Line x tester analysis to estimate combining ability in grain sorghum (*Sorghum bicolor* L.)

Análisis línea x probador para estimar la aptitud combinatoria en sorgo de grano (*Sorghum bicolor* L.)

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Abstract

Sorghum in Mexico ranks third in grain production. This study aimed to estimate general combining ability (GCA) and specific combining ability (SCA) for commercial and experimental sorghum grain parents and hybrids. The combining ability was estimated using the line x tester method described by Kempthorne. The experiment was established during the spring-summer 2018 cycle at INIFAP, Las Huastecas, México. It consisted of five lines, eight testers and 40 hybrids; in a randomized block design with three replications. The ANOVA showed highly significant differences for lines, testers, and line x testers, suggesting the existence of a broad base of genetic variability. GCA and SCA differences were statistically significant for grain yield, specific grain weight and plant height, indicating additive gene relevance, dominance and epistasis. For grain yield, the experimental lines: RB214A, RB225A and RB248A, and the testers RB133 and RB221, resulted significantly higher in GCA and superior to commercial RB225A line and RTx430 and RTx437 testers. Seventeen experimental hybrids were found to have significantly higher in SCA and were superior to INIFAP commercial hybrids.

Keywords
Sorghum bicolor L. • plant breeding • hybrids • parental lines • grain production

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Resumen

El sorgo en México ocupa el tercer lugar en producción de grano. El objetivo del estudio fue estimar la aptitud combinatoria general (ACG) y especifica (ACE) en progenitores e híbridos comerciales y experimentales de sorgo para grano. La aptitud combinatoria se estimó mediante el método de línea x probador descrito por Kempthorne. El experimento se estableció durante el ciclo primavera-verano 2018 en INIFAP, Huastecas, México. Consistió de cinco líneas, ocho probadores y 40 híbridos; en un diseño de bloques al azar con tres repeticiones. El ANOVA detectó diferencias altamente significativas para líneas, probadoras y línea x probador; sugiriendo la existencia de una amplia base de variabilidad genética. Para rendimiento de grano, peso específico de grano y altura de planta, la ACG y ACE, fueron significativas lo cual indica la relevancia de genes aditivos de dominancia y epistasis. Para rendimiento de grano las líneas experimentales: RB214A, RB225A y RB248A y, los probadores RB133 y RB221, fueron altamente significativos en ACG y fueron superiores a la línea RBSBA25 y los probadores RTx430 y RBTx437 comerciales. Se encontró diecisiete híbridos experimentales con diferencias significativas en ACE y fueron superiores que los híbridos comerciales del INIFAP.

Palabras clave

Sorghum bicolor L. • mejoramiento genético • híbridos • progenitores • producción de grano

Introduction

In México, sorghum [*Sorghum bicolor* (L.) Moench] is the third largest grain crop produced after corn, *Zea mays* (L.) and common bean, *Phaseolus vulgaris* (L.) (21). Tamaulipas is the main sorghum-producing state, contributing in 2017 with 2,205,000 tons of grain, equivalent to 45.45% of national production (1). However, this supply is not enough for the national demand, making it necessary to increase productivity (18).

The discovery of cytoplasmic male sterility by Stephens and Holland (1954), was of vital importance for the commercial production of hybrid seed, allowing significant production improvement (19). In the United States of America, 35% to 40% of total profit obtained in grain production, is attributed to this technology (4). In this sense, a successful hybridization program largely depends, on selecting the proper parental lines and knowing the different types of gene action (9). General combining ability (GCA) and specific combining ability (SCA) are key tools in plant genetic improvement (3, 15). The line x tester mating method for GCA and SCA determination suggested by Kempthorne (1957) is appropriate for parent and higher hybrid identification (7). In this context, using productive hybrid seed with enhanced environmental adaptation has been fundamental for obtaining higher yields. Available Mexican seed varieties provide job positions in production activities while reducing capital flight (26). In this sense, The Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP), Río Bravo Experimental Station, Tamaulipas, México, began working on genetic sorghum breeding in 1973, generating varieties and hybrids for northern México (28): RB-2000, RB-2020, RB-3030, RB-3006, RB-4000, RB-Patrón, RB-4040, RB-Huasteco, RB-Norteño; and RB-Paloma, RB-Gaviota, RB-Williams and Arcos varieties.

