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Multi-location trials identify stable high-yielding spring bread and durum wheat cultivars in Mexico

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Abstract

Determining the stability and consistency of grain yield performance requires accurate evaluation of genotypes in different environments. In Mexico, annual national spring wheat irrigated trials (ENTRI) are conducted to assess elite bread (*Triticum aestivum* L.) and durum (*Triticum durum* L.) wheat performance in different testing environments (TEs) in the main wheat-growing areas. These trials provide data supporting release of new cultivars and aim to also address Mexican wheat value chain grain needs. This study analyzed grain yield performance of 30 bread and durum wheat cultivars grown in trials in the 2012–2013 and 2013–2014 growing cycles conducted across TEs in northwest, north, and central Mexico. Environmental variability (location, sowing timing, and irrigation schemes) across the ENTRI enabled genotype by environment interaction to be effectively evaluated. Bread and durum wheat genotypes with high and stable grain yield were also identified and compared across TEs of the wheat-growing areas of Mexico. The bread wheat cultivars Bacorehuis F2015 and Borlaug100 F2014, and the durum cultivars Barobampo C2015, CONASIST C2015, and Anatoly C2011 were high yielding and gave stable performance in most of the TEs. This analysis demonstrates the utility of multi-year,

Abbreviations: AEC, average environment coordination; ANOVA, analysis of variance; ASED, average standard error of the differences in means; BLUP, best linear unbiased predictor; C IMMYT, International Maize and Wheat Improvement Center; CV, coefficient of variation; ENTRI, national spring wheat irrigated trials; GEI, genotype by environment interaction; GGE, genotype and genotype by environment interaction; INIFAP, National Wheat Program of the National Forestry, Agricultural and Livestock Research Institute; LSD, least significant difference; PC, principal component; TEs, testing environments; TPEs, target population of environments.

multi-environment testing and analysis to identify improved wheat cultivars to meet wheat production demand in Mexico. It also provides useful testing and analysis methods for selection of suitable broadly as well as locally adapted varieties in other wheat producing regions of the world.

1 | INTRODUCTION

Wheat is one of the most important staple crops in Mexico, providing 10% of the calories for household diet in the country (USDA, 2022). During 2020, 52% of the national durum wheat production was exported to different world markets while 54% of the bread wheat for domestic consumption was imported (FIRA, 2021). Northwest Mexico is the most important wheat-growing area with 70% of the total production in 2021 followed by central and northern regions that account for 25% and 4%, respectively (SIAP, 2023). In Mexico, genetic gains for wheat productivity have been steady (Figure 1) and the long-term collaboration in varietal development between International Maize and Wheat Improvement Center (CIMMYT) and the National Forestry, Agricultural and Livestock Research Institute (INIFAP) continues to support this (Villaseñor-Mir et al., 2021). Wheat breeding in Mexico aims to develop material with high and stable yield potential, resilience to biotic and abiotic stress, and superior end use quality (Crespo-Herrera et al., 2017). Selection of cultivars with these attributes requires multi-environment testing under near optimum conditions in order to select for yield potential as well as specific screening for abiotic and biotic stresses in each environment (Braun et al., 1996). The resulting cultivars should possess yield potential along with favorable gene accumulation for broad-spectrum resistance to diseases and tolerance to abiotic stresses. Selection for target population of environments (TPEs) is key to designing strategies for crop improvement (Atlin et al., 2000). A recent analysis of spring wheat performance in India defined TPEs, showing that there is an opportunity to further refine breeding targets based on current and future environmental parameters (Crespo-Herrera et al., 2021).

Identifying outstanding genotypes is complicated by the genotype by environment interaction (GEI) because ranking of the best genotypes can vary between environments (Asfaw et al., 2009). Strategies such as stratification of environments into mega-environments with specific biotic and abiotic stress profiles can be applied to reduce this difficulty (Yan et al., 2000). Several statistical methodologies have also been developed to identify superior high-yielding and stable cultivars, termed “reliable genotypes” (Annicchiarico, 2002).

Static stability (type 1 or biological) refers to a constant expression of a character in relation to the environmental variation (phenotypic variation across environments = 0). Dynamic stability (type 2 or agronomical) refers to a character expression pattern which is parallel to the environmental variation, indicating the absence of GEI (Annicchiarico, 2002; Becker & Léon, 1988). Static stability is useful with characters (quality, disease resistance, etc.) that have to be permanently fixed across environments (Becker & Léon, 1988). However, it is also commonly associated with poor response capacity to environmental changes and targeting static stability alone can lead to low yield potential. Therefore, dynamic stability is more appropriate to assess grain yield stability (Lin et al., 1986) as it allows for selection of environmental responsiveness.

One of the most commonly used methodologies for evaluating dynamic stability is the linear regression coefficient (b_i) from the environmental mean for a given trait (Eberhart & Russell, 1966). Based on this methodology, a stable genotype would have a $b_i = 1$, whereas genotypes that have $b_i \neq 1$ are sensitive to environmental changes. A genotype with $b_i > 1$ tends to respond better to high-yielding environments, whereas $b_i < 1$ usually performs better in low-yielding environments (Eberhart & Russell, 1966). Multivariate methods, namely genotype and genotype by environment interaction (GGE) biplots, have arisen as an alternative to evaluate the GEI in multi-environmental trials (Kroonenberg, 1995; Tinker et al., 2006). This analysis uses the genotype (G) and genotype by environment (GE) effects to create graphical representations of genotype performance across multiple environments (Yan et al., 2000). GGE biplots are constructed using the first two principal components (PC 1 and PC 2) obtained from a single value decomposition of environment-centered yield data (Yan et al., 2000). The primary use of GGE biplots is to identify cultivars that have the best performance across a set of environments (Yan et al., 2000).

In wheat, most previous studies have aimed to identify similarities and correlations between yield and yield components when bread (*Triticum aestivum* L.) and durum (*Triticum durum* L.) wheat species were compared (Cossani et al., 2011; Marti & Slafer, 2014). In this study, our primary aim was to assess the overall yield performance and stability of performance of both elite bread and durum wheat under irrigated conditions in Mexico. Although overall durum and bread wheat performance could be inferred, this was not the core focus of the study. The work reported builds on previous work to assess yield stability under rainfed conditions in central Mexico (Rodríguez-Pérez et al., 2002). The current study is novel as it considers the major testing regions and environments used across Mexico for targeting broad as well as local performance potential. The specific objectives were to (a) analyze the effect of environmental variation on the performance of genotypes from national spring bread and durum wheat in different testing environments (TEs); (b) compare phenotypic stability of genotypes; and (c) identify high-yielding stable cultivars.

Core Ideas

- We identified cultivars with high and stable grain yield in Mexico.
- Environmental variability enabled G × E interaction to be effectively evaluated.
- Multi-year, multi-environment testing and analysis is useful to identify improved wheat cultivars.

2 | MATERIALS AND METHODS

2.1 | Trials and germplasm

Genotypes evaluated in the national spring wheat irrigated trials (ENTRI) of the INIFAP were grown in the 2012–2013 and 2013–2014 winter growing seasons in eight locations with different testing envrionments (TEs) in northwest, north, and central Mexico (temperature and precipitation for this locations are provided in Figures S1 and S2). The genotypes tested included eight bread and eight durum wheat cultivars (Table 1; with low variation in phenology and plant height), which were planted in eight representative locations from the three major wheat-growing regions in Mexico (Table 2). Four TEs were defined using a combination of sowing dates (optimum and late) and irrigation management (full and reduced), resulting in a total of 30 trials (Table 2) in eight locations across Mexico (Figure 2). The trials were characterized by the following factors: growing season, location, irrigation management, and in some cases sowing date. All experiments were sown using a randomized complete block design with two replicates. Experimental units consisted of plots of 3 m length and 1.2 m width with four plant rows. Agronomic, pest, and disease control management followed standard INIFAP procedures for each wheat-growing region. Grain yield (reported at 12% moisture content) was obtained by harvesting the entire experimental plot after maturity.

2.2 | Statistical analysis

The restricted maximum likelihood procedure was implemented using the multienvironment trial analysis in R (META-R) program to calculate variance components and broad-sense heritability estimates for combined analysis and individual environments (trials) considering all factors as random effects (Alvarado et al., 2020) (Equation 1) as follows:

$$y_{ijk} = \mu + G_i + E_j + G \times E_{ij} + R_{k_{(j)}} + \varepsilon_{ijk} \qquad (1)$$

where y_{ijk} is the trait of interest; μ is the mean effect; G_i is the genetic effect of the ith genotype; E_j is the effects of the jth environment; $G \times E_{ij}$ is the genotype × environment interaction effect; R_k is the effect of the kth replicate nested within the jth environment; and ε_{ijk} is the residual.

Least significant difference ($LSD_{0.05}$) was used to compare the best linear unbiased predictor (BLUP) in the genotype combined analysis (Equation 2) as follows:

$$\mathrm{LSD} = t_{(1-0.05,\, df\,Error)}\mathrm{ASED} \qquad (2)$$

where the t is the cumulative studentsťs distribution with a level of significance of 5%, *dfError* is the degrees of freedom of the error, and ASED is the average standard error of the differences in means (Alvarado et al., 2020).

Heritability estimates for individual environment and combined analysis were calculated as in Equations (3) and (4), respectively.

$$H^2 = \frac{\sigma_g^2}{\sigma_g^2 + \frac{\sigma_\varepsilon^2}{n\mathrm{Reps}}} \qquad (3)$$

$$H^2 = \frac{\sigma_g^2}{\sigma_g^2 + \frac{\sigma_{ge}^2}{n\mathrm{Envs}} + \frac{\sigma_\varepsilon^2}{n\mathrm{Envs} \times n\mathrm{Reps}}} \qquad (4)$$

where H^2 is broad-sense heritability, σ_g^2, σ_{ge}^2, and σ_ε^2 are genotype, genotype × environment, and error variances,

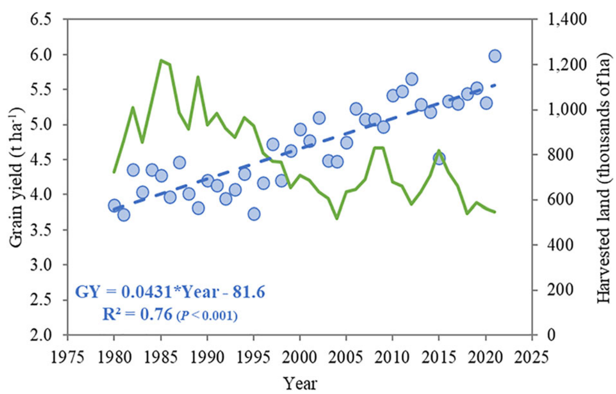

FIGURE 1 On-farm grain yield (GY) and harvested land for wheat from 1980 to 2021 in Mexico (data from SIAP, 2023).

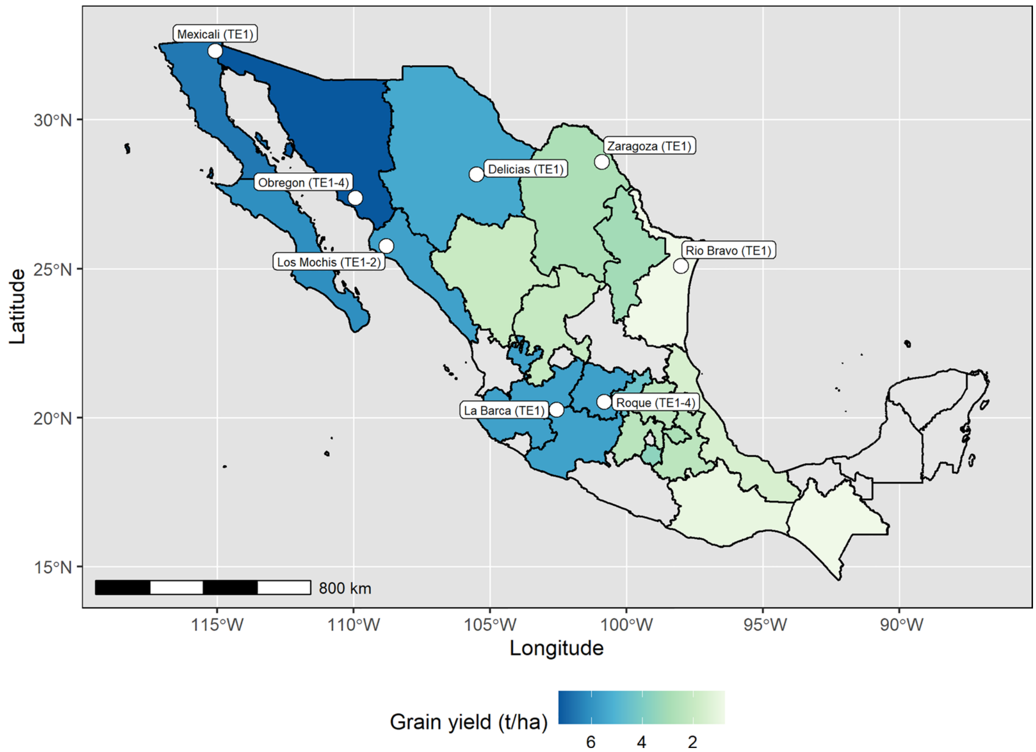

FIGURE 2 Locations with each target environment (TE) and grain yield per state in Mexico. Data for grain yield corresponds to 2021 mean per state (SIAP, 2023). States in gray denote no available data.

respectively, nReps is the number of replications, and $nEnvs$ is the number of environments. Environments with H^2 below 0.05 were eliminated from the analysis (resulting in the removal of trial E30 [Table 2]).

The (Eberhart & Russell, 1966) stability parameter b_i and the GGE biplot analysis were used to determine stability and GEI. The GGE biplots were generated using the first two principal components, which explained most of the G and GE variability based on the model (Equation 5) (Yan & Tinker, 2005) as follows:

$$(y_{ij} - \beta_j)/s_j = \lambda_1 \xi_{i1} \eta_{1j} + \lambda_2 \xi_{i2} \eta_{2j} + \varepsilon_{ij} \quad (5)$$

where y_{ij} is the mean of the i genotype in the j environment; β_j is the mean yield in environment j; s_j is the standard deviation in the environment j; λ_1 and λ_2 are the singular values of PC1 and PC2, respectively; ξ_{i1} and ξ_{i2} are the eigenvectors of the genotype i for PC1 and PC2, respectively; and η_{1j} and η_{2j} are the eigenvectors of environment j for PC1 and PC2, respectively; and ε_{ij} is the residual of the genotype i and environment j. Equation (5) is reorganized to obtain the PC scores of ith genotype and jth environment as follows:

$$(y_{ij} - \beta_j)/s_j = \lambda_1 g_{i1} e_{1j} + \lambda_2 g_{i2} e_{2j} + \varepsilon_{ij} \quad (6)$$

where $l = 1, 2$; g_{il} is the PC scores for genotype ith (ξ_{il}), and e_{lj} PC scores for the jth environment (η_{lj}).

The (Eberhart & Russell, 1966) analysis of variance (ANOVA) and stability parameters were obtained using the "plantbreeding" package (Umesh, 2014) implemented in R (R Core Team, 2020). The GGE biplots "which-won-where" and "means versus stability" were created using the "gge" and "GGEBiplots" packages in R (Dumble et al., 2017; R Core Team, 2020; Wright & Laffont, 2018). The genetic correlation among environments using the dendrogram and biplot were performed using META-R (Alvarado et al., 2020). The biplots were generated using the 16 genotypes in all 29 trials to determine major TEs based on the grain yield genotypic performance and to identify genotypes with high and stable yield.

3 | RESULTS

3.1 | Environmental and GEI impacts on yield performance

A large portion of grain yield variation was explained by the environment (trials), followed by GEI and genotype. The combined ANOVA showed statistically significant differences ($p < 0.01$) for all sources of variation (Table S1). The per environment grain yield varied significantly, ranging from 8.3 ton ha^{-1} in E5 (TE 1: Mexicali full irrigation with optimum sowing date in 2012–2013) to 1.52 ton ha^{-1} in E11

TABLE 1 Cultivars included in the 2012–2013 and 2013–2014 trials.

Cultivar name	Wheat type[a]	Pedigree
Tacupeto F2001	Bread	BABAX*2/9/KENTANA/BAGE//FRONTANA/URQUIZA_O_GRAL.URQUIZA/3/-BONZA/4/TORIM F 73/5/ALDAN/6/SERI M82/7/YECORA F 70/8/OPATA M 85
Kronstad F2004	Bread	VEERY/KOEL//SIREN/3/ARIVECHI M 92
Urbina S2007	Bread	CIANO T 79/PARULA//CHILERO/3/CUBA/4/CASILDA/CENTELLA
Roelfs F2007	Bread	TACUPETO F2001*2/KUKUNA
Villa Juarez F2009	Bread	WEEBILL1*2/BRAMBLING
Borlaug 100 F2014	Bread	ROELFSF2007/4/BOBWHITE/NEELKANT//CATBIRD/3/CATBIRD/5/FRET2/-TUKURU//FRET2
Conatrigo F2015	Bread	THELIN/2*WBLL1
Bacorehuis F2015	Bread	ROELFSF2007*2/5/REH/HARE//2*BACANORA_T88/3/CROC_1/-AE.SQUARROSA(213)//PAPAGO M 86/4/HUITES F 95
Gema C2004	Durum	SN TURK MI83-84 375/NIGRIS_5//TANTLO_1
CIRNO C2008	Durum	SOOTY_9/RASCON_37//CAMAYO
Sawali Oro C2008	Durum	MUSK_1//ACO89/FNFOOT_2/4/MUSK_4/3/PLATA_3//CREX/ALLA/5/OLUS*2/-ILBOR//PATKA_7/YAZI_1
Cevy Oro C2008	Durum	SCRIP_1//DIPPER_2/BUSHEN_3/4/ ARMENT// SRN_3/NIGRIS_4/3/CANELO_9.1
Anatoly C2011	Durum	GEMA*2/ACONCHIC89
Movas C2009	Durum	CMH83.2578/4/D88059//WARD/YAV79/3/ACO89/5/2*SOOTY_9/RASCON_37/6/-1A.1D5+106/3*MOJO/3/AJAIA_12/ F3LOCAL(SEL.ETHIO.135.85)//PLATA_13
CONASIST C2015	Durum	TRINAKRIA//D21563/ANHINGA/3/BD2080/4/BD2339/5/RASCON_37/TARRO_2//-RASCON_37/6/AUK/GUILLEMOT//GREENSHANK
Barobampo C2015	Durum	GODRIN/GUTROS//DUKEM/3/THKNEE11/4/DUKEM1//PATKA7/YAZI1/3/PATKA7/-YAZI1AJAIA12/F3LOCAL(SEL.ETHIO.135.85) //PLATA13/3/ADAMAR

Note: According to Mexican classification, code in the cultivar name indicated gluten type and year of release (letter F and S are to indicate bread wheat with strong and soft gluten, respectively; letter C is to indicate durum wheat).

[a]All genotypes with interemediate phenology, except for Villa Juarez F2009 and Urbina S2007 which are classified as early.

(TE 4: Roque reduced irrigation and late planting in 2012–2013) (Table 3). Significant differences were also found in the variance of individual environments for nine out of the 29 environments (ranging from $p < 0.01$ and < 0.001). Heritability estimates for each experiment ranged from 0.09 to 0.93 but 20 environments had estimates >0.5; the coefficient of variation (CV) ranged from 3.10% to 23.2% with 22 environments having a CV < 15%. Most of the high yielding environments were located in the northwestern region of Mexico with lower yielding environments in the central region (Table 3).

The genetic correlations between trials were also determined (Figure 3a,b) showing that trials that belong to the northern region clustered together (Figure 3a in blue) and central region trials located mostly in one of the two mega-clusters (except for E27) (Figure 3a in red). Interestingly, for the northwestern region no consistent pattern was observed (Figure 3a in yellow).

3.2 | Stability assessment identifies genotypes with high potential across environments

Genotype rankings differed across environments, justifying the evaluation of cross-environment yield stability. The BLUPs per genotype (Table 4) demonstrate overall variation in grain yield differences. The bread wheat cultivars Bacorehuis F2015 and Borlaug100 F2014 and the durum wheat cultivars Barobampo C2015, Conasist C2015, and Anatoly C2011 had an overall grain yield of >5.1 ton ha^{-1}.

The stability analysis ANOVA (Eberhart & Russell, 1966) indicated that genotypes and GE (linear) were statistically different, meaning that there were differences among the cultivars regression from the environmental index (Table S2). For the bread wheat cultivars, only Villa Juarez F2009 (perform better in favorable environments) and Urbina S2007 showed

TABLE 2 Summary of the trials established in the 2012–2013 and 2013–2014 growing seasons in Mexico, including four testing envrionments (TE).

Code	Growing cycle	Location	Longitude and latitude	Region	TE[ab]
E1	2012–2013	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	1
E2	2012–2013	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	2
E3	2012–2013	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	3
E4	2012–2013	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	4
E5	2012–2013	Mexicali, Baja California	32°32′ N, 115°24′ W	Northwest	1
E6	2012–2013	Los Mochis, Sinaloa	25°45′ N, 108°48′ W	Northwest	1
E7	2012–2013	Los Mochis, Sinaloa	25°45′ N, 108°48′ W	Northwest	2
E8	2012–2013	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	1
E9	2012–2013	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	2
E10	2012–2013	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	3
E11	2012–2013	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	4
E12	2012–2013	La Barca, Jalisco	20°52′ N, 102°42′ W	Central	1
E13	2012–2013	Delicias, Chihuahua	28°10′ N, 105°29′ W	North	1
E14	2012–2013	Rio Bravo, Tamaulipas	25°57′ N, 98°00′ W	North	1
E15	2012–2013	Zaragoza, Coahuila	28°35′ N, 100°54′ W	North	1
E16	2013–2014	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	1
E17	2013–2014	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	2
E18	2013–2014	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	3
E19	2013–2014	Cd. Obregon, Sonora	27°22′ N, 109°55′ W	Northwest	4
E20	2013–2014	Mexicali, Baja California	32°32′ N, 115°24′ W	Northwest	1
E21	2013–2014	Los Mochis, Sinaloa	25°45′ N, 108°48′ W	Northwest	1
E22	2013–2014	Los Mochis, Sinaloa	25°45′ N, 108°48′ W	Northwest	2
E23	2013–2014	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	1
E24	2013–2014	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	2
E25	2013–2014	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	3
E26	2013–2014	Roque, Guanajuato	20°34′ N, 100°48′ W	Central	4
E27	2013–2014	La Barca, Jalisco	20°52′ N, 102°42′ W	Central	1
E28	2013–2014	Rio Bravo, Tamaulipas	25°57′ N, 98°00′ W	North	1
E29	2013–2014	Zaragoza, Coahuila	28°35′ N, 100°54′ W	North	1
E30	2012–2013	La Barca, Jalisco	20°52′ N, 102°42′ W	Central	2

[a]Full irrigation, four irrigation events after sowing; reduced irrigation, three irrigation events between sowing and flowering. Full irrigation with optimum sowing date (1), reduced irrigation with optimum sowing date (2), full irrigation with late sowing date (3), and reduced irrigation with late sowing date (4).

[b]Optimum sowing date was performed within the recommended sowing dates for each location, and the late sowing date was performed 15 days after the recommended sowing date.

regression coefficients different from 1 (Table 4; Table S2 for significant differences) and can be considered good cultivars for favorable and unfavorable environments, respectively. The latest released genotypes, Bacorehuis F2015, Barobampo C2015, CONASIST C2015, Borlaug100 F2014, along with Anatoly C2011 (Table 4) met the previously defined requirements of a reliable (stable) genotype (Annicchiarico, 2002). All the durum cultivars showed regression coefficients from the environmental index statistically similar to $b_i = 1$ (Table 4) which means they were stable.

The GGE analyses allowed visualization of the best genotype for each environment (Yang et al., 2009) (Figure 4) as well as for identification of the most stable genotype (Yan, 2001) (Figure 4). The percentage of the total sum of squares explained by PC 1 and PC 2 of the GGE model was 54% and the biplot was divided into six sectors delimited by gray dotted lines in Figure 4 (S1–S6). The 29 environments were grouped in sectors S1, S4, S5, and S6, vectors for northwest and central regions were located in sector S5 and north region vector was located in sector S6. TE 1 (full irrigation with optimum sowing date) was distributed in sectors S1, S4, S5, and S6, TE 2 (reduced irrigation with optimum sowing date) in sectors S5 and S6, TE 3 (optimum irrigation with late sowing date) in sectors S4 and S5, and TE 4 (reduced

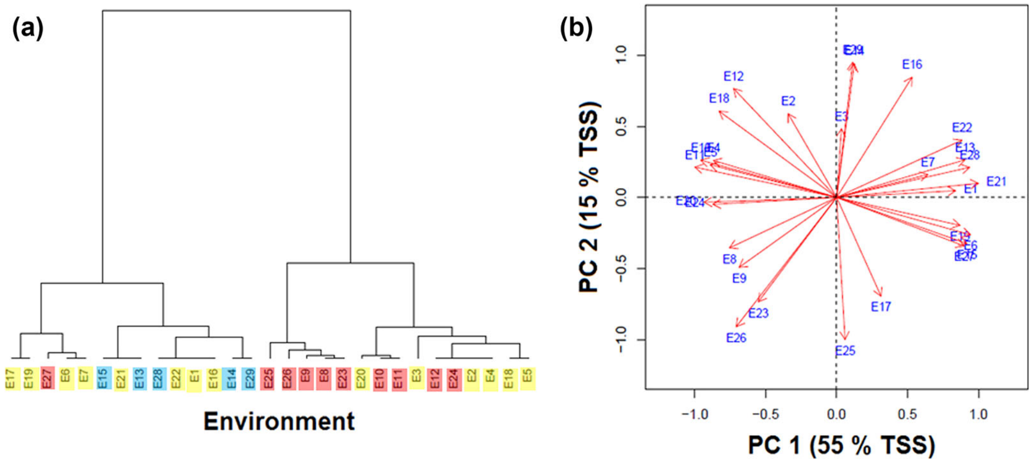

FIGURE 3 Clustering of trials (a) dendrogram (northwest in yellow, north in blue, and central in red) and (b) biplot using the two principal components for environments clustering according to their genetic correlation. See Table 2 for trial code.

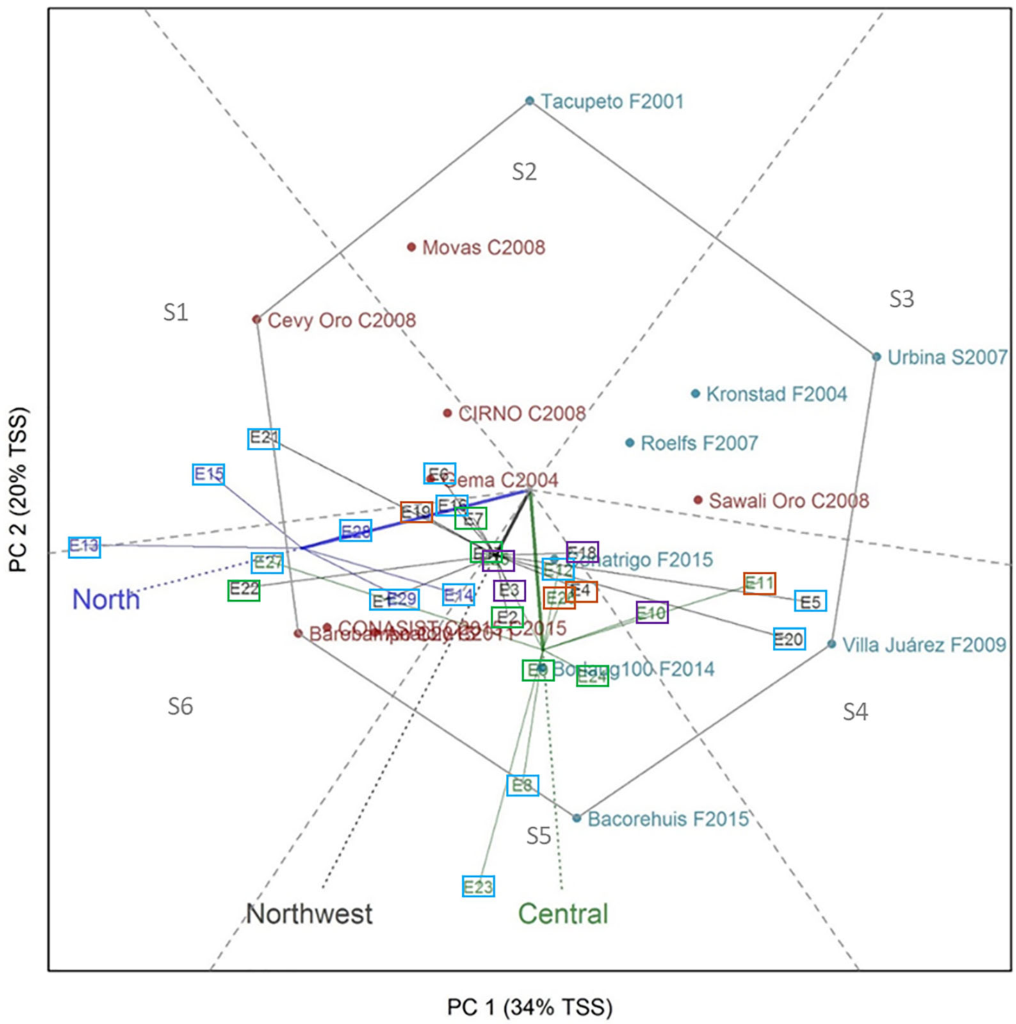

FIGURE 4 Which-won-where biplot with a polygon view obtained from the first two principal components (PC 1 and PC 2) for grain yield of bread (blue) and durum (red) wheat established during winter-spring of 2012/2013 and 2013/2014 at north (blue navy), northwest (black), and central (green) Mexico. Blue, green, purple, and red squares indicated testing environments (TEs) 1, 2, 3, and 4, respectively. See Table 2 for trial code and TEs. TSS, total sum of squares.

TABLE 3 Variation for individual environment variance components, broad-sense heritability, grain yield means, and coefficient of variation in 29 environments

	Variance components				
Trial	**Genotype**	**Residual**	**Heritability**	**Grain yield mean (ton ha^{-1})**	**Coefficient of variation (%)**
E1	0.239*	0.178	0.72	7.95	5.30
E2	0.149*	0.158	0.65	5.58	7.10
E3	0.218***	0.044	0.90	6.69	3.10
E4	0.560	0.110	0.48	4.67	7.35
E5	0.490	0.820	0.54	8.30	10.92
E6	0.850	0.140	0.54	5.82	6.51
E7	0.080	0.140	0.54	5.82	6.51
E8	0.370*	0.340	0.69	3.95	14.83
E9	0.190	0.330	0.54	2.64	21.61
E10	0.230**	0.130	0.79	3.65	9.77
E11	0.370	0.050	0.93	2.12	10.99
E12	0.030	0.240	0.22	2.52	19.30
E13	0.510	1.620	0.39	5.48	23.21
E14	0.180	0.470	0.44	3.28	21.01
E15	0.480	0.690	0.58	3.59	23.15
E16	0.030	0.460	0.12	5.20	13.09
E17	0.030	0.190	0.27	4.59	9.48
E18	0.040	0.110	0.44	4.53	7.39
E19	0.150*	0.100	0.75	5.06	6.37
E20	0.270	1.310	0.30	7.74	14.76
E21	0.300*	0.220	0.74	6.13	7.63
E22	0.480	0.570	0.63	5.45	13.86
E23	0.910	0.230	0.89	5.94	8.01
E24	0.020	0.550	0.09	4.82	15.38
E25	0.130	0.270	0.50	4.58	11.31
E26	0.140*	0.130	0.69	3.94	9.16
E27	0.460	0.680	0.58	5.78	14.26
E28	0.250	0.290	0.63	3.52	15.35
E29	0.400*	0.41	0.66	4.43	14.50

Symbols *, **, and ***statistically significant with $p < 0.05$, < 0.01, and < 0.001, respectively.

irrigation with late sowing date) in sectors S4, S5, and S6.

The GGE biplot in Figure 4 indicated highest yielding genotypes located at the polygon vertices for each sector. Bacorehuis F2015 was the highest yielding cultivar for the northwest and central regions (sector S5), whereas Barobampo C2015 was the highest yielding cultivar in the northern region (sector S6). Villa Juarez F2009 was the highest yielding cultivar in the sector S4 and Cevy Oro C2008 was the highest yielding in sector S1. Cultivars in vertices of sectors S2 and S3 had poor performances in most environments.

Another feature of the GGE analysis is the comparison of means versus stability (Figure 5) in which the red arrowed line indicates the average environment coordination (AEC) abscissa that points to the higher mean genotype. The dashed blue lines are the projection from the AEC coordinate, for which shorter lines mean higher grain yield stability (Yan et al., 2007). The results obtained corroborate the findings of the Eberhart and Russell (1966) stability analysis (Table 4) indicating that Conatrigo F2015, Roelfs F2007, and Gema C2004 are among the most stable cultivars given the short projection from the AEC ordinate. Barobampo C2015, CONASIST C2015, Anatoly C2011, Borlaug100 F2014, CIRNO C2008, Sawali Oro C2008, and Kronstad F2004 also had relatively short projection and therefore classified as stable. In Figure 5, Bacorehuis F2015 was also identified as the high yielding cultivar but was unstable. When comparing

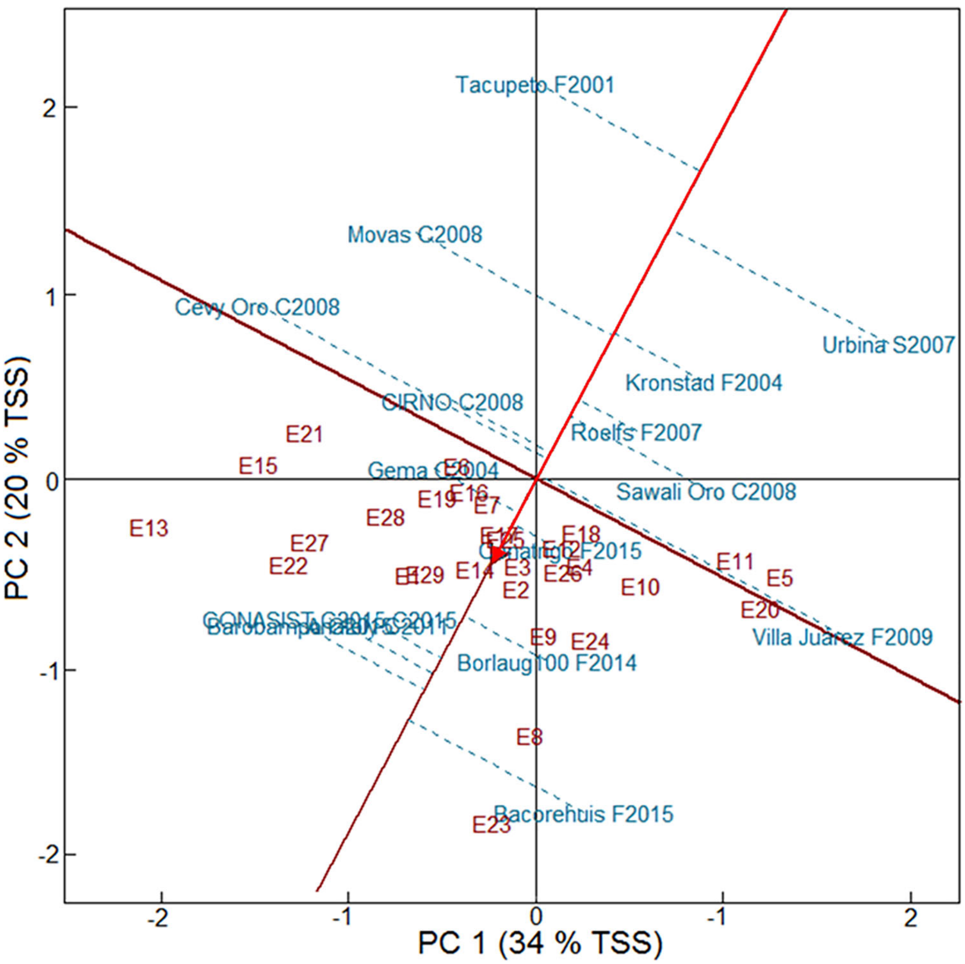

FIGURE 5 GGE biplot for stability versus grain yield obtained from the first two principal components (PC 1 and PC 2) for grain yield of bread and durum wheat established during winter–spring of 2012/2013 and 2013/2014 at the north, northwest, and central Mexico. See Table 2 for trial code. GGE, genotype and genotype by environment interaction; TSS, total sum of squares.

the number of stable genotypes, a greater number of durum wheat cultivars were stable compared to bread wheat with a frequency of six and four, respectively.

4 | DISCUSSION

Previous work has reported that bread wheat yields more in high-yielding potential conditions while durum wheat is more productive in marginal conditions (Marti & Slafer, 2014). However, further reports have shown that durum cultivars have superior performance in high-yielding conditions (full irrigation and/or optimal sowing date) and are similar to bread cultivars under marginal conditions (reduced irrigation and/or late sowing date) (Valenzuela-Antelo et al., 2018). In this section, our aim was to describe grain yield performance and stability of bread and durum wheat under different TEs in irrigated regions of Mexico.

