Indian J. Genet. Plant Breed., (2025); 85(3): 418-425

https://doi.org/10.31742/ISGPB.85.3.7

ISSN: 0975-6906

www.isgpb.org

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^{-1}, 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^{-3} 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 40th ESWYT-33, 40th ESWYT-07, 40th ESWYT-37 and RWP-2018-32, were found promising for GY and WUE at 80% ET, while 40th 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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How to cite this article: Meena R.P., Kumar V., Venkatesh K., Sujatha H.T., Tripathi S.C., Nargund R. and Nataraj V. 2025. Multi-trait-based identification of water use efficient genotypes in bread wheat (*Triticum aestivum* L.). Indian J. Genet. Plant Breed., **85**(3): 418-425.

Source of support: ICAR, DARE, Govt. of India.

Conflict of interest: None.

Received: March 2024 **Revised:** July 2025 **Accepted:** Aug. 2025

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^{-3} 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^2 (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 $hour^{-1}$ $emitter^{-1}$. The experimental crop was managed as per the standard package of practices. Material was planted on 16th November and 14th 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^2 (TPMS), plant height (PH) and ear-head length (EHL), and NDVI values before (NDVIB) and

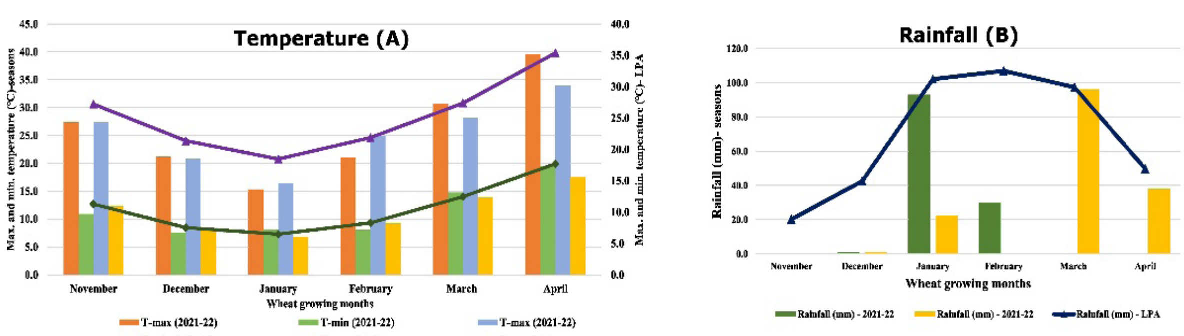

Fig. 1. Monthly mean, maximum and minimum temperature (A) and monthly total rainfall (B) at IIWBR, Karnal, during experimental years compared with historical mean (1972 to 2021)

Table 1. Pedigree details of the genotypes under study

S. No.	Genotype	Symbol	Parentage
1	40th 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	40th ESWYT-26	G3	CHIPAK/3/SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU
4	DBW173	G4	KAUZ/AA//KAUZ//PBW602
5	40th ESWYT-32	G5	SUP152/BAJ #1*2/3/KACHU//WBLL1*2/BRAMBLING
6	RWP-2018-32	G6	HD3131/DBW 90
7	40th ESWYT-50	G7	KACHU*2/3/ND643//2*PRL/2*PASTOR/4/2*KACHU/DANPHE
8	DBW322	G8	CIMMYT165/PBW585
9	40th 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	40th ESWYT-37	G11	NADI#2*2/6/BECARD #1/5/KIRITATI/4/2*SERI.1B*2/3/KAUZ*2/BOW//KAUZ
12	40th 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 × 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^{-1} (DBW166) to 5531.33 (40th ESWYT-26) at 100% ET. The check variety DBW222 ranked second with an average GY of 5438.17 Kg ha^{-1}, followed by 40th ESWYT-07 (5364.83 Kg ha-1) and 40th ESWYT-32 (5327.83 Kg ha^{-1}). The identified promising water-efficient genotypes, namely, DBW243 (G16) and DBW166 (G17), showed a mean GY of 5017.83 and 4909.67 Kg ha^{-1}, respectively (Table 2). At 80% ET, the GY across the years ranged from 4475.0 Kg ha^{-1} (RWP-2019-14) to 40th ESWYT-33 (5292.17 Kg ha^{-1}), whereas the minimum GY of 3969.0 g ha^{-1} was recorded for the genotype DBW325 at 60% ET, and the highest was depicted for the genotype 40th ESWYT-07 (4970.33 Kg ha^{-1}). The genotype 40th ESWYT-33 showed a minimum reduction of 0.07 at 80% ET, followed by 40th ESWYT-37 (2.19%), 40th ESWYT-25 (2.64%), and 40th ESWYT-50 (2.67%). Whereas, at 60% ET, the genotypes, namely RWP-2018-326, DBW322, 40th ESWYT-07, 40th ESWYT-25, and 40th 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, 40th ESWYT-26, DBW222, and 40th ESWYT-07, showed the highest WUE at 100% ET, whereas the genotypes 40th ESWYT-33 (2.30), 40th ESWYT-07 (2.23), and 40th ESWYT-26 (2.19) were found promising at 80% ET (Table 2). At 60% ET, the genotype 40th ESWYT-07 showed the highest WUE (2.85) followed by the check variety DBW222 (2.81) and RWP-2018-326 (2.79). The genotype 40th 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

NDVIB (17.81%), followed by 40th ESWYT-32 (19.01%), DBW166 (19.19%), and DBW325 (21.06%).

The mean grain yield at 100% ET was observed as 5178.26 Kg ha^{-1}, which was reduced by 5.28 and 11.40% at 80 and 60% ET, respectively (Table 3). A reduction of 6.46% was recorded with reduced irrigation from 80 to 60%. Similarly, the AGBM, TGW, TPMS, and EHL showed reductions of 1.80, 4.19, 7.15, and 2.21%, respectively, with curtailed irrigation to 80% ET. The variation in plant height was almost negligible with different irrigation levels. The deviation of 8.50% and 3.37% was recorded for NDVIB and NDVIA at 80% ET. Conversely, the WUE increased by 17.88% at 80% ET, which was further enhanced by 47.49 at 60% ET.

Correlations

At 100% ET, GY showed a positive and significant correlation with WUE (r=0.99***) and exhibited positive but non-significant correlations with TGW, NDVIA, AGBM, NDVIB, PHT, and EAR. NDVIB was found to be significantly associated with NDVIA (r=0.51*), and AGBM revealed a positive and significant association with NDVIBRP. However, AGBM was negatively correlated with TPMS and TGW. The WUE depicted a positive but non-significant association with TPMS, TGW, NDVIARP, NDVIBRP, PH, and EHL (Fig. 2a). At 60% ET, the GY and WUE were found to be positively associated (r=0.99***) at the reduced irrigation level of 60% ET. The NDVIBRP showed a positive association with NDVIARP (r=0.85***) and EHL (r=0.58*). AGBM was found to be positively correlated with NDVIARP but negatively correlated with TPMS. TPMS also showed a negative and significant association with NDVIARP and NDVIBRP (Fig. 2b).

WAASB-based stability analysis

Stability analysis of genotypes was carried out based on the traits GY and WUE. WAASB-based stability analysis for grain yield revealed that genotype G14 (3.3) was highly stable, followed by (fb) G2 (3.6), G3 (5.0), G16 (5.1) and G15 (6.1). Whereas, genotype, G9 (21.7) was found to be highly unstable fb G8 (19.4), G10 (16), G7 (12.8), G1 (11.3) and G4 (11.2). Further, G14 (0.05) was found highly stable for water use efficiency (WUE) trait fb G2 (0.08), G16 (0.11), G15 (0.13), G13 (0.14) and G11 (0.15). In case of WAASB biplot for WUE, in the first quadrant, highly unstable genotypes having their mean below the grand mean (G17, G16 and G13) were included. The widely adapted, high-water use efficient (genotype mean greater than grand mean) genotypes (G1, G4, G3, G11, G5, and G6) with low WAASB scores were included in the fourth quadrant. The most discriminating environment that is farthest from the biplot center was E6 (60 % ET during 2021-22) followed by E3 (60 % ET during 2020-21) (Fig. 3).

