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Planting Period Effects on Wheat Productivity and Water Footprints: Insights through Adaptive Trials and APSIM Simulations

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Abstract: Scarcity of fresh water and climate change are the two main threats for wheat production in South Asia. Tweaking wheat planting period could be an effective cost-smart strategy to mitigate these stresses. To evaluate the performance of three leading wheat varieties under different planting periods in pragmatic on-farm environments, trials were carried out during 2019–2020 and 2020–2021. Further, to have greater insights on long-term temporal scale, 22 years (2000 to 2021) of crop simulation data were analyzed to identify the optimum planting period of wheat for higher yield and water productivity using the APSIM cropping systems simulation model. The result showed that first fortnight of November (PD1)-sown crop resulted in higher grain yield and more irrigation water use efficiency. Wheat sown during PD1 and in the second fortnight of November (PD2) had 20–25% lower blue water requirement than the second fortnight of December (PD4) crop in the long run. To produce one tonne of wheat grain required an additional 20, 60 and 83 m^3 irrigation water when the crop was sown at PD1, PD2, PD3 (first fortnight of December) and PD4, respectively. It was observed that PD4 reduced wheat yields by 20–22% compared to sowing on PD1 and PD2 and every 15 days' delay in wheat planting after 15 November reduced the length of the crop growing season by 4–5 days. Hence, the early wheat planting is proven superior in harnessing maximum yield with minimum burden on blue water resources.

Keywords: adaptive trials; APSIM modelling; blue water; sowing time; water productivity

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1. Introduction

Water scarcity is an alarming issue in South Asia as many of geographical areas of the region are facing bad water crises. The situation is going to be even worse in coming years due to climate change [1], population pressure and industrial development [2,3]. This may have serious implications for the agricultural sustainability and long-term food security of the region, as nearly 70% of the blue water (water that has been sourced from surface or ground water resources) is being used for agricultural purposes only [2]. Wheat (*Triticum aestivum* L.), the second most important crop of this part of the world, depends almost entirely on blue water to complete its life cycle as the crop is cultivated during the dry post-monsoon winters [4]. In addition to its role in food security, wheat crop is an important source of livestock fodder and contributes significantly to the rural economy and livelihood [5,6].

High yielding and medium early maturing wheat cultivars are widely sown in India. The irrigated wheat crop is generally planted between November and December (depending on the duration of the previous sown crop in rotation) and harvested in the month of April [3]. Wheat planting generally is delayed when rice, cotton, sugarcane, pigeon pea, potato and toria are grown before wheat. This late-sown crop faces low temperature at early establishment and higher temperature at the reproductive phase and needs a comparatively higher number of irrigations [4]. Yield penalty is quite obvious in late-sown wheat due to its exposure to less favourable climatic factors, especially maximum and minimum temperatures that play a crucial role in determining the production and productivity of the crop [7,8]. Even a single-day exposure to an abnormally high temperature during the grain filling phase can cause a considerable loss in grain yield [9]. Temperatures above 30 °C at the reproductive stage negatively affect grain filling rate and duration, and ultimately such terminal heat stress reduce wheat productivity drastically [10]. Contrary to this, early sown wheat escapes the risk of terminal heat stress and thus produces better yield [11–14]. Higher temperature during later stages of late-sown wheat may increase evapotranspiration losses, thus extending irrigation requirement and water footprints. A modification in planting periods could be an appropriate cost-effective adaptation strategy under the changing climate, especially to avoid the negative effect of terminal heat stress on yield and blue water use [11].

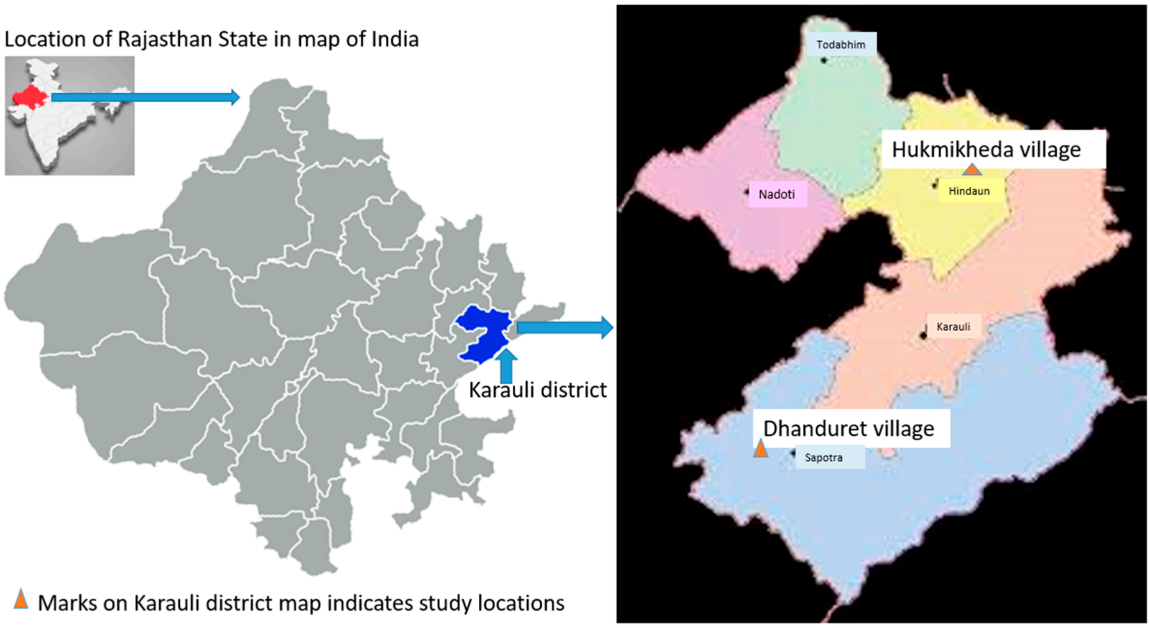
Many on-station and short-term studies on planting period adjustments in wheat have been done in various agro-ecologies [11–14], but information on realistic on-farm conditions is lacking. Likewise, it is yet to be known how altering sowing time affects yield and water productivity across annual weather variations. To see the effect of such changes in sowing dates under long-term environmental conditions, experimentation on such aspects are time consuming and expensive. Therefore, well-tested cropping system simulation models can be useful tools in understanding crop yield gaps and the biophysical drivers of cropping system performance in the long run. Modelling studies can significantly reduce the need for costly and prolonged field experimentation, providing the means to quantify the effects of climate, soil and management factors on crop phenology, yield and long-term variability of production [15–17]. The Agricultural production Systems Simulator (APSIM) model was developed to imitate crop production under diverse management and climatic conditions, including planting time and water use [18]. Gaydon et al. [16] successfully used the APSIM model under South Asian regions for diverse cropping systems, managements and agro-ecologies. Balwinder-Singh et al. [19] also carried out APSIM studies to simulate the effect of planting dates, cultivars and supplemental irrigation on water productivity and yield of rice at Eastern Indo-Gangetic Plains (IGP). APSIM model also has been firmly evaluated and used for wheat crop for water management [20] and effect of various conservation agricultural practices on water productivity [21] in Trans-Gangetic Plains (TGP) of India. Mohanty et al. [22] studied soil organic carbon dynamics under different nutrient management practices in wheat crop under Indian conditions. However, no simulation studies have been done to evaluate optimum planting dates with respect to higher yield, water productivity and water footprints under wheat crop. Further, no research information is available on long-term effects of planting period adjustment on wheat phenology, yield sustainability and water use. Moreover, a knowledge gap also exists on the performance of leading wheat varieties under realistic on-farm environments under diverse planting periods.

