cropping strategies and enhancing sustainability.

2. Materials and Methods

2.1 Site, Soil, and Climatic Conditions

A two-year field study was conducted at the Krishi Vigyan Kendra in Lunkaransar, associated with Swami Keshwanand Rajasthan Agricultural University in Bikaner, India (longitude 73°-76° E, latitude 31°-26° N, elevation 135 m) during the cropping seasons of 2021-22 and 2022-23. The soil in this region is characterized as loamy sand. A chemical analysis indicated that the soil had a pH of 7.6, 0.38% organic matter, an electrical conductivity of 0.35 dSm^{-1}, a total nitrogen content of 0.05%, extractable phosphorus of 6.88 mg kg^{-1}, and extractable potassium of 163 mg kg^{-1}.

2.2 Experimental Details

The experiment aimed to evaluate the economics and profitability of five wheat varieties: Raj-765, Raj-4120, HD-3226, DBW-187, and DBW-222, sown across seven different wheat-based cropping systems. These cropping systems included fallow wheat, groundnut wheat, sesamum wheat, cluster bean wheat, green gram wheat, moth bean wheat, and pearl millet wheat. The experimental design employed a split-plot arrangement, with the cropping systems assigned to the main plots and the wheat varieties arranged in sub- plots, all replicated three times.

2.3 Date of Sowing

In the kharif season, groundnut was sown on June 15 in both years, while the other kharif crops were sown on July 15. The wheat varieties for the rabi season were planted on November 15 of the respective years. However, in the groundnut-wheat system, all wheat varieties were sown on December 1 due to the delayed harvesting of groundnut.

2.4 Crop Husbandry
Before seedbed preparation, a pre-soaking irrigation of 4 inches was applied to ensure adequate moisture. Seedbeds were prepared once the soil reached field capacity according to the assigned treatments. Throughout the growing season, a total of six irrigations were provided to the wheat crop to alleviate moisture stress. All crops were harvested manually upon reaching maturity. At harvest, eleven central rows from each plot were collected, sun-dried for one week, threshed manually, and the grains were separated and weighed to calculate grain yield, which was expressed in quintals per hectare. Grain yields of all crops were adjusted to a moisture content of 10%.

2.5 Data Collection
Grain yield data from the wheat crop were utilized to assess the economics and profitability of each cropping system. Additionally, yield data from all crops were recorded for comprehensive economic analysis.

2.6 Expenses Incurred
Variable and fixed costs were calculated using current market rates of inputs in Indian Rupees (₹). For kharif crops, fixed costs included fertilizer transport and application. The costs associated with land preparation, seeds, sowing, irrigation, fertilizers, and harvesting varied among the rabi crops. For the wheat crop, fixed costs covered seed cost, sowing, transportation of fertilizers, irrigation, and harvesting, while land preparation was classified as a variable cost. Total expenditure was determined by summing the variable and fixed costs for both kharif and rabi crops across the respective treatments.

3. Results
3.1 Effect of preceding crops on phenological components of wheat varieties
The phenological traits of wheat, including days to emergence, booting, ear emergence, flowering, and maturity, were analyzed to assess their potential influence by preceding crops. The results, as presented in Table 1 and Fig. 1 and Fig. 2, clearly demonstrate that these traits were significantly impacted by the preceding crops.

Table 1. Phenological performance and growth parameters of wheat varieties under different cropping systems (Pooled of two years).

Treatments	Phenological performance in wheat					Dry matter accumulation (g metre row length^{-1})				Plant height at harvest (cm)
	Days to emergence	Days to booting	Days to ear head emergence	Days to flowering	Days to Maturity	30 DAS	60 DAS	90 DAS	Harvest	
Cropping systems										
Fallow- wheat	6.2	69.9	78.7	84.2	117.9	11.7	58.9	161.6	188.4	82.8
Groundnut-wheat	7.0	67.9	76.2	81.9	105.1	9.0	44.2	131.2	148.0	71.6
Sesame-wheat	6.8	67.5	75.8	81.5	114.7	8.8	42.8	128.4	144.3	70.6
Cluster bean-wheat	8.1	71.3	80.4	85.9	119.9	11.5	58.0	159.7	186.0	82.2
Green gram-wheat	7.3	68.8	77.3	83.0	116.4	9.7	47.9	138.8	158.1	74.4
Moth bean-wheat	7.1	68.4	76.9	82.5	115.9	9.4	46.5	135.9	154.2	73.3
Pearl millet-wheat	6.3	66.0	74.0	79.8	112.6	7.6	36.0	114.4	125.6	65.4
S.Em.±	0.1	1.3	1.6	1.5	1.8	0.20	1.09	2.25	2.99	0.76
CD at 5%	0.3	3.7	4.5	4.3	5.1	0.57	3.19	6.56	8.73	2.21
wheat varieties										
Raj- 3765	6.4	67.1	75.2	81.0	112.6	8.6	41.5	125.8	140.8	69.6
Raj- 3077	6.7	67.7	76.0	81.7	113.4	9.1	44.4	131.7	148.7	71.8
Raj- 4120	7.1	68.8	77.4	83.0	115.0	9.9	49.1	141.4	161.6	75.4
DBW- 187	7.2	69.3	77.9	83.5	115.6	10.1	50.3	143.8	164.8	76.3
DBW- 222	7.5	69.9	78.7	84.2	116.5	10.7	53.4	150.2	173.2	78.6
S.Em. ±	0.1	0.6	0.8	0.7	0.8	0.14	0.77	1.58	2.11	0.54
CD at 5%	0.2	1.7	2.1	2.0	2.4	0.39	2.16	4.44	5.91	1.51

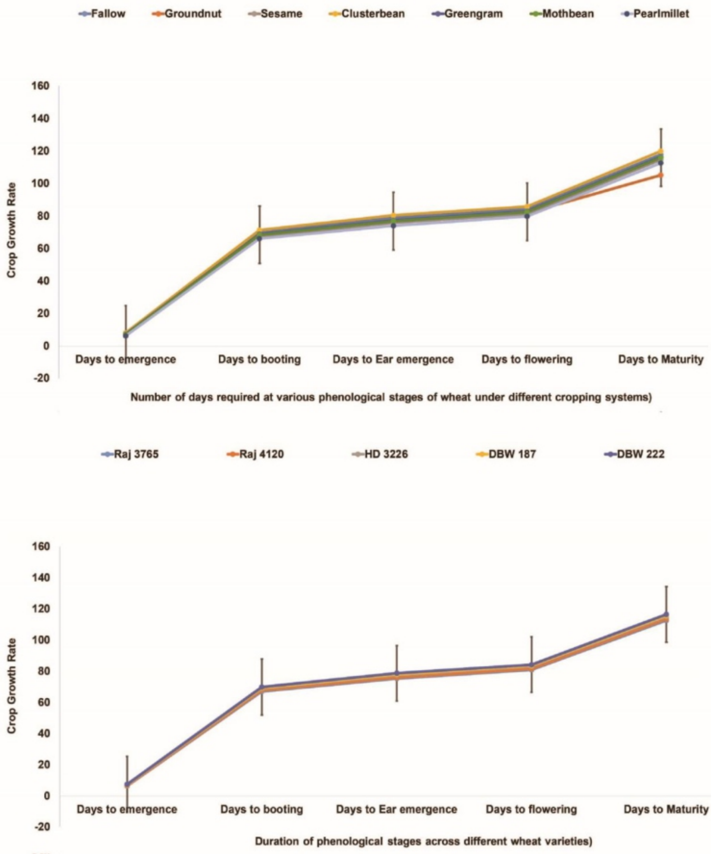

Fig. 1. Duration of each phenological stage in wheat development. (A) Cropping system. (B). Different wheat varieties.

