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Potential of Tropically-Adapted Exotic Acid Tolerance White Maize Donor Lines in Sub-tropical Breeding Programmes for Low pH Adaptation

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Abstract

Low pH in soils is attributed as the main contributor to the low yields characteristic in maize production regions of Angola. Here, eight white-kernel acid soil tolerant donor lines (ASTDLs) sourced from CIMMYT-Colombia (testers) were crossed with eight white elite lines adapted to the mid-altitude climatic conditions from CIMMYT-Zimbabwe, in order to identify donor lines, which can be potential sources of acid tolerance genes in breeding programmes in Angola. The two groups of parents were crossed using a line by tester (L×T) mating design, yielding 47 crosses with sufficient seed, which were evaluated alongside eight acid tolerant commercial hybrids, during the 2014-16 cropping seasons at nine sites, representing acid and non-acid soils in Angola and Zimbabwe. Effects of general combining ability (GCA) due to lines and testers, as well as specific combining ability (SCA) on grain yield were significant ($P < 0.05$) under acid soils. From the CIMMYT-Zimbabwe breeding programme, inbred lines identified as ZW1, ZW4 and ZW5 together with the CIMMYT-Colombia ASTDLs (*i.e.*, CW4 and CW8) seemed to be ideal parents for crosses that can do well under both the acid and non-acid soils. The best specific cross for acid soils was identified as ZW1 × CW8 (CH142512), whereas for non-acid soils, ZW3 × CW4 (CH142500) was identified. Interestingly, the cross ZW1 × CW8 was also observed as stable under both acid and non-acid soil conditions. Overall, data showed potential of exotic acid tolerance donor lines for enhancing low-pH adaptation in sub-tropical maize populations.

Keywords: Acid soil, white maize, combining ability, genotype, acid soil tolerant donor lines (ASTDLs)

1. Introduction

In Angola, maize is a very important food and nutritional security crop but it is also key in livestock production systems as a source of feed. The maize crop is cultivated across the whole country, but production is much more pronounced in the high and mid-altitude zones, which receives rainfall averaging 800-1200 mm, annually. However, maize productivity is very low across the whole country, with yields averaging 0.7-1 t ha^{-1} being reported (MINAGRIF, 2020) and this phenomenon requires maize breeders in the country to come up with tangible solutions that can be implemented to promote food and nutrition security at household and national level. Globally, soil acidity is a huge problem, limiting crop production on 30-40% of the world's arable land, and causing yield losses of up to 70% (Haug, 1983) and up to 60% in many African countries (Dewi-Hayati et al., 2014; Tandzi et al., 2015, 2018), including Angola.

Strategies including, liming (Tandzi et al., 2015) and fallowing (Tonye et al., 1997; Mwangi et al., 2002) have traditionally been practiced to minimise effects of soil acidity. Although these technologies have proved to be effective, their application, especially use of lime is limited under smallholder farming systems which are dominated by resource-poor farmers (Thé et al., 2005). On the other hand, use of lime requires a lot of skill, which the majority of farmers does not have, and is not an economically and environmentally sustainable solution (Tandzi et al., 2015; Ndeke & Tembo, 2019). On the other hand, fallowing cannot be a viable solution under the predicted socio-economic scenarios where land size suitable for agriculture is expected to dwindle (Tonye et al., 1997). Due to the above reasons, developing crop varieties adapted to acid soil conditions remains the most viable and sustainable means to improve maize productivity.

Previous studies suggest existence of genetic variability for tolerance to acid soils in maize, which can be exploited in developing high-yielding, acid-tolerant maize genotypes (Tandzi et al., 2018). For example, a study in Cameroon showed that using adapted local inbred lines and crossing them with acid tolerant inbred lines from the International Maize and Wheat Improvement Centre (CIMMYT)-Colombia, could minimize grain yield losses due to soil acidity (Tandzi et al., 2015; Petmi et al., 2016). In Indonesia, evaluation of maize single-cross hybrids on acidic soils showed that several hybrids, which were progeny of crosses between acid soil tolerant or moderately acid soil-tolerant inbred lines, yielded reasonably high (Dewi-Hayati et al., 2014). Regardless of this warm evidence; potential of acid tolerant maize germplasm for boosting yields under acid soils has not yet been explored in Angola.