Therefore, the study was designed to evaluate the major wheat varieties under different planting periods with regard to their yield performance, profitability and irrigation water use efficiency and to see the sowing window adjustment effects on long-term seasonal dynamics on crop phenology, yield, water productivity and water footprints of wheat. The present experiment was carried out to test the hypothesis that the APSIM model is able to simulate the effects of different planting dates and also to test that planting time will affect crop yield and water productivity.

2. Materials and Methods

2.1. Experimental Location

To test leading wheat cultivar performance under different planting periods under a realistic on-farm scenario, adaptive trials were carried out at farmers' field in Dhanduret [Latitude 26°298′ N; Longitude 76°730′ E] and Hukmikheda [Latitude 26°783′ N; Longitude 76°882′ E] villages of Karauli district of Rajasthan, India (Figure 1A). In Dhanduret village the soils were sandy clay loam with low depth (20–50 cm) with 7.4–8.6 pH range. Available N, P and K were in the range of 145–187, 12.3–14.7, 245–274 kg/ha, respectively. The soils in Hukmikheda village were sandy loam in texture with decent drainage and good depth. The soils pH range was 7.4–8.2 (1:2.5 soil:water) with available N, P and K ranged between 135 and 208, 8.8 and 10.7, and 209 and 263 kg/ha, respectively. The mean monthly maximum and minimum temperature, radiation and rainfall data from 2000–2021 of Karauli district are given in Figure 1B.



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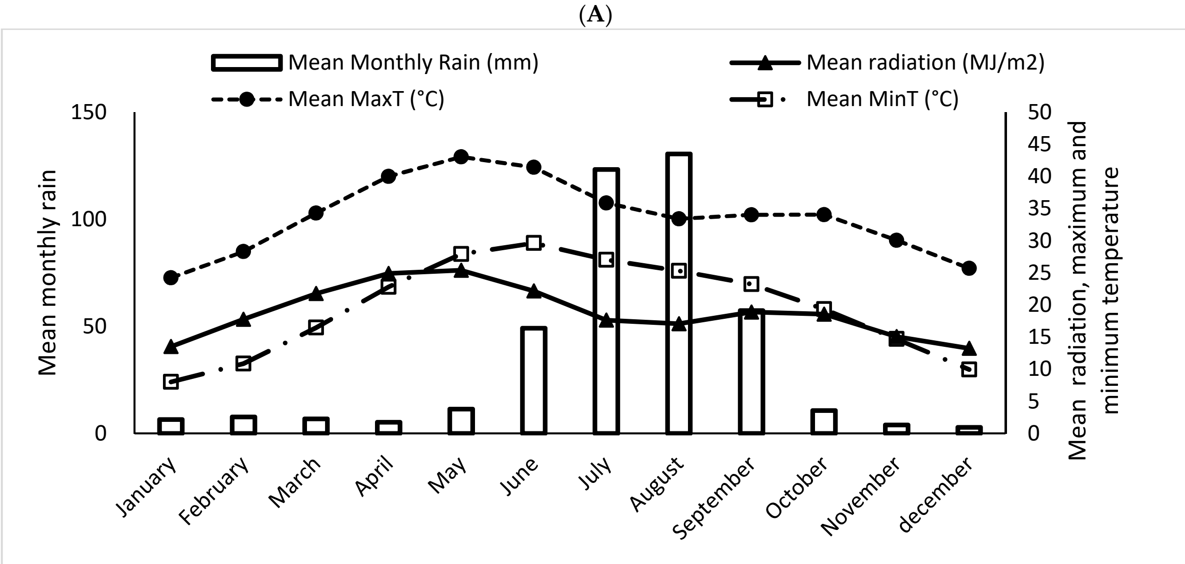


(**B**)

Figure 1. (**A**) Location map of study area; (**B**) Monthly average solar radiation, temperature and rainfall of Karauli based on 22 years (2000–2021) daily weather data.

2.2. Treatment Details

The experiment was carried out at farmer' fields during the winter season of 2019–2020 and 2021–2021. Split plot design was used to conduct the experiment and data from farmers' field (n = 8) from both the study location were collected. In main-plot three medium early maturing group wheat cultivars viz. HD-2967, HD-3237 and HD-3086 were planted. Whereas, four sowing dates (first fortnight of November (PD1); second fortnight of November (PD2); first fortnight of December (PD3) and second fortnight of December (PD4)) treatments were applied in the sub-plots. The grain and stover yield were recorded from 100 m^2 plots and the values were converted into t/ha. Cost of wheat cultivation was estimated based on the rapid survey carried out at the study site. Prevailing market price of stover (INR 3.0/kg) and minimum support price for grain during 2019 (INR 18.40/kg) and 2020 (INR 19.75 kg) were used for calculation of gross returns. Mean prevailing conversion rate for November 2021 (74.9:1) was used to convert INR into USD.

2.3. Crop Management

Sowing was done as per treatments at 4 farmers' field in each village using 100 kg/ha seed rate at 22.5 cm row spacing. Gap filling and thinning was done as necessary 15 days after sowing (DAS). Fertilizer nitrogen (N), phosphorus (P) and potassium (K) were applied as urea (46% N), single superphosphate (16% P_2O_5) and muriate of potash (60% K_2O), respectively. Wheat was fertilized with 120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}. One-third of the N and all the amount of P and K were applied at sowing, while the remaining N was broadcast between 30 days after sowing (DAS) and 75 DAS.

2.4. Statistical Analysis

All the sample data obtained from the two-year experiment were analyzed using the F-test. Tukey's HSD test was performed to see the significant difference (at p value = 0.05) between the treatments means.

2.5. APSIM Model Calibration and Validation

For the present study, the APSIM version 7.9 was run on daily time scale. APSIM-Wheat module was used in the simulations with the 'tillage', 'sow using a variable rule', 'fertilize', 'irrigate' and 'harvest' management rules.

2.5.1. Meteorological Data

Weather data for the Karauli district were extracted from NASAPOWER (https://power.larc.nasa.gov/data-access-viewer/ (accessed on 4 July 2021) as per the procedure described by Sparks, 2018. Met file was prepared using daily rainfall, solar radiation, maximum and minimum temperature. The raw data were converted into ".met" format and checked for accuracy. Mean data of 22 years (2000–2021) are presented in Figure 1B.

2.5.2. Soil

Layer wise soil samples were collected from the Hukmikheda village and were analyzed at IARI, New Delhi laboratory. The data on field capacity (DUL), permanent wilting point (LL15), saturation water content (SAT), clay content, soil pH and organic matter for the experimental area at (Table 1) were taken and converted as per APSIM format.