MTSI analysis

The traits showing significant GEI (GY, WUE, TGW, PHT, EAR and AGBM) were considered in multi-trait stability analysis. Based on MTSI at 10% selection intensity, G10 (RWP-2018-296) and G4 (DBW173) showed MTSI scores of 0.534 and 0.826 and were selected. The mean yield of selected genotypes (4911 kg ha^{-1}) was greater than the grand mean (4890 kg ha^{-1}) and the mean water use efficiency (WUE) of the selected genotype (2.19 kg m^{-3}) was higher than the grand mean (2.18 kg m^{-3}). Selection differentials for the trait means were 20.9 and 0.01 for grain yield and WUE, respectively. The percent selection differentials for the trait means for grain yield and WUE were 0.43 and 0.33, respectively. Similarly, selection differentials for the traits TGW, PH, EHL and AGBM were 0.53, 0.65, -0.12 and 0.13, respectively. The percent selection differentials of TGW, PH, EHL and AGBM were 1.38, 0.64, -1.12 and 1.08, respectively (Fig. 4).

Discussion

Water use efficiency (WUE) is one of the major criteria in modern breeding programs for yield sustainability (Rosa et

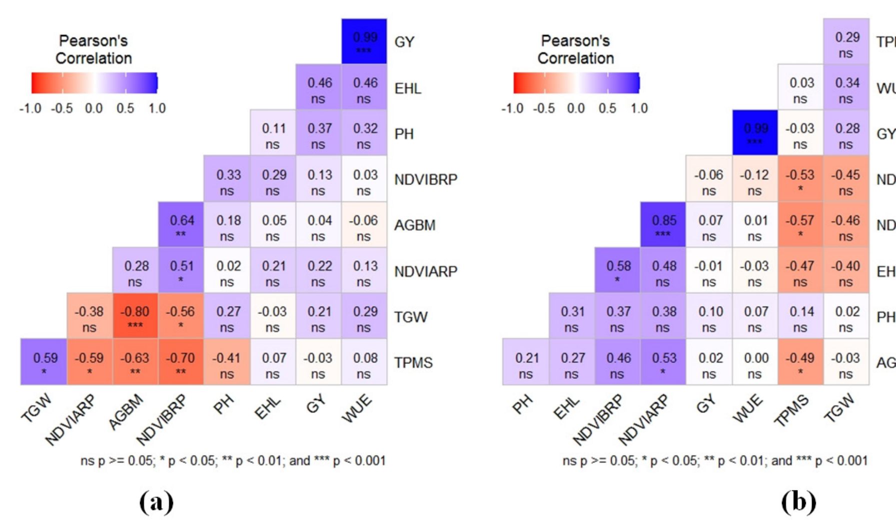

Fig. 2. Correlation analysis among the traits under study at (a) 100% ET and (b) at 60% ET