Unlike in other African countries, were people prefer either white or yellow maize, in Angola, the country can be divided into two product profiles based on taste preferences due to kernel colour. Almost half of the population prefer yellow maize, while the other half prefers white kernel maize (MINAGRIF, 2018). Due to this background, it is important to design breeding programmes that caters for the needs of these two distinct product profiles. With this in mind, exotic white acid donor inbred lines were sourced from CIMMYT-Colombia, which needed to be assessed for their combining ability with germplasm adapted to the mid-altitude climatic conditions, under acid and non-acid conditions in Angola. In addition, stability of the corresponding single-cross hybrids between the white acid donor lines and the elite white mid-altitude adapted lines under acid and non-acid conditions remains unexplored. Assessing the combining ability (both the GCA and the SCA) between these two groups of parental lines helps in identifying acid tolerant donor lines that can be potential sources of acid tolerance genes in breeding programmes within the mid-altitude climatic zones, including Angola. Also, potential crosses that can be used as pedigree starting populations for developing new inbred lines adapted to soil acidity and other stress factors common in Angola, can be identified. On the other hand, stability analysis will help in assessing and identifying crosses that can be targeted for commercial release. Therefore, the specific objectives of this study were: (i) to identify acid tolerance white maize donor lines that can potentially improve adaptation of mid-altitude adapted germplasm under acid and non-acid conditions; and, (ii) to identify high yielding local (CIMMYT-Zimbabwe) × exotic (CIMMYT-Colombia) hybrids with stable grain yield performance under acid and non-acid conditions. We hypothesised that the exotic white maize donor lines from CIMMYT-Colombia can contribute to improvement of maize productivity under both, acid and non-acid soil conditions in Angola.

2. Materials and Methods

2.1 Germplasm Description and F_1 Formation

A total of eight white-kernel acid soil tolerant donor inbred lines (ASTDLs) were sourced from the CIMMYT-Colombia breeding program in 2014. Four of these lines are classified into heterotic group A, while the rest were in heterotic group B. In the same year, white-kernel inbred lines adapted to the mid-altitude climatic conditions were sourced from the CIMMYT-Zimbabwe program. Six of these are classified in heterotic group A, whereas the rest are in heterotic group B (Table 1). A line × tester (L×T) design crossing nursery was established for these two groups of germplasm in Muzarabani (latitude 16°19′60″ S, longitude 31°10′0″ E), during the winter season (May-August) of 2014. In the crossing design, CIMMYT-Zimbabwe lines were used as female parents (lines), and the CIMMYT-Colombia ASTLs as male parents (testers) (Table 1). The L×T nursery yielded a total of 64 F_1s, but 17 of them were discarded because they did not have sufficient seed for multi-environmental trial evaluations (Table 2).

Table 1. Lines and testers used in developing single cross hybrids

#	Code	Origin	Parental category	Heterotic group
Lines				
1	ZW1	Zimbabwe	Line	A
2	ZW2	Zimbabwe	Line	A
3	ZW3	Zimbabwe	Line	B
4	ZW4	Zimbabwe	Line	A
5	ZW5	Zimbabwe	Line	A
6	ZW6	Zimbabwe	Line	B
7	ZW7	Zimbabwe	Line	A
8	ZW8	Zimbabwe	Line	A
Testers				
1	CW1	Colombia	Tester	B
2	CW2	Colombia	Tester	B
3	CW3	Colombia	Tester	B
4	CW4	Colombia	Tester	A
5	CW5	Colombia	Tester	A
6	CW6	Colombia	Tester	A
7	CW7	Colombia	Tester	A
8	CW8	Colombia	Tester	B

2.2 F_1 Hybrid Evaluation and Sites Description

The 47 L×T crosses which had sufficient seed for evaluation across nine sites (Table 2), were evaluated alongside eight commercial check hybrids at nine locations in Zimbabwe and Angola (Table 3), thereby making a total of 55 hybrids per trial (Table A1). Trials were established during the 2014-16 cropping seasons under acid and non-acid conditions. Sites with sandy soils, but with a historic record of receiving normal to above normal rains, and those known to be acidic (such as low P and low pH) were chosen as acid soil sites. On the other hand, optimal and random stress sites were classified as non-acid sites. Briefly, low P sites were those where non-leguminous crops were repeatedly grown without use of phosphate fertilizers, and crop residues were removed from the field immediately after harvesting. Optimal sites were those where the crop was subjected to all the recommended agronomic measures including fertilization and supplemental irrigation during water-deficit periods. These sites also occurred naturