Indian J. Genet. Plant Breed., (2024); 84(2): 156-167
https://doi.org/10.31742/ISGPB.84.2.2

ISSN: 0975-6906
www.isgpb.org

RESEARCH ARTICLE

Unraveling the effects of genotype, environment and their interaction on quality attributes of diverse wheat (*Triticum aestivum* L.) genotypes

Rajappa Harisha[$], Arvind K. Ahlawat[#], Adithya P. Balakrishna, Beera Bhavya, Sumit K. Singh, Shaily Singhal, Sneh Narwal[1], J. P. Jaiswal[2], J. B. Singh[3], Rajeev R. Kumar[4], Sanjay K. Singh and Anju M. Singh[@*]

Abstract

Understanding the impact of genotype, environment and their interaction on the expression of quality attributes aids in precise selection for improving wheat quality in breeding programmes. The present study analyzed 41 diverse wheat genotypes grown at three different environments during rabi 2019-20 for 15 quality traits. Location Indore showed high genotypic performance for most of the traits, followed by Delhi, indicating favorable environments for quality trait expression. AMMI and pooled ANOVA analyses revealed significant E+GEI effects for Fe (89.14%), Zn (87.68%), test weight (76.97%), and grain protein content (75.43%). Polyphenol oxidase activity (87.42%) and sedimentation value (66.35%) showed strong genotypic effects, highlighting substantial genetic diversity influencing these traits. GGE biplot analysis identified C306 (G34), C273 (G38), C518 (G39), and C591 (G40) as the best-performing and stable genotypes across locations for grain protein content, gluten components traits, Fe, Zn, and grain hardness. AEC view of GGE biplot highlighted ideal genotypes C273 (G38) and C518 (G39) for falling number, GW322 (G35) and C518 (G39) for damaged starch, and C306 (G34), CS46 (G10), and C591 (G40) for total sugars. C273 (G38), C518 (G39), C591 (G40), and C306 (G34) were identified as highly desirable for multiple quality traits, showcasing their value as parents for simultaneous improvement in wheat breeding programme.

Keywords: G × E interaction, AMMI analysis, grain quality parameters, RWF and WWF quality parameters, GGE biplot

Introduction

Wheat (*Triticum* spp.) is a most important leading cereal food grain crop produced, consumed and traded around the world, including India and it plays a vital role in food security and nutrition (Shiferaw et al. 2013). In recent decades, India's wheat production has increased significantly, and this trend has continued in recent years. Wheat covers 30.54 million hectares with a production of 112.18MT during the *rabi* 2022-23 and contributes roughly 34% of India's total food grain basket (Indian statista. 2022-23). The ability to produce distinctive food products and the increasing intake of them as a result of industrialization and modernity are the main drivers of increased worldwide demand for wheat. In particular, the special qualities of the gluten protein fraction make it possible to process wheat to make bread, noodles, *chapati,* pasta and, biscuits *etc.* (Shewry and Hey 2015; Chaudhary et al. 2016).

Wheat end-use quality is determined by an array of physico-chemical parameters of grain, refined and whole wheat flour. Wheat grain primary components such as proteins, lipids and carbohydrates significantly define the end product quality (Reynolds and Braun 2022). Proteins are amongst the most studied components of wheat (Orth 1972). The quantity of protein in grain is only moderately inherited and highly reliant on the environment, particularly

---

Division of Genetics, ICAR-Indian Agricultural Research Institute, New Delhi110 012, India

[1]Division of Biochemistry, ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

[2]Govind Ballabh Pant University of Agriculture and Technology, Pantnagar 233 145, Uttrakhand, India

[3]Indian Agricultural Research Institute, Regional Station, Indore 452 001, Madhya Pradesh, India

[4]ICAR-Indian Agricultural Statistics Research Institute, New Delhi 110 012, India

[$]Present address: Host Plant Division, CSB-Central Muga Eri Research and Training Institute, Lahdoigarh, Jorhat 785 700, Assam, India

[#]Krishi Vigyan Kendra, ICAR-Central Institute of Post-Harvest Engineering and Technology, Regional Station Abohar, Fazilka, Punjab 152 116, India

[@]Division of Germplasm Conservation, ICAR-National Bureau of

Plant Genetic Resources, New Delhi 110 012, India

***Corresponding author:** Anju Mahendru Singh, Division of Germplasm Conservation, ICAR-National Bureau of Plant Genetic Resources, New Delhi 110 012, India, E-Mail: anju.singh@icar.gov.in

How to cite this article: Harisha R., Ahlawat A.K., Balakrishna A.P., Bhavya B., Singh S.K., Singhal S., Narwal S., Jaiswal J.P., Singh J.B., Kumar R.R., Singh S.K. and Singh A.M. 2024. Unraveling the effects of genotype, environment and their interaction on quality attributes of diverse wheat (*Triticum aestivum* L.) genotypes. Indian J. Genet. Plant Breed., **84**(2): 156-167.

Source of support: IARI and CSIR, Govt. of India. New Delhi.

Conflict of interest: None.

Received: July 2023 **Revised:** Feb. 2024 **Accepted:** March 2024

the amount of nitrogen in the soil and the amount of moisture during the crop growth stages (Bushuk 1997). Gluten constitutes the major portion of the wheat protein, responsible for the visco-elasticity properties of flour/ dough (Sapirstein and Fu, 1998; Shewry and Tatham 1990). The gluten strength is most important quality parameter of wheat flour measured by several methods including sedimentation test and it determines the wheat suitability for specific product making.

The conventional parameters for determining grain physical quality are the grain component traits such as test weight, thousand kernel weight, and grain hardness. They play a significant role in the grading of wheat types and influence the flour recovery, potential processing quality and milling quality of grains (Wang and Fu 2020). Grain hardness determines the grain's resistance to breaking, milling efficiency, water absorption, and baking quality (Pasha et al. 2010; Kundu et al. 2017). Despite being a heritable feature, grain hardness can be significantly impacted by unusual weather, such as excessive amounts of rainfall during harvest (Bushuk 1997). Softer-textured wheat kernels are easier to break, resulting in finer flour with less starch damage. They are suitable for pastries and cookies due to their poor water absorption. Conversely, harder-textured grains are more difficult to crush, leading to coarser flour with more starch damage. They have greater water absorption capacity and are better suited for bread and chapati making (Guzmán et al. 2022). Ash content reflects the degree of separation between bran, germ, and endosperm during milling. Higher ash content indicates less refined flour, while lower ash content suggests higher refinement (Piironen et al. 2009). Polyphenol oxidase (PPO), an enzyme found in the wheat grain's outer layers, contributes to undesirable browning and discoloration of end products (Hemalatha et al. 2007; Harisha et al. 2023). Factors such as wheat type, cultivar, milling fractions, growing region, and year contribute to variations in ash content and PPO activity (Park et al. 1997; Piironen et al. 2009; Harisha et al. 2023). The falling number measures alpha-amylase activity in flour and indicates sprout damage (Mathewson and Pomeranz, 1978). A high falling number indicates minimal enzyme activity and sound quality of wheat flour, while a low falling number indicates significant enzyme activity and sprout damage in wheat flour.

The wheat quality parameters are physiologically complex in nature and are governed by polygenes. Studies on environmental influences and the interaction of genotype with environment are limited for certain quality traits while others, like protein content, are well studied. Environmental effect is often greater than genetic effect for expressing quality traits (Daniel et al. 2000; Rharrabti et al. 2001). A few of these characteristics could be soil type, fertilizer content, particularly nitrogen (Abedi et al. 2011), rainfall distribution (Faridi et al. 1989), and late-season variables (Lookhart et al. 1984). Another main environmental factor influencing grain quality is temperature during grain filling (Randall and Moss 1990).Therefore, it is crucial to assess and determine the extent to which variables like the environment (E) and the genotype x environment interaction (GEI) contribute to phenotypic variance in the traits. The goal of the present investigation was to quantify the magnitude of environment and G×E interaction impact on the expression of various quality traits in diverse wheat genotypes, as well as to identify promising and stable genotypes by AMMI and GGE models to be employed as donors in the quality breeding programme to develop high-yielding wheat varieties with improved quality traits.

