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Challenges and the prospects of wheat (*Triticum aestivum*) improvement for limited irrigation in diverse production environments

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ABSTRACT

An experiment was conducted at ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana in which performance of wheat (*Triticum aestivum* L.) varieties recommended for limited irrigation was compared utilizing the data generated in coordinated trials conducted during the period 2018–19 to 2022–23 at fixed sites in four agro-climatic zones of India. The yield loss, yield fluctuations, yield sustainability, shift in grain quality, physiological expressions and the key contributing traits were compared for the wheat varieties specific to such environments. In Indo-Gangetic plains (IGP), characterized as ME-1 by CIMMYT that includes two zones of northern India i.e. north-western plains zone (NWPZ) and north-eastern plains zone (NEPZ), limited irrigation expressed no abiotic stress on plant height, days to heading, maturity duration and grain weight and only grain bearing was adversely affected. In the warmer central-peninsular India (CPI) i.e. central zone (CZ) and peninsular zone (PZ) which is included in ME-5, there was a significant reduction in all the five traits. Yield reduction was highly significant in each zone and the yield loss varied zone-wise from 16% in NWPZ to 38% in PZ. It was more difficult to sustain wheat productivity under such situations. Protein content declined in IGP but CPI registered a significant gain in protein and gluten strength. Location specificity was apparent in each zone and durum was unsuitable for deficit irrigation. Farmer's preference was restricted only to two zones namely CZ and NWPZ. For improving wheat varietal prospects under high temperature, supplementary irrigation has to be ensured at the time of heading beside CRI (crown root initiation) stage. This study suggested that irrigated wheat varieties can be tried for limited irrigation. The varieties that are particularly bred to tolerate moisture deficits should be preferred as the key yield contributing traits differ.

Keywords: Production environments, Restricted irrigation, Wheat, Wheat improvement, Wheat quality

Water resources are depleting in many parts of world and concerted efforts are required for their efficient use in irrigated agriculture. Deficit irrigation, an advance approach and optimized tool for irrigation management, is slowly becoming a promising pathway to save water for irrigated wheat (*Triticum aestivum* L.) (Du *et al.* 2015, Mohan 2023). Realising relevance of restricted irrigation in wheat, certain water saving strategies had been formulated in many countries (Galindo *et al.* 2018, Lindi *et al.* 2021). Wheat breeders have started paying attention to this emerging need but are often sceptical whether it can be rewarding under all production environments. Relevance of limited irrigation has been realized well in a country like India where trials to screen varieties for this practice are being conducted in agro-climatically diverse production environments. The wheat improvement programme of India started addressing this issue because a large part of wheat cultivation in Central and Peninsular India (CPI) falls in the water deficit area where irrigations are restricted to only one or two. CIMMYT has characterized IGP as Mega-Environment 1 (ME-1) and CPI as ME-5. The wheat crop under such ME-5 suffers from the abiotic stress occurring predominantly in the vegetative phase. In the 21st century, fast depletion in the water table of the Indo-Gangetic Plains (IGP) has gained attention (Fishman 2018, Zaveri and Lobell 2019). Taking cognizance of the emerging situation, the All India Coordinated Research Project on Wheat and Barley started identifying suitable genotypes for limited irrigation. This programme has been successful to identify the wheat varieties which are specific for this type of cultivation and the varieties recommended are specific for each region. In this study, the normal irrigated timely-sown wheat and the restricted irrigation wheat have been compared to i) examine the yield loss and yield variations between and within the zones, ii) explore location specificity, and iii) study divergence in yield and grain quality components.