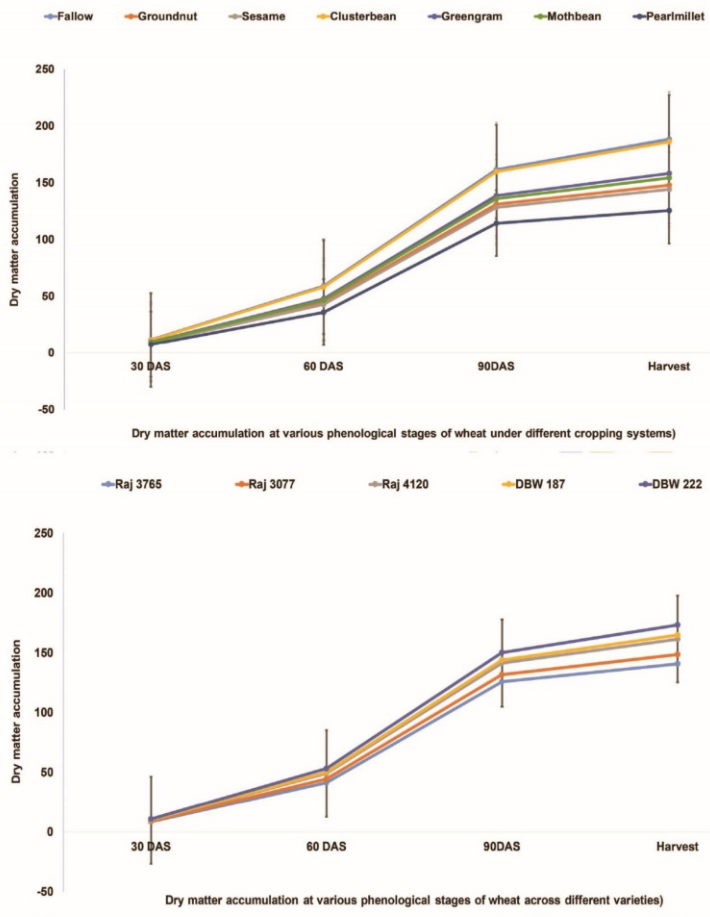

Fig. 2. Dry matter accumulation in wheat at various phenological stages under (A) different cropping systems and (B) across various wheat varieties.

Among the cropping systems, the shortest time to emergence was observed in the fallow-wheat system (6.2 days), followed closely by the pearl millet-wheat system (6.3 days). The sesame-wheat system showed a slightly longer emergence time of 6.8 days, while the groundnut-wheat system and moth bean-wheat system recorded 7.0 and 7.1 days, respectively. The green gram-wheat system showed an emergence time of 7.3 days. The cluster bean-wheat system exhibited the longest emergence time, with wheat taking 8.1 days to emerge. The days to booting, ear head emergence, flowering, and maturity varied across cropping systems. The cluster bean-wheat system exhibited the longest durations, with days to booting, ear head emergence, flowering, and maturity being 71.3, 80.4, 85.9, and 119.9, respectively. In contrast, the pearl millet-wheat system recorded the shortest durations, with 66.0, 74.0, 79.8, and 112.6 days, respectively. Other systems such as fallow-wheat and green gram-wheat showed intermediate values, indicating variability in phenological progression across systems. The cropping systems also influenced dry matter accumulation at various growth stages. At 30 days after sowing (DAS), the highest accumulation was observed in the fallow-wheat system (11.7 g), followed closely by the cluster bean-wheat system (11.5 g). The lowest value was recorded in the pearl millet-wheat system (7.6 g). A similar trend was observed at 60, 90 DAS, and at harvest, where fallow-wheat consistently outperformed other systems with values of 58.9, 161.6, and 188.4 g, respectively. The cluster bean-wheat system closely followed these values, while the pearl millet-wheat system recorded the lowest values of 36.0, 114.4, and 125.6 g, respectively. At harvest, plant height varied significantly across cropping systems. The tallest plants were recorded in the fallow-wheat system (82.8 cm), followed by the cluster bean-wheat system (82.2 cm). The shortest plants were observed in the pearl millet-wheat system (65.4 cm).

The wheat varieties also exhibited variation in their days of emergence. Raj-3765 emerged in 6.4 days, which was the shortest time among the varieties, followed by Raj-3077 (6.7 days). Raj-4120 and DBW-187 exhibited emergence times of 7.1 and 7.2 days, respectively. The longest emergence time was recorded for DBW-222, which took 7.5 days. Among the wheat varieties, DBW-222 showed the longest durations for days to booting (69.9), ear head emergence (78.7), flowering (84.2), and maturity (116.5), whereas Raj-3765 exhibited the shortest durations with 67.1, 75.2, 81.0, and 112.6 days, respectively. Dry matter accumulation was significantly higher in DBW-222, with values of 10.7, 53.4, 150.2, and 173.2 g at 30, 60, and 90 DAS, and harvest, respectively. In contrast, Raj-3765 recorded the lowest values at all stages, with 8.6, 41.5, 125.8, and 140.8 g, respectively. At harvest, the tallest plants were observed in DBW-222 (78.6 cm), while the shortest plants were recorded in Raj-3765 (69.6 cm).

3.2 Effect of preceding crops and wheat varieties on growth components

We also analyzed the impact of preceding crops on growth components, including plant height at harvest, dry matter accumulation, crop growth rate, and relative growth rate. The findings, detailed in Tables 2 and illustrated in Fig. 2 reveal that these growth parameters of wheat were significantly influenced by the preceding crops.

Table 2. Performance of crop growth rate (CGR) and relative growth rate (RGR) of wheat varieties under different cropping systems (Pooled of two years).

Treatments	Crop growth rate (CGR) (g m-2 day-1)				Relative growth rate (RGR) (mg g-1 day-1)			Net photosynthetic rate (umol/m-2/s)	Transpiration rates (mmol/m-2/s)	Stomatal conductance (mmol/m-2/s)
	0-30 DAS	30-60 DAS	60-90 DAS	90DAS- Harvest	30-60 DAS	60-0 DAS	90DAS- Harvest			
Cropping systems										
Fallow- wheat	1.94	7.88	17.10	4.48	133.98	168.38	173.36	62.19	3.55	469
Groundnut- wheat	1.50	5.86	14.50	3.36	124.16	161.40	198.23	44.27	2.79	391
Sesame- wheat	1.46	5.68	14.27	2.65	123.24	160.74	164.42	48.79	2.98	411
Cluster bean- wheat	1.92	7.76	16.95	4.38	133.68	168.11	173.07	65.67	3.69	485
Green gram- wheat	1.61	6.37	15.16	3.22	127.12	163.39	167.58	56.82	3.32	446
Moth bean- wheat	1.57	6.17	14.90	3.06	126.01	162.63	166.68	52.85	3.16	429
Pearl millet- wheat	1.26	4.74	13.06	1.87	117.16	156.77	159.60	40.30	2.63	374
S.Em.±	0.03	0.15	0.19	0.13	0.74	0.52	0.63	1.65	0.07	7
CD at 5%	0.09	0.44	0.56	0.37	2.17	1.52	1.85	4.82	0.20	21
wheat varieties										
Raj- 3765	1.43	5.50	14.04	2.56	121.80	159.86	167.91	46.20	2.88	400
Raj- 3077	1.51	5.89	14.55	2.90	124.24	161.47	169.93	50.36	3.05	418
Raj- 4120	1.65	6.54	15.38	3.45	127.58	163.80	172.76	54.46	3.22	436
DBW- 187	1.69	6.70	15.59	3.59	128.51	164.43	173.54	55.90	3.28	442
DBW- 222	1.78	7.12	16.13	3.94	130.27	165.75	175.09	58.00	3.37	451
S.Em. ±	0.02	0.11	0.14	0.09	0.57	0.39	0.49	1.15	0.05	5
CD at 5%	0.06	0.30	0.38	0.26	1.59	1.08	1.36	3.23	0.14	14

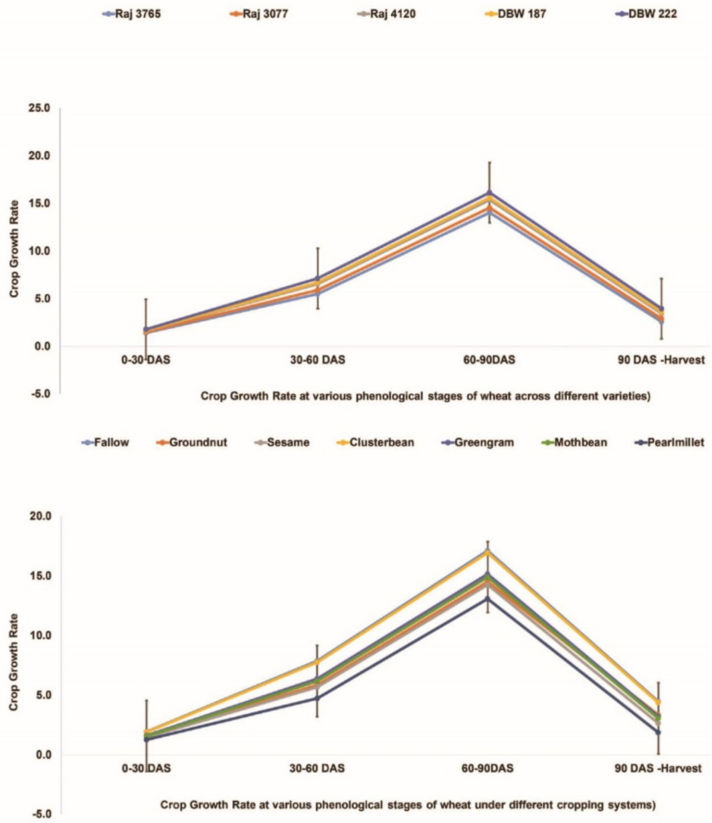

Fig. 3. Crop Growth Rate at various phenological stages of wheat under (A) different cropping systems and (B) across various wheat varieties.

The CGR varied across different growth stages and cropping systems. During the initial phase (0–30 DAS), the highest CGR was recorded in the fallow-wheat system (1.94 g m^{-2} day^{-1}), closely followed by the cluster bean-wheat system (1.92 g m^{-2} day^{-1}), while the lowest CGR was observed in the pearl millet-wheat system (1.26 g m^{-2} day^{-1}). From 30–60 DAS, the CGR remained highest in the fallow-wheat system (7.88 g m^{-2} day^{-1}), and the trend persisted during 60–90 DAS, with the fallow-wheat system (17.10 g m^{-2} day^{-1}) maintaining its lead. During 90 DAS to harvest, the fallow-wheat system (4.48 g m^{-2} day^{-1}) and the cluster bean-wheat system (4.38 g m^{-2} day^{-1}) exhibited the highest CGR, whereas the pearl millet-wheat system (1.87 g m^{-2} day^{-1}) consistently showed the lowest values across all stages. The RGR showed significant variation across cropping systems at different stages. The highest RGR during 30–60 DAS was observed in the fallow-wheat system (133.98 mg g^{-1} day^{-1}), followed by the cluster bean-wheat system (133.68 mg g^{-1} day^{-1}), whereas the lowest was noted in the pearl millet-wheat system (117.16 mg g^{-1} day^{-1}). During 60–90 DAS, the fallow-wheat system (168.38 mg g^{-1} day^{-1}) exhibited the highest RGR, while the pearl millet-wheat system (156.77 mg g^{-1} day^{-1}) recorded the lowest. A similar trend was observed during 90 DAS to harvest, with the groundnut-wheat system (198.23 mg g^{-1} day^{-1}) recording the highest RGR and the pearl millet-wheat system (159.60 mg g^{-1} day^{-1}) the lowest. Among wheat varieties, DBW-222 consistently showed the highest CGR across all growth stages, with values of 1.78, 7.12, 16.13, and 3.94 g m^{-2} day^{-1} for 0–30 DAS, 30–60 DAS, 60–90 DAS, and 90 DAS to harvest, respectively. The lowest CGR was recorded for Raj-3765, with values of 1.43, 5.50, 14.04, and 2.56 g m^{-2} day^{-1} across the respective stages. For RGR, DBW-222 exhibited the highest performance during all stages, recording 130.27, 165.75, and 175.09 mg g^{-1} day^{-1} during 30–60 DAS, 60–90 DAS, and 90 DAS to harvest, respectively. In contrast, Raj-3765 showed the lowest RGR with values of 121.80, 159.86, and 167.91 mg g^{-1} day^{-1} across the respective stages.

3.3 Effect of preceding crops on physiological components of wheat varieties

We further investigated the physiological performance of wheat following different preceding crops. Our results showed significant variations in key parameters, including the net photosynthetic rate (NPR), transpiration rate, and stomatal conductance. The findings, detailed in Tables 2 revealed that the net photosynthetic rate varied significantly across cropping systems, with the cluster bean-wheat system exhibiting the highest rate (65.67 μmol m^{-2} s^{-1}), followed by the fallow-wheat system (62.19 μmol m^{-2} s^{-1}). The green gram-wheat system also performed well, recording a rate of 56.82 μmol m^{-2} s^{-1}. On the other hand, the pearl millet-wheat system had the lowest net photosynthetic rate (40.30 μmol m^{-2} s^{-1}), followed by the groundnut-wheat system (44.27 μmol m^{-2} s^{-1}). The transpiration rate was highest in the cluster bean-wheat system (3.69 mmol m^{-2} s^{-1}), closely followed by the fallow-wheat system (3.55 mmol m^{-2} s^{-1}) and the green gram-wheat system (3.32 mmol m^{-2} s^{-1}). The lowest transpiration rate was observed in the pearl millet-wheat system (2.63 mmol m^{-2} s^{-1}), with intermediate values recorded in the groundnut-wheat (2.79 mmol m^{-2} s^{-1}) and Sesame-wheat systems (2.98 mmol m^{-2} s^{-1}). Stomatal conductance showed significant variation, with the cluster bean-wheat system (485 mmol m^{-2} s^{-1}) recording the highest value, followed by the fallow-wheat system (469 mmol m^{-2} s^{-1}). The green gram-wheat system (446 mmol m^{-2} s^{-1}) and moth bean-wheat system (429 mmol m^{-2} s^{-1}) also demonstrated relatively high conductance. In contrast, the pearl millet-wheat system showed the lowest stomatal conductance (374 mmol m^{-2} s^{-1}). Among wheat varieties, DBW-222 consistently outperformed others, recording the highest net photosynthetic rate (58.00 μmol m^{-2} s^{-1}), transpiration rate (3.37 mmol m^{-2} s^{-1}), and stomatal conductance (451 mmol m^{-2} s^{-1}). DBW-187 followed closely with values of 55.90 μmol m^{-2} s^{-1}, 3.28 mmol m^{-2} s^{-1}, and 442 mmol m^{-2} s^{-1}, respectively. Raj-3765 showed the lowest performance among varieties, with values of 46.20 μmol m^{-2} s^{-1}, 2.88 mmol m^{-2} s^{-1}, and 400 mmol m^{-2} s^{-1} for net photosynthetic rate, transpiration rate, and stomatal conductance, respectively.

3.4 Effect of preceding crops on yield components of wheat varieties

We analyzed the influence of preceding crops on various yield attributes of wheat, including total tillers, effective tillers, ear head length, grains per ear head, and test weight. The performance of yield-attributing parameters in wheat varieties showed significant variation across different cropping systems and wheat varieties under the pooled analysis of two years (Table 3).

Table 3. Performance of yield attributing parameters, yield and harvest index of wheat varieties under different cropping systems (Pooled of two years).

Treatments	Yield attributing parameters in wheat varieties					Yield (q ha^{-1})			Harvest Index (%)
	Total No of Tillers (metre row length^{-1})	Effective Tillers (metre row length^{-1})	Ear head length (cm)	Grains per ear head	Test Weight (g)	Grain yield (q ha^{-1})	Straw yield (q ha^{-1})	Biological yield (q ha^{-1})	
Cropping systems									
Fallow-wheat	79.6	62.4	11.7	39.0	41.03	48.01	71.22	119.23	40.09
Groundnut-wheat	78.5	57.2	10.8	31.5	40.73	35.84	56.97	92.81	38.46
Sesame-wheat	76.9	62.9	10.5	34.2	40.50	38.43	59.06	97.49	39.28
Cluster bean- wheat	82.6	67.0	13.5	40.7	43.05	51.31	72.94	124.25	41.15
Green gram-wheat	80.7	63.1	11.5	36.3	41.35	42.70	60.35	103.04	41.32
Moth bean-wheat	81.0	60.9	11.2	35.7	41.11	41.49	59.99	101.47	40.74
Pearl millet-wheat	76.6	56.2	9.4	31.3	39.36	32.63	53.32	85.95	37.79
S.Em.±	1.09	1.47	0.20	0.42	0.17	0.84	0.56	1.25	0.39
CD at 5%	3.17	4.28	0.58	1.22	0.49	2.46	1.63	3.64	1.15
wheat varieties									
Raj- 3765	73.1	56.1	9.9	33.4	41.73	37.72	59.84	97.56	38.59
Raj- 3077	76.3	58.5	10.5	34.6	41.90	39.93	60.50	100.43	39.70
Raj- 4120	81.5	62.8	11.5	36.1	41.18	42.11	62.65	104.76	39.94
DBW- 187	82.9	64.6	11.7	36.2	39.90	42.87	62.94	105.81	40.26
DBW- 222	83.2	65.0	12.5	37.5	40.39	44.80	63.96	108.76	40.68
S.Em. ±	0.78	1.06	0.14	0.29	0.12	0.60	0.30	0.82	0.30
CD at 5%	2.20	2.97	0.40	0.82	0.33	1.67	0.85	2.31	0.83

The total number of tillers per meter row length was highest in the cluster bean-wheat system (82.6), followed closely by the moth bean-wheat system (81.0) and the green gram-wheat system (80.7). In contrast, the lowest number of tillers was observed in the pearl millet-wheat system (76.6). Effective tillers followed a similar trend, with the cluster bean-wheat system (67.0) recording the highest value, while the pearl millet-wheat system (56.2) had the least. Ear head length was also significantly higher in the cluster bean-wheat system (13.5 cm), outperforming other systems, while the shortest ear heads were observed in the pearl millet-wheat system (9.4 cm). The number of grains per ear head was maximized in the cluster bean-wheat system (40.7), followed by the fallow-wheat system (39.0). The lowest grain count was seen in the pearl millet-wheat system (31.3). Test weight, which is an important indicator of grain quality, was highest in the cluster bean-wheat system (43.05 g) and lowest in the pearl millet-wheat system (39.36 g). Among wheat varieties, DBW-222 consistently outperformed others with the highest total tillers (83.2), effective tillers (65.0), ear head length (12.5 cm), and grains per ear head (37.5). DBW-187 and Raj-4120 also showed strong performance in these parameters, with values close to DBW-222. Conversely, Raj-3765 exhibited the lowest values in all parameters, including total tillers (73.1), effective tillers (56.1), ear head length (9.9 cm), and grains per ear head (33.4). Test weight was highest in Raj-3077 (41.90 g), followed by Raj-3765 (41.73 g), while the lowest value was observed in DBW-187 (39.90 g).

3.5 Effect of preceding crops on yield of wheat varieties

We also investigated the effect of preceding crops on wheat yield. The performance of yield and harvest index in wheat varieties under different cropping systems revealed significant variations when analyzed as a pooled result over two years

(Table 3). The cluster bean-wheat system recorded the highest grain yield (51.31 q ha^{-1}), straw yield (72.94 q ha^{-1}), and biological yield (124.25 q ha^{-1}), with a harvest index of 41.15%. This was closely followed by the fallow-wheat system, which produced a grain yield of 48.01 q ha^{-1}, straw yield of 71.22 q ha^{-1}, and biological yield of 119.23 q ha^{-1}, with a harvest index of 40.09%. The green gram-wheat system also performed well, producing a grain yield of 42.70 q ha^{-1}, straw yield of 60.35 q ha^{-1}, and biological yield of 103.04 q ha^{-1}, coupled with the highest harvest index among systems at 41.32%. On the other hand, the pearl millet-wheat system showed the lowest performance across all yield parameters, with a grain yield of 32.63 q ha^{-1}, straw yield of 53.32 q ha^{-1}, and biological yield of 85.95 q ha^{-1}, and the lowest harvest index at 37.79%. Among the wheat varieties, DBW-222 exhibited the best performance, with the highest grain yield (44.80 q ha^{-1}), straw yield (63.96 q ha^{-1}), and biological yield (108.76 q ha^{-1}), achieving a harvest index of 40.68%. DBW-187 followed closely with a grain yield of 42.87 q ha^{-1}, straw yield of 62.94 q ha^{-1}, and biological yield of 105.81 q ha^{-1}, with a harvest index of 40.26%. Raj-4120 and Raj-3077 demonstrated moderate performance, producing grain yields of 42.11 q ha^{-1} and 39.93 q ha^{-1}, respectively. Raj-3765 showed the lowest performance among the varieties, with a grain yield of 37.72 q ha^{-1}, straw yield of 59.84 q ha^{-1}, and biological yield of 97.56 q ha^{-1}, coupled with the lowest harvest index of 38.59%.

The interaction between cropping systems and wheat varieties showed significant differences in grain and straw yield, highlighting the combined effect of these factors on wheat performance over two years of pooled data (Table 4 and Fig. 4).

Table 4. Grain and straw yield of wheat varieties under different cropping systems (pooled).

Treatments	Grain yield of wheat (q ha^{-1})					Straw yield of wheat (q ha^{-1})				
Cropping systems	Raj- 3765	Raj- 3077	Raj-4120	DBW-187	DBW-222	Raj- 3765	Raj- 3077	Raj-4120	DBW-187	DBW-222
Fallow- wheat	40.69	43.79	49.70	50.87	55.00	69.28	69.88	71.66	72.01	73.26
Groundnut-wheat	41.50	42.13	33.12	32.41	30.05	51.38	51.84	59.62	59.79	62.20
Sesame- wheat	34.27	36.36	39.33	40.14	42.03	57.81	58.44	59.34	59.58	60.15
Cluster bean-wheat	43.95	47.44	52.92	54.33	57.91	70.73	71.78	73.43	73.85	74.93
Green gram-wheat	37.39	39.90	43.84	44.92	47.42	58.75	59.51	60.69	61.02	61.77
Moth bean-wheat	37.26	39.20	42.42	43.28	45.29	58.71	59.30	60.27	60.52	61.13
Pearl millet-wheat	28.97	30.70	33.43	34.17	35.90	52.21	52.74	53.56	53.78	54.30
	Cropping systems	wheat varieties				Cropping systems	wheat varieties			
S.Em. ±	0.84	0.87				0.56	0.37			
CD at 5%	2.46	2.43				1.63	1.04			

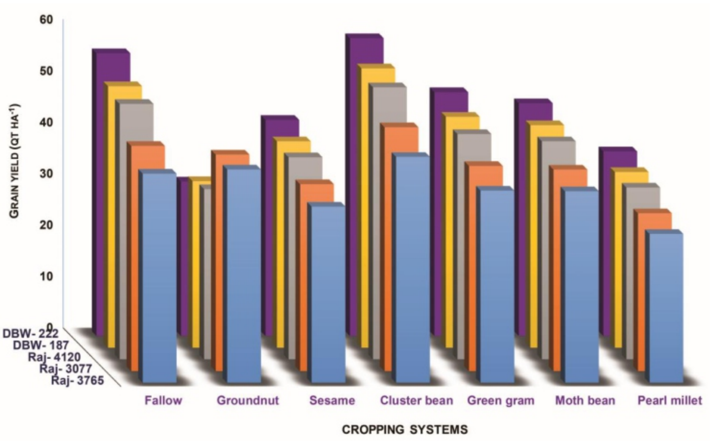

Fig. 4. Grain yield of wheat varieties across different cropping systems.

