



## RESEARCH ARTICLE

# Multi-trait-based identification of water use efficient genotypes in bread wheat (*Triticum aestivum* L.)

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## Abstract

The present study was conducted to identify high-yielding and water-use-efficient bread wheat genotypes. Seventeen genotypes were grown at three irrigation levels (WL), including 100, 80, and 60% of the reference evapotranspiration (ET), which were estimated based on a decision support tool. The pooled analysis of variance depicted significant genotype × environment interactions (GEI) ( $p < 0.001$ ) for all the traits studied, except number of tillers/sq. m and NDVI before reproductive phase (NDVIB) and NDVI after reproductive phase (NDVIA). The average grain yield (GY) at 100% ET was 5178 kg ha<sup>-1</sup>, which was reduced by 5.28 and 11.40% at 80 and 60% ET, respectively. NDVIB and NDVIA were remarkably decreased by 22.09 and 11.38% at 60% ET. The water use efficiency (WUE) showed an increasing trend with reduced irrigation levels and varied from 1.72-1.90, 1.93-2.30, and 2.27-2.85 kg m<sup>-3</sup> at 100, 80, and 60% ET, respectively. The GY and WUE revealed positive and significant correlation ( $r=0.99^{***}$ ) at the 60% ET. The genotypes, namely 40<sup>th</sup> ESWYT-33, 40<sup>th</sup> ESWYT-07, 40<sup>th</sup> ESWYT-37 and RWP-2018-32, were found promising for GY and WUE at 80% ET, while 40<sup>th</sup> ESWYT-07 also performed better at the 60% ET.

**Keywords:** Wheat, evapotranspiration, WUE, MTSI, WAASB.

## Introduction

Bread wheat is one of the extensively arable crops in India, where the country contributes nearly 14.5 and 33% of the global and Asian wheat production (Kumar et al. 2025). The crop is grown during the winter season with assured irrigations, as 80% of the annual rainfall is received during the monsoon period in India. Over-exploitation of groundwater is being done for irrigation and other purposes, leading to a decline in groundwater level (Asoka and Mishra 2020; Sahadevan and Pandey 2023). India contributes nearly 25% of the world's extraction (Sahadevan and Pandey 2023), which is unsustainable in the long run. The utilization of electric pumps and subsidized power supply has led to a significant surge in groundwater extraction (Mishra et al. 2018; Asoka and Mishra 2020). The annual rate of decline in the groundwater level is highest in India (Jain et al. 2021), ranging from 2 cm/year in northern India to 1 to 2 cm/year in southern India (Asoka et al. 2017). In the Indo-Gangetic Plains (IGPs) of India (north-western India), the water table declined at a rate of 1.0 meters per year from 2000 to 2006 (Yadvinder et al. 2014; Khedwal et al. 2023). The decline in water table depth in this region is attributed to the rice-wheat cropping system (Yadvinder et al. 2014). Gravity Recovery and Climate Experiment (GRACE) based data analysis from 2002 to 2016 revealed that groundwater storage decline in the region is

not solely attributed to rice cultivation but also extends to crops grown during the winter season (Asoka and Mishra 2020). The indiscriminate use of groundwater for flood

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irrigation during the winter season, especially in wheat, is due to inefficient irrigation methods and low water-use efficient of genotypes.

The water productivity of wheat in India is very low; it ranges between 0.8 and 1.0 kg m<sup>-3</sup> of water depending on the type of genotype, location, soil type, and agronomic management practices. The low seedling survivability under water stress is one of the major yield-limiting factors along with various other factors (Tomar and Kumar 2004). Further, irrigation water demand in agriculture has been estimated to increase by 60% by the year 2025 as compared to the year 2018 (UNESCO World Water Assessment Programme 2018). In the present scenario, food security in South Asia and globally can be assured by increasing the water productivity of crops (Meena et al. 2019). To evaluate the stability and adaptability of genotypes across different levels of environments, a BLUP (best linear unbiased prediction) based stability analysis- WAASB and superiority analysis (WAASBY) have been employed for traits (Nataraj et al. 2021). These indices are proven to have high prediction accuracy since they are based on BLUP values (Olivoto et al, 2019a). Further, a multi-trait stability index (MTSI) developed by Olivoto et al. (2019b) has been extensively employed in identifying stable genotypes based on multiple traits (Patel et al. 2023; Khandelwal et al. 2024; Mandalapu et al. 2025). Therefore, the present study was carried out to identify stable, high-yielding, and water-use-efficient bread wheat genotypes under varied irrigation regimes.

## Materials and methods

### Plant material used

A total of fourteen bread wheat genotypes, along with three checks, namely, DBW166, DBW222, and DBW243, were evaluated at three different soil moisture levels, i.e., 60, 80, and 100% of ET (Evapotranspiration). The genotype selection was based on yield superiority and desirable agronomic traits, which were recorded in preliminary yield trials and nurseries, including a few CIMMYT (International Maize and Wheat Improvement Center) trials conducted in India. The pedigree details of the genotypes under study

are given in Table 1.