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MATERIALS AND METHODS

Study material and production environments: Data generated for grain yield, yield related agronomic traits and some grain quality characteristics in the Advanced Varietal Trials conducted by AICRP-Wheat and Barley in the India plains i.e. north-western plains zone (NWPZ), north-eastern plains zone (NEPZ), central zone (CZ) and peninsular zone (PZ) for irrigated timely sown wheat (TSW) and restricted irrigation wheat (RIW) were examined. Agro-climatic variations and geographical representation of these zones in the Indian map have been presented earlier by Mohan *et al.* (2022). These multi-location trials were conducted in randomized block design (RBD) with four replications in a plot size of 14.4 m^2. Data reported for the released varieties used as checks in the yield evaluation trials were examined for the five consecutive crop seasons of 2018–19 to 2022–23. Since the genotypes advised for each production condition are zone-specific, the study material varied across different zones, but within each zone, it remained the same for each testing location. Number of entries (observations) and the test sites in each zone is given in Table 1. Some durum genotypes were included in the study material in CZ and PZ because durum is also cultivated in these zones. Sowing of RIW (October 25–November 10) was completed at least one week before TSW (first fortnight of November). The fertilizer dose in trials was 150 N: 60 P_2O_5: 40 K_2O kg/ha in TSW of NWPZ and NEPZ, and 120 N: 60 P: 40 K kg/ha in TSW of PZ and CZ. In RIW trials, fertilizer dose was reduced to 90 N: 60 P_2O_5:4 0 K_2O kg/ha and it was same in all the four zones. The TSW trials were provided irrigations as per need of the crop whereas the RIW trials were provided only two irrigations across all zones i.e. one as pre-sown and second at 40–45 days after sowing. No chemical was sprayed for disease and pest control. Weeds were controlled by a combination of chemical and hand weeding. Besides yield, data were also analyzed for the important traits like plant height (HT), days to heading (DH), days to maturity (DM) and 1000-grain weight (TGW). Days for grain filling (DGF) was derived as difference between DH and DM. Grain number per m^2 was also computed as ratio between yield and TGW and it was presented in thousands. Yield loss in RIW was computed by comparing it with TSW at the common test sites. The common test sites were 9 each in NWPZ and NEPZ, 8 in CZ and 5 in PZ. Zone mean was used to compare grain protein content (GPC), sedimentation value and some physical grain quality parameters like gain appearance score, test weight (hectoliter weight) and grain hardness index.

Statistical analysis: The "t" test was applied to test significant difference between two categories of wheat at P=0.001. Yield flux (YF) was derived for each test site to assess the magnitude of yield fluctuations under different crop seasons and was calculated as percent yield loss in the most unfavourable crop season in comparison to the best. Coefficient of determination (R^2) was computed through regression analysis to examine relationship between yield and the major yield related traits. Data of each zone were standardized to apply this analysis. The yield sustainability index (SI), proposed by Singh *et al.* (1990), was computed to assess the variations in yield sustainability using the formula:

$$SI = [(\text{Mean yield} - \text{Standard deviation})/\text{Maximum value}] \times 100$$

RESULTS AND DISCUSSION

Divergence between and within the mega zones: Like TSW, per hectare productivity of RIW varied in different zones but the productivity status was maintained in both types of wheat, being highest in NWPZ and lowest in PZ (Table 1). Yield reduction in each zone was highly significant (P<0.001) but the yield loss varied as it was lowest in NWPZ and highest in PZ. The yield potential in TSW matched in all the four zones and the range was 71–77 q/ha. However, the margin of difference was large in RIW as the maximum yield in NWPZ (82 q/ha) was much higher in comparison to PZ (45 q/ha). The yield potential achieved in RIW of NWPZ was 5 q/ha higher than in TSW. In NEPZ and CZ, yield potential of normal crop was 5–8 q/ha higher in comparison to limited irrigation wheat. This gap turned extremely wide in PZ as the difference amounted 28 q/ha in RIW. Barring PZ, SI in each zone was decreased in RIW by a margin of ≥10%. Since maximum yield was quite less in RIW, SI of RIW was comparable with TSW of PZ. In this study, impact of deficit irrigation was examined on traits such as plant height, crop phenology, grain bearing (grain number/m^2) and TGW. Results showed that it was only the grain bearing which recorded highly significant reduction in each zone. For other traits, the trend varied zone wise. In NWPZ, height and maturity improved whereas there was no effect on TGW. In NEPZ, TGW was also increased along with height and maturity duration.

There is always yield advantage when irrigation is applied in the moisture deficit wheat crop (Tari 2016, Zampieri *et al.* 2017, Mohan and Gupta 2011). Yield advantage in comparison to rainfed crop is eminent under restricted irrigation but when comparison is made between fully irrigated and deficit irrigation; decline in yield is also inevitable but it has not been assessed. This study made it abundantly evident that, notwithstanding differences in regional yield loss, wheat yield reduction under restricted irrigation is unavoidable in all conditions due to lower grain bearing (Table 1). The quantum of yield loss depends on the degree of stress the crop experiences. This study confirms that in comparison to IGP, reduction in plant height and the grain weight is a certainty in wheat grown in CPI and it was eminent in durum as well as bread wheat. Consequently, the yield loss in IGP was less than CPI. This study demonstrated that effect of crop year fluctuations under limited irrigation was severe on CPI wheat in comparison to IGP wheat (Fig. 1). The stress can be severest in areas like PZ where every yield component is affected under restricted irrigation. It emphasizes that in areas where crop duration is already short, the crop be badly affected by inadequate irrigation. This study also suggested that limited irrigation

Table 1 Comparison of irrigated timely sown and limited irrigation wheat varieties in different production environments

Parameter	NWPZ		NEPZ		CZ		PZ	
	RIW	TSW	RIW	TSW	RIW	TSW	RIW	TSW
Number of entries	31	29	22	29	33	24	33	30
Average productivity (q/ha)	49.2	58.3	38.0	47.2	39.4	53.9	30.1	48.4
Maximum yield (q/ha)	82.3	77.3	65.8	70.7	65.3	73.8	45.2	73.7
Yield loss (%)	15.7	-	19.3	-	26.8	-	37.7	-
Sustainability index (%)	49.5	64.3	44.8	56.2	48.2	60.2	53.4	53.1
Plant height (cm)	**105**	101	**97.7**	95.4	85.3	**88.2**	81.0	**86.0**
Maturity days	**149**	145	**129**	126	119	118	105	**109**
Grains/m^2 ('000)	12.3	**14.5**	8.71	**11.5**	9.39	**11.8**	7.59	**10.8**
1000-grain weight (g)	40.0	40.0	**43.7**	41.2	42.3	**46.0**	39.7	44.1

NWPZ, North-western plains zone; NEPZ, North-eastern plains zone; CZ, Central zone; PZ, peninsular zone; RIW, Restricted irrigation wheat; TSW, Irrigated timely sown wheat.

Bold figures indicate significantly higher value.

should not be practiced to grow durum because durum with lesser grain weight will not acceptable in the grain market. It is apparent that the yield sustainability will also decline in a moisture-stressed environment. Indication of reduced yield sustainability under dry and hot climate had been reported by Mohan *et al.* (2020). This study further stated that yield sustainability is unavoidably reduced when the growth conditions become stressful under limited irrigation. This investigation suggests that even if the yield potential match between the normal and limited irrigation crops, it is more difficult to sustain the yield levels and the yield potential of wheat under limited irrigation.

Deficit irrigation caused minimal yield reduction in NWPZ and all the location except one, expressed at least 45 q/ha grain yield. Even if water table is a big concern in this region, the climatic conditions favour good yield under such conditions. Location that can yield more than 35 q/ha with good consistency are few in NEPZ as out of 9, just four locations could meet such criteria. The idea of deficit irrigation in India was first introduced in the CZ area. Madhya Pradesh state in CZ suits the most for RI wheat as limited irrigation in Gujarat state brings wheat productivity below 35 q/ha. In PZ, there is no justification for promoting wheat grown under restricted irrigation as yield is non-remunerative (<30 q/ha) or the yield fluctuations are too high.