The objective of this study was to estimate general combining ability (GCA) effects for females and males, and specific combining ability (SCA) effects for grain sorghum hybrids, identifying high-yield hybrids with earliness and adequate harvest height.

Materials and methods

The Genetic material considered in this study comprised the commercial lines: A/B: SBA12/SBB12, parents of RB-3030; SBA25/SBB25 parents of RB-4000, RB-Patron and RB-Huasteco hybrids. R Lines (testers): RTx430 (11) and RTx437 (17), originated at Texas

A&M University. INIFAP experimental lines A/B: RB214A/RB214B, RB225A/ RB225B, RB248A/RB248B, and testers: RB128, RB133, RB135, RB221, RB256 and RB373. These genotypes were generated by hybridization in 2003. Maintainer lines were generated from SBB-25, parent of RB-Patrón hybrid (27), LRB-118B, parent of RB-4040 hybrid (25) and VAR-B, generated by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India. Experimental testers were generated from crosses between RTx437, LRB-210 and SBR-24. RTx437, originated in Texas A&M University (16); LRB-210, parent of RB-4040, INIFAP hybrid (24); SBR-24, parent of RB-4000 INIFAP hybrid. In F2 generations, row by panicle selection or pedigree was performed along five generations for large panicle length, higher grain volume, plant height, non-senescent plant, charcoal rot tolerance [*Macrophomina phaseolina* (Tassi) Goid], Head smut [*Sporisorium reilianu* (Kühn)] Langdon and Fullerton, and foliar diseases. In Marin Experimental Station, Marin, Nuevo León, México, Universidad Autónoma de Nuevo León (UANL), from 2010 to 2017, the described selection process continued while sterilization of best maintainer lines (B) was carried out, by 7 generations backcrosses.

The genetic material was increased at the mentioned Experimental Station, during spring-summer 2017 and fall-winter 2017-2018. A and B lines and R were increased, and F1 hybrids were developed under line × tester (5 × 8) crossing scheme. The experiment was established under rain-fed conditions during the spring-summer 2018 in INIFAP, Las Huastecas Experimental Station, located at Altamira municipality, Tamaulipas, Mexico; 22°33' LN/ 98°09' LW, and 20 m above sea level. It has a warm sub-humid climate (Aw0) with summer and winter rain (5); average annual temperature of 24.5°C and 842 mm annual rainfall (6). This experiment consisted of 40 possible hybrid combinations, including INIFAP´s commercial hybrids; RB-3030, RB-Patrón and RB-Huasteco, five fertility maintaining lines, eight testers and the commercial hybrids Pioneer P83P27 and P85P20. The B lines or fertility-maintaining lines were used to determine maternal *per se* performance.

The experimental design was a randomized block with 55 treatments and three replications, distributed in a one-row plot of 5 m long and 0.80 m apart. Sowing was on August 15, 2018. Fertilization was 90-40-00 with triple superphosphate and ammonium nitrate. Thinning was done 20 days after emergence leaving a population of 250 thousand plants ha^{-1}. Weed control was carried out at 10, 20 and 25 days after plant emergence. The yellow aphid [*Melanaphis sacchari* (Zehntner)] was controlled with Toreto (Sulfoxaflor) 21.8% at a dose of 0.06 l ha^{-1}.