Materials and methods

Experimental material, field trials and test environments

Forty-one diverse wheat genotypes, includes exotic lines, breeding lines, modern and traditional elite Indian varieties constitute the experimental materials (Table 1). The wheat genotypes were grown at three locations viz., IARI-Delhi, IARI-Indore and GBPUA&T-Pantnagar, during *rabi* 2019-20. Table 2 provides information on location details, sites, weather conditions, sowing date, and harvesting date. Sowing was done under optimal irrigated conditions in mid-November at all locations, using a randomized complete block design (RCBD) with two replications and 5 row plots of 2.5m each. Standard agronomic practices were followed throughout the crop growth. Harvesting was done manually at physiological maturity when grains were thoroughly dry in the field. The grains were dried to a safe moisture level following manual threshing and cleaning before being stored. Each genotype's seeds (2kg) were packed in airtight polythene covers and stored in a 4°C refrigerator for future use.

Quality analysis

Grain quality parameters

The grain protein content (GPC) was measured using the

Infra-red transmittance-based instrument Infra-tec 1125 and results were expressed as percentage. The hectoliter weight apparatus developed by ICAR-IIWBR, Karnal was used to determine test weight (TW). To measure thousand kernel weights (TKW),200 grains from a random batch of each genotype were counted and weighed in duplicate. The average weight obtained was multiplied by five and represented in grams. Grain hardness index (GHI) was measured using Perten Instruments' Single Kernel Characterization System (SKCS 4100, Perten Australia). A bench-top energy-dispersive X-ray fluorescence spectrometer (ED-XRF) apparatus (model X-Supreme 8000; Oxford Instruments plc., Abingdon, UK) calibrated for high-throughput screening of mineral concentration of whole-grain wheat was used to determine the concentration of Zn and Fe content (Paltridge et al. 2012). Grain Fe and Zn contents were expressed as mg/Kg. Polyphenol oxidases (PPO) activity of whole grain wheat was estimated using the standard procedure outlined by Anderson and Morris in 2001.

Refined wheat flour (RWF) quality parameters

Wheat grain samples (500g) were ground with the Quadrumat Senior mill (Brabender, Germany) to produce refined wheat flour (Maida). The damaged starch (DaS) content was determined following the American Association of Cereal Chemists method (AACC 2000) using the starch damage analyzer (Erkaya apparatus), and the results were expressed as a percentage. Gluten components, including gluten index (GI), wet gluten (WG), and dry gluten (DG) were assessed using the Glutomatic 2200 (Perten Instruments) and the falling number (FN) was determined using the falling number tester apparatus following the standard AACC (2000) procedures. The SDS-Sedimentation value (SV) of the refined flour samples was evaluated using the standard method described by Axford et al. in 1979.

Whole wheat flour (WWF) quality parameters

Cleaned wheat grain samples weighing 500g were ground with an electric Atta maker (Atta chakki,Natraj) equipped with grinding stones to obtain whole wheat flour (Atta). A 1mm sieve was used with the machine to achieve 98% extraction rate. The total sugar (TS) content of the RWF samples was analyzed using the Phenol-sulphuric acid method as outlined by Dubois et al. in 1956. The ash content (AC) of the whole wheat flour samples was determined following the standard AACC (2000) method utilizing a Muffle furnace.

Statistical analysis

Variance and pooled ANOVA were analyzed for data of all quality parameters of test environments using the PB tools software developed at IRRI Philippines. The Additive main effects and multiplicative interaction (AMMI) was used to quantify the effects of G, E and G×E interactions on quality attributes and GGE biplot analysis was performed using the R software to identify the highly responsive and stable genotypes.

Results and discussion

ANOVA and genetic variations

Analysis of variance conducted on 15 quality traits revealed highly significant differences ($p<0.01$) among the genotypes, environments and their interactions across the locations. The large range of variation was observed for GHI (15.5–93), SV (35.5–64.5 mL), DaS (2.84–6.78%) and FN (238.5–859sec). The high pooled coefficient of variation (CV) was recorded for Zn content (6.21%), followed by GPC (6.02%) and SV (5.99%), suggesting that presence of substantial genetic variation among the genotypes. The lowest CV was observed in GI (1.75%) and WG (1.79%) among the quality traits. Gluten component traits (WG, DG, GI), FN, DaS, PPO activity and GHI had high heritability of >0.90% across environments, while GPC, TW, and Fe were showed low heritability of 0.11 to 0.56% (Table 3). Selection of traits with high heritability is very effective since involvement of genetic components in the expression of phenotype.

Mean performance across the environment

Genotypic performance for quality traits varied significantly across locations. Delhi and Indore exhibited the highest means for most traits, suggesting favorable environments for full genetic expression (Table 3). Traits GPC (13.1%), WG (29.29%), DG (10.42%), and SV (52.30ml) were had the highest mean values in Delhi, while Pantnagar recorded the lowest at 10.4, 20.63, 6.89%, and 49 mL, respectively. This is may be due to high irrigation and soil application of N fertilizers. Water management and nitrogen application are critical factors in wheat grain yield and protein quality (Zhang et al. 2017). Krishnappa et al. (2019) have earlier reported the lowest mean for GPC and SV in Pantnagar, with the highest value observed in Pusa Bihar in RIL population. Regarding grain micronutrients, Delhi had the highest mean for Zn (42.80 mg/kg), and Indore had the highest mean for Fe (42.90 mg/kg). This indicates that these locations are ideal for implementing effective wheat bio-fortified breeding programs to enhance Zn and Fe grain concentrations.

For PPO activity (19.10 min g^{-1} 10^{-3}), AC (1.80%), and GI (93N), Pantnagar had the highest site mean value however, lower genotypic performance for these traits is preferable due to their adverse effects on wheat end products (Hemalatha et al. 2007; Harisha et al. 2023). Indore had the highest site mean values for DaS (5.59%), FN (721sec), TW (81.05gm), and TKW (43.03gm), followed by Delhi and Pantnagar. This suggests that Indore produced exceptionally hard, lustrous, sound, and bold grains. However, for GHI, mean value did not vary significantly between Delhi (77.54) and Indore (76.02), while lowest mean was found

Table 1. A list of genotypes with their pedigree and source of origin used in the present study

Code	Genotypes	Pedigree information	Release
G1	PBW752	BW621/4/PBW343//.YR10/6*AVOCET/3/3*PBW343/5/PBW621	PAU, Ludhiana, Punjab
G2	PBW725	PBW621//Glupro/3*PBW 568/3/ PBW 621	PAU, Ludhiana, Punjab
G3	PBW771	PBW550//YR15/6*AVOCET/3/2*PBW550)	PAU, Ludhiana, Punjab
G4	DBW16	RAJ 3765/WR 484//HUW 468	IIWBR, Karnal, Haryana
G5	DBW173	KAUZ/AA//KAUZ/P BW602	IIWBR, Karnal, Haryana
G6	DBW187	NAC/TH/AC//3*PVN/3/MIRLO/BUC/4/2*PASTOR/5/KACHU/6/KACHU	IIWBR, Karnal, Haryana
G7	DBW222	SAUAL*ATTILA*2/PBW65/6/PVN//CAR422/ANA/5/BOW/CROW//BUC/PVN/3/YR/4/TRAP#1/7/ATTILA/2*PASTOR	IIWBR, Karnal, Haryana
G8	CS5	PUB94.15.1.12/WBLL1	CIMMYT, Mexico
G9	CS28	W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1	CIMMYT, Mexico
G10	CS46	BAV92/SERI	CIMMYT, Mexico
G11	CS86	SB187	CIMMYT, Mexico
G12	CS110	NORD-DESPREZ/VG9144//KALYANSONA/BLUEBIRD/3/YACO/4VRY-5	CIMMYT, Mexico
G13	DBW51	SITELLA/MILAN	IIWBR, Karnal, Haryana
G14	QBP13-9	REH/HARE//2*BCN/3/CROC_1/AE.SQUARROSA(213)//PGO/4/HUITES/5/T.SPELTA PI348599/6/REH/HARE//2*BCN/3/CROC_1/AE.SQUARROSA(213)//PGO/4/HUITES/7/QUAIU	Breeding line
G15	QBP19-1	QUAIU #1/3/T.DICOCCON PI94625/AE.SQUARROSA(372)//3*PASTOR/4/QUAIU #2*2/5/SUP152/BECARD	Breeding line
G16	QBP19-4	FRANCOLIN #1/3/IWA 8600211//2*PBW343*2/KUKUNA/4/MUCUY	Breeding line
G17	QBP19-5	QUAIU #1/SOLALA//QUAIU #2/3/MANKU/4/KACHU #1/KIRITATI//KACHU	Breeding line
G18	BOB WHITE	AVRORA//KALYANSONA/BLUEBIRD/3/(SIB)WOODPECKER	CIMMYT, Mexico
G19	SEMMONG2	NA	Breeding line
G20	K1006	PBW343/HP1731	CSAUA &T, Kanpur, Uttar Pradesh
G21	YANG MAI-6	DAFENG-1087/ZAO-5	Breeding lines
G22	VL907	DYBR 1982- 83/842 ABVD 50/VW9365//P BW 343	VPKAS, Almora, Uttarkhand
G23	4HPAN61	KINDE/4/CMH75A.66//H567.71/5*PVN/3/SERI	Breeding line, CIMMYT, Mexico
G24	4HPAN84	KINDE/4/CMH75A.66//H567.71/5*PVN/3/SERI	Breeding line, CIMMYT, Mexico
G25	ASOCMAP173	NA	Breeding line, CIMMYT, Mexico
G26	HUW666	HUW206/ALTAR84//VEE/MILAN	BHU, Varanasi, Uttar Pradesh
G27	HI1531	HI 1182/ CPAN 1990	IARI RS, Indore, Madhya Pradesh
G28	HD2851	CPAN 3004/WR426//HW 2007	IARI, New Delhi
G29	HD2982	PBW175/PRIVIA//HW2006/LOK1	IARI, New Delhi
G30	HD2985	PBW 343/ PASTOR	IARI, New Delhi
G31	HD3059	KAUZ//ALTAR84/ AOS/3/MILAN/KA UZ/4/HUITES	IARI, New Delhi
G32	HD3226	GRACKLE/HD2894	IARI, New Delhi
G33	HD3249	PBW343*2/KUKUNA//SRTU/3/PBW343*2/KHVAKI	IARI, New Delhi
G34	C306	RGN/CSK3//2*C5 91/3/C217/N14 //C281	CCS HAU, Hisar, Haryana
G35	GW322	GW 173/GW 196	RARS, Vijapur, Gujarath
G36	HD3086	DBW14/HD2733//HUW468	IARI, New Delhi
G37	HI1544	HINDI62/BOBWHI TE/CPAN 2099	IARI RS, Indore, Madhya Pradesh
G38	C273	C591/C209	Department of Agriculture, Punjab
G39	C518	ENJAB-TYPE-8-A/PENJAB-TYPE-9	Department of Agriculture, Punjab
G40	C591	ENJAB-TYPE-8-B/PENJAB-TYPE-9	Department of Agriculture, Punjab
G41	HD2967	ALD/COC//URES/HD216 0M/HD2278	IARI, New Delhi

NA- Not available

Table 2. Locations and description of environmental conditions of test locations

Location/Environments site		ICAR-IARI, New Delhi	IARI-Regional Station Indore	GBPAU&T, Pantnagar
Altitude (AMSL)		228.61	553	243.84
Longitude (E, °.)		77.12	75.50	79.30
Latitude(N, °.)		28.08	22.44	29
Sowing date		17/11/2019	14/11/2019	19/11/2019
Harvesting date		22/4/2020	17/4/2020	20/4/2020
Rainfall (mm)		233.1	184	257.33
Mean temperature (°C)	Min	1.6	5.5	1.5
	Max	40.2	36.4	35.3
Zone		NWPZ	CZ	NWPZ

in Pantnagar (53.07). Similarlyfor TS, site mean value did not vary significantly among the environments. Nadaf and Uppinal (2017) was recorded significantly higher total carbohydrates content in the Dharwad location (74.17%) compared to Arabhavi location (70.47%) in the studied *T. aestivum* varieties. Fig. 1 displaying boxplots of 15 quality traits, illustrates the distribution of mean values among the environments.

G, E and G × E effects on the quality attributes

AMMI analysis of variance reveals that genotype, environment and G×E interactions were significantly influence the expression of quality attributes (Table 4). However, for some traits,greater environmental influences were seen than genetic and their interaction effects. The IPCA1 and IPCA2, representing the first and second principal component analysis axis, and were found significant (p <0.05) for the studied quality traits. The environment had the highest contribution to total variance in Fe content (E-82.84%), followed by Zn content (E-79.45%), TW (E-70.43%), and GPC (E-65.0%). The environmental factors such as soil fertility, soil type, climate, irrigation and nitrogen application were significantly influences the grain nutritional quality parameters (Thavarajah et al. 2009; Zhang et al. 2017). IPCA1 explained 86.5 and 65% of the total variations in Zn and Fe content, while IPCA2 explained 13.5 and 35% of the variations, respectively. TKW (31%) and DG (30.59%) were exhibited the substantial G×E interactions. The significant G×E interactions for quality attributes indicated diverse genotypic responses across different test environments. These pronounced interactions make it challenging to accurately estimate trait heritability, potentially resulting in reduced genetic gain through selection (Ceccarelli, 1989). Kumar et al. (2018) identified this as a major obstacle in cultivar development for improved quality. Significant genotypic effects were observed in PPO activity (87.42%), SV (66.35%), GI (60.03%), and AC (52.71%), indicating a substantial additive contribution to the total variation. This suggests that selecting appropriate wheat genotypes for direct quality breeding or production is viable. IPCA1 accounted for approximately 60-70% of the total variation, while IPCA2 accounted for around 30 to 40% for these traits. For traits GHI and DaS, the G, E, and G×E interactions contributed 53.92 to 54.69%, 29 to 35.08%, and 5.39 to 15.67% to the total variation, respectively. These findings indicate that both genotypes and environment significantly contribute to the expression of GHI and DaS. However, Krishnappa et al. (2019) noted that the environment minimally influences kernel hardness compared to other quality traits in their evaluation of RIL populations. IPCA1 and IPCA2 explained 61.1 and 38.9% of the variations for GHI, and 56.2 and 43.8% for DaS. Regarding FN and WG quality criteria, E and G×E interaction together accounted for approximately 50% of the phenotypic variance, with genotype accounting for the remaining variance. In contrast, high E (89.1%) and low G (4.83%) and G×E interaction (4.65%) effects was observed in glutenin content and quality attributes (Thungo et al. 2020).

Identification of best performing genotypes using GGE biplot

GGE which-won-where biplot gives a graphical representation for identify the best and highly responsive genotypes for specific environment as well as mega environment differentiation (Yan and Tinker 2006). In GGE biplot, vertex genotypes were connected to establish a polygon (Fig. 2(A-O), further subdivided into sectors by rays originating from the biplot's origin and extending perpendicular to the polygon's sides. This segmentation facilitates genotype recommendations for specific sectors (Gauch 2013). The genotype at the polygon's vertex performs exceptionally well or poorly in one or more environments (Yan and Tinker 2006).

The biplot showed that G38 (C273) was the high protein genotype for Delhi and Indore locations, while G31 (HD3059) high protein content vertex genotypes for Pantnagar (Fig. 2A). With regards to gluten content (WG and DG), G38(C273) and G39(C518) were found to be most appropriate genotype for all the locations (Fig. 2 B and C). The protein quantity and quality are the important grain quality parameter that significantly influences the dough properties (Sharma et

Table 3. Genetic parameters for quality traits of diverse wheat genotypes across the environments

Traits	Delhi				Indore				Pantnagar				Pooled		
	Mean ± SD	Range	CV (%)	h^2 (bs)	Mean ± SD	Range	CV (%)	h^2 (bs)	Mean ± SD	Range	CV (%)	h^2 (bs)	Mean ± SD	CV (%)	h^2 (bs)
GPC (%)	13.1 ± 0.71	11.7-14.95	5.46	0.51	11.1 ± 0.58	9.97-12.3	5.25	0.56	10.4 ± 0.68	9.1-12.15	6.67	0.29	11.51 ± 0.47	6.02	0.33
TW (g/hL)	80.41 ± 1.96	75.65-83.6	2.45	0.44	81.05 ± 2.02	75.55-85.25	2.50	0.56	73.37 ± 1.60	70.05-77.86	2.19	0.31	78.28 ± 1.53	2.05	0.60
TKW (g)	41.32 ± 2.42	35.23-47.26	5.86	0.54	43.03 ± 2.60	38.86-49.27	6.07	0.49	39.79 ± 3.55	33.36-47.91	8.94	0.81	41.37 ± 2.15	4.53	0.78
GHI	77.54 ± 16.47	26.5-90	21.25	0.92	76.02 ± 14.17	34-93	18.65	0.91	53.07 ± 13.7	15.5-77.5	25.82	0.95	68.88 ± 14.1	5.83	0.96
Fe (mg/kg)	34.68 ± 1.30	30.05-36.95	3.76	0.34	42.90 ± 1.62	39.3-45.75	3.81	0.39	30.22 ± 2.12	26.05-35.05	7.02	0.42	35.92 ± 0.92	5.60	0.45
Zn (mg/kg)	42.80 ± 5.29	31.55-50.05	12.35	0.80	30.50 ± 2.03	27.05-35.55	6.68	0.67	23.70 ± 3.01	20.15-31.75	12.70	0.61	32.35 ± 2.67	6.21	0.82
PPO Activity (min^{-1} g^{-1} 10^{-3})	16.45 ± 6.01	5.39-28.23	36.55	0.98	17.61 ± 6.61	5.73-28.04	37.59	0.98	19.10 ± 6.28	6.90-30.14	32.91	0.98	17.72 ± 6.01	4.34	0.99
SDS-SV(ml)	52.30 ± 6.47	39-64.5	12.39	0.76	51.50 ± 6.96	35.5-63	13.52	0.76	49.00 ± 6.21	36-62	12.68	0.85	50.93 ± 5.78	5.99	0.89
GI (N)	82.4 ± 17.70	44.30-99.76	21.48	0.99	89.90 ± 12.88	59.92-99.92	14.33	0.98	93.00 ± 8.38	67-99.29	9.01	0.97	88.42 ± 11.01	1.75	0.99
WG (%)	29.29 ± 4.41	22.93-48.33	15.09	0.99	24.74 ± 4.95	14.28-43.26	20.02	0.99	20.63 ± 6.20	12.34-41.19	30.09	0.99	24.88 ± 4.46	1.79	0.99
DG (%)	10.42 ± 1.93	8.16-18.81	18.57	0.98	8.72 ± 2.07	4.40-17.61	23.86	0.98	6.89 ± 2.32	1.33-16.31	33.74	0.99	8.67 ± 1.56	2.65	0.99
FN (sec)	632.5 ± 117.3	366.5-859	18.56	0.98	721.04 ± 121.6	296.5-854.5	16.87	0.97	524.73 ± 148	238.5-803.5	28.22	0.96	626.6 ± 108	3.40	0.98
DaS (%)	4.69 ± 0.68	2.91-6.08	14.66	0.95	5.59 ± 0.84	3.49-6.78	15.06	0.97	4.43 ± 0.78	2.84-5.94	17.69	0.96	4.90 ± 0.68	2.91	0.96
AC (%)	1.51 ± 0.26	0.95-2.10	17.75	0.87	1.41 ± 0.23	0.8-1.89	16.58	0.90	1.80 ± 0.27	1.12-2.22	15.10	0.90	1.58 ± 0.22	5.52	0.94
TS (%)	73.60 ± 2.71	69.38-79.53	3.69	0.20	75.50 ± 2.71	69.10-81.76	4.28	0.45	72.4 ± 4.12	62.45-80.32	5.69	0.76	73.08 ± 2.84	3.66	0.59

CV = Coefficient of variation; h^2(bs) = Broad sense heritability; GPC = Grain Protein content; TW = Test weight; TKW = Thousand kernel weight; GHI-Grain hardness index; Fe = Iron content; Zn = Zinc content; PPO = Polyphenol oxidases activity; SDS = SV-Sedimentation value; GI = Gluten index; WG-Wet gluten; DG = Dry gluten; FN = Falling number; DaS = Damaged starch; AC = Ash content and TS = Total sugar content

Table 4. Additive main effects and multiplicative interaction (AMMI) analysis of variance for quality traits studied among the forty-one diverse wheat genotypes grown in three test locations of rabi 2019-20

Sources of variations	Environment (E) (df:2)		Replication (Environment) (df:3)		Genotypes (G) (df:40)		G×E Interaction (df:80)		IPCA1 (df: 41)		IPCA2 (df = 39)		Residual (df:120)	
Traits	MSS	TVE (%)	MSS	TVE (%)	MSS	TVE (%)	MSS	TVE (%)	MSS	G×E (%)	MSS	G×E (%)	MSS	TVE (%)
GPC	160.05**	65.00	3.06**	1.86	1.35**	10.98	0.64	10.43	0.73*	58.6	0.54	41.4	0.48	11.72
TW	1487.16**	70.43	28.96**	2.01	14.22**	13.47	3.44	6.54	4.12*	61.3	2.74	38.7	2.64	7.55
TKW	215.84**	14.96	1.37	0.15	27.97**	38.77	11.35**	31.46	13.79**	62.3	8.78**	37.7	3.52	14.66
GHI	15417.88*	35.08	47.87**	2.64	1202.06**	54.69	59.19**	5.39	70.62**	61.1	47.18**	38.9	16.14	2.20
Fe	3380.11**	82.84	65.00**	2.39	5.13	2.51	6.42*	6.30	8.15**	65.0	4.60	35.0	4.04	5.96
Zn	7669.46**	79.45	59.80**	0.93	42.79**	8.87	19.85**	8.23	33.53**	86.5	5.48	13.5	4.04	2.52
PPO Activity	144.40**	2.91	0.29	0.01	216.73**	87.42	11.08**	8.94	14.95**	69.1	7.02**	30.9	0.59	0.71
SDS-SV	245.47**	4.07	56.33**	1.39	200.70**	66.35	28.67**	18.96	33.84**	60.5	23.24**	39.5	9.31	9.23
GI	2407.69**	10.09	8.26*	0.06	716.27**	60.03	174.35**	29.22	214.00**	62.9	132.68**	37.1	2.38	0.60
WG	1536.68**	31.66	0.54	0.01	119.76**	49.37	22.69**	18.71	24.22**	54.7	21.09**	45.3	0.21	0.25
DG	255.97**	32.07	0.06	0.01	14.738**	36.93	6.10**	30.59	8.89**	74.6	3.17**	25.4	0.05	0.4
FN	792595.82**	28.01	2736.00**	0.14	70066.16**	49.27	15472.34**	21.76	18489.12**	61.2	12300.87**	38.8	453.32	0.95
DaS	29.95**	29.00	0.16**	0.22	2.78**	53.92	0.40**	15.67	0.44**	56.2	0.36**	43.8	0.02	1.19
AC	3.30**	27.83	0.01	0.23	0.31**	52.71	0.04**	15.37	0.05**	66.8	0.03**	33.2	0.01	3.86
TS	194.47**	9.29	50.14**	3.58	48.84**	46.61	10.33*	19.72	12.73**	67.2	7.94**	37.3	7.32	20.80

DF = Degrees of freedom; IPCA = Interactive principle component axis; MSS = Means sum of square; TVE = Total variation explained; GPC = Grain Protein content; TW-Test weight; TKW = -Thousand kernel weight; GHI = Grain hardness index; Fe = Iron content; Zn = Zinc content; PPO = Polyphenol oxidases activity; SDS = SV-Sedimentation value; GI = Gluten index; WG = Wet gluten; DG = Dry gluten; FN = Falling number; DaS = Damaged starch; AC = Ash content; TS = Total sugar content; ** Significance at p<0.01; * Significance at p <0.1

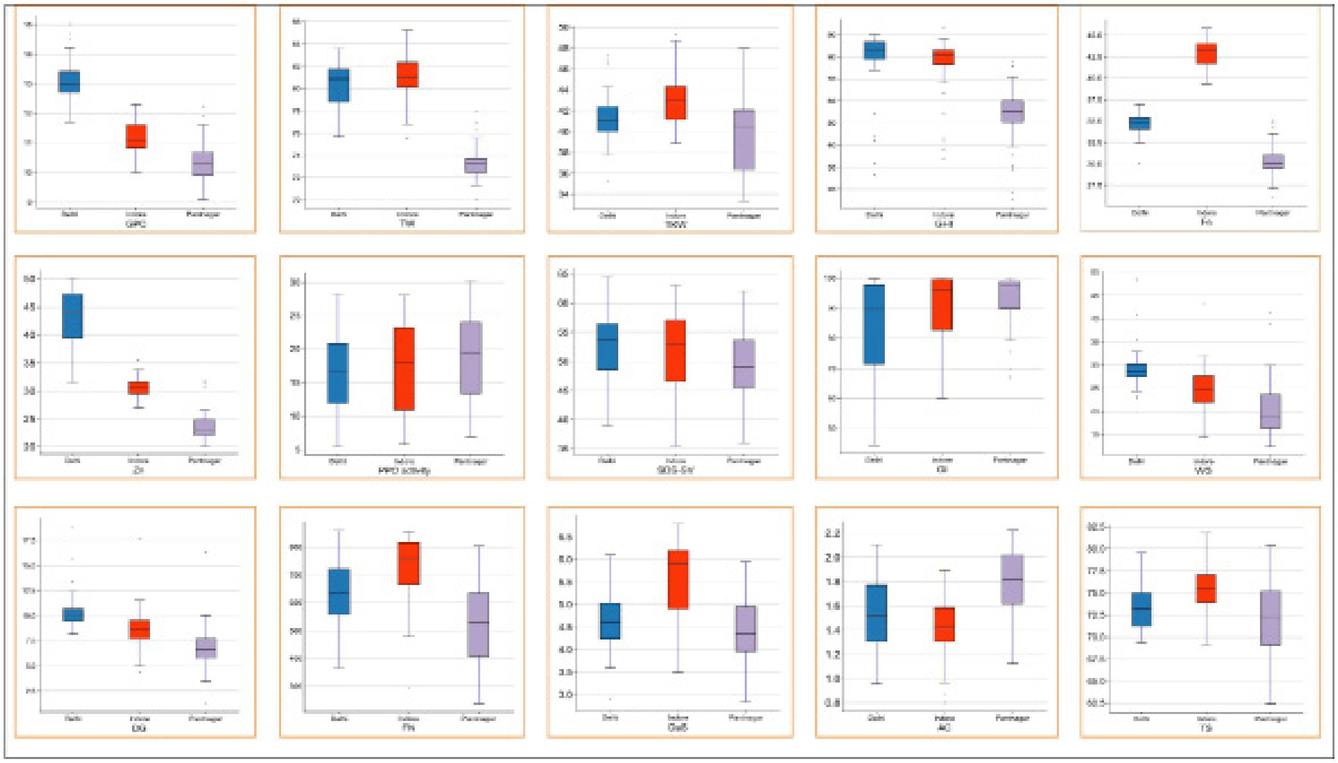

Fig. 1. Box plot for the quality traits of diverse wheat genotypes evaluated across three locations during *rabi* 2019-20; GPC = Grain protein content; TW = Test weight; TKW = Thousand kernel weight; GHI = Grain hardness index; Fe = Iron content; Zn = Zinc content; PPO = Poly phenol oxidases activity; SDS = SV-Sedimentation value; GI = Gluten index; WG = Wet gluten, DG = Dry gluten; FN = Falling number; DaS = Damaged starch;AC = Ash content; TS = Total sugar

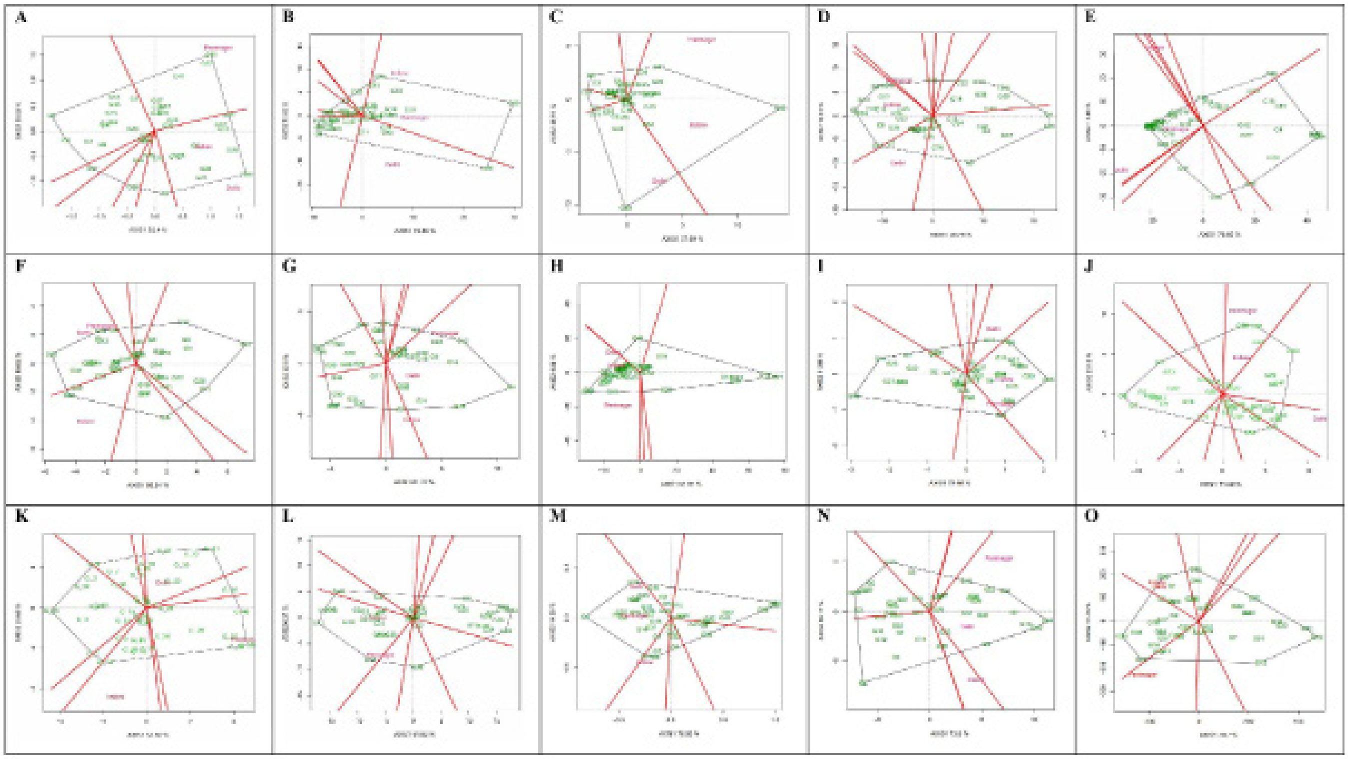

Fig. 2. The 'which-where-won' view of GGE biplot showing which genotypes performed best in which environment for (A) Grain protein content, (B) Wet gluten, (C) Dry gluten, (D) Sedimentation value, (E) Gluten index, (F) Test weight, (G) Thousand kernel weight, (H) Grain hardness index, (I) Damaged starch, (J) Zn content, (K) Fe content, (L) PPO activity, (M) Ash content, (N) Total sugar, (O) Falling number

al. 2020), and it is highly influenced soil fertility, particularly nitrogen availability, and favourable climate conditions during grain filling stages, optimal temperature and moisture levels (Bushuk 1997; Araus et al. 2008)

The gluten quality and strength of the flour and their potential utility in specific product-making was determined by GI and SV (Cubadda et al. 1992; Krishnappa et al. 2019). Genotype G33(HD3249) performed well in Delhi, while G1(PBW752), G12(CS110) and G27(HI1531) were specifically adapted to Indore and Pantnagar environments for SV respectively (Fig. 2D). Further genotypes including G2(PBW725), G6(DBW187), G8(CS5), G28(HD2851), G31(HD3059), and G32(HD3226) were located at the vertex of the polygon and performed exceptionally well for GI across locations(Fig. 2(E). The genotypes with high gluten quality and strength were more suitable for making of breads.On the other hand, genotypes G38(C273), G30(HD2985), G40(C591), G34(C306), and G14(QBP13-9) showed low performance for GI, while genotypes G4(DBW16), G20(K1006), G9(CS28), G34(C306) and G13(DBW51) showed low performance for SV, as they were located at the vertex of the polygon without any corresponding environment falling within that sector (Fig. 2 D and E). These genotypes are most suitable for making chapatti and biscuit since they have low gluten quality and strength. Similarly, few researchers employed the GGE biplot method to analyze and rank wheat genotypes for quality traits based on their performance in different environments (Kendal and Sener 2015).

The G5(DBW173), G18(Bobwhite) and G29(HD2982) were the most appropriate genotypes in Delhi and Pantnagar locations, whereas G40(C591) in Indore location for TW (Fig. 2 (F). All three locations fell in a single mega environment for TKW, indicating that genotypes located within this sector viz., G8(CS5), G12(CS110), G15(QBP19-1) and G7(DBW222) performed equally well in all locations (Fig. 2G). Similarly, for GHI genotypesG38(C273) and G34(C306) were found to performwell across the locations (Fig. 2H).Genotype G35(G322) showed high performance and specific adoption for DaS at Indore and Pantnagar locations, while, genotype G9(CS28) was the winning genotype in Delhi (Fig. 2I). Despite being one of the important quality parameters of wheat, significantly influences the water absorption during the end-product making; however, there are no reported studies on this trait.

GGE biplot showed that G20(K1006) had narrow adoption in Delhi whereas G38(C273) and G39(C518)were showed specific adoption and high performance for grain Zn content in both Indore and Pantnagar (Fig. 2J). For grain Fe content, genotype G13(DBW51) in Indore, G38(C273) and G40(C591) in Pantnagar, G41(HD2967) and G34(C306) in Delhi, were the winning genotypes (Fig. 2K).

Wheat type, cultivar, milling fractions, growing region and seasons were significantly influences the AC and PPO activity (Park et al. 1997; Piironen et al. 2009; Harisha et al. 2023). Due to the detrimental effects of high PPO activity and AC on the quality attributes, genotypes with low performance for these traits are strongly recommended (Fuerst et al. 2006; Panghal et al. 2019). The GGE biplot illustrates that genotypes like G12 (CS110), G18(Bobwhite), and G19(Semmong2) had low performance for PPO activity (Fig. 2L), while G34(C306), G38(C273) and G39(C518) had low performance for ash content across locations (Fig. 2M), as they were located on the outer part of the polygon in a single sector without any corresponding environment falling within that sector. The genotypes G9(CS28), G40(C591), G34(C306), G18(Bobwhite) and G21(Yangmai6) were identified as highly responsive and adaptive genotypes across all three locations for TS (Fig. 2N). With regards to FN, genotype G33(HD3249) showed a specific performance to the Delhi and Indore locations, whereas G32(HD3226) showed a specific performance to Pantnagar (Fig. 2O).

Selection of ideal genotypes

Quality traits for determining an end-use of a wheat genotype are many and bringing them together in a single genotype is challenging for breeders. However, it is essential to develop wheat varieties with superior quality traits for both market value and human nutrition (Li et al. 2013; Guzmán et al. 2017). Fig. 3(A-O) depicts the GGE-biplot. Average-Environment Coordination (AEC) view to rank wheat genotypes in relation to ideal genotypes for quality attributes. The arrowhead in the centre of the concentric circle denotes the ideal genotype and genotypes located closer to ideal genotypes are considered as highly desirable (Yan and Tinker, 2006). High mean performance and stability across the environments are the features of ideal genotypes (Yan and Tinker, 2006). GGE biplot showed that, G13(DBW51) and G32(HD3226) were the most ideal genotypes for GPC (Fig. 3A). In addition, G39(C518), G34(C306) and G38(C273) were some of most highly desirable genotypes, since they located near ideal genotype for GPC. Further, genotype G39(C518) was found to be ideal for both WG and DG (Figs. 3B and C). Genotypes G9(CS28) and G3(PBW771) were among the non-ideal genotypes for GPC, WG and DG, situated farthest from the centric circle. Genotypes G1(PBW752), G28 (HD2851) and G32(HD3226) were found most ideal genotypes for both SV and GI (Figs. 2 D and E). These genotypes have high mean value and stability for both GI and SV, indicating the high gluten quality and strength and these were highly suitable for bread making (Rai et al. 2019). Similarly, G4 (DBW16), G20 (K1006), G34 (C306), G37 (HI1544) and G39 (C518) are the non-ideal genotypes situated farthest from the centric circle, indicating the low mean performance for GI and SV and these genotypes expected to have low gluten strength and were suitable for cookies and *chapati* making (Kundu et al. 2017).

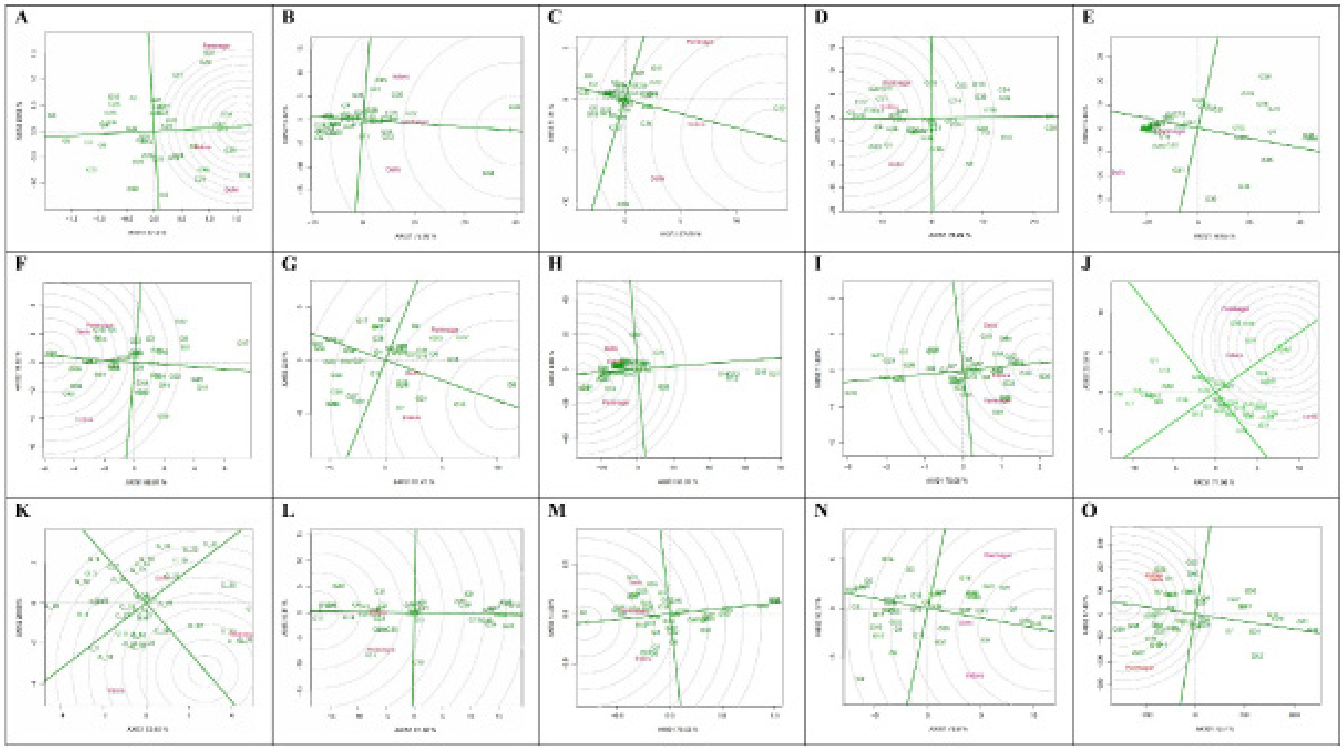

Fig. 3. Average –environment coordination (AEC) view of GGE biplot to rank wheat genotypes relative to the ideal genotypes (the center of the concentric circle) for (A) Grain protein content, (B) Wet gluten, (C) Dry gluten, (D) Sedimentation value, (E) Gluten index, (F) Test weight, (G) Thousand kernel weight, (H) Grain hardness index, (I) Damaged starch, (J) Zn content, (K) Fe content, (L) PPO activity, (M) Ash content, (N) Total sugar, (O) Falling number

With respect to grain physical traits, G29(HD2982) and G8(CS5) were the ideal genotypes for TW and TKW, respectively (Fig. 2 F and G). For GHI, genotypes G34(C306) and G38(C273) were found to be ideal (Fig. 2 H). Genotypes G35(G322) G36 (HD3086) and G39(C518), was found to be ideal, across the locations for DaS (Fig. 2I). These identified genotypes were very useful for breeding for high DaS. The wheat genotype such as, G38(C273), G18(Bobwhite) and G20(K1006) were found to be ideal for grain Fe concentration (Fig. 3K), While, G40(C591), G39(C518), G38(C273) and G34(C306) genotypes were an ideal grain Zn concentration (Fig. 3J). Identified genotypes can serves as valuable sources for wheat bio-fortification program. Due to the negative effects of PPO activity and ash on wheat end-products quality (Fuerst *et al.* 2006; Harisha et al. 2023), the genotypes G27(HI1531), G28(HD2851), G29(HD2982), G18(Bobwhite) and G12(CS110) were regarded as most desirable ones (Fig. 3L), for PPO activity, while G38(C273), G39(C518), and G34(C306) were considered as ideal genotypes for AC (Fig. 2M), since they located farthest from origin and had low mean performance consistently across the environments. In the GGE biplot, G10(CS46), G34(C306) and G40(C591) genotypes were found to be ideal genotypes for the TS (Fig. 2N), while Genotypes G38(C273) and G39(C518) were the most desirable for FN (Fig. 2O).

Genotypes with multiple desirable traits and stability in performance across environments

Genotype with multiple desirable quality traits is a dream for breeder. However, their availability is very scare, but highly suitable for selective breeding intended to increase genetic gains for wheat quality parameters (Thungo et al. 2020). In our study, we found that genotypes G38(C273), G39(C518), G40 (C591) and G34(C306) were the most desirable and stable across the locations for multiple traits such as GPC, DG, WG, WB, GHI, FN and TS, as well as grain micronutrient content (Fe and Zn). In addition, these genotypes had the optimum DaS and low PPO activity and AC, which is highly desirable in quality perspective. Genotypes G1(PBW752), G28(HD2851), G12(CS110), G41(HD2967), G27(HI1531) and G6(DBW187) were the best performing, highly stable and most desirable across the locations for SV and GI. In addition these genotypes have optimum GPC, GHI and DaS. These identified genotypes have high value in quality improvement breeding programs and can act as potential donors in breeding for simultaneous improvement of multiple quality traits in wheat.

Breeding for elite genotypes combining yield, disease resistance, and quality is challenging. Breeders often hesitate to use crop wild relatives and other germplasm such as landraces due to issues like linkage drag in resulting populations. Therefore, understanding the quality aspects of elite germplasm, including both old and new varieties, can aid hybridization programs to incorporate desirable quality traits into mainstream breeding efforts. Additionally, assessing the influence of genotypes, environment, and genotype-environment interaction on the expression of wheat quality attributes helps in precise selection for quality improvement in breeding programs. The present study has shown that environmental factors and genotype-environment interaction have a greater impact on the expression of most quality parameters compared to genotypes alone. Ideal genotypes with high mean performance and stability across environments for quality parameters have been identified and selected for future breeding to enhance quality. As most of these genotypes are already released varieties and possess high yield potential, breeders can use them as parents in their varietal development programs.

Author's contributions

Conceptualization of research (AMS, RH); Designing of the experiments (AMS, RH, AKA); Contribution of experimental materials (AMS, RH, AKA, JPJ, JBS); Execution of field/lab experiments and data collection (RH, AKA, SN, APB,SS, BB, SKS); Analysis of data and interpretation (RH, RRK, SN); Preparation of the manuscript (RH, AMS, SKS).

Acknowledgment

The first author acknowledges the ICAR-Indian Agricultural Research Institute (IARI) and Council of Scientific and Industrial Research (CSIR), New Delhi for providing the fellowship and facilities to complete this work as part of Ph.D. thesis.

References

AACC. 2000. Approved Methods of the AACC. 10th Edition, American Association of Cereal Chemists, St. Paul.

Abedi T., Alemzadeh A. and Kazemeini S.A. 2011. Wheat yield and grain protein response to nitrogen amount and timing. Aus. J. Crop Sci., **5**(3): 330-336.

Anderson J.V. and Morris C.F. 2001. An improved whole-seed assay for screening wheat germplasm for polyphenol oxidase activity. Crop Sci., **41**(6): 1697-1705. https://doi.org/10.2135/cropsci2001.1697

Araus J.L., Slafer G.A., Royo C. and Serret M.D. 2008. Breeding for yield potential and stress adaptation in cereals. Crit. Rev. Plant Sci., **27(**6): 377-412. https://doi.org/10.1080/07352680802467736

Axford D. 1979. Note on the sodium dodecyl sulphate test of breadmaking quality: comparion with Pelshenke and Zeleny tests. Cereal Chem., **56**: 582-583.

Bushuk W. 1997. Wheat breeding for end-product use. In: Braun H.J., Altay F., Kronstad W.E., Beniwal S.P.S., McNab A. (eds) Wheat: Prospects for Global Improvement. Developments in Plant Breeding, vol 6. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-4896-2_27

Ceccarelli S. 1989. Wide adaptation: How wide?. Euphytica, **40**: 197-205. https://doi.org/10.1007/BF00024512

Chaudhary N., Dangi P. and Khatkar B. S. 2016. Assessment of molecular weight distribution of wheat gluten proteins for chapatti quality. Food Chem., **199**: 28-35. https://doi.org/10.1016/j.foodchem.2015.11.106

Cubadda R., Carcea M. and Pasqui L. 1992. Suitability of the gluten index method for assessing gluten strength in durum wheat and semolina. Cereal Foods World, **37**(12): 866-869.

Daniel C. and Triboi E. 2000. Effects of temperature and nitrogen nutrition on the grain composition of winter wheat: effects on gliadin content and composition. J. Cereal Sci., **32**(1): 45-56. https://doi.org/10.1006/jcrs.2000.0313

DuBois M., Gilles K.A., Hamilton J.K., Rebers P.T. and Smith F. 1956. Colorimetric method for determination of sugars and related substances. Anal. Chem., **28**(3): 350-356.

Faridi H., Finley J.W. and D'Appolonia B. 1989. Improved wheat for baking. Crit. Rev. Food Sci. Nutr., **28**(2): 175-209.

Fuerst E.P., Anderson J.V. and Morris C.F. 2006. Polyphenol oxidase in wheat grain: whole kernel and bran assays for total and soluble activity. Cereal Chem., **83**(1): 10-16. http://dx.doi.org/10.1094/CC-83-0010

Gauch Jr, H.G. 2013. A simple protocol for AMMI analysis of yield trials. Crop Sci., **53**(5): 1860-1869. https://doi.org/10.2135/cropsci2013.04.0241

Guardia-Velarde L., Liu H., Cope J.E., Westerbergh A. and Weih M. 2023. Differential breeding targets in wheat influence non-target traits related to grain quality, but not crop nitrogen requirement. Front. Agron., **5**: 1151015. https://doi.org/10.3389/fagro.2023.1151015

Guzmán C., Autrique E., Mondal S., Huerta-Espino J., Singh R.P., Vargas M., Crossa J., Amaya A. and Peña R.J. 2017. Genetic improvement of grain quality traits for CIMMYT semi-dwarf spring bread wheat varieties developed during 1965–2015: 50 years of breeding. Field Crops Res., **210**: 192-196. https://doi.org/10.1016/j.fcr.2017.06.002

Guzmán C., Ibba M.I., Álvarez J.B., Sissons M. and Morris C. 2022. Wheat Quality. In: Reynolds, M.P., Braun, HJ. (eds) Wheat Improvement. Springer, Cham: 177–193 https://doi.org/10.1007/978-3-030-90673-3_11

Harisha R., Singh S.K., Ahlawat A. K., Narwal S., Jaiswal J. P., Singh J. B., Kumar R.R., Singhal S., Adithya P Balakrishnan, Shukla P., Bhavya B., Agrawal A., Singh S. K and Singh A.M. 2023. Elucidating the effects of poly phenol oxidase activity and allelic variation of poly phenol oxidase genes on dough and whole wheat derived product color parameters. Int. J. Food Prop., **26**(2): 2716-2731.