Quality comparison: To determine any difference in the physical grain quality and GPC of wheat amongst the zones, the 5-year data were compared and only bread wheat was included in this exercise as no durum genotype was included in trials in IGP. The test weight, grain hardness, and grain appearance did not differ significantly. Differences did occur in GPC and sedimentation value. GPC was decreased in RIW of NWPZ (TSW: 11.7%, RIW: 11.2%) and NEPZ (TSW: 11.5%, RIW: 11.0%). Just the opposite occurred in CPI, where the GPC of RIW was greater than that of TSW and this difference was highly significant in CZ (TSW: 11.0%, RIW: 12.2%). Except NWPZ, sedimentation value of RIW was higher than TSW in all other zones and this difference was significant in CZ (TSW: 43 ml, RIW: 56 ml) and PZ (TSW: 45 ml, RIW: 57 ml). On the contrary, TSW in NWPZ had better sedimentation value compared to RIW (TSW: 57 ml, RIW: 53 ml). Environment and genotypes play big role in wheat quality (Mohan and Gupta 2011, Tari 2016, Anjum *et al.* 2021). When changes occur at both the levels, it is natural to have some deviations in quality characteristics. Some alterations in grain quality can also be expected under limited irrigation. Limited irrigation wheat grown in areas like IGP (ME-1) may result in poorer protein content as GPC was 11.6% in TSW and 11.1% in RIW. In comparison, when grain weight is adversely affected in warmer and drier regions of ME-5 (CPI), limited irrigation may be advantageous to enhance protein content (TSW: 11.5%; RIW: 12.0%) and sedimentation value (TSW: 43 ml; RIW: 57 ml).

Location specificity: Every location was examined for the extent of yield loss during the five-years testing. In each zone, those locations were identified which were good exclusively for the timely-sown wheat as the yield loss was more than 20% in RIW (Table 2). In IGP; two locations in NWPZ and three in NEPZ could be located which were good exclusively for irrigated timely sown wheat. Number of such sites increased in CPI as at least two-third locations recorded yield loss higher than the threshold value. Search was also made to note the test sites where SI was substantially lowered (≥10%). There was only one such location in NWPZ i.e. Ganganagar. In comparison, there were four such sites in NEPZ namely Varanasi, Ranchi, Pusa and Ayodhya. Such locations were observed in CZ (Udaipur) and PZ (Pune) as well.

Location specificity for the normal and limited irrigation wheat crop is crucial in a mega-zone. Location differences in wheat productivity are quite common in the Indian sub-continent (Kaya and Akcura 2014, Mohan *et al.* 2020). This investigation underlined that not every location is suited for limited irrigation. If decline in wheat productivity and yield

Table 2 Location differences in wheat productivity and the yield loss under limited irrigation

Test sites	Mean yield (q/ha)		Yield loss	Test sites	Mean yield (q/ha)		Yield loss
	RIW	TSW	(%)		RIW	TSW	(%)
North-western plains zone				*North-eastern plains zone*			
Karnal	58.1	61.0	04.7	Ranchi	46.1	56.3	18.1
Delhi	52.8	59.9	11.9	Kanpur	43.2	48.7	11.3
Pantnagar	51.9	59.7	13.2	Ayodhya	42.9	54.1	20.8
Hisar	48.6	59.3	18.0	Pusa	38.3	47.7	19.7
Bulandshar	47.9	58.8	18.5	Chianki	37.7	46.2	18.5
Ganganagar	46.7	59.7	21.8	Varanasi	35.5	46.8	24.2
Ludhiana	47.1	60.4	21.9	Sabour	33.3	45.8	27.5
Jammu	45.2	52.2	13.4	Kalyani	33.2	40.4	17.9
Gurdaspur	44.1	48.8	09.6	Burdwan	32.4	39.9	18.7
Central zone				*Peninsular zone*			
Udaipur	44.7	54.3	17.7	Niphad	31.8	46.5	31.5
Indore	41.4	53.6	22.8	Pune	31.4	58.6	46.5
Jabalpur	39.8	51.0	21.9	Parbhani	29.2	47.6	38.6
Powarkheda	39.4	58.4	32.4	Dharwad	28.0	42.0	33.3
Vijapur	34.7	62.0	44.0	Nasik	30.2	47.2	36.1
Bilaspur	36.3	44.0	17.4				

RIW, Restricted irrigation wheat; TSW, Irrigated timely sown wheat.

sustainability is considered together, out of 9 trial locations, there were only 2 locations in NWPZ and 4 in NEPZ which did not fit well for limited irrigation. In comparison; every test site of PZ and majority of the test sites in CZ (5 out of 6) were unsuitable for restricted irrigation wheat.

Crop year effect: To assess year wise variations in a zone, genotypes and locations were fixed for each year and their annual mean was compared in RIW. There were four varieties in each zone namely HD 3043, HI 1628, PBW 644 and NIAW 3170 in NWPZ; DBW 252, HI 1612, HD 3171 and K 1317 in NEPZ; DBW 110, MP 3228, DDW 47(d) and HI 8627(d) in CZ; HI 1605, NIAW 3170, NIDW 1149(d) and UAS 446(d) in PZ. The results of this study showed that IGP experienced less year-to-year yield volatility than CPI. Yield flux was minimal in NWPZ (8.8%) and highest in PZ (17.1%). It underlined that yield irregularity is too high to promote RI wheat in PZ.

Grain weight reduction in CPI (ME-5) suggests that besides CRI stage, it is necessary to provide supplementary irrigation for proper grain ripening in the warmer environments. This investigation demonstrates that the template of irrigation scheduling applicable in IGP (ME-1) is not suited for in harsh environments ME-5. Usually, CRI stage is considered the most sensitive for rearing wheat crop under moisture stress condition (Sarkar 2013, Lindi *et al.* 2021). A recent review has indicated that both irrigation scheduling and irrigation methods intricately influence wheat physiology, affect plant growth and development, and regulate grain yield and quality (Si *et al.* 2023). In water stress studies, the most yield sensitive stimulated growing stage is the grain filling period. Applying a second supplementary irrigation is consequently crucial for healthy grain development in hot and dry environments. Bolder grains have been traditionally the valuable characteristic feature of wheat grown in central India (Mohan 2023). An improvement in grain weight will retain the grain superiority and improve the wheat productivity under deficit irrigation.

Divergence in yield linked traits: An attempt was made to understand whether there was any similarity

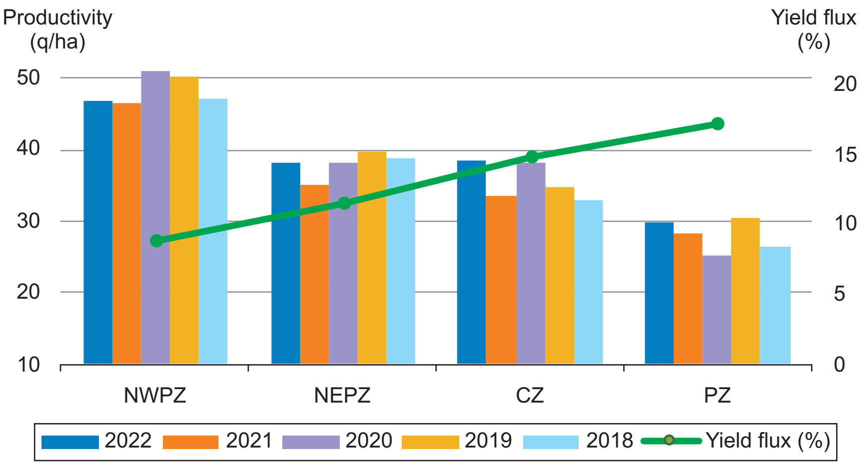

Fig. 1 Year-wise yield variations and yield shift in limited irrigation wheat.

Table 3 Relationship of yield with key yield determinants as determined by coefficient of determination R^2

Parameter	NWPZ		NEPZ		CZ		PZ	
	TSW	RIW	TSW	RIW	TSW	RIW	TSW	RIW
R^2 - individual traits								
Plant height	0.04	0.01	0.00	0.06	0.19	0.00	0.01	0.69^{***}
Heading days	0.01	0.00	0.00	0.15	0.32^{*}	0.03	0.19	0.03
Maturity days	0.04	0.24^{***}	0.01	0.16	0.28^{*}	0.00	0.15	0.00
Grain filling days	0.28^{***}	0.22^{**}	0.00	0.03	0.17	0.12	0.16	0.14
1000-grain weight	0.26^{***}	0.26^{**}	0.20^{*}	0.20^{*}	0.01	0.42^{**}	0.07	0.14
R^2- key determinants	0.52^{***}	0.50^{***}	0.20^{*}	0.38^{**}	0.64^{***}	0.42^{**}	0.23	0.69^{***}
Beta value								
Plant height	0.47^{*}	-0.31^{*}	-	-	-	-	-	0.83^{***}
Heading days	-1.58^{***}	-	-	0.43^{*}	1.02^{***}	-	-	-
Maturity days	1.35^{***}	0.40^{**}	-	-	-	-	-	-
1000-grain weight	-	0.54^{***}	0.44^{*}	0.49^{**}	0.73^{***}	0.72^{**}	-	-

RIW, Restricted irrigation wheat; TSW, Irrigated timely sown wheat.

between TSW and RIW in relationship of the yield determinants. Regression analysis revealed that there were some differences in coefficient of determination R^2 in IGP. In NWPZ, DGF and TGW expressed highly significant relationship with yield in TSW as well RIW (Table 3). In NEPZ, TGW was significantly related with yield in both categories of wheat. In wheat crop phenology was important for TSW whereas TGW was the chief determinant in RIW of the region.

Step-down regression analysis was applied to identify the key yield determinants and the magnitude of their collective impact on grain yield revealed that the key yield related economic traits differed in two production conditions of every zone. In this relationship; days to heading was of no consequence in RIW of NWPZ whereas early heading was crucial in TSW (Table 3). Similarly, TGW didn't contribute in TSW whereas it was the chief yield determinant in RIW of NWPZ. Plant height in NEPZ was important for RIW but not for TSW. In CZ, delayed heading i.e. longer vegetative duration contributed in yield of TSW but it had no role to play in RIW.

Wheat breeding strategies can be improved by routinely assessing the breeding results for yield gain (Xiao *et al.* 2012). Results indicate that it's not absolutely necessary to have specific varieties for limited irrigation as some key characters are common. It's because some key attributes that affect yield are in both categories of wheat like maturity duration and grain weight in NWPZ, and grain weight in NEPZ and CZ (Table 3). However, it's always better if varieties are bred specifically for limited irrigation as there can also be certain essential yield governing traits that are different from the irrigated timely sown wheat genotypes. Results of this study support that separate selection criteria will be beneficial to augment yield under limited irrigation. This study suggests improved grain weight, and extended maturity but shorter plant height will be advantageous for wheat varieties in NWPZ, whereas a larger vegetative period and higher grain weight can benefit in NEPZ. Similarly, grain weight in crucial in CZ whereas height can add yield in PZ (Table 3).

Saving irrigation water is crucial to sustain wheat production in future but it cannot be put into effect without a premium on wheat output. Disparity exists between and within the zones for yield, yield sustainability and quality of the grains. Limited irrigation is suited in cooler environment favourable for wheat growth. Yield penalty can be minimal under such situations but reduction in grain protein content cannot be averted. Limited irrigation may turn out to be a big failure in a region where abiotic stress is already very high. Existing normal sown wheat varieties may not be totally misfit but separate breeding strategy will be more useful to enhance the prospects restricted irrigation in future.

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