Among cropping systems, the cluster bean-wheat system consistently recorded the highest grain yields across all wheat varieties. DBW-222 achieved the maximum grain yield of 57.91 q ha^{-1} under this system, followed closely by DBW-187 (54.33 q ha^{-1}) and Raj-4120 (52.92 q ha^{-1}). The fallow-wheat system also demonstrated high productivity, with DBW-222 yielding 55.00 q ha^{-1} and DBW-187 50.87 q ha^{-1}. In contrast, the pearl millet-wheat system produced the lowest grain yields across all varieties, with Raj-3765 yielding 28.97 q ha^{-1} and Raj-3077 30.70 q ha^{-1}. Similarly, the groundnut-wheat system also resulted in reduced grain yields, with DBW-222 yielding only 30.05 q ha^{-1}, the lowest for this variety across all systems. The cluster bean-wheat system also excelled in straw yield, with DBW-222 recording the highest value of 74.93 q ha^{-1}, followed by DBW-187 (73.85 q ha^{-1}) and Raj-4120 (73.43 q ha^{-1}). The fallow-wheat system was comparable, with DBW-222 achieving a straw yield of 73.26 q ha^{-1} and DBW-187 at 72.01 q ha^{-1}. Conversely, the pearl millet-wheat system yielded the least straw across all varieties, with Raj-3765 producing 52.21 q ha^{-1} and Raj-3077 52.74 q ha^{-1}. The groundnut-wheat system also displayed moderate straw yields, with Raj-4120 and DBW-222 yielding 59.62 q ha^{-1} and 62.20 q ha^{-1}, respectively.

3.6 Effect of preceding crops on wheat equivalent yield of wheat varieties

We also evaluated the impact of preceding crop on wheat equivalent yield (WEY), economic performance, production efficiency and LRUE of wheat varieties cultivated under different cropping systems. The data in Table 5 reveals the impact of cropping systems and wheat varieties on WEY across pooled years.

Table 5. wheat Equivalent yield, economic performance, production efficiency and land resource use efficiency of wheat varieties under different cropping systems (Pooled of two years).

Treatments	wheat Equivalent Yield during kharif (q ha-1)	wheat Equivalent Yield of Systems (q ha-1)	Economic performance of wheat		Economic performance of system		Total duration (days)	Production efficiency (kg/ha/day)	LRUE (%)
			Net returns (₹ ha-1)	BC ratio	Net Returns (₹ ha-1)	BC ratio			
Cropping systems									
Fallow-wheat	-	48.01	85231	3.13	85231	3.13	118	40.80	32.29
Groundnut - wheat	106.12	141.96	55005	2.38	248878	3.93	253	56.20	69.21
Sesame-wheat	18.09	56.52	61056	2.53	85539	2.64	224	25.26	61.27
Cluster bean-wheat	43.66	94.97	92570	3.31	169131	3.82	223	42.51	61.19
Green gram-wheat	46.72	89.41	70171	2.75	142887	3.20	207	43.21	56.68
Moth bean-wheat	23.04	64.53	67594	2.69	101003	2.84	195	33.12	53.39
Pearl millet-wheat	12.41	45.04	47084	2.18	66788	2.28	222	20.30	60.71
S.Em.±	0.37	1.01	1833	0.05	2227	0.05	1.8	0.35	0.48
CD at 5%	1.08	2.94	5351	0.13	6501	0.13	5.1	1.02	1.40
wheat varieties									
Raj- 3765	42.35	74.02	59938	2.50	121373	2.97	204	35.82	55.84
Raj- 3077	41.68	75.66	64661	2.62	124772	3.04	205	36.60	56.06
Raj- 4120	41.19	77.41	69911	2.75	129095	3.14	206	37.45	56.50
DBW- 187	43.41	80.09	71567	2.79	134918	3.24	207	38.69	56.67
DBW- 222	39.73	78.86	75858	2.90	132311	3.22	208	38.16	56.90
S.Em. ±	0.39	0.68	1284	0.03	1465	0.03	0.8	0.35	0.23
CD at 5%	1.10	1.89	3597	0.09	4105	0.07	2.4	0.97	0.65

LRUE= land resource use efficiency

The groundnut-wheat system achieved the highest WEY during kharif at 106.12 q ha^{-1}, significantly outperforming all other cropping systems due to the high productivity of groundnut during the kharif season. The green gram-wheat system followed with a WEY of 46.72 q ha^{-1}, and the cluster bean-wheat system recorded 43.66 q ha^{-1}. Lower WEY values were observed for systems such as Sesame-wheat (18.09 q ha^{-1}), moth bean-wheat (23.04 q ha^{-1}), and pearl millet-wheat (12.41 q ha^{-1}), indicating limited contributions from the Kharif crops in these systems. In terms of overall system WEY, the groundnut-wheat system again led with 141.96 q ha^{-1}, showcasing its superior performance across both seasons. This was followed by the cluster bean-wheat system (94.97 q ha^{-1}) and the green gram-wheat system (89.41 q ha^{-1}). Comparatively lower system WEY values were noted for the moth bean-wheat (64.53 q ha^{-1}), Sesame-wheat (56.52 q ha^{-1}), and pearl millet-wheat (45.04 q ha^{-1}) systems, while the fallow-wheat system recorded 48.01 q ha^{-1}, reflecting the sole contribution of wheat yield. Among wheat varieties, DBW-187 recorded the highest system WEY at 80.09 q ha^{-1}, followed by DBW-222 (78.86 q ha^{-1}) and Raj-4120 (77.41 q ha^{-1}). However, Raj-3077 and Raj-3765 recorded system WEYs of 75.66 q ha^{-1} and 74.02 q ha^{-1}, respectively. These results highlight the consistent performance and adaptability of the DBW varieties across diverse cropping systems.

3.7 Effect of preceding crops on economic performance

We also analyzed the impact of preceding crops on the economic performance of wheat, focusing on net returns (NR) and benefit-cost ratios (BCR) under various cropping systems. The economic performance of wheat varieties under different cropping systems, pooled over two years, is presented in Table 5, which highlights the net returns and benefit-cost (BC) ratios for both wheat and the overall system. The cluster bean-wheat system achieved the highest net returns for wheat, amounting to ₹92,570 per hectare, with a BC ratio of 3.31. This indicates the most favorable return on investment within the cropping systems analyzed. The fallow-wheat system also exhibited strong economic performance with net returns of ₹85,231 per hectare and a BC ratio of 3.13. In contrast, the Sesame-wheat system recorded net returns of ₹61,056 per hectare, with a BC ratio of 2.53, and the groundnut-wheat system had net returns of ₹55,005 per hectare, along with a BC ratio of 2.38. The pearl millet-wheat system was the least profitable, yielding ₹47,084 per hectare in net returns and a BC ratio of 2.18. In terms of system-wide economic performance, the groundnut-wheat system outperformed all others, delivering ₹2,48,878 per hectare in net returns, coupled with a BC ratio of 3.93, the highest of all cropping systems. This suggests that integrating groundnut with wheat significantly boosts overall system profitability. The cluster bean-wheat system came next, generating ₹1,69,131 per hectare in net returns with a BC ratio of 3.82, indicating a high economic advantage. The green gram-wheat system also provided substantial returns, with ₹1,42,887 per hectare in net returns and a BC ratio of 3.20. The fallow-wheat system, despite having decent wheat net returns, contributed the lowest system returns (₹85,231 per hectare) due to the absence of a second crop, and its BC ratio remained at 3.13. Lastly, the pearl millet-wheat system showed the lowest system net returns of ₹66,788 per hectare, along with a BC ratio of 2.28.