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

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

*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

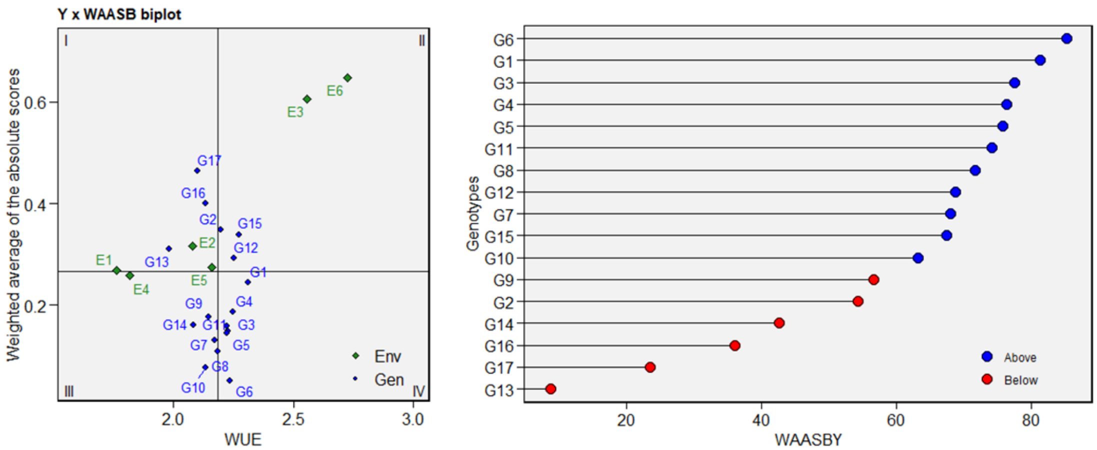

Fig. 3. WAASB biplot and WAASBY analysis for WUE

al. 2020; Mohammed et al. 2023). Crop lands globally utilize 8266 km^3/year of water, with 5406 km^3 from green water and 2860 km^3 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_2, 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 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.

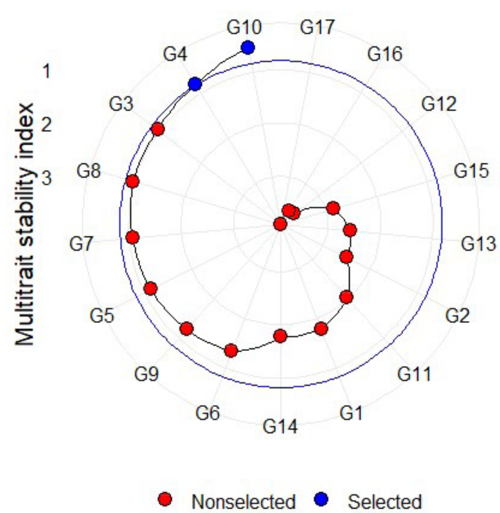

Fig. 4. MTSI analysis of genotypes based on multiple traits

The genotype 40th 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 40th ESWYT-33, 40th ESWYT-07, 40th ESWYT-26, 40th ESWYT-37, 40th ESWYT-50, 40th ESWYT-32, RWP-2018-32, DBW325 and DBW173 outperformed the check variety DBW222 (4881.17 g ha^{-1}). Among the top yielders, genotype 40thESWYT-33 displayed the most resilience with a minimal GY reduction of 0.07%, followed by 40th ESWYT-37 (2.19%), 40th ESWYT-50 (2.67%), RWP-2018-32 (2.81%), 40th ESWYT-07 (3.28%), DBW325 (3.86%), and DBW173 (5.41%). Based on WUE at 80% ET, the genotypes 40th ESWYT-33, 40th ESWYT-07, 40th ESWYT-37, and RWP-2018-32 demonstrated high WUE. At 60% ET, only the genotype 40thESWYT-07 was significantly superior to the check variety DBW222, with an average GY of 4970.33 kg ha^{-1}. It also exhibited the highest WUE of 2.85 at 60% ET. The genotype 40th 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 WI1 and WI3, 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 40th ESWYT-07, 40th ESWYT-33, 40th ESWYT-37 and RWP-2018-32 were found promising for GY and WUE at 80% ET, whereas 40th 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).

Acknowledgments

The first author expresses his gratitude to the financial support given by the Indian Council of Agricultural Research, Govt. of India, to conduct the research. All the authors are thankful to the technical staff for providing kind support during the study.

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