Days to flowering (DF) were observed at 50% flowering. One week before physiological maturity, the following traits were measured: plant height (PH, in cm, from the ground to the panicle apex), panicle length (PL, in cm, from the base to the apex), and exertion length (EL, in cm, from the ligule of the flag leaf to base panicle). The entire plot was harvested and threshed. Then, grain moisture was determined, estimating grain yield (GY). Results were reported in t ha^{-1} (GY, at 12% moisture) and specific grain weight (SGW, in kg per hectoliter). Line × Tester analysis was done according to Kempthorne (8) estimating general combining ability (GCA) effects for females and males and specific combining ability (SCA) effects for hybrids. Statistics were carried out with R platform (16).

Results and discussion

The ANOVA (table 1, page 15), revealed highly significant differences ($p \leq 0.01$) between parents and hybrids for all traits. In this regard, Mohammed (2009) found similar results in forage sorghum for days to flowering and plant height. In parents x hybrids, highly significant differences were observed in DF, PH, PL and GY variables, while significant differences resulted for EL. In lines x tester, highly significant differences were observed in DF and PH, while significant differences were found in GY. Likewise, highly significant differences in EL and PL were found for treatments, parents, crosses and lines. Results indicate a broad base of genetic variability among the used germplasm, favoring an appropriate selection of parents and hybrids.

SGW: specific grain weight (kghl^{-1}); DF: days to flowering; PH: plant height (cm); EL: exertion length (cm); PL: panicle length (cm); and GY: grain yield (kgha^{-1}). C.V.; coefficient of variation (%). *, **: Significant at 0.05 and 0.01% probability levels, respectively.

SGW: peso específico del grano (kg hl^{-1}); DF: días a floración; PH: altura de planta (cm); EL: longitud de excersión (cm); PL: longitud de panícula (cm); y GY: rendimiento de grano (kg ha^{-1}). C.V.: coeficiente de variación (%). *, **: Significativo al nivel de 0,05 y 0,01% de probabilidad, respectivamente.

Table 1. Line x tester ANOVA for agronomic traits. INIFAP, Las Huastecas Experimental Station, Altamira, Municipality, Tamaulipas, México. 2018, Spring-Summer cycle.

Tabla 1. Análisis de varianza por el método de línea x probador de las variables agronómicas. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

Source	D. F.	SGW (kg/hl^{-1})	DF (days)	PH (cm)	EL (cm)	PL (cm)	GY (kg/ha^{-1})
Replications	2	2832.31	32.96*	345.82*	37.09*	398.35**	5446408**
Treatments	53	5794.01**	32.45**	1605.31**	22.41**	32.42**	5837857**
Parents	13	11821.49 **	31.23**	1246.35**	28.15**	37.75**	5279849**
Parents x crosses	1	51.82	205.91**	25055.93**	47.78*	704.26 **	74015669**
Crosses	39	3932.08**	28.41**	1123.67**	19.85**	13.42**	4275711**
Lines	4	15762.24**	130.86**	1155.88**	58.68**	42.90**	5378067**
Testers	7	6652.71**	63.54**	4298.37**	39.26**	26.71**	14027875**
Lines x testers	28	1561.90	4.99**	325.39**	9.45	5.89	1680190*
Error	109	1656.18	9.44	98.58	9.99	8.45	1068553
C.V.		5.9	5.07	5.7	26.61	11.6	22.8

General combining ability (GCA) in lines (table 2), showed four out of five lines with significant values (p≤0.01) for GY, of which three corresponded to experimental lines. For SGW, PH and PL, three out of five lines showed high GCA values. For GY, genotypes RB214A, RB225A, RB248A and SBA-25 showed highly significant values (p≤0.01). In addition, the experimental line RB225A presented highly significant values for SGW, DF, PH and EL. For PH, negative GCA values are desirable (9), given that low-PH sorghums are preferred. The reason for the commercial line SBA-25 showing a positive GCA value for GY, in contrast to SBA-12, (which showed a negative value), was due to possible differences in obtention periods, around the '90s (13) and '50s (28), respectively. Thus, in the first line, more recently created, greater recombination and genetic advance were achieved. The agronomic traits showing predominant general combining ability, respond to present additive genes. Zewdie *et al.* (2001), working with hot pepper, and Khan *et al*. (2009) with sunflower, suggested that for this type of predominating genes, recurrent reciprocal selection allows good genetic improvement.

SGW: specific grain weight (kg hl^{-1}); DF: days to flowering; PH: plant height (cm); EL: excertion length (cm); PL: panicle length (cm); and GY: grain yield (kg ha^{-1}). *, **: Significant at 0.05 and 0.01% probability levels, respectively.

SGW: peso específico del grano (kg hl^{-1}); DF: días a floración; PH: altura de planta (cm); EL: longitud de excersión (cm); PL: longitud de panícula (cm); y GY: rendimiento de grano (kg ha^{-1}). *, **: Significativo al nivel de 0,05 y 0,01% de probabilidad, respectivamente.

Table 2. Estimates of general combining ability (GCA) in lines for agronomic traits in INIFAP, Las Huastecas Experimental Station, Altamira, Municipality, Tamaulipas, México. 2018, Spring-Summer cycle.

Tabla 2. Valores estimados de los efectos de aptitud combinatoria general (ACG) en líneas, para las variables agronómicas. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

Lines	SGW (kg/hl^{-1})	DF (days)	PH (cm)	EL (cm)	PL (cm)	GY (kg/ha^{-1})
RB214A	-22.275	0.300	6.467**	0.250	0.992**	264.575**
RB225A	29.392**	3.300**	4.133**	2.375**	-0.300	346.117**
RB248A	6.933**	-0.158	2.800**	0.125	0.742**	185.283**
SBA-12	16.642**	-3.283	-10.950	-1.000	-2.217	-819.550
SBA-25	-30.692	-0.158	-2.450	-1.750	0.783**	23.575**

The GCA for GY (table 3), in the genotypes RB133, RB221 and RTx430, was highly significant and higher than commercial RTx437, which presented a negative response. For GSW, four out of eight testers presented positive and highly significant values of GCA.

Table 3. Estimates of general combining ability (GCA) in testers for agronomic traits. INIFAP, Las Huastecas Experimental Station, Altamira, Municipality, Tamaulipas, México. 2018, Spring-Summer cycle.

Tabla 3. Efectos de aptitud combinatoria general (ACG) estimada para las variables agronómicas en los probadores. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

Tester	SGW (kg hl^{-1})	DF (days)	PH (cm)	EL (cm)	PL (cm)	GY (kg ha^{-1})
RB128	9.542**	-0.292	-10.292	0.792**	-0.683	-213.792
RB133	4.475**	0.042	4.508**	0.525*	2.383**	811.275**
RB135	-38.992	2.708**	-4.358	-2.542	-0.683	-328.192
RB221	30.342**	3.108**	40.375**	-2.075	1.517**	1678.808**
RB256	-12.458	-2.292	-8.625	0.258	-0.150	-805.925
RB373	17.608**	0.242	-7.692	2.458**	-1.750	-1452.525
RTx430	-9.258	-1.025	-6.692	-0.142	0.050	388.475**
RTx437	-1.258	-2.492	-7.225	0.725**	-0.683	-78.125

SGW: specific grain weight (kg hl^{-1}); DF: days to flowering; PH: plant height (cm); EL: excertion length (cm); PL: panicle length (cm); and GY: grain yield (kg ha^{-1}). *, **: Significant at 0.05 and 0.01% probability levels, respectively.

SGW: peso específico del grano (kg hl^{-1}); DF: días a floración; PH: altura de planta (cm); EL: longitud de excersión (cm); PL: longitud de panícula (cm); y GY: rendimiento de grano (kg ha^{-1}). *, **: Significativo al nivel de 0,05 y 0,01% de probabilidad, respectivamente.