2.5.3. Management

For model calibration, on-farm experimental data of the 2019–2020 season from Hukmikheda village were used. The calibrated model output was validated with the field data of 2020–2021 from the same trial. In the experiment, wheat variety 'HD 2967' was sown at 22.5 cm row and 5 cm plant spacing. The variety falls in medium-early maturity group and suitable for irrigated, timely-sown conditions in north-western plain zones. Nitrogen was applied at 120 kg N ha^{-1} to the crop in three equal splits at pre-sowing, 30 DAS and 75 DAS. Irrigations (70 mm depth) were scheduled at 50% depletion of available soil moisture.

Table 1. Soil profile parameters (Hukmikheda village) used for APSIM simulations.

Soil Depth (cm)	DUL ^ (%)	LL15 ^^ (%)	SAT ^^^ (%)	Clay Content (%)	Soil pH	Organic Carbon (%)
0–15	24.1	6.6	37.7	16.3	7.8	0.41
15–30	25.4	9.1	41.3	18.8	7.7	0.30
30–45	26.2	9.2	41.9	19.9	7.5	0.25
45–60	28.4	9.6	43.8	21.3	7.7	0.18
60–75	30.0	9.8	44.6	21.1	8.3	0.13

^ DUL-Drainage upper limit (field capacity); ^^ LL15- Lower limit (Permanent wilting point); ^^^ SAT-saturation water content.

2.5.4. Model Parametrization

After uploading metfile, soilfile, observed output file and crop management data, 'ini' file was adjusted to closely match observed and simulated phenology, grain yield and biomass production. The genetic coefficients (obtained from field study data calibration and validation) for wheat cultivar "HD 2967" were: startgf to mat (grain filling duration in degree days, °C) = 525, phyllochron (phyllochron interval, °C) = 70.0, vern sens (sensitivity to vernalisation) = 1.8, photop sens (photoperiod sensitivity) = 2.85. Using the above genetic coefficients, the model was run and the model output on simulated crop phenology, yield and biomass during 2019–2020 and 2020–2021 were juxtaposed with field experiment data (Figure 2). Likewise, number of irrigations and quantum of water applied during the experimental period were compared with the simulated data and it was observed that the model was showing 210 mm of water use (3 irrigations) and 2020–2021, which were equivalent to the observed data (three irrigations).

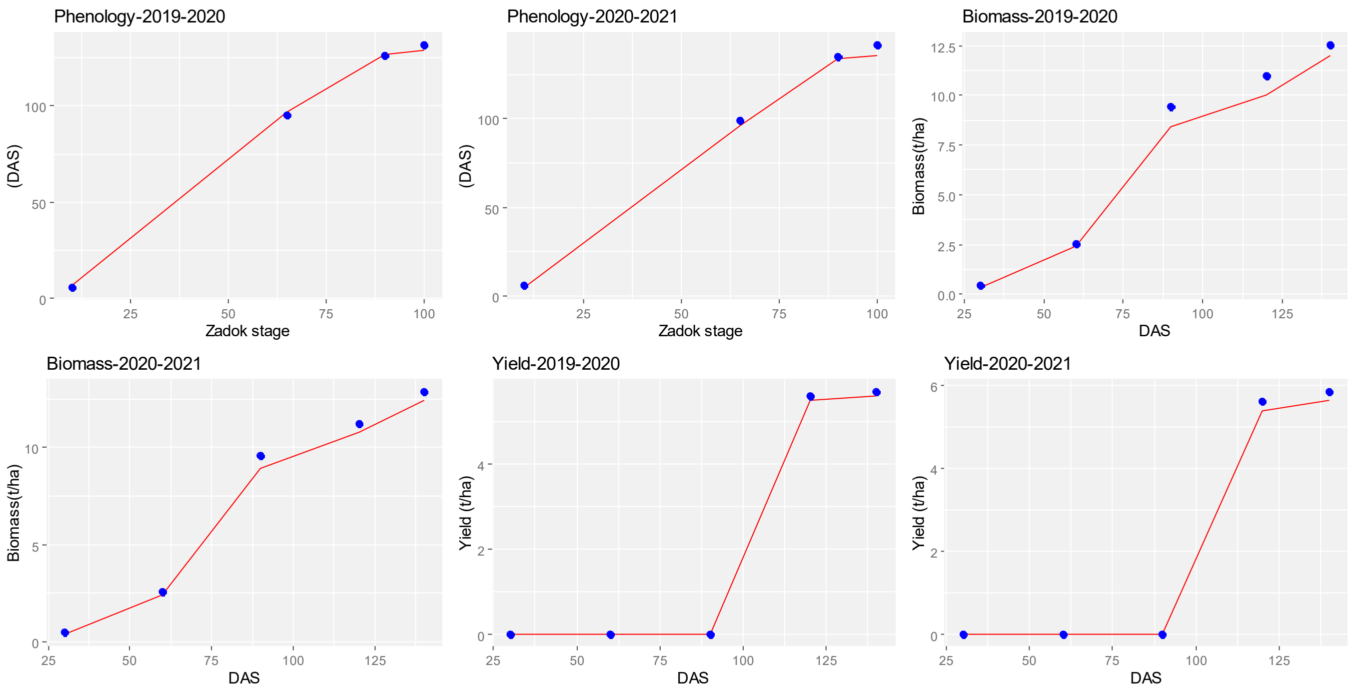


Figure 2. Calibration and validation of APSIM model for wheat phenology, biomass and yield. DAS = Days after sowing; red line indicating simulated whereas blue marker indicating observed data. Blue dot is indicating observed value and red line representing simulated data.

The observed and simulated data were collated to test the accuracy of model performance with root mean square error (RMSE).

$$\mathrm{RMSE} = \sum_{i=1}^{n}\left[(\mathrm{Si}-\mathrm{Ai})^2/\mathrm{n}\right]^{1/2}$$

Here Si and Ai are simulated and values are observed, respectively, and n is the number of observations. RMSE value for observed and simulated grain yield and biomass were 177 kg/ha and 659 kg/ha, respectively. As the APSIM model validation was satisfactory, the simulation was used for scenario analysis.

2.5.5. Scenario Simulation

In the studied region, wheat is generally sown between mid-November to the end of December depending on duration of previous crop, variety used, soil type and management protocols. The parameterized and calibrated model was run for 22 years (2000–2021) to find out the optimum sowing date of wheat in terms of yield and water use. For this purpose, four wheat sowing date treatments (15 November (PD1), 30 November (PD2), 15 December (PD3) and 31 December (PD4)) were used for scenario analysis.

Water productivity was calculated by dividing grain yield with total amount of irrigation water applied. B:C was calculated by dividing gross returns with cultivation cost. The blue water footprints were calculated by the equation suggested by Hoekstra and Chapagain [23].

Blue water footprints (m^3/t) = water applied as irrigation (m^3/ha)/yield (t/ha).

Green water footprints (m^3/t) = water received as rainfall (m^3/ha)/yield (t/ha).

Total water footprints ((m^3/t) = Total water used to produce crop (rainfall and irrigation) (m^3/ha)/yield (t/ha).