### Experimental site

The experiment was conducted for two consecutive years, 2020-21 and 2021-22, during the *rabi* season at the research farm of ICAR-Indian Institute of Wheat & Barley Research, Karnal (29°43'N, 76°58'E, 245 m above mean sea level), Haryana, India. The average annual maximum and minimum air temperatures are 29.9 and 17.1°C, respectively. Out of the total annual rainfall of 744 mm, nearly 80 percent was received during the southwest monsoon period (July–September). Meteorological information, i.e., temperature (maximum and minimum) and rainfall of the study location and period, is presented in Fig. 1.

### Experiment details

The experiment was conducted in a split-plot design with three replications. The main plot consisted of 3 irrigation levels (100, 80, and 60% of ET) and 17 genotypes in subplots. The plot size was 12.8 m<sup>2</sup> (8.0 × 1.60 m). The experimental field was equipped with micro-irrigation facilities, and the genotypes were precisely irrigated using a drip irrigation system. The drip lines were laid 60 cm apart with emitters spaced at 30cm, having a discharge rate of 2.4 litres hour<sup>-1</sup> emitter<sup>-1</sup>. The experimental crop was managed as per the standard package of practices. Material was planted on 16<sup>th</sup> November and 14<sup>th</sup> November in the field in *rabi* during 2020 and 2021, respectively. The water requirement of the crop was calculated using the decision support tool CROPWAT 8.0, a computer-based program developed by the Land and Water Development Division of FAO. A buffer zone of one meter was maintained between plots of each replication to avoid moisture seepage. The irrigation water for each treatment was measured using the built-in water meter in the drip irrigation system. The crop was irrigated as per pre-decided treatments once the cumulative pan evaporation (CPE) of 20 mm was reached after the previous irrigation. The data were recorded on grain yield (GY), water use efficiency (WUE), above-ground biomass (AGBM), 1000 grain weight (TGW), tillers/m<sup>2</sup> (TPMS), plant height (PH) and ear-head length (EHL), and NDVI values before (NDVIB) and

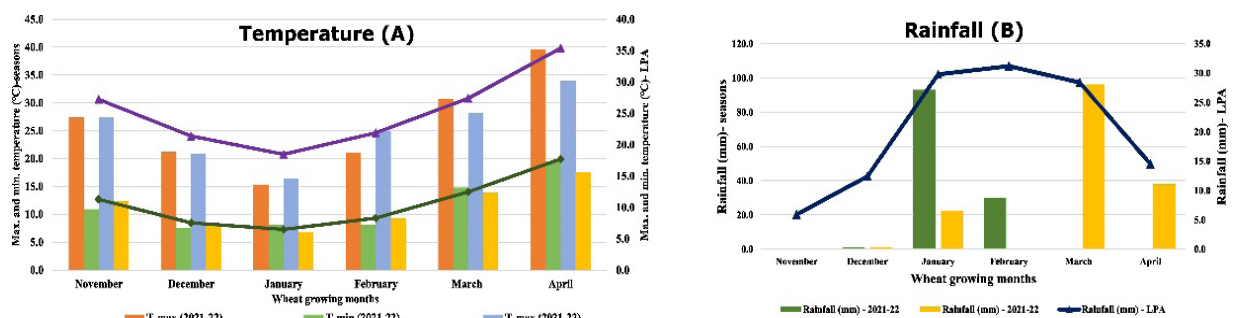


Fig. 1. Monthly mean, maximum and minimum temperature (A) and monthly total rainfall (B) at IIWBR, Karnal, during experimental years compared with historical mean (1972 to 2021)

**Table 1. Pedigree details of the genotypes under study**

S. No.	Genotype	Symbol	Parentage
1	40 <sup>th</sup> ESWYT-07	G1	FRANCOLIN #1//WBLL1*2/BRAMBLING/4/WBLL1*2/ KURUKU*2/3/KIRITATI//PBW65/2*SERI.1B/5/MUTUS/AKURI
2	RWP 2018-326	G2	CROC_1AE.SQ(205)//BORL95/3/PRL/SARA//TSI/
3	40 <sup>th</sup> ESWYT-26	G3	CHIPAK/3/SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU
4	DBW173	G4	KAUZ/AA//KAUZ//PBW602
5	40 <sup>th</sup> ESWYT-32	G5	SUP152/BAJ #1*2/3/KACHU//WBLL1*2/BRAMBLING
6	RWP-2018-32	G6	HD3131/DBW 90
7	40 <sup>th</sup> ESWYT-50	G7	KACHU*2/3/ND643//2*PRL/2*PASTOR/4/2*KACHU/DANPHE
8	DBW322	G8	CIMMYT165/PBW585
9	40 <sup>th</sup> ESWYT 25	G9	CHIPAK/3/SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU
10	RWP-2018-296	G10	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/MASSIV/PPR47.89C
11	40 <sup>th</sup> ESWYT-37	G11	NADI#2*2/6/BECARD #1/5/KIRITATI/4/2*SERI.1B*2/3/KAUZ*2/BOW//KAUZ
12	40 <sup>th</sup> ESWYT-33	G12	MUTUS*2/MUU//2*MUCUY
13	RWP-2019-14	G13	HD 3108/HD 2967
14	DBW325	G14	CHIPAK/GS83
15	DBW222 (c)	G15	KACHU/SAUAL/8/ATTILA/*2/PBW65/6/PVN/CAR422/ANA/5/BOW/ CROW/BUC/PVN/3/YR/4/TRAP#A/7/ATTILA/2*PASTOR
16	DBW243 (c)	G16	BECARD/KACHU (Becard=WEEBILL-1*2/KIRITATI; KACHU=KAUZ//ALTAR-84/(AOS) AWNED-ONAS/3/MILAN/KAUZ/4/HUITES)
17	DBW166 (c)	G17	DANPHE/CHONTE

after reproductive phases (NDVIA). The data were subjected to analysis of variance using R version 4.1.1, and treatment means were compared with LSD test for year, water level, and genotype effects. Correlation and stability analyses were computed as per the R package «metan» (Olivoto and Lucio 2020).

## Results

The analysis of variance exhibited significant genotypic (G) and environmental (E) effects ( $p < 0.001$ ) for all the traits under study. The genotype  $\times$  environment interactions (GEI) were also significant ( $p < 0.001$ ) for the considered traits, except TPMS, NDVIBRP and NDVIARP. The pooled data on GY over the years ranged from 4909.67 Kg ha<sup>-1</sup> (DBW166) to 5531.33 (40<sup>th</sup> ESWYT-26) at 100% ET. The check variety DBW222 ranked second with an average GY of 5438.17 Kg ha<sup>-1</sup>, followed by 40<sup>th</sup> ESWYT-07 (5364.83 Kg ha<sup>-1</sup>) and 40<sup>th</sup> ESWYT-32 (5327.83 Kg ha<sup>-1</sup>). The identified promising water-efficient genotypes, namely, DBW243 (G16) and DBW166 (G17), showed a mean GY of 5017.83 and 4909.67 Kg ha<sup>-1</sup>, respectively (Table 2). At 80% ET, the GY across the years ranged from 4475.0 Kg ha<sup>-1</sup> (RWP-2019-14) to 40<sup>th</sup> ESWYT-33 (5292.17 Kg ha<sup>-1</sup>), whereas the minimum GY of 3969.0 g ha<sup>-1</sup> was recorded for the genotype DBW325 at 60% ET, and the highest was depicted for the genotype 40<sup>th</sup> ESWYT-07

(4970.33 Kg ha<sup>-1</sup>). The genotype 40<sup>th</sup> ESWYT-33 showed a minimum reduction of 0.07 at 80% ET, followed by 40<sup>th</sup> ESWYT-37 (2.19%), 40<sup>th</sup> ESWYT-25 (2.64%), and 40<sup>th</sup> ESWYT-50 (2.67%). Whereas, at 60% ET, the genotypes, namely RWP-2018-326, DBW322, 40<sup>th</sup> ESWYT-07, 40<sup>th</sup> ESWYT-25, and 40<sup>th</sup> ESWYT-37, revealed the minimum GY reduction of 4.45, 7.32, 7.35, 7.43, and 7.89%, respectively.

The WUE showed an increasing trend with reduced irrigation levels and varied from 1.72-1.90, 1.93-2.30, and 2.27-2.85 at 100%, 80%, and 60% ET, respectively. The genotypes, namely, 40<sup>th</sup> ESWYT-26, DBW222, and 40<sup>th</sup> ESWYT-07, showed the highest WUE at 100% ET, whereas the genotypes 40<sup>th</sup> ESWYT-33 (2.30), 40<sup>th</sup> ESWYT-07 (2.23), and 40<sup>th</sup> ESWYT-26 (2.19) were found promising at 80% ET (Table 2). At 60% ET, the genotype 40<sup>th</sup> ESWYT-07 showed the highest WUE (2.85) followed by the check variety DBW222 (2.81) and RWP-2018-326 (2.79). The genotype 40<sup>th</sup> ESWYT-33 exhibited the minimum reduction of 0.28% at 60% ET for TGW, followed by RWP-2019-14 (1.16%), RWP-2018-296 (1.91%), and RWP-2018-326 (2.28%). The PH and EHL did not show much variation with different irrigation levels up to 60% ET, indicating the involvement of major underlying gene effects. NDVIB showed a higher reduction at 60% ET, ranging from 17.81-26.56%, compared to NDVIA. The check variety DBW222 showed the minimum reduction for



**Table 2. Mean performance of genotypes for different traits under study at different irrigation levels**

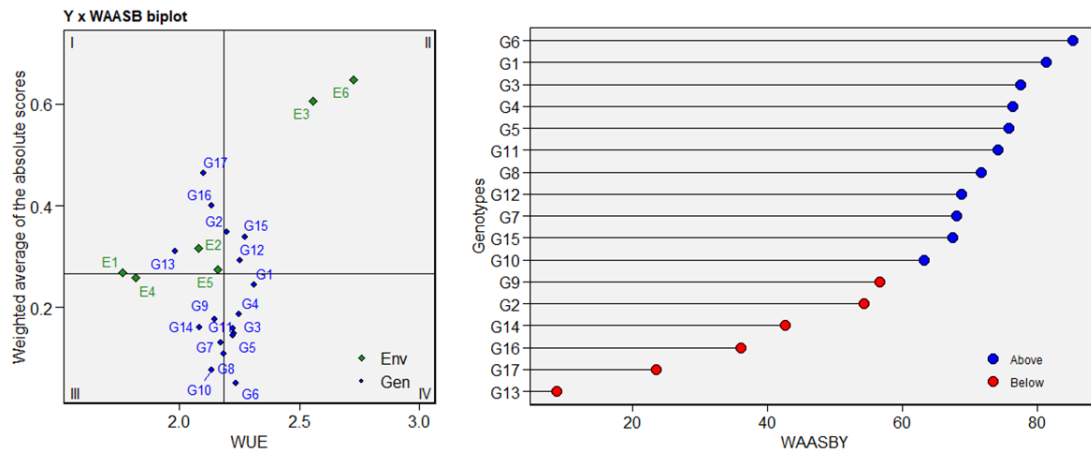
S.No.	Genotype	GY (Kg ha <sup>-1</sup> )						WUE						TGW (g)						TPMS		
		1*	2	3	P	1	2	3	P	1	2	3	P	1	2	3	P	1	2	3	P	
1	40 <sup>th</sup> ESWYT-07	5364.83	5188.67	4970.33	5174.61 <sup>a</sup>	1.85	2.23	2.85	2.30 <sup>a</sup>	40.06	39.42	38.17	39.21 <sup>c</sup>	443.33	377.5	350	390.27 <sup>g</sup>					
2	RWP-2018-326	5113	4752.33	4885.5	4916.94 <sup>bcd</sup>	1.76	2.04	2.79	2.19 <sup>bcd</sup>	37.76	37.97	37.1	37.60 <sup>d</sup>	436.67	405	391.67	411.11 <sup>cdef</sup>					
3	40 <sup>th</sup> ESWYT-26	5531.33	5075.5	4512.67	5039.83 <sup>abc</sup>	1.9	2.19	2.59	2.22 <sup>abcde</sup>	40.16	35.08	33.99	36.41 <sup>efg</sup>	446.67	420.83	386.67	418.05 <sup>cde</sup>					
4	DBW173	5310.67	5023.17	4789.33	5041.05 <sup>abc</sup>	1.84	2.16	2.75	2.24 <sup>abc</sup>	39.17	36.73	35.26	37.05 <sup>def</sup>	430	349.17	364.17	381.11 <sup>g</sup>					
5	40 <sup>th</sup> ESWYT-32	5327	4890.17	4745.17	4987.44 <sup>bc</sup>	1.83	2.11	2.72	2.22 <sup>abcde</sup>	39.36	36.43	35.59	37.12 <sup>de</sup>	437.5	455.83	465.83	453.05 <sup>b</sup>					
6	RWP-2018-32	5185	5039.5	4760.5	4995.0 <sup>abc</sup>	1.79	2.17	2.74	2.23 <sup>abcd</sup>	38.35	36.43	35.18	36.65 <sup>def</sup>	438.33	410.83	428.33	425.83 <sup>cd</sup>					
7	40 <sup>th</sup> ESWYT-50	5066	4930.5	4597.17	4864.55 <sup>cde</sup>	1.75	2.13	2.64	2.16 <sup>defgh</sup>	38.02	35.07	33.19	35.42 <sup>ghi</sup>	425	386.67	411.67	407.77 <sup>def</sup>					
8	DBW322	5074	4864.33	4702.33	4880.22 <sup>bcd</sup>	1.75	2.1	2.7	2.18 <sup>bcd</sup>	39.74	37	35.53	37.41 <sup>de</sup>	432.5	411.67	432.5	425.55 <sup>cd</sup>					
9	40 <sup>th</sup> ESWYT-25	4960.33	4829.17	4591.83	4793.78 <sup>def</sup>	1.72	2.09	2.63	2.14 <sup>efgh</sup>	35.58	35.29	34.34	35.07 <sup>hi</sup>	445.42	388.33	349.17	394.30 <sup>efg</sup>					
10	RWP-2018-296	5050.33	4768.5	4524.83	4781.22 <sup>def</sup>	1.75	2.05	2.6	2.13 <sup>efgh</sup>	39.79	40.7	39.92	40.12 <sup>bc</sup>	459.17	436.67	410	435.27 <sup>bc</sup>					
11	40 <sup>th</sup> ESWYT-37	5125.67	5013.33	4721.5	4953.5 <sup>bcd</sup>	1.77	2.17	2.73	2.22 <sup>abcde</sup>	41.86	40.39	38.09	40.11 <sup>bc</sup>	399.17	387.5	401.67	396.11 <sup>efg</sup>					
12	40 <sup>th</sup> ESWYT-33	5296	5292.17	4536	5041.39 <sup>abc</sup>	1.83	2.3	2.63	2.25 <sup>abc</sup>	40.89	40.81	40.69	40.79 <sup>b</sup>	429.17	409.17	363.33	400.55 <sup>defg</sup>					
13	RWP-2019-14	5057.33	4475	3986.67	4506.33 <sup>g</sup>	1.75	1.93	2.27	1.98 <sup>i</sup>	37.48	33.16	32.78	34.47 <sup>i</sup>	420	402.5	370	397.50 <sup>efg</sup>					
14	DBW325	5203.33	5002.67	3969	4725.0 <sup>ef</sup>	1.8	2.16	2.29	2.08 <sup>h</sup>	37.51	36.27	34.25	36.01 <sup>gh</sup>	432.5	389.17	391.67	404.44 <sup>defg</sup>					
15	DBW222 (c)	5438.17	4881.17	4836	5051.78 <sup>ab</sup>	1.89	2.12	2.81	2.27 <sup>ab</sup>	42.87	41	38.57	40.82 <sup>b</sup>	528.33	479.17	447.92	485.27 <sup>a</sup>					
16	DBW243 (c)	5017.83	4714.5	4460	4730.78 <sup>ef</sup>	1.75	2.05	2.59	2.13 <sup>fgh</sup>	43.69	43.6	41.73	43.01 <sup>a</sup>	521.83	480	482.08	494.72 <sup>a</sup>					
17	DBW166 (c)	4909.67	4639.5	4401.67	4650.28 <sup>fg</sup>	1.72	2.02	2.56	2.10 <sup>gh</sup>	41.54	40.34	37.61	39.83 <sup>bc</sup>	499.08	490	525	504.77 <sup>a</sup>					

\*1, 2 and 3 are irrigation levels at 100, 80 and 60% ET and P=pooled;

GY= Grain yield; WUE = Water user efficiency; TGW = 1000 grain weight; TPMS = Tillers per meter square

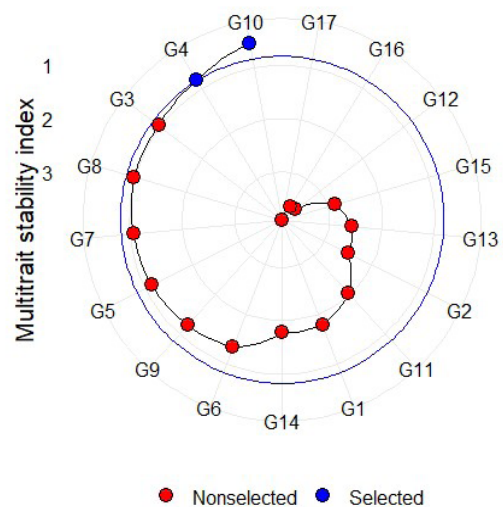
**Table 3. Percent reduction/gain of different characters at three irrigation levels**

Comparison of irrigation level	GY	AGBM	TGW	TPMS	PH	EHL	NDVIBRP	NDVIARP	WUE (gain %)
WL (100-80%) ET	5.28	1.8	4.19	7.15	0.97	2.21	8.5	3.37	17.88
WL (100-60%) ET	11.4	10.48	7.7	8.57	0.64	2.69	22.09	11.38	47.49
WL (80-60%) ET	6.46	8.84	3.66	1.53	-0.34	0.49	14.86	8.29	25.12



**Fig. 3. WAASB biplot and WAASBY analysis for WUE**

al. 2020; [Mohammed et al. 2023](#)). Crop lands globally utilize 8266 km<sup>3</sup>/year of water, with 5406 km<sup>3</sup> from green water and 2860 km<sup>3</sup> from blue water ([Mohammed et al. 2023](#)). Global water availability has decreased significantly, and per capita water availability under Indian conditions is projected to further reduce in the coming years (PIB, 2022). As a result, cultivating wheat with 6-7 irrigations would not be feasible, and water is expected to become the most limiting factor in the future ([Abbate et al. 2004](#); [Fan et al. 2018](#)). On the other hand, approximately 70% of semi-dwarf wheat varieties possessing the PH gene(s) *Rht-B1*, *Rht-D1*, and *Rht8* gene(s) are input-responsive, leading to a co-linear association between wheat yields, agro-chemicals, and increased irrigation levels at different critical growth stages ([Wurschum et al. 2017](#); [Wang et al. 2020](#)). Under varying irrigation regimes, NDVIB and NDVIA significantly declined to 22.09 and 11.38%, respectively, at 60% ET, while GY and AGBM were reduced to 11.40 and 10.48%, respectively. Alongside reductions in other traits, WUE showed an increment of 17.88 and 47.49% at 80 and 60% ET, respectively. This is likely due to plant stress mitigation strategies such as stomatal closure leading to reduced transpiration rates at 60 and 80% ET ([Abbate et al. 2004](#)). [Zhao et al. \(2020\)](#) reported that stomatal conductance, intercellular CO<sub>2</sub>, and net photosynthesis and transpiration rates decrease under water stress conditions in wheat. In general, PH is reduced with skipped irrigation scheduling, but in our study, water was available to the genotypes, but in different quantities at different growth



**Fig. 4. MTSI analysis of genotypes based on multiple traits**

stages. Therefore, PH was not greatly influenced at 100%, 80%, and 60% ET. [Dencic et al. \(2000\)](#) also reported that PH and kernels/spike are less affected under water stress conditions than kernel number/spike in wheat.