When evaluating yield performance and stability, a differential expression of yield in different TEs in Mexico was found. In addition, the phenotypic plasticity, or magnitude of response was different depending on the genotype. Studies have shown that higher yield stability is due to greater responsiveness or plasticity, attributed to the ability of some genotypes to modulate yield components (Cossani et al., 2011; Sadras & Slafer, 2011). In both bread and durum wheat, the two major yield components that affect yield stability are the number of grain per m^2 and grain size (Marti & Slafer, 2014). These authors showed that bread wheat tends to have higher grain per meter square, whereas durum tends to has bigger grain. Interestingly, Lopes et al. (2012), found that the genetic gain in bread wheat elite lines from the CIMMYT was linearly associated with increments in grain size. This linear association between high grain yield and grain size could be one of the reasons explaining similar stability for grain yield reported in the present study, as the tested

TABLE 4 Grain yield overall best linear unbiased predictor (BLUP) and stability parameters (b_i) (Eberhart & Russell, 1966) for bread and durum wheat cultivars

Cultivar	BLUP (ton ha^{-1})	Stability parameters (b_i)
Bread wheat		
Bacorehuis F2015	5.30a	1.00[a]
Borlaug100 F2014	5.14ab	0.87[a]
Conatrigo F2015	4.98bcd	1.01[a]
Villa Juarez F2009	4.95bcd	1.05[b]
Roelfs F2007	4.91cd	1.02[a]
Kronstad F2004	4.85de	0.92[a]
Tacupeto F2001	4.66ef	1.10[a]
Urbina S2007	4.57f	0.84[c]
Durum wheat		
Barobampo C2015	5.31a	1.10[a]
CONASIST C2015	5.14ab	0.91[a]
Anatoly C2011	5.13abc	1.04[a]
CIRNO C2008	4.97bcd	1.12[a]
Gema C2004	4.96bcd	0.89[a]
Cevy Oro C2008	4.90d	0.93[a]
Sawali Oro C2008	4.90d	1.22[a]
Movas C2009	4.76def	0.94[a]
Overall LSD$_{(0.05)}$	0.226	

Note: LSD (least significant difference, $p = 0.05$) for all the cultivars; within a cultivar, means not sharing a common letter are significantly different at $p = 0.05$.
[a]Stable genotypes ($b_i = 1$).
[b]Genotypes that perform better in favorable environments ($b_i > 1$).
[c]Genotypes that perform better in unfavorable environments ($b_i < 1$).

cultivars are the product of a INIFAP-CIMMYT breeding network (Villaseñor-Mir, 2015) that uses grain size as a primary trait for selection.

Given the similar yield responsiveness seen in this study, differences in yield components between bread and durum wheat in Mexico are lower than previously reported in other regions (Pfeiffer et al., 2001). In addition, similar grain yield stability could be the result of substantial breeding efforts made to improve spike fertility, which is a determinant factor that affects yield when genotypes are subject to different photoperiod and temperature regimes (Reynolds et al., 2012). Further work using defined genetic stocks and/or material developed for enhanced physiological parameters is required to dissect the drivers of the yield stability identified in this study.

Yield stability was determined using two methods: Eberhart and Russell (1966) stability parameters and GGE biplots. Both identified a similar set of stable cultivars, as has been previously reported (Alwala et al., 2010; Blanche et al., 2007). Concordance was found between sector groups in the "which-won-where biplot" and the dendrogram genetic correlations between trials. This highlights three points: first, the trials simulating TEs with a combination of irrigation level and sowing date (E1–E7 and E16–E22) in the three northwest region locations (Obregon, Mexicali, and Los Mochis) were highly diverse according to the GEI of the genotypes and correlated with other trials in other regions. Second, the TEs from the north and central regions tended to cluster together. Third, the which-won-where biplot showed a clear trend in the adaptation by wheat type with the durum cultivars tending to perform better in the northern environments, whereas the bread wheat cultivars performed well in the central region environments. Durum cultivars have dominated northwest wheat growing areas due to their great yield potential, resistance to Karnal bunt and rapid adoption of superior varieties by farmers (Fischer et al., 2022). These findings indicate that a relative low number of trials targeting the TEs used in this study in the northwestern region of Mexico are sufficient for the identification of high-yielding and stable cultivars. In contrast, TEs trials in the northern and central regions may maximize the identification of superior cultivars with local rather than broad adaptation.

The cultivars tested and analyzed in this study had outstanding performance across TEs and were the best performers in the ENTRI prior to their release (Villaseñor-Mir, 2015). This indicates that in most cases they have accumulated favorable alleles that permit them to respond consistently across environments. The analysis methods used in this study were useful to identify outstanding genotypes with high yield potential and stability to provide consistent productivity in Mexican wheat production environments. Moreover, regular studies should be conducted with updated germplasm relevant to producers over time.

5 | CONCLUSION

Overall, the bread cultivars Bacorehuis F2015 and Borlaug100 F2014, and the durum cultivars Barobampo C2015, CONASIST C2015, and Anatoly C2011 showed outstanding high-yielding in most environments and were stable depending on at least one methodology. These commercial cultivars were developed and released over different time periods, but all have been adopted and remain important for production in Mexico.

AUTHOR CONTRIBUTIONS

Jorge L. Valenzuela-Antelo: Conceptualization; data curation; formal analysis; investigation; methodology; writing–original draft; writing–review and editing. **Ignacio Benitez-Riquelme and Julio Huerta-Espino**: Supervision; writing–review and editing. **Mateo Vargas-Hernandez**: Formal analysis; supervision; writing–review and editing. **Alison R. Bentley**: Funding acquisition; writing–review and

editing. **Hector E. Villaseñor-Mir**: Conceptualization; funding acquisition; investigation; project administration; writing–review and editing. **Francisco J. Piñera**: Funding acquisition; supervision; writing–original draft; writing–review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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