3. Results and Discussion

3.1. Water Use Efficiency and Water Footprints

The pooled mean of two-years on-farm data shows that irrigation water use efficiency (IWUE) varies from 23.6 to 25 kg/ha/mm (Figure 3). From each mm of irrigation water applied, wheat cultivar HD 2967 had produced 1.4 and 0.7 kg/ha more yield compared to HD 3237 and HD 3086, respectively. The IWUE was also significantly affected by sowing time. Early planting in the first fortnight of November was found more efficient in water use having the maximum IWUE (27.3 kg/ha/mm). Contrary to this, late plating in the second fortnight of December had the least IWUE (20.4 kg/ha/mm). Compared to PD1, IWUE decreased by 0.94, 4.25, 6.80 kg/ha/mm due to PD2, PD3, PD4, respectively.

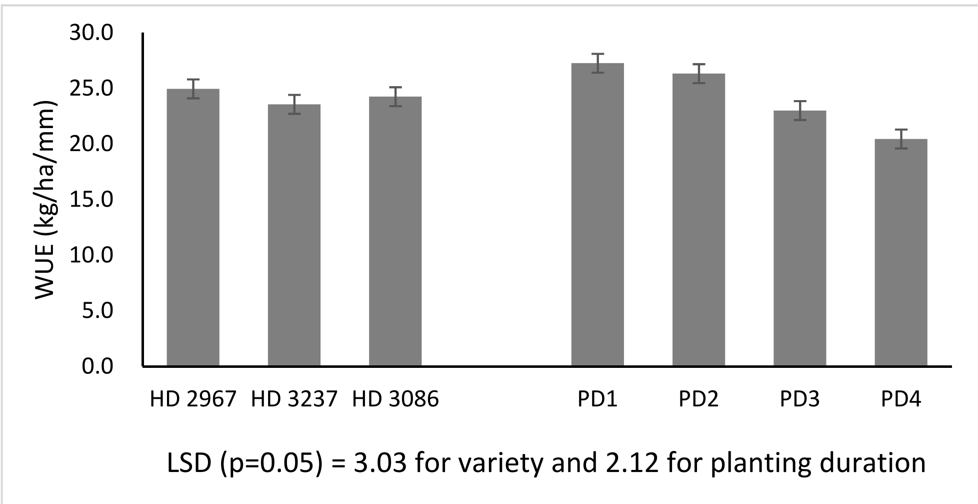
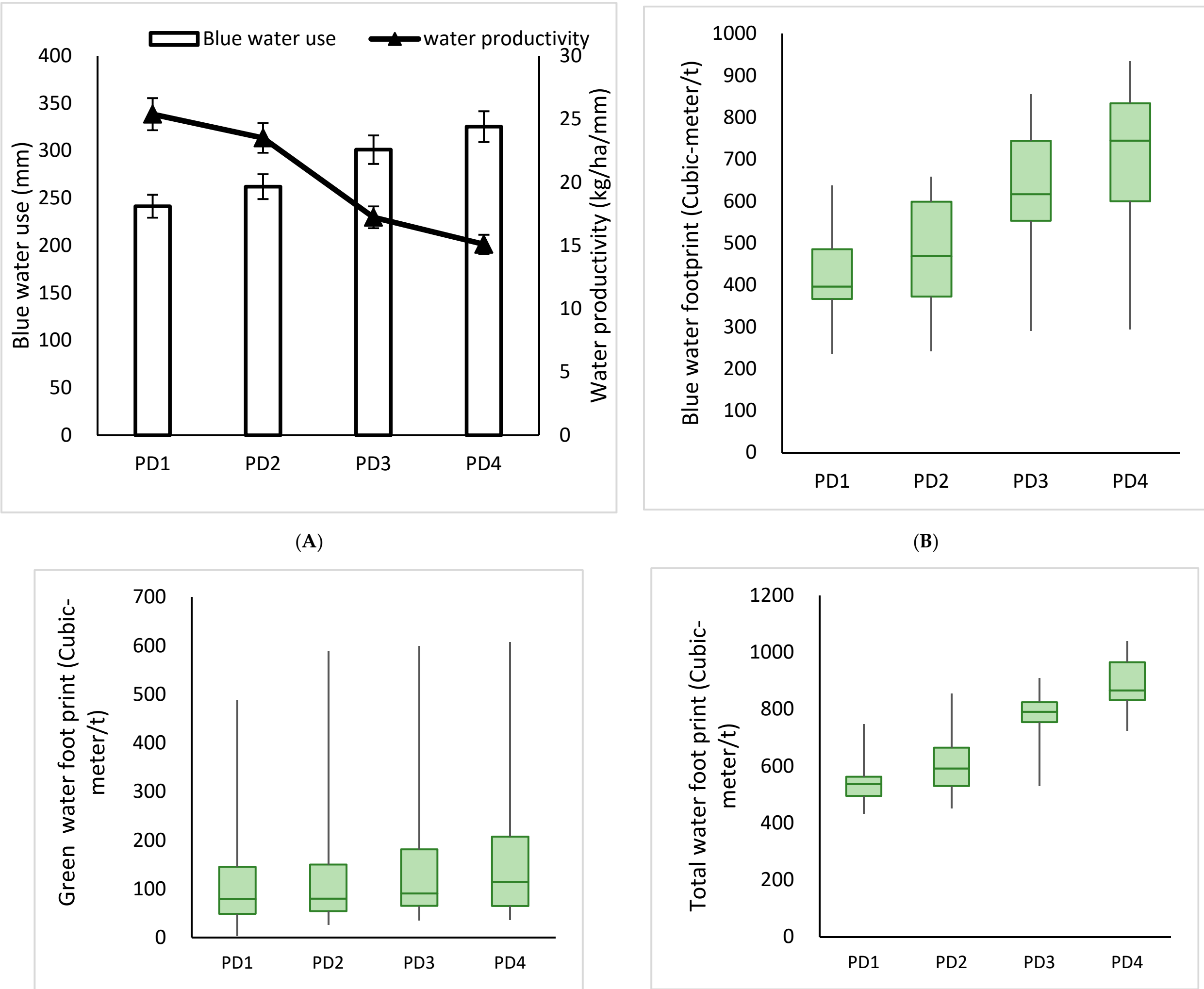


Figure 3. Irrigation water use efficiency under different planting periods (pooled mean of two years) at on-farm environments. PD1 = 1–15 November; PD2 = 16–30 November; PD3 = 1–15 December; PD4 = 16–31 December.

Long-term simulation of blue water use pattern in wheat indicated that blue water use was at maximum under PD4 (325 mm) followed by PD3 (301 mm) (Figure 4A). Whereas, PD1 showed the lowest blue water use (241 mm) among different planting dates. Each day delay from PD1 increased blue water use by 1.3–2.0 mm. It showed that 34.7% blue water use can be saved merely by adjusting planting dates and PD1 was found to be the most suitable planting time in the long-run from the blue water use point of view.



(A) (B)

(C) (D)

Figure 4. Effect of sowing dates on (**A**) blue water use, water productivity (**B**) blue water footprints (**C**) Green water footprints and (**D**) Total water footprints under different sowing dates (from 22-year simulations). PD1 = 15 November; PD2 = 30 November; PD3 = 15 December; PD4 = 31 December.