Specific combining ability (SCA) for GY in table 4 (page 17), shows 17 experimental highly significant hybrids ($p \leq 0.01\%$), while INIFAP´s commercial hybrids, RB-3030, RB-4000 and RB-Huasteco, presented a negative response. Positive effects of SCA, indicate dominant and epitasis genes. On the other hand, genotypes presenting negative values show parental unfavorable combinations. The SCA importance for sorghum GY has already been reported (3, 23, 24). For SGW, half the hybrids showed highly significant differences, indicating non-additive gene importance. Regarding PH, 11 hybrids resulted highly significant and 11 significant.

This turns favorable for hybrid selection considering suitable plant height. DF, PL and EL, showed few significant differences.

Table 5 (page 18) shows proportional line contribution and lines x tester for six agronomic traits. Lines played an evident role in SGW (41.11%) and DF (47.24%), indicating maternal predominance. Testers showed more influence in DF (40.14), PH (68.65%), EL (35.49%), PL (35.71%) and GY (58.88%). Previously, Mohammed (2009), found the same results in forage sorghum for lines in green fodder and dry fodder production, while Pataki *et al*. (2007) found greater line influence on plant height.

A positive and significant correlation was found for grain yield ($p \leq 0.001$) and panicle length (figure 1, page 18), in coincidence with Makanda *et al*. (2010) and Bunphan *et al*. (2015). Williams *et al*. (2015) mentioned that the highest-yielding hybrids had higher panicle lengths. In addition, a significant correlation ($p \leq 0.001$) was also found for grain yield in kg ha^{-1} and plant height (Sarvari and Behesthi, 2012). This significant correlation between PH and PL is given by the fact that taller plants and greater panicle length are correlated with higher grain yield. A positive correlation was also found between SGW, PH, PL and GY.

Table 4. Estimation effects of specific combining ability (SCA) in agronomic traits. INIFAP, Las Huastecas Experimental Station, Altamira, Municipality, Tamaulipas, Mexico. 2018, Spring-Summer cycle.

Tabla 4. Estimación de los efectos de aptitud combinatoria específica (ACE) en las variables agronómicas. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