The genotype 40<sup>th</sup> ESWYT-26 was the highest yielder at 100% ET with the contributing traits EHL and NDVIBRP coupled with good biomass, TKW and NDVIA. At 80% ET, nine genotypes, namely 40<sup>th</sup> ESWYT-33, 40<sup>th</sup> ESWYT-07, 40<sup>th</sup> ESWYT-26, 40<sup>th</sup> ESWYT-37, 40<sup>th</sup> ESWYT-50, 40<sup>th</sup> ESWYT-32,

RWP-2018-32, DBW325 and DBW173 outperformed the check variety DBW222 (4881.17 g ha<sup>-1</sup>). Among the top yielders, genotype 40<sup>th</sup>ESWYT-33 displayed the most resilience with a minimal GY reduction of 0.07%, followed by 40<sup>th</sup>ESWYT-37 (2.19%), 40<sup>th</sup>ESWYT-50 (2.67%), RWP-2018-32 (2.81%), 40<sup>th</sup>ESWYT-07 (3.28%), DBW325 (3.86%), and DBW173 (5.41%). Based on WUE at 80% ET, the genotypes 40<sup>th</sup>ESWYT-33, 40<sup>th</sup>ESWYT-07, 40<sup>th</sup>ESWYT-37, and RWP-2018-32 demonstrated high WUE. At 60% ET, only the genotype 40<sup>th</sup>ESWYT-07 was significantly superior to the check variety DBW222, with an average GY of 4970.33 kg ha<sup>-1</sup>. It also exhibited the highest WUE of 2.85 at 60% ET. The genotype 40<sup>th</sup>ESWYT-07 was further analysed for its associated traits, and it was found to have the highest NDVI values both before and after the reproductive phase, as well as the longest EHL, with the minimum reduction in TGW at 60% ET.

Here, the traits, namely TGW, EHL and NDVI, played a crucial role in water stress resilience and high WUE at reduced water levels. Previous study by Banerjee et al. 2020 has also highlighted the importance of kernel weight under water stress in wheat. Additionally, the significant role of NDVI in maintaining higher GY under stress conditions has been observed by (Condorelli et al. 2018; Hazratkulova et al. 2012; Kumar et al. 2023). The number of effective tillers is typically considered a yield-associated trait, but in this investigation, we found that TPMS was not a decisive factor for yield and WUE at 60% ET. The correlations at 100% and 60% ET further support this, as TPMS was negatively correlated with NDVIBRP, NDVIARP, and AGBM. Interestingly, NDVIBRP showed negative correlations with TGW at W1 and W3, suggesting that highly green-leaved plants may yield well but could have shrivelled grains. On the other hand, the association between AGBM and NDVI revealed that NDVIBRP was positively associated with AGBM at 100% ET, while NDVIARP showed positive correlations at 60% ET. This indicates that NDVI after the reproductive phase plays a key role under curtailed water level conditions compared to favorable environments.

NDVI is linked to leaf greenness, and NDVIARP might contribute to traits like stay green, leading to higher yields under stress conditions. Plants that stay green for a longer duration have higher chlorophyll content and can synthesize more photosynthates, resulting in increased yield under water stress (Christopher et al. 2021; Kumar et al. 2022). In conclusion, the genotypes 40<sup>th</sup>ESWYT-07, 40<sup>th</sup>ESWYT-33, 40<sup>th</sup>ESWYT-37 and RWP-2018-32 were found promising for GY and WUE at 80% ET, whereas 40<sup>th</sup>ESWYT-07 also outperformed checks at the 60% ET. Through MTSI, DBW173 and RWP-2018-296 were selected and can be considered for ideotype breeding.

### Authors' contribution

Conceptualization of research (RPM, VK, KV, SCT); Designing of the experiments (RPM, SHT); Contribution of experimental

materials (RPM, KV); Execution of field experiments and data collection (RPM, SCT, SHT); Analysis of data and interpretation (VK, RN, VN); Preparation of the manuscript (VK, RPM, RN, VN).