The economic performance of wheat varieties, including net returns and benefit-cost (BC) ratios for both wheat and the overall cropping system, is summarized in the provided data (Table 5). Among the wheat varieties, DBW-222 recorded the highest net returns of ₹75,858 per hectare with a BC ratio of 2.90, indicating the most favorable economic performance for the wheat crop itself. It was closely followed by DBW-187, which produced ₹71,567 per hectare in net returns and a BC ratio of 2.79. The variety Raj-4120 also demonstrated good economic performance, with net returns of ₹69,911 per hectare and a BC ratio of 2.75. Raj-3077 achieved net returns of ₹64,661 per hectare and a BC ratio of 2.62, while Raj-3765 had the lowest net returns at ₹59,938 per hectare, with a BC ratio of 2.50. These results suggest that DBW-222 and DBW-187 were more profitable wheat varieties in comparison to the other varieties. When considering the overall system performance, DBW-187 again demonstrated the highest system net returns of ₹1,34,918 per hectare, with a BC ratio of 3.24, reflecting the highest profitability when combined with the associated cropping system. Raj-4120 produced system net returns of ₹1,29,095 per hectare, accompanied by a BC ratio of 3.14, making it the second most profitable in system performance. DBW-222 followed closely, with system net returns of ₹1,32,311 per hectare and a BC ratio of 3.22. Raj-3077 resulted in system net returns of ₹1,24,772 per hectare and a BC ratio of 3.04, while Raj-3765 recorded system net returns of ₹1,21,373 per hectare, with a BC ratio of 2.97. These findings indicate that DBW-187 not only performed well in wheat yield but also offered superior returns when considering the complete cropping system.

The interaction of wheat varieties with different cropping systems significantly influenced the net returns of both wheat and the entire system (Table 6 and Fig 5).

Table 6. Net returns of wheat varieties under different cropping systems (pooled).

Treatments	Net returns of wheat (₹ ha^{-1})					Net returns of system (₹ ha^{-1})				
Cropping systems	Raj- 3765	Raj- 3077	Raj- 4120	DBW- 187	DBW- 222	Raj- 3765	Raj- 3077	Raj- 4120	DBW- 187	DBW- 222
Fallow- wheat	69702	76196	88818	91307	100130	69702	76196	88818	91307	100130
Groundnut- wheat	64165	65626	50584	49228	45421	263493	257308	243197	247524	232867
Sesame- wheat	52188	56644	62985	64715	68750	76510	81906	87032	90158	92090
Cluster bean- wheat	76848	84302	96015	99024	106663	153197	162379	171029	180806	178245
Green gram- wheat	58848	64203	72619	74914	80270	132866	136332	143709	154453	147076
Moth bean- wheat	58564	62702	69581	71418	75702	92745	96301	102403	108533	105031
Pearl millet- wheat	39251	42956	48777	50365	54070	61101	62982	67476	71644	70737
	Cropping systems	wheat varieties				Cropping systems	wheat varieties			
S.Em. ±	1833	1882				2227	2231			
CD at 5%	5351	5274				6501	6252			

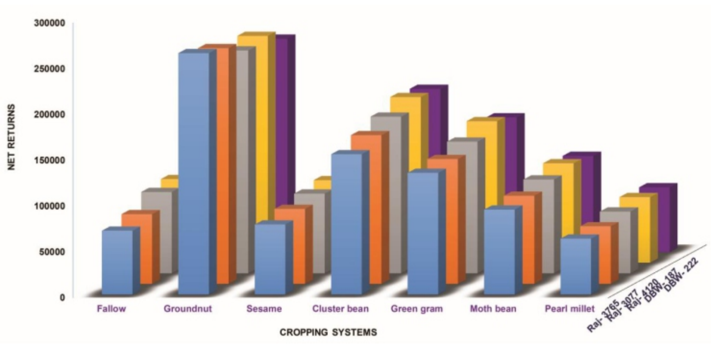

Fig. 5. System net returns of wheat varieties under various cropping systems.

In terms of wheat net returns, DBW-222 consistently outperformed the other wheat varieties in most cropping systems, especially in systems like fallow-wheat and cluster bean-wheat. For instance, under fallow-wheat, DBW-222 achieved the highest net returns of ₹1,00,130 per hectare, followed by DBW-187 with ₹91,307 per hectare. The Raj varieties generally yielded lower net returns, with Raj-3765 recording ₹69,702 per hectare. When considering the net returns for the entire system, DBW-222 again led, particularly under fallow-wheat and cluster bean-wheat, with system net returns of ₹1,00,130 and ₹1,78,245, respectively. Raj-3765, while showing lower returns for wheat, still performed relatively well in fallow-wheat systems, showing a system net return of ₹69,702. However, under groundnut-wheat, the system net returns were drastically reduced for all varieties, with the lowest recorded for DBW-222 at ₹45,421. The cluster bean-wheat system produced the highest system net returns for all varieties, with DBW-222 leading at ₹1,78,245. In contrast, the pearl millet-wheat system produced the lowest system returns, with Raj-3765 yielding ₹61,101.

The interaction of wheat varieties with different cropping systems significantly influenced the Benefit Cost Ratio (BCR) for both wheat and the overall system (Table 7).

Table 7. Benefit Cost Ratio during rabi and systems of wheat varieties under different cropping systems (pooled).

Treatments	Benefit Cost Ratio during wheat					Benefit Cost Ratio during system				
Cropping systems	Raj- 3765	Raj- 3077	Raj-4120	DBW-187	DBW-222	Raj- 3765	Raj- 3077	Raj-4120	DBW-187	DBW-222
Fallow- wheat	2.74	2.90	3.22	3.28	3.50	2.74	2.90	3.22	3.28	3.50
Groundnut-wheat	2.60	2.64	2.26	2.23	2.14	4.10	4.03	3.86	3.91	3.74
Sesame- wheat	2.30	2.42	2.57	2.62	2.72	2.47	2.58	2.67	2.73	2.77
Cluster bean-wheat	2.92	3.11	3.40	3.48	3.67	3.55	3.71	3.85	4.01	3.97
Green gram-wheat	2.47	2.61	2.82	2.87	3.01	3.04	3.10	3.21	3.38	3.26
Moth bean-wheat	2.46	2.57	2.74	2.79	2.89	2.69	2.75	2.86	2.97	2.91
Pearl millet-wheat	1.98	2.07	2.22	2.26	2.35	2.18	2.21	2.30	2.38	2.36
	Cropping systems	**wheat varieties**				**Cropping systems**	**wheat varieties**			
S.Em. ±	0.05	0.05				0.05	0.04			
CD at 5%	0.13	0.13				0.13	0.12			

Under the fallow-wheat system, DBW-222 recorded the highest BCR for both wheat (3.50) and the system (3.50), indicating strong economic performance. Other varieties such as DBW-187 (BCR of 3.28 for wheat and 3.28 for the system) also showed favorable returns. In contrast, Raj-3765 had relatively lower BCR values of 2.74 for wheat and 2.74 for the system. For the groundnut-wheat system, the wheat BCR values were generally lower across all varieties. Raj-3765 showed the highest wheat BCR of 2.60, while DBW-222 recorded the lowest wheat BCR of 2.14. However, the groundnut-wheat system itself performed better in terms of BCR, with Raj-3765 achieving a system BCR of 4.10, followed closely by Raj-3077 at 4.03, demonstrating that the inclusion of groundnut in the cropping system boosted the overall profitability significantly. In the Sesame-wheat system, DBW-222 again outperformed other varieties with a wheat BCR of 2.72 and a system BCR of 2.77. The wheat BCR for Raj-3765 was 2.30, while its system BCR was lower at 2.47. Similarly, the cluster bean-wheat system showed a remarkable BCR, with DBW-222 achieving a system BCR of 3.97, followed by Raj-3765 at 3.55. The wheat BCR was also high in this system, with DBW-222 recording the highest at 3.67. The green gram-wheat and moth bean-wheat systems displayed a moderate economic performance, with DBW-222 maintaining relatively high BCR values in both wheat and system levels. For example, DBW-222 had a wheat BCR of 3.01 and a system BCR of 3.26 under the green gram-wheat system. The pearl millet-wheat system resulted in the lowest BCR values, with Raj-3765 having a wheat BCR of 1.98 and a system BCR of 2.18, indicating lower profitability from this system.

3.8 Effect of preceding crops on production efficiency and land resource use efficiency of wheat varieties

We also investigated the influence of preceding crops on the production efficiency and land resource use efficiency of wheat under different cropping systems (Table 5 and Fig. 6).

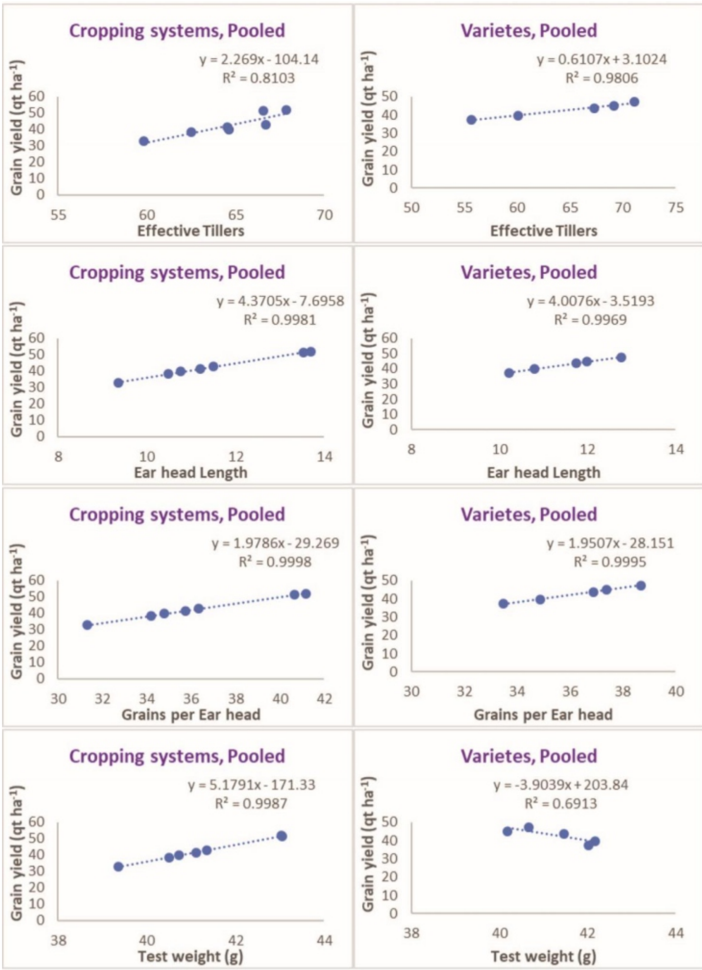

Fig. 6. Regression coefficients linking yield attributes with the grain yield of wheat.

The total duration, production efficiency, and land resource use efficiency (LRUE) of wheat varieties under different cropping systems (pooled over two years) revealed significant variations in all three parameters.

Among the cropping systems, the fallow-wheat system had the shortest duration of 118 days, with a relatively low production efficiency of 40.80 kg/ha/day and an LRUE of 32.29%. On the other hand, the groundnut-wheat system had the longest duration of 253 days, which resulted in the highest production efficiency of 56.20 kg/ha/day and the highest LRUE of 69.21%, reflecting optimal resource utilization over an extended period. The Sesame-wheat system had a total duration of 224 days, with a production efficiency of 25.26 kg/ha/day and an LRUE of 61.27%, while the cluster bean-wheat system had a similar duration of 223 days, but with a production efficiency of 42.51 kg/ha/day and an LRUE of 61.19%, both showing a better balance between duration, production, and resource use efficiency. The green gram-wheat system took 207 days and had a production efficiency of 43.21 kg/ha/day, with an LRUE of 56.68%. The moth bean-wheat system had a shorter duration of 195 days, with a production efficiency of 33.12 kg/ha/day and an LRUE of 53.39%. The pearl millet-wheat system, with a duration of 222 days, exhibited the lowest production efficiency of 20.30 kg/ha/day and an LRUE of 60.71%. As for wheat varieties, DBW-187 had the longest duration of 207 days, the highest production efficiency of 38.69 kg/ha/day, and an LRUE of 56.67%, performing well across all three metrics. Raj-3765 had a duration of 204 days, with a production efficiency of 35.82 kg/ha/day and an LRUE of 55.84%. Raj-3077 followed closely with 205 days, a production efficiency of 36.60 kg/ha/day, and an LRUE of 56.06%. Raj-4120 had a slightly longer duration of 206 days, with a production efficiency of 37.45 kg/ha/day and an LRUE of 56.50%. DBW-222 had the longest duration of 208 days, with a production efficiency of 38.16 kg/ha/day and the highest LRUE of 56.90%.

4. Discussion

Wheat among the oldest and most extensively cultivated cereal crops, remains a staple food for populations worldwide. However, its growth and productivity are increasingly jeopardized by the adverse effects of climate change. In this study, we examine the economic viability and profitability of five wheat varieties such as Raj-765, Raj-4120, HD-3226, DBW-187, and DBW-222 under arid and hot climate conditions. The phenological traits of wheat were significantly influenced by the preceding crops, as illustrated in Table 1, Fig. 1, and Fig. 2. The fallow-wheat system exhibited the shortest emergence time (6.2 days), closely followed by the pearl millet-wheat system (6.3 days). Conversely, the cluster bean-wheat system required the longest emergence time (8.1 days). Notably, the cluster bean-wheat system recorded the longest durations for days to booting (71.3), ear head emergence (80.4), flowering (85.9), and maturity (119.9), while the pearl millet-wheat system consistently showed the shortest durations for these traits (66.0, 74.0, 79.8, and 112.6 days, respectively). Among wheat varieties, Raj-3765 emerged earliest (6.4 days) and exhibited the shortest durations for booting, ear head emergence, flowering, and maturity (67.1, 75.2, 81.0, and 112.6 days, respectively). In contrast, DBW-222 showed the longest durations (69.9, 78.7, 84.2, and 116.5 days, respectively). Dry matter accumulation was highest in DBW-222 across all stages, whereas Raj-3765 recorded the lowest values. These results highlight the significant influence of both preceding crops and wheat varieties on phenological development, dry matter accumulation, and plant height, emphasizing the importance of cropping system selection for optimizing wheat performance. These differences are linked to factors like nutrient cycling, soil structure, moisture retention, pest pressure, and allelopathy. Legumes like cluster bean enhance nitrogen levels through atmospheric fixation and residue decomposition, fostering early growth and vigor in wheat. Similarly, deep-rooted crops like green gram improve soil structure and moisture retention, resulting in resilient wheat varieties, better yields, and sustainable farming [33, 34]. The influence of preceding crops on key growth parameters of wheat, including plant height at harvest, dry matter accumulation, CGR, and RGR was significant (Table 2; Fig. 2). The fallow-wheat system had the highest CGR (1.94 g m^{-2} day^{-1}), while the pearl millet-wheat system recorded the lowest (1.26 g m^{-2} day^{-1}). The fallow-wheat system (133.98 mg g^{-1} day^{-1}) and cluster bean-wheat system (133.68 mg g^{-1} day^{-1}) showed the highest RGR, with the pearl millet-wheat system (117.16 mg g^{-1} day^{-1}) being the lowest. Among wheat varieties, DBW-222 consistently demonstrated superior CGR across all growth stages, while Raj-3765 showed the lowest CGR across the respective stages. The findings highlight the importance of selecting the appropriate preceding crop and variety to improve wheat growth performance. Legumes like cluster bean improve soil fertility and microbial activity through nitrogen fixation and residue decomposition, leading to increased chlorophyll production, photosynthesis, and biomass [34, 35]. Pearl millet, with minimal contributions to soil fertility, had the lowest growth parameter values.