Crosses	SGW (kg hl^{-1})	DF (days)	PH (cm)	EL (cm)	PL (cm)	GY (kg ha^{-1})
RB214A*RTx430	-37.325	0.233	-12.933	2.350**	-2.592	136.358**
RB225A*RTx430	8.342**	-1.767	-0.600	1.558	1.033	745.483**
RB248A*RTx430	35.467**	-1.308	-0.600	-1.858	-1.008	-269.350
SBA12*RTx430[1]	-22.908	0.483	12.483**	-1.733	0.283	-568.183
SBA25*RTx430[2]	16.425**	2.358*	1.650	-0.317	2.283**	-44.308
RB214A*RTx437	-19.992	-0.967	-6.733	-0.183	0.808	314.292**
RB225A*RTx437	30.342**	0.033	3.600**	-1.308	-0.567	-437.583
RB248A*RTx437	-18.533	0.492	5.267**	-0.725	0.725	410.917**
SBA12*RTx437	11.758**	0.617	-6.317	2.067*	-0.650	-223.250
SBA25*RTx437[3]	-3.575	-0.175	4.183**	0.150	-0.317	-64.375
RB214A*RB128	-4.125	-0.167	-3.667	0.083	-0.192	-566.042
RB225A*RB128	10.875**	1.833*	4.333**	2.958**	0.433	-5.250
RB248A*RB128	6.667**	-0.042	-1.667	-1.125	1.058	511.250**
SBA12*RB128	0.958	-0.917	2.417*	-1.000	0.017	704.750**
SBA25*RB128	-14.375	-0.708	-1.417	-0.917	-1.317	-644.708
RB214A*RB133	20.942**	-0.500	1.867*	1.017	0.742	-184.108
RB225A*RB133	13.275**	-1.167	0.200	-1.108	0.700	1415.350**
RB248A*RB133	1.067	-0.375	-3.800	-0.192	0.325	-1180.817
SBA12*RB133	-39.308	2.417*	-3.717	0.600	-1.717	-596.650
SBA25*RB133	4.025**	-0.375	5.450**	-0.317	-0.050	546.225**
RB214A*RB135	16.408**	0.833	37.733**	0.083	1.475	1000.692**
RB225A*RB135	-16.592	0.833	-17.600	-2.042	-1.900	-279.517
RB248A*RB135	-6.133	-1.042	2.067*	0.875	2.392**	231.317**
SBA12*RB135	14.825**	-1.583	-6.517	1.000	0.017	534.150**
SBA25*RB135	-8.508	0.958	-15.683	0.083	-1.983	-1486.642
RB214A*RB221	13.742**	0.767	0.000	0.950	-1.392	-427.642
RB225A*RB221	-30.258	0.100	-4.667	-2.842	0.900	-402.183
RB248A*RB221	-27.133	1.892*	1.333	0.075	-2.142	-514.350
SBA12*RB221	24.158**	-2.317	-2.917	0.533	0.817	-121.183
SBA25*RB221	19.492**	-0.442	6.250**	1.283	1.817*	1465.358**
RB214A*RB256	-9.458	-0.500	-4.333	-3.383	0.942	77.758**
RB225A*RB256	8.875**	-0.500	2.667**	0.492	-1.100	-381.783
RB248A*RB256	-2.000	0.958	-3.000	3.075**	-0.142	-297.950
SBA12*RB256	26.958**	1.417	6.083**	0.867	0.817	265.883**
SBA25*RB256	-24.375	-1.375	-1.417	-1.050	-0.517	336.092**
RB214A*RB373	19.808**	0.300	-11.933	-0.917	0.208	-351.308
RB225A*RB373	-24.858	0.633	12.067**	2.292**	0.500	-654.517
RB248A*RB373	10.600**	-0.575	0.400	-0.125	-1.208	1108.983**
SBA12*RB373	-16.442	-0.117	-1.517	-2.333	0.417	4.483**
SBA25*RB373	10.892**	-0.242	0.983	1.083	0.083	-107.642

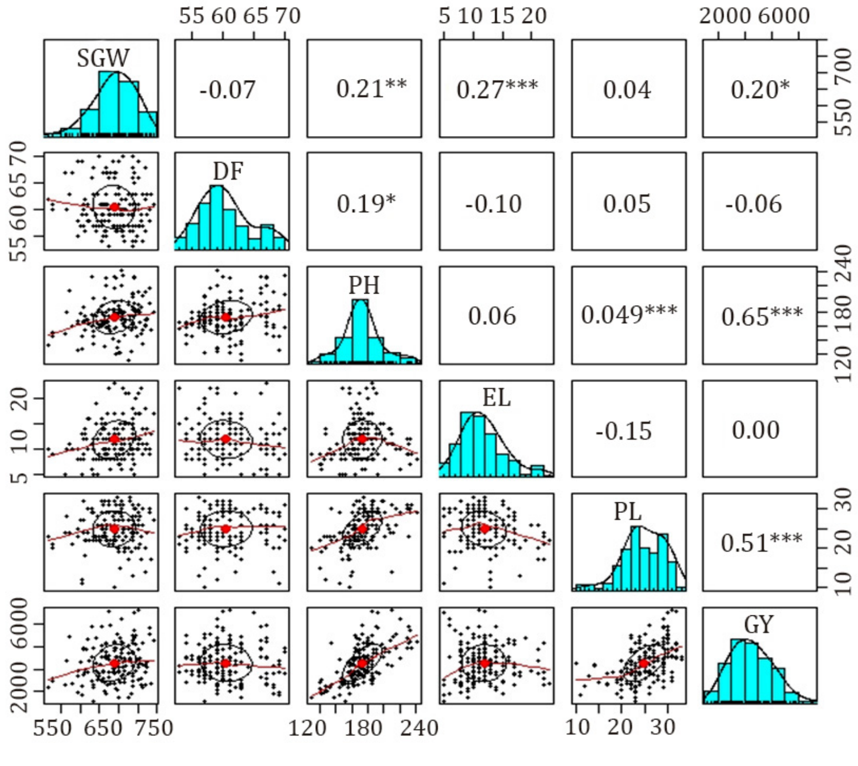
SGW: specific grain weight (kg hl^{-1}); DF: days to flowering; PH: plant height (cm); EL: excertion length (cm); PL: panicle length (cm); and GY: grain yield (kg ha^{-1}). *, **: Significant at 0.05 and 0.01 % probability levels, respectively. [1]RB-3030. [2]RB-Patrón. [3]RB-Huasteco.