In the IWUE modelling of wheat crop, it was observed that maximum IWUE (water productivity) was found under PD1 (25.4 kg/ha/mm) and lowest under PD4 (15.1 kg/ha/mm) (Figure 4A). A sharp decline in IWUE was seen when the sowing was delayed beyond 30 November. IWUE reduction from PD1 to PD2 was merely 1.8 kg ha/mm/day, but from PD2 to PD3 it was 6.27 kg ha/mm/day. Whereas, in comparison to PD2 and PD3 the per day decline in IWUE under PD4 was 0.28 and 0.14 kg ha/mm/day, respectively. In post-rainy season crops such as wheat, the contribution of green water is very limited due to lack of rainfall; therefore blue water is crucial. Irrigation requirement increased with delays in wheat planting. Higher temperatures during reproductive phases of December-sown wheat may increase ET demands, hence the need for more frequent irrigation. Vashisht et al. [17] also observed the effect of ET demands on IWUE under field and simulation studies in wheat under identical agro-ecologies.

The 22-year APSIM modelling data indicated that among the various planting dates, the most delayed planting reported the highest blue water footprints (715 m^3/t) (Figure 4B).

In comparison to PD4, wheat planting at early dates such as PD1, PD2 and PD3 required 292, 248, 90 m^3 lesser water to produce one tonne of grain. In simple terms, PD1 had a 40% lesser blue water footprint than PD4. Kumar et al. [24] also reported similar water productivity and resource use efficiency trends in wheat crop.

Green water footprint also followed a similar trend although the variations among different treatments were relatively narrow (Figure 4C). The least value of green water footprint was seen in PD1 (120 m^3/t) < PD2 (129 m^3/t) < PD3 (150 m^3/t) and highest under PD4 (172 m^3/t).

Total water footprint in wheat was observed in the range of 422–715 m^3/t (Figure 4D). Similar to green and blue water footprint, the total water footprint was also highest in PD4 and lowest in PD1. Wheat planted at PD1 consumed only 422 m^3 water, that is 10, 32, 40% less than PD2, PD3 and PD4, respectively.

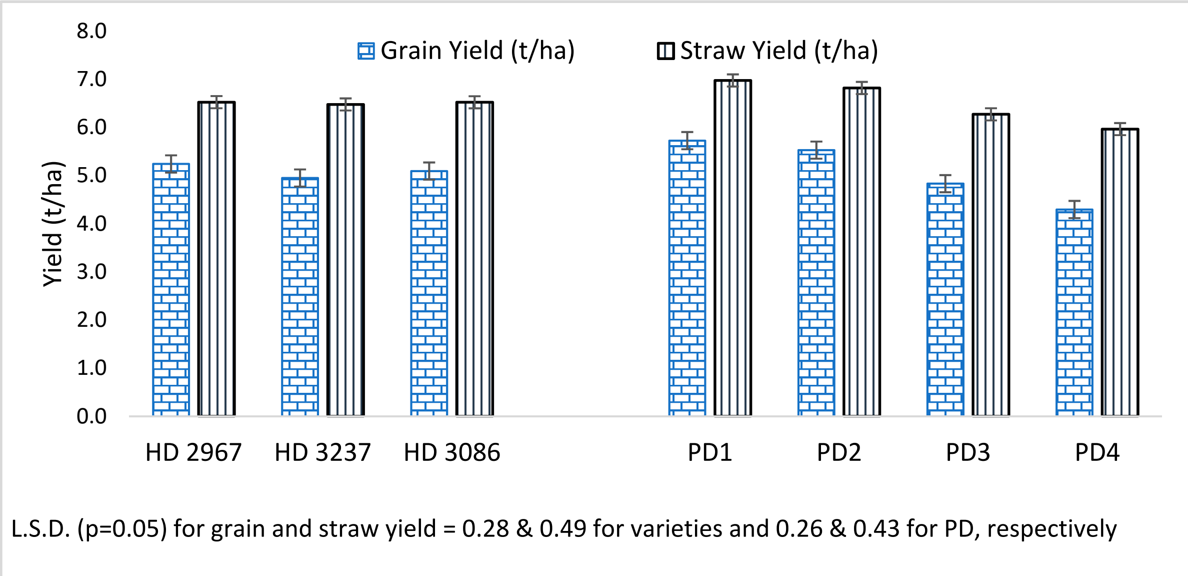
3.2. Yield under On-Farm Environments

Grain yield (2-year pooled mean) was found significantly affected by different wheat cultivars (Figure 5A). The wheat variety HD 2967 out yielded (5.2 t/ha) than the other two cultivars, whereas HD 3237 (4.9 t/ha) produced the least yield. The yield penalty with HD 3237 and HD 3086 were 5.6% (0.3 t/ha) and 2.8% (0.15 t/ha). Straw yield under different cultivars was statistically at par (Figure 5A). Significant variation in grain yield was noticed under various planting periods. Figure 5A illustrated a declining trend between grain yield and delayed sowing. Compared to PD1, 25%, 16% and 3.5% lesser yield was produced at PD4, PD3 and PD2, respectively. The straw yield ranged between 6.0 and 7.0 t/ha among various planting dates. Sowing during the first fortnight of November and the first fortnight of December, respectively, had the highest and lowest straw yields. In comparison to PD1, PD2, PD3 and PD4 had 0.2, 0.7 and 1 t/ha lower value of straw yield. The interaction effect was found to be significant for both grain and straw yields. Among the various treatment combinations, HD 2967 planting at PD1 had maximum grain (Figure 5B) and straw yields (Figure 5C). Whereas, HD 3237 with PD4 had the least grain yield and HD 2967 with PD4 had the least straw yield. It is evident from (Figure 5) that compared to the other two cultivars, HD 2967 performed well at all planting periods in terms of grain yield. Harvest indexes differ significantly both by cultivars and sowing dates. Among the cultivars, HD 2967 had the maximum HI (44.5) while HD 3237 had the least (43.2). A delay in wheat planting resulted in a decline in HI. Wheat planting during the first fortnight of November converted the maximum amount of biomass into grain yield whereas most delayed planting was found least effective in biomass conversion into yield. Compared to PD1, maximum decline in HI was noticed at PD4 and least at PD2. Among the varieties, the least decline was found in HD 2967 and most significant decline was under HD 3237.

Early planted wheat has extended the life cycle that helps in greater biomass synthesis and higher yield [14]. Comparatively lesser ambient temperatures during early seedling stage could hampered the plant establishment and tillering under late-planted wheat [11]. Moreover, heat stress during the grain filling stage might had reduced growth period, produced shriveled and smaller grain with little test weight consequently leading to lower wheat yield [11,12]. Higher grain yield in timely planted wheat may be owing to more accumulation of photo-thermal units, photosynthates and yield contributing characters in wheat. Normal-sown wheat roughly takes 15 days more to be harvested than late-sown crop (data not presented). Higher plant height, dry matter accumulation and extended tillers under timely sowing dates can be a reason for higher yield under early-sown crop (data not presented).