Wheat physiological performance varied significantly with preceding crops, as shown by NPR, transpiration rate, and stomatal conductance (Table 2). The cluster bean-wheat system recorded the highest NPR (65.67 μmol m^{-2} s^{-1}), transpiration rate (3.69 mmol m^{-2} s^{-1}), and stomatal conductance (485 mmol m^{-2} s^{-1}), attributable to enhanced soil structure and nutrient availability –[36], while the pearl millet-wheat system had the lowest NPR (40.30 μmol m^{-2} s^{-1}), transpiration rate (2.63 mmol m^{-2} s^{-1}), and poor stomatal conductance, reflecting its limited contribution to soil fertility [37, 38]. The moth bean-wheat system also showed high conductance (429 mmol m^{-2} s^{-1}), whereas pearl millet-wheat had the lowest (374 mmol m^{-2} s^{-1}). Among wheat varieties, DBW-222 performed best, with the highest NPR (58.00 μmol m^{-2} s^{-1}), transpiration rate (3.37 mmol m^{-2} s^{-1}), and stomatal conductance (451 mmol m^{-2} s^{-1}). Raj-3765 had the lowest values for all parameters: NPR (46.20 μmol m^{-2} s^{-1}), transpiration rate (2.88 mmol m^{-2} s^{-1}), and stomatal conductance (400 mmol m^{-2} s^{-1}). These results emphasize the crucial role of cropping systems and wheat variety selection in maximizing wheat productivity. Furthermore, the influence of preceding crops on yield components were significant across cropping systems and wheat varieties (Table 3). The highest total tillers per meter row length were recorded in the cluster bean-wheat system (82.6), followed by the moth bean-wheat (81.0) and green gram-wheat (80.7) systems. The pearl millet-wheat system exhibited the lowest total tillers (76.6). Among wheat varieties, DBW-222 consistently demonstrated superior yield attributes. Conversely, Raj-3765 exhibited the lowest values for total tillers (73.1), effective tillers (56.1), ear head length (9.9 cm), and grains per ear head (33.4). These results underscore the critical role of preceding crops and variety selection in determining yield attributes. Cluster bean and other legumes enriched soil with nitrogen, improving tillering, grain filling, and overall yield [39, 40]. Non-legumes like pearl millet and sesame provided fewer soil fertility benefits, resulting in lower yield attributes [41, 42].

Our findings also highlight significant variations in wheat yield and harvest index across cropping systems and wheat varieties when analyzed as a pooled result over two years (Table 3).

Legumes contributed to higher yields through nitrogen fixation, improved soil structure, and nutrient cycling –[43, 44]. Non-legumes like pearl millet had limited effects on soil fertility, underscoring the importance of legume-based rotations for enhanced productivity [45]. The interaction between cropping systems and wheat varieties revealed significant yield differences (Table 4, Fig. 4). The cluster bean-wheat system maximized grain yields across all varieties, with DBW-222 achieving the highest yield (57.91 q ha^{-1}), followed by DBW-187 (54.33 q ha^{-1}) and Raj-4120 (52.92 q ha^{-1}). The fallow-wheat system also supported high productivity, with DBW-222 yielding 55.00 q ha^{-1} and DBW-187 50.87 q ha^{-1}, in line with studies advocating the selection of high-yielding, cost-effective varieties for profitability [46, 47]. In contrast, the pearl millet-wheat system consistently resulted in the lowest yields, with Raj-3765 yielding 28.97 q ha^{-1} and Raj-3077 30.70 q ha^{-1}. The WEY analysis across different cropping systems and wheat varieties demonstrated significant variability, underscoring the importance of the preceding crop on overall system productivity (Table 5). The groundnut-wheat system stands out for its superior productivity and overall system WEY, driven by the high performance of groundnut in the kharif season. Wheat varieties such as DBW-187 and DBW-222 also demonstrate strong adaptability, performing well across different cropping systems and contributing to high WEY values. The higher WEY and WEY in systems involving leguminous crops, such as groundnut, are attributed to their nitrogen fixation, which improves soil fertility and benefits subsequent wheat crops [48]. In contrast, pearl millet, while productive, offers minimal soil fertility benefits, resulting in lower wheat yields [49]. The economic performance of wheat, as influenced by the preceding crops and the wheat varieties used, reveals important insights into the profitability and efficiency of different cropping systems. The cluster bean-wheat system recorded the highest net returns for wheat, amounting to ₹92,570 per hectare, with a favorable BC ratio of 3.31. This indicates a strong return on investment in this cropping system. On the other hand, the groundnut-wheat system recorded net returns of ₹55,005 per hectare, with a BC ratio of 2.38, lower than the fallow and cluster bean systems. The pearl millet-wheat system demonstrated the least profitability, yielding ₹47,084 per hectare in net returns and a BC ratio of 2.18. Among wheat varieties, DBW-222 recorded the highest net returns of ₹75,858 per hectare and a BC ratio of 2.90, making it the most economically viable wheat variety. Raj-3077 and Raj-3765 showed relatively lower net returns and BC ratios, with Raj-3765 recording the lowest at ₹59,938 per hectare and a BC ratio of 2.50. Leguminous crops reduce fertilizer needs and enhance profitability by improving soil fertility and crop yields –[48, 50]. Non-leguminous systems, such as pearl millet-wheat, had lower PE and LRUE, highlighting the benefits of crop rotations with legumes –[36, 51]. The interaction between wheat varieties and cropping systems had a significant impact on net returns for both wheat and the entire system. DBW-222 consistently outperformed other varieties in most systems, particularly under fallow-wheat and cluster bean-wheat. For example, under the fallow-wheat system, DBW-222 achieved the highest net returns of ₹1,00,130 per hectare. Under the cluster bean-wheat system, DBW-222 again led with system net returns of ₹1,78,245, highlighting its adaptability and economic viability across different cropping systems. However, under the groundnut-wheat system, all varieties showed reduced system net returns, with DBW-222 recording the lowest at ₹45,421. Studies by Kamble et al. and Rajput et al. emphasize the role of leguminous crops like groundnut in improving soil fertility, which enhances wheat yields [39, 52]. These results emphasize the importance of selecting high-efficiency varieties to boost productivity and sustainability [53]. The economic performance of wheat is influenced by both the preceding crop and the variety used. The groundnut-wheat system, while having lower wheat-specific returns, proved to be the most profitable overall due to its high returns from the preceding groundnut crop. Among wheat varieties, DBW-222 and DBW-187 demonstrated superior economic performance, with DBW-222 leading in wheat-specific profitability and DBW-187 excelling in system-wide returns. The interaction between cropping systems and wheat varieties significantly impacted net returns and BCR, highlighting the importance of choosing the right combination for maximizing profitability. These results underscore the importance of selecting varieties based on preceding crops to optimize wheat yield, as noted by [54]. Our study underscores the critical role of cropping systems and wheat varieties in optimizing production efficiency and LRUE. Cropping systems like groundnut-wheat and cluster bean-wheat exhibit higher production efficiency and better land use, with the groundnut-wheat system showing the most outstanding performance. Among wheat varieties, DBW-222 demonstrated the highest LRUE and strong production efficiency, reflecting its adaptability and resource efficiency across various cropping systems. By understanding the dynamics of these systems and varieties, we can optimize wheat production, boosting both productivity and sustainability. In conclusion, this study highlights the importance of choosing the right wheat varieties and cropping systems to maximize productivity and profitability in arid and hot climates. Notably, DBW-222 in the cluster bean-wheat system yielded the highest outputs, net returns, and BCR. Other varieties, such as DBW-187 and Raj-4120, also performed well across different systems, offering farmers viable alternatives. This research emphasizes the need for strategic crop rotation and variety selection to enhance sustainability and economic viability in wheat cultivation, ultimately supporting food security and agricultural resilience in India and similar regions.

Future scope of study: We can extend our study with more number of varieties with different cropping systems.

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