SGW: peso específico del grano (kg hl^{-1}); DF: días a floración; PH: altura de planta (cm); EL: longitud de excersión (cm); PL: longitud de panícula (cm); y GY: rendimiento de grano (kg ha^{-1}). *, **: Significativo al nivel de 0,05 y 0,01% de probabilidad, respectivamente.

Table 5. Contribution of Lines, testers, and lines x testers to the total variance in agronomic traits. INIFAP, Las Huastecas Experimental Station, Altamira, Municipality, Tamaulipas, México. 2018, Spring-Summer cycle.

Tabla 5. Contribución de las líneas, probadores y líneas x probadores en la varianza para las variables agronómicas estudiadas. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

	Contribution (%)		
Trait	**Lines**	**Testers**	**Line x tester**
Specific grain weight	41.11	30.36	28.51
Days to flowering	47.24	40.14	12.61
Plant height	10.50	68.65	20.79
Excertion length	30.31	35.49	34.19
Panicle length	32.77	35.71	31.15
Grain yield	12.90	58.88	28.21



SGW: specific grain weight (kg hl^{-1}); DF: days to flowering; PH: plant height (cm); EL: excertion length (cm); PL: panicle length (cm); and GY: grain yield (kg ha^{-1}). *, **, ***: Significant at 0.05, 0.01 and 0.001 % probability levels, respectively.

SGW: peso específico del grano (kg hl-1); DF: días a floración; PH: altura de planta (cm); EL: longitud de excersión (cm); PL: longitud de panícula (cm); and GY: rendimiento de grano (kg ha-1); *,**,***: Significativo al nivel de 0,05 y 0,01% de probabilidad, respectivamente.

Figure 1. Correlation coefficients between agronomic variables for hybrids and sorghum parents. INIFAP, Las Huastecas Experimental Station, Altamira Municipality, Tamaulipas, México. 2018, Spring-Summer cycle.

Figura 1. Coeficientes de correlación entre las variables agronómicas para híbridos y progenitores de sorgo. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

Table 6 shows the mean values of the best experimental and commercial hybrids for grain yield, ranging from 3941 to 8108 kg ha^{-1}, where SBA25xRB221 experimental hybrid showed more than 8,000 kg ha^{-1}. In this regard, Williams *et al*. (2015), conducted evaluations of experimental and commercial hybrids during three years in INIFAP, obtaining maximum grain yields of 6400 kg ha^{-1}, under favorable soil moisture and management conditions. Table 6 shows that 11 experimental hybrids resulted statistically equal ($p<0.05$) in grain yield to the commercial controls: Pioneer® P83P27 and P85P20, RB-Patrón and RB-Huasteco. Within this group, two experimental hybrids, SBA25xRB221 and RB225AxRB133, were superior to RB-3030 and seven other experimental hybrids. In both cases, parental lines showed highly significant values for GCA (table 2, page 15, and table 3, page 16) while the hybrids showed high SCA (table 4, page 17). Williams *et al*. 2015 indicated that tall plant hybrids usually present lodging problems, and difficult mechanical harvesting. Therefore, we considered the experimental hybrid SBA25xRB221, 225 cm high, not suitable for commercial planting. Hybrid height depends on parental GCA and hybrid SCA height (table 2, page 15; table 3, page 16, and table 4, page 17). We concluded that the experimental hybrid RB225AxRB133 showed the best grain yield and plant height combination.