Hemalatha M.S., Manu B.T., Bhagwat S.G., Leelavathi K. and Prasada Rao U.J. 2007. Protein characteristics and peroxidase activities of different Indian wheat varieties and their relationship to chapati-making quality. Eur Food Res. Technol., **225**: 463–471. https://doi.org/10.1007/s00217-006-0441-7

Indian Statista. 2022-23. Indian Statista statistical database, Volume of food grains produced in India in financial year 2022-23. https://www.statista.com/statistics/621131/food-grain-production-by-type-india.

Kendal E. and Sener O. 2015. Examination of genotype× environment interactions by GGE biplot analysis in spring durum wheat. Indian Journal of Genetics and Plant Breeding, **75**(3): 341-348.https://doi.org/10.5958/0975-6906.2015.00054.1

Krishnappa G., Ahlawat A.K., Shukla R.B., Singh S.K., Singh

S.K., Singh A.M. and Singh G.P. 2019. Multi-environment analysis of grain quality traits in recombinant inbred lines of a biparental cross in bread wheat (*Triticum aestivum L.*). Cereal Res. Commun., **47**(2): 334-344. https://doi.org/10.1556/0806.47.2019.02

Kumar J., Thavarajah D., Kumar S., Sarker A., Singh N.P. 2018. Analysis of genetic variability and genotype × environment interactions for iron and zinc content among diverse genotypes of lentil. J. Food Sci. Technol., **55**(9): 3592-3605. https://doi.org/10.1007/s13197-018-3285-9

Kundu M., Khatkar B.S. and Gulia N. 2017. Assessment of chapatti quality of wheat varieties based on physicochemical, rheological and sensory traits. Food chem., **226**: 95-101. http://dx.doi.org/10.1016/j.foodchem.2016.12.046

Li Y.F., Wu Y., Hernandez-Espinosa N. and Peña R.J. 2013. Heat and drought stress on durum wheat: Responses of genotypes, yield, and quality parameters. J. Cereal Sci., **57**(3): 398-404. https://doi.org/10.1016/j.jcs.2013.01.005

Lookhart G.L., Finney K.F. and Bruinsma B.L. 1984. Polyacrylamide gel electrophoresis of wheat gliadins: the effect of environment and germination. Cereal Chem., **61**(6): 496-499.

Mathewson P.R. and Pomeranz Y. 1978. On the relationship between alpha amylase and falling number in wheat. J. Food Sci., **43**(2): 652-653. https://doi.org/10.1111/j.1365-2621.1978.tb02382.x

Nadaf S. and Uppinal N.F. 2017. Effect of environment on quality parameters of wheat. Int. J. Pure App. Biosci., **5**(6): 1275-1283. http://dx.doi.org/10.18782/2320-7051.3073

Orth R. A. 1972. A comparative study of protein of wheats of diverse baking qualities. Cereal Chem., **49**: 268-275

Paltridge N.G., Milham P.J., Ortiz-Monasterio J.I., Velu G., Yasmin Z., Palmer L.J., Guild G.E. and Stangoulis J.C. 2012. Energy-dispersive X-ray fluorescence spectrometry as a tool for zinc, iron and selenium analysis in whole grain wheat. Plant and Soil, **361**(41306): 261-269. https://doi.org/doi:10.1007/s11104-012-1423-0

Panghal A., Chhikara N. and Khatkar B.S. 2019. Characterisation of Indian wheat varieties for chapatti (flat bread) quality. J. Saudi Soc. Agric. Sci., **18**(1): 107-111.https://doi.org/10.1016/j.jssas.2017.02.005

Park W.J., Shelton D.R., Peterson C.J., Martin T.J., Kachman S.D. and Wehling R.L. 1997. Variation in polyphenol oxidase activity and quality characteristics among hard white wheat and hard red winter wheat samples. Cereal Chem., **74**(1): 7-11. https://doi.org/10.1094/CCHEM.1997.74.1.7

Pasha I., Anjum F.M and Morris C.F. 2010. Grain hardness: a major determinant of wheat quality. Food Sci. Technol. Int. **16**(6): 511-22. https://doi.org/10.1177/1082013210379691

Piironen V., Lampi A.M., Ekholm P., Salmenkallio-Marttila M. and Liukkonen K.H. 2009. Micronutrients and phytochemicals in wheat grain. In: Wheat: chemistry and technology, (Ed. 4), American Association of Cereal Chemists, Inc (AACC), St. Paul, Minnesota, USA: 179-222. https://doi.org/10.1094/9781891127557.007

Rai A., Singh A.M., Ganjewala D., Kumar R.R., Ahlawat A.K., Singh S.K., Sharma P. and Jain N. 2019. Rheological evaluations and molecular marker analysis of cultivated bread wheat varieties of India. J. Food Sci. Technol., **56**(4): 1696-1707. https://doi.org/10.1007/s13197-019-03593-0

Randall P.J. and Moss H.J. 1990. Some effects of temperature regime during grain filling on wheat quality. Aus. J. Agri. Res., **41**(4): 603-617. https://doi.org/10.1071/AR9900603

Reynolds M.P. and Braun H. J. 2022. Wheat improvement: food security in a changing climate. Springer Nature: 629. https://doi.org/10.1007/978-3-030-90673-3

Rharrabti Y., Villegas D., García del Moral L.F., Aparicio N., Elhani S. and Royo C. 2001. Environmental and genetic determination of protein content and grain yield in durum wheat under Mediterranean conditions. Plant Breed., **120**(5): 381-388. https://doi.org/10.1046/j.1439-0523.2001.00628.x

Sapirstein H.D. and Fu B.X. 1998. Intercultivar variation in the quantity of monomeric proteins, soluble and insoluble glutenin, and residue protein in wheat flour and relationships to breadmaking quality. Cereal Chem., **75**(4): 500-507. https://doi.org/10.1094/CCHEM.1998.75.4.500

Sharma A., Garg S., Sheikh I., Vyas P. and Dhaliwal H.S. 2020. Effect of wheat grain protein composition on end-use quality. J. Food Sci. Technol., **57**(8): 2771-2785. https://doi.org/10.1007/s13197-019-04222-6

Shewry P.R. and Tatham A.S. 1990. The prolamin storage proteins of cereal seeds: structure and evolution. Biochem J., **267**(1): 1-12. https://doi.org/10.1042/bj2670001.

Shewry P.R. and Hey S.J. 2015. The contribution of wheat to human diet and health. Food and energy secur., **4**(3): 178-202. https://doi.org/10.1002/fes3.64

Shiferaw B., Smale M., Braun H., Duveiller E., Reynolds M.P. and Muricho G. 2013. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. Food Sec., **5**: 291–317. https://doi.org/10.1007/s12571-013-0263-y

Surma M., Adamski T., Banaszak Z., Kaczmarek Z., Kuczyńska H., Majcher M., Ługowska B., Obuchowskił W., Salmanowicz B. and Krystkowiak K. 2012. Effect of genotype, environment and their interaction on quality parameters of wheat breeding lines of diverse grain hardness. Plant Prod. Sci., **15**(3): 192-203. https://doi.org/10.1626/pps.15.192

Thavarajah D., Thavarajah P., Sarker A. and Vandenberg A. 2009. Lentils (*Lens culinaris Medikus* Subspecies culinaris): a whole food for increased iron and zinc intake. J. Agric. Food Chem., **57**(12): 5413-5419. http://dx.doi.org/10.1021/jf900786e

Thungo, Z., Shimelis, H., Odindo, A. and Mashilo, J. 2020. Genotype-by-environment effects on grain quality among heat and drought tolerant bread wheat (*Triticum aestivum* L.) genotypes. J. Plant Interact., **15**(1): 83-92. http://dx.doi.org/10.1080/17429145.2020.1748732

Wang K. and Fu B.X. 2020. Inter-Relationships between test weight, thousand kernel weight, kernel size distribution and their effects on durum wheat milling, semolina composition and pasta processing quality. Foods, **9**(9): 1308. https://doi.org/10.3390/foods9091308.

Yan W. and Tinker N.A. 2006. Biplot analysis of multi-environment trial data: Principles and applications. Can. J. Plant Sci., **86**(3): 623-645. https://doi.org/10.4141/P05-169

Zhang P., Ma G., Wang C., Lu H., Li S., Xie Y., Ma D., Zhu Y. and Guo T. 2017. Effect of irrigation and nitrogen application on grain amino acid composition and protein quality in winter wheat. PLoS One, **12**(6): 0178494.https://doi.org/10.1371/journal.pone.0178494