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### References

- Abbate P. E., Dardanelli J. L., Cantarero M. G. Maturano M., Melchiori R. J. M and Suero E. E. 2004. Climatic and Water Availability Effects on Water-Use Efficiency in Wheat. *Crop Sci.*, **44**(2): 474–483. <https://doi.org/10.2135/cropsci2004.4740>
- Asoka A., Gleeson T., Wada Y. and Mishra V. 2017. Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nat. Geosci.*, **10**(2): 109–117. <https://doi.org/10.1038/ngeo2869>
- Asoka A. and Mishra V. 2020. A Strong Linkage between Seasonal Crop Growth and Groundwater Storage Variability in India. *J. Hydrometeorol.*, **22**(1): 125–138. <https://doi.org/10.1175/JHM-D-20-0085.1>
- Banerjee K., Krishnan P. and Das B. 2020. Thermal imaging and multivariate techniques for characterizing and screening wheat genotypes under water stress condition. *Ecol. Indic.*, **119**: 106829. <https://doi.org/10.1016/j.ecolind.2020.106829>
- Christopher M., Paccapelo V., Kelly A., Macdonald B., Hickey L., Richard C., Verbyla A., Chenu K., Borrell A., Amin A. and Christopher J. 2021. QTL identified for stay-green in a multi-reference nested association mapping population of wheat exhibit context dependent expression and parent-specific alleles. *Field Crops Res.*, **270**: 108181. <https://doi.org/10.1016/j.fcr.2021.108181>
- Condorelli G. E., Maccaferri M., Newcomb M., Andrade-Sanchez P., White J. W., French A. N., Sciara G., Ward R. and Tuberosa R. 2018. Comparative aerial and ground based high throughput phenotyping for the genetic dissection of NDVI as a proxy for drought adaptive traits in durum wheat. *Front. Plant Sci.*, **9**: 893.
- Dencic S., Kastori R., Kobiljski B. and Duggan B. 2000. Valuation of grain yield and its components in wheat cultivars and landraces under near optimal and drought conditions. *Euphytica*, **113**(1): 43–52. <https://doi.org/10.1023/A:1003997700865>
- Fan Y., Wang C. and Nan Z. 2018. Determining water use efficiency of wheat and cotton: A meta-regression analysis. *Agric. Water Manag.*, **199**: 48–60. <https://doi.org/10.1016/j.agwat.2017.12.006>
- Hazratkulova S., Sharma R. C., Alikulov S., Islomov S., Yuldashev T., Ziyaev Z., Khalikulov Z., Ziyadullaev Z. and Turok J. 2012. Analysis of genotypic variation for normalized difference vegetation index and its relationship with grain yield in winter wheat under terminal heat stress. *Plant Breeding*, **131**(6): 716–721. <https://doi.org/10.1111/pbr.12003>
- Jain M., Fishman R., Mondal P., Galford G.L., Bhattarai N., Naeem S., Lall U., Balwinder S and DeFries R. S. 2021. Groundwater