For grain yield, some experimental lines, testers and hybrids turned out superior to commercial ones. For grain yield, specific grain weight and plant height, additive genes as well as dominance and epistasis genes resulted important. The general combining ability in lines was proportionally higher in genotype number for specific grain weight, plant height and grain yield than testers. Results indicated that experimental lines and testers are promising for hybrid development and breeding.

Table 6. Sorghum hybrids and tested agronomic traits. INIFAP, Las Huastecas Experimental Station, Altamira Municipality, Tamaulipas, México. 2018, Spring-summer cycle.

Tabla 6. Híbridos de sorgo y variables agronómicas evaluadas. INIFAP, Campo Experimental las Huastecas, Municipio de Altamira Tamaulipas, México, ciclo primavera-verano 2018.

GENEALOGY	GY (kg ha^{-1})	SGW (kg hl^{-1})	DF (days)	PH (cm)	EL (cm)	PL (cm)
SBA25xRB221	8108 a	708 a-e	62 a-h	225 ab	10 a-d	30 a
RB225AxRB133	7513 ab	736 a-d	62 a-h	190 c-f	14 a-d	29 a-c
RB225AxRB221	6563 a-c	718 a-e	66 a-d	221a-c	10 a-d	28 a-c
RB214AxRB221	6456 a-c	711 a-e	64 a-h	228 a	11 a-d	27 a-d
RB225AxTx430	6421 a-d	717 a-e	60 a-h	178 d-j	16 a-d	27 a-d
SBA25xRB133	6322 a-e	667 a-f	59 a-h	188 c-h	11 a-d	29 ab
RB248AxRB221	6290 a-e	699 a-e	65 a-g	225 ab	10 a-d	26 a-d
RB214AxRB135	5878 a-f	644 a-f	64 a-h	221 a-c	10 a-d	28 a-c
PioneerP83P27 (C)	5834 a-g	745 a-d	54 h	155 h-n	12 a-d	25 a-d
RB214AxRB133	5832 a-g	692 a-f	60 a-h	194 b-e	14 a-d	30 a
PioneerP85P20 (C)	5813 a-g	708 a-e	68 ab	189 c-g	10 a-d	26 a-d
RB214AxTx430	5730 a-g	620 c-f	59 a-h	168 e-l	15 a-d	25 a-e
SBA12xRB221	5679 a-g	760 ab	57 b-h	207a-d	10 a-d	26 a-d
RB-Patrón (C)	5308 a-h	665 a-f	61 a-h	173 e-k	10 a-d	29 ab
RB-Huasteco (C)	4822 a-h	653 a-f	57 c-h	175 d-k	11 a-d	26 a-d
RB-3030 (C)	3941 c-h	673 a-f	56 d-h	176 d-k	9 a-d	24 a-e

GY: grain yield (kg ha^{-1}), SGW: specific grain weight (kg hl^{-1}); DF: days to flowering; PH: plant height (cm); EL: excertion length (cm); PL: panicle length (cm); (C) Controls. Different letters (a, b, c) in each trait and within the same group denote statistical significance (Tukey; p=0.05).

GY: rendimiento de grano (kg ha^{-1}); SGW: peso específico del grano (kg hl^{-1}); DF: días a floración; PH: altura de planta (cm); EL: longitud de excersión (cm); PL: longitud de panícula (cm); (C): Controles. Literales diferentes (a,b,c) en cada variable y dentro del mismo grupo denotan significancia estadística (Tukey; p=0,05).

Conclusions

The results showed that general combining ability (GCA) and specific combining ability (SCA) were important for grain yield, grain-specific weight and plant height. For grain yield, the experimental lines RB214A, RB225A and RB248A, and the testers RB133 and RB221, resulted superior in GCA than commercial ones. Seventeen experimental hybrids were found to have better SCA than INIFAP commercial hybrids.

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