3.3. Simulated Grain Yield in Long-Term

The 22-year long modelling demonstrated that wheat sown at PD1 produced the highest mean grain yield (5.7 t/ha) closely followed by PD2 (5.6 t/ha) (Table 2). However, delay in wheat sowing beyond 30 November resulted in significant decline in yield and the lowest yield was observed at PD4 (4.5 t/ha). As compared to PD1 the per day yield decline was 7.4, 29.2, 31.6 kg/ha for PD2, PD3, and PD4, respectively. Early planted wheat has an extended life cycle that helps in greater biomass synthesis and higher yield [14]. Whereas, the increasing trend of maximum temperature during April-May could be the basic reason for yield decline with delayed planting (Figure 1). Meena et al. [12] and Dubey et al. [13] also reported that seasonal high mean temperature (+2.2 °C) in late-planted wheat (December-sown) caused significant yield decline as compared to November planting. Heat stress at the reproductive phase of wheat shortened the grain-filling duration and thereby negatively influenced grain-filling rate and biomass partitioning to grain that resulted into poor yield [14,17,25].



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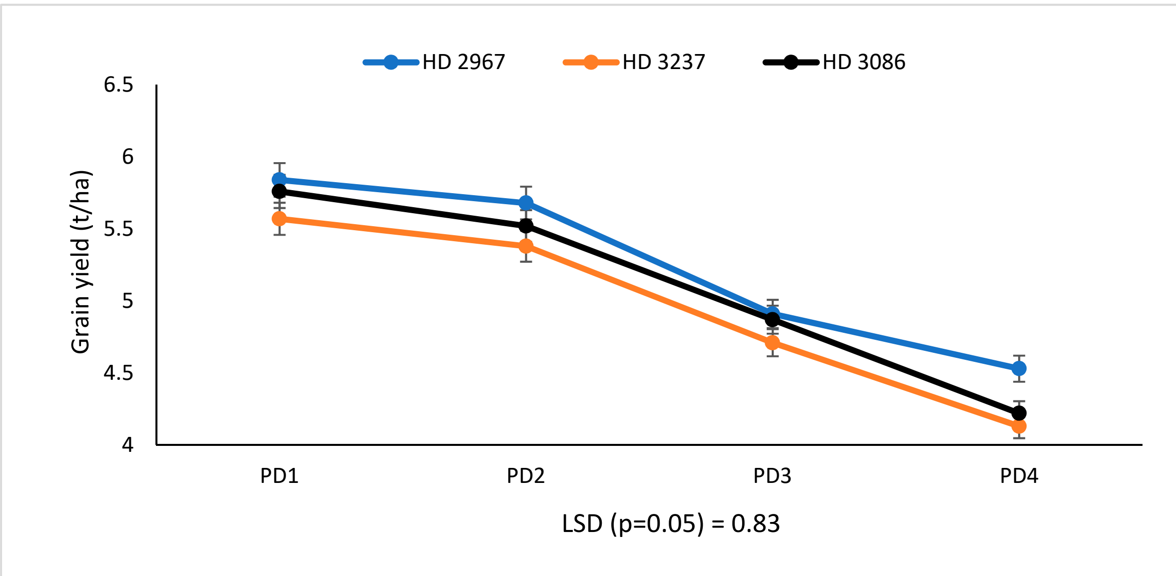

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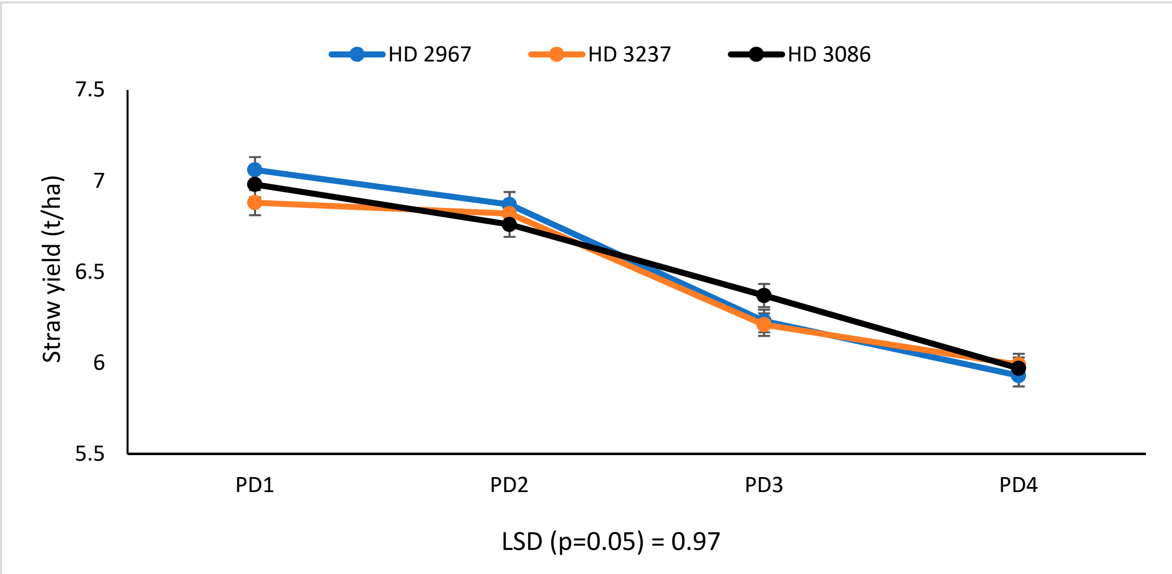

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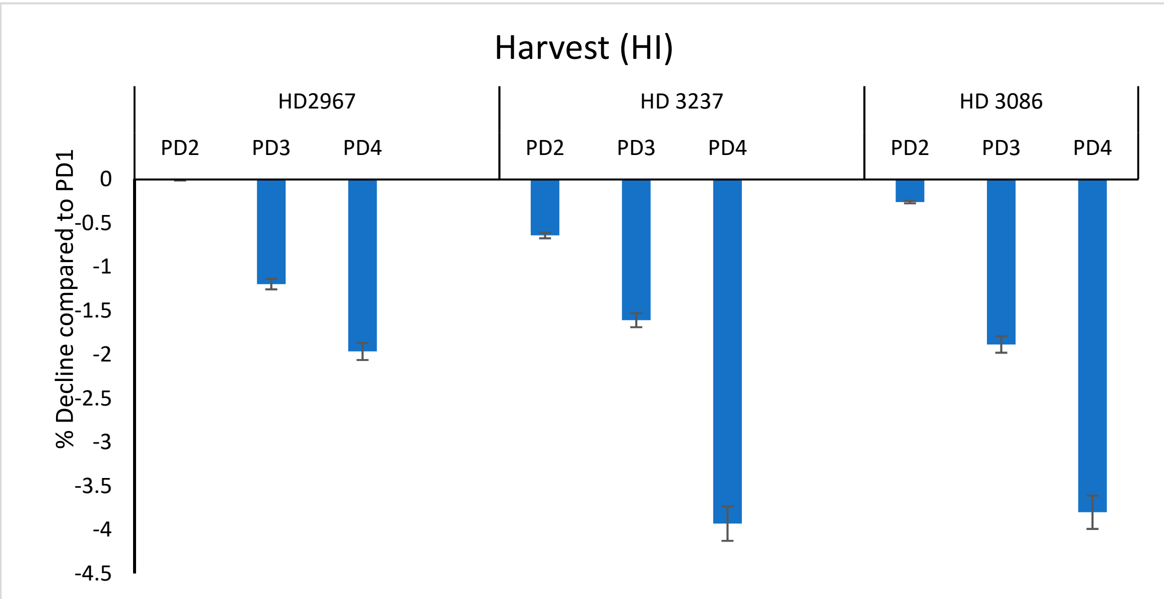

(**D**)

Figure 5. (**A**) Planting period and varietal effects on wheat yield (**B**) variety × planting-duration interaction effects on grain yield (**C**) straw yield and (**D**) harvest index at on-farm environments. PD1 = 1–15 November; PD2 = 16–30 November; PD3 = 1–15 December; PD4 = 16–31 December.

Table 2. Simulated average wheat grain yield (22 years) and coefficient of variation (CV) under different sowing dates.

Parameter	Planting Date #			
	PD1	**PD2**	**PD3**	**PD4**
Yield (t/ha)	5.72	5.60	4.84	4.58
Standard deviation over 22 years (t/ha)	0.18	0.19	0.24	0.29
CV (%)	3.07	3.32	4.90	6.31

PD1 = 15 November; PD2 = 30 November; PD3 = 15 December; PD4 = 31 December.

3.4. Seasonal Variation Effects in Simulated Yield

The yield data under PD4 treatment recorded the highest standard deviation (0.29 t/ha) as well as coefficient of variation (6.3%) for 22-year seasonal variation of data. Whereas, the PD1 and PD2 have lowest year-to-year yield deviation. Hence, early planting dates also provided more stable yield compared to late planting. The cumulative probability curve (Figure 6) at different sowing dates indicates that at 50% probability levels the highest and lowest yields were obtained under PD1 and PD4, respectively. The yield gap between late- and early-planted crops increased with decreasing probability. During most of the years, yield performance of PD1 and PD2 was not much different. At a probability level of 0.8 and above, the variations between PD2 and PD 3 was narrow, which shows that during the best 20% of the years of wheat cultivation, PD2 and PD3 produce similar yields, but during 80% of the seasons PD2 will perform better. Time-series analysis of wheat yield as influenced by diverse planting dates (Figure 7) also indicated a similar trend. The temporal variations were maximum under late-planted wheat, whereas, the yield levels were quite stable under timely planting.

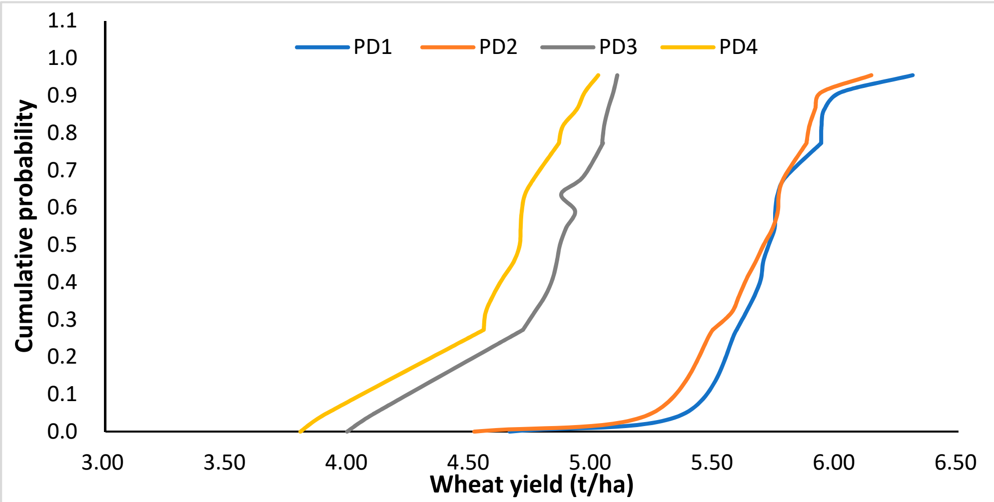

Figure 6. Cumulative probability curve of wheat yield under diverse planting dates (from 22-year simulations). PD1 = 15 November; PD2 = 30 November; PD3 = 15 December; PD4 = 31 December.

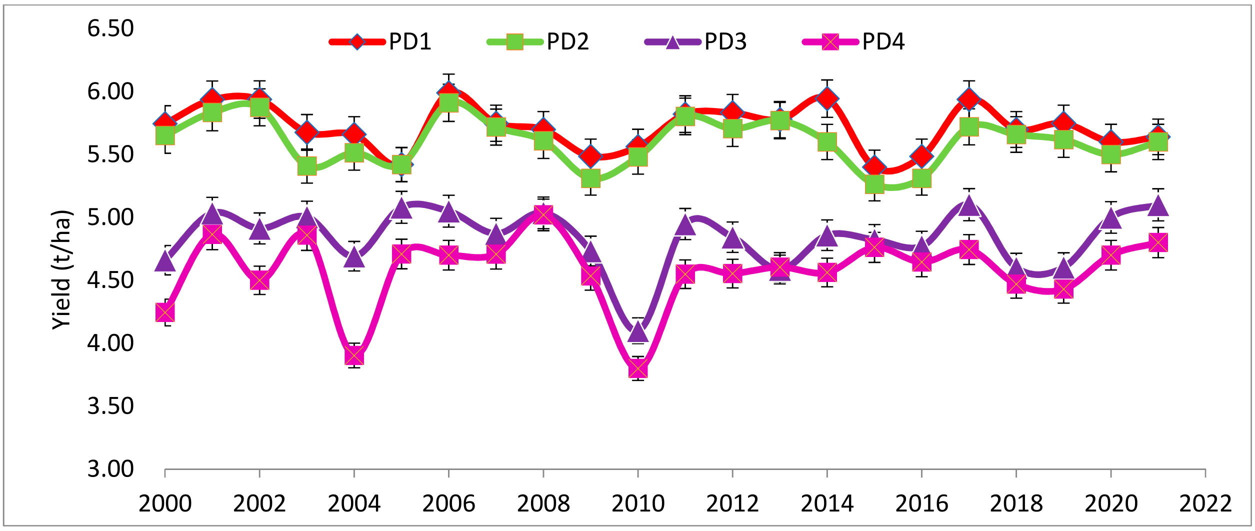

Figure 7. Time-series analysis of simulated wheat yield under diverse planting durations from year 2000–2021. PD1 = 1–15 November; PD2 = 16–30 November; PD3 = 1–15 December; PD4 = 16–31 December.

3.5. Net Returns at On-Farm Environments

Net returns varied between 949 and 1025 USD/ha among the wheat cultivars. The highest net returns were obtained (1025 USD/ha) when HD 2967 was planted (Figure 8). This cultivar had resulted in 76 and 38 USD/ha more net returns compared to HD 3237 and HD 3086. Among different planting periods, early planting of wheat in first fortnight of November (1166 USD/ha) was found more profitable followed by PD2 (1110 USD/ha), PD3 (910 USD/ha) and PD4 (761 USD/ha). Considerable economical loss was happened when wheat was planted in December. Compared to PD1, 5%, 22%, 35% lesser net profit was obtained at PD2, PD3 and PD4, respectively. Like net returns, B:C was also found maximum with HD 2967 (1.8) followed by HD 3086 (1.73) and HD 3237 (1.66). The B:C with different planting periods varied from 1.33 to 2.04. Least benefit per unit of cost incurred was at PD4, which was 0.26, 0.61, 0.71 lesser than PD3, PD2 and PD1. The higher values of net returns under PD1 were due to high yield and since the sowing time is a non-monetary input, therefore the cost of cultivation remained the same under all the treatments [4]. In the like manner, cost of cultivation remained same under all the varieties and the highest yield performer variety gave maximum profits. The results are in conformity with Bana et al. [26,27] and Pal et al. [28].

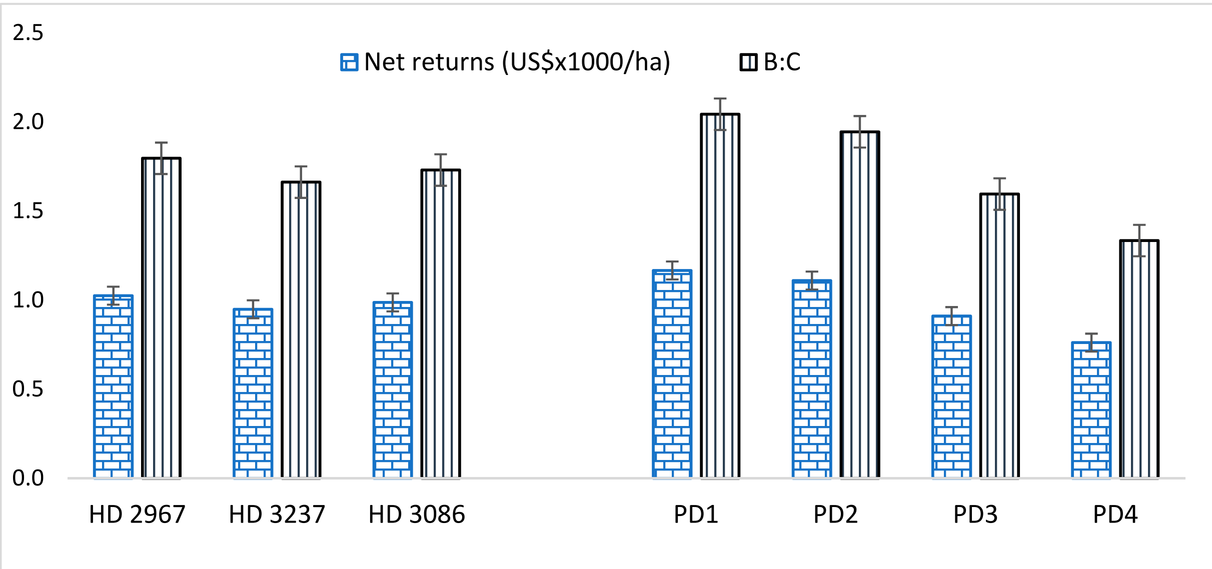

Figure 8. Net returns and B:C (benefit:cost) ratio of wheat under diverse planting durations in adaptive trials. PD1 = 1–15 November; PD2 = 16–30 November; PD3 = 1–15 December; PD4 = 16–31 December.

3.6. Days Taken to Physiological Maturity (Simulated)

Sowing time plays a major role in deciding the phenological development and crop duration. Delayed planting reduced the days taken to complete the crop life cycle, hence forcing the maturity to commence early (Figure 9). The similar effect of delay planting on wheat phenology was also reported by Arora and Gajri [29]; Ortiz et al. [25] and Lobell et al. [30]. The longest crop period (130 days) was observed in PD1 which was reduced to 117 days in PD4. Compared to PD1; PD2, PD3 and PD4 took 4, 8, and 13 days lesser to commence to maturity, respectively. This may be due the speedup of crop development rate owing to heat stress [31]. Lobell et al. [30] also found that higher temperature during the reproductive phase of late-sown wheat had increased the grain filling rate that shortened the crop duration.

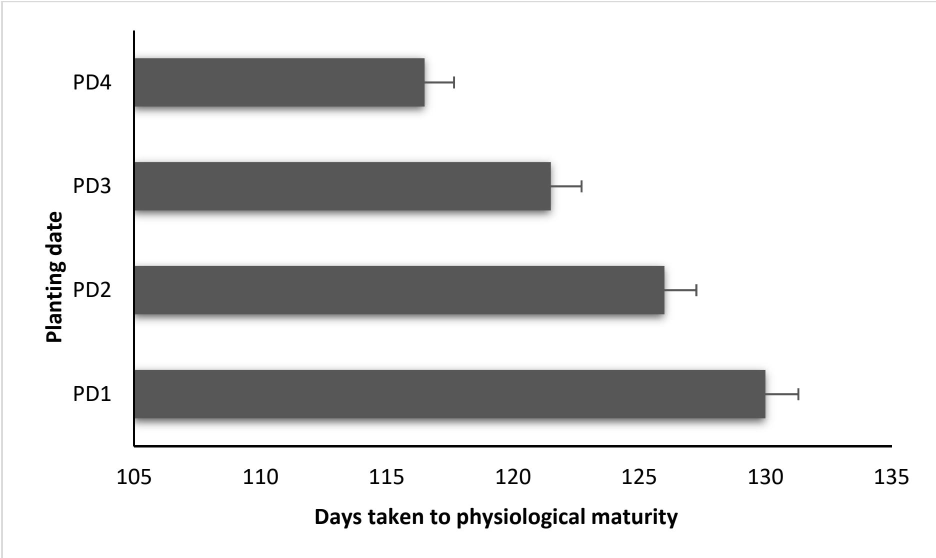

Figure 9. Effect of sowing duration on days taken to physiological maturity in simulation study. PD1 = 1–15 November; PD2 = 16–30 November; PD3 = 1–15 December; PD4 = 16–31 December.

4. Conclusions

Under a changing scenario, planting of wheat during the first fortnight of November results in maximum yield stability and profits and lower water footprints under on-farm environments. As is evident from the calibration followed by validation with two years' field trial, it can be concluded that the APSIM model performs well for wheat crop in north Indian conditions. Model evaluation showed that it can be used for optimization of sowing dates, irrigation strategies and other agronomic interventions to support and extend field experiments. The long-term (22 years) APSIM simulation indicated that adjustment in the wheat planting period could be an effective measure to enhance crop and water productivity, and planting up to 15 November results in higher productivity with the least blue water footprints. It was observed that a delay of every 15 days in wheat planting reduces crop duration by 4–5 days and wheat sowing at the end of December caused 20% yield decline as compared to 15 November planting. The temporal fluctuations in yields were more if wheat is planted at the end of December with coefficient of variation as high as 6.3%. Furthermore, November planting reduces blue water requirement by around 20–25% than December-end planting of wheat crop. Therefore, based on the present on-farm cum simulation study, it can be recommended to plant wheat crop early in the season to achieve higher yields and reduce water footprints. A delay up to 30 November may be acceptable, but planting beyond that results in double burden by reducing both yields and water productivity. If the fields are not vacated on time, either modification of the cropping pattern by adopting short duration crops or cultivar of previous crops or adoption of newer technologies such as zero tillage are suggested to avoid delay in wheat sowing.

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