- depletion will reduce cropping intensity in India. *Science Advances*, **7**(9): eabd2849. <https://doi.org/10.1126/sciadv.abd2849>
- Khandelwal V., Reddy S., Satyavathi C. T., Gupta, P. C., Jain S. K., Mungra K. D., Tripathi M. K., Yadav D., Solanki R. K. and Patroti P. 2024. Identification of stable cultivars of pearl millet (*Pennisetum glaucum* (L.) R. Br.) based on GGE Biplot and MTSI index. *Indian J. Genet. Plant Breed.*, **84**(04): 668–678.
- Khedwal R.S., Chaudhary A., Sindhu V. K., Yadav D. B., Kumar N., Chhokar R. S., Poonia T. M., Kumar Y. and Dahiya S. 2023. Challenges and technological interventions in rice–wheat system for resilient food–water–energy–environment nexus in North-western Indo-Gangetic Plains: A review. *Cereal Res. Commun.*, <https://doi.org/10.1007/s42976-023-00355-9>
- Kumar M., Mishra V. K., Chand R., Sharma S., Kumar U., Jaiswal J. P., Choudhary M., Mahato A., Ashutosh Singh P. and Joshi A. K. 2023. NDVI and grain fill duration are important to be considered in breeding for terminal heat stress tolerance in wheat. *Agron. Crop Sci.*, **209**(4): 489–501. <https://doi.org/10.1111/jac.12637>
- Kumar R., Harikrishna, Barman, D., Ghimire, O. P., Gurumurthy, S., Singh, P. K., Chinnusamy, V., Padaria J. C and Arora A. 2022. Stay-green trait serves as yield stability attribute under combined heat and drought stress in wheat (*Triticum aestivum* L.). *J. Plant Growth Regul.*, **96**(1): 67–78. <https://doi.org/10.1007/s10725-021-00758-w>
- Kumar V., Shekhawat P. S., Kumar S., Gangwar O. P., Tyagi B. S., Gupta A., Gupta V. and Singh G. P. 2025. Inheritance studies for stripe rust and identification of multiple rust resistant genotypes in bread wheat (*Triticum aestivum* L.). *Indian J. agric. Sci.*, **95**(4): 371–375. <https://doi.org/10.56093/ijas.v95i4.154766>
- Meena R. P., Karnam V., Rinki, Sharma R. K., Tripathi S. C. and Singh, G. P. 2019. Identification of water use efficient wheat genotypes with high yield for regions of depleting water resources in India. *Agric. Water Manag.*, **223**: 105709. <https://doi.org/10.1016/j.agwat.2019.105709>
- Mishra V., Asoka A., Vatta K. and Lall U. 2018. Groundwater Depletion and Associated CO<sub>2</sub> Emissions in India. *Earth's Future*, **6**(12): 1672–1681. <https://doi.org/10.1029/2018EF000939>
- Mohammed N., El-Hendawy S., Alsamin B., Mubushar M and Dewir Y. H. 2023. Integrating Application Methods and Concentrations of Salicylic Acid as an Avenue to Enhance Growth, Production, and Water Use Efficiency of Wheat under Full and Deficit Irrigation in Arid Countries. *Plants*, **12**(5): 1019. <https://doi.org/10.3390/plants12051019>
- Nataraj V., Bhartiya, A., Singh, C.P, Devi, H.N., Deshmukh, M.P., Verghese, P., Singh, K., Mehtre S. P., Kumari V., Maranna S., Kumawat G., Ratnaparkhe M. B., Satpute G. K., Rajesh V., Chandra S., Ramteke R., Khandekar N. and Gupta S. 2021. WAASB-based stability analysis and simultaneous selection for grain yield and early maturity in soybean. *Agron. J.*, **113**: 3089–3099.
- Olivoto T. and Lucio A. D. 2020. *metan*: An R package for multi-environment trial analysis. *Methods Ecol. Evol.*, **11**(6): 783–789. <https://doi.org/10.1111/2041-210X.13384>
- Olivoto T., Lucio A. D., Silva J. A. G., Marchioro V. S., Souza V. Q. and Jost E. 2019a. Mean performance and stability in multi-environment trials I: Combining Features of AMMI and BLUP techniques. *Agron. J.*, **111** (6): 2949–2960. <https://doi.org/10.2134/agronj2019.03.0220>
- Olivoto T., Lucio A. D., Silva J. A. G., Sari B. G. and Diel M. I. 2019b. Mean performance and stability in multi-environment trials II: Selection based on multiple traits. *Agron. J.*, **111**(6): 2961–2969. <https://doi.org/10.2134/agronj2019.03.0221>
- Patel R., Parmar D. J., Kumar S., Patel D. A., Memon J., Patel M. B. and Patel J. K. 2023. Dissection of genotypex environment interaction for green cob yield using AMMI and GGE biplot with MTSI for selection of elite genotype of sweet corn (*Zea mays* conva. Saccharata var. rugosa). *Indian J. Genet. Plant Breed.*, **83**(01): 59–68.
- Rosa L., Chiarelli D. D., Rulli M. C., Dell'Angelo J. and D'Odorico P. 2020. Global agricultural economic water scarcity. *Science Advances*, **6**(18): eaaz6031. <https://doi.org/10.1126/sciadv.aaz6031>
- Sahadevan D. K. and Pandey A. K. 2023. Groundwater over-exploitation driven ground subsidence in the himalayan piedmont zone: Implication for aquifer health due to urbanization. *J. Hydrol.*, **617**: 129085. <https://doi.org/10.1016/j.jhydrol.2023.129085>
- Tomar S. M. S. and Kumar G. T. 2004. Seedling survivability as a selection criterion for drought tolerance in wheat. *Plant Breed.*, **123**(4): 392–394. <https://doi.org/10.1111/j.1439-0523.2004.00993.x>
- UNESCO World Water Assessment Programme. 2018. Nature-based solutions for water, world water development report. <https://www.unwater.org/publications/world-water-development-report-2018>
- Wang Z., Hu H., Jiang X., Tao Y., Lin Y., Wu F., Hou S., Liu S., Li C., Chen G. and Liu Y. 2020. Identification and Validation of a Novel Major Quantitative Trait Locus for Plant Height in Common Wheat (*Triticum aestivum* L.). *Front. Genet.*, **11**: 602495. <https://doi.org/10.3389/fgene.2020.602495>
- Wurschum T., Langer S. M., Longin C. F. H., Tucker M. R. and Leiser W. L. 2017. A modern Green Revolution gene for reduced height in wheat. *The Plant J.*, **92**(5): 892–903. <https://doi.org/10.1111/tpj.13726>
- Yadvinder, Kukal S. S., Jat M. L. and Sidhu H. S. 2014. Improving Water Productivity of Wheat-Based Cropping Systems in South Asia for Sustained Productivity. In *Advances in Agronomy* (Vol. 127, pp. 157–258). Elsevier. <https://doi.org/10.1016/B978-0-12-800131-8.00004-2>
- Zhao W., Liu L., Shen Q., Yang J., Han X., Tian F. and Wu J. 2020. Effects of Water Stress on Photosynthesis, Yield, and Water Use Efficiency in Winter Wheat. *Water*, **12**(8): 2127. <https://doi.org/10.3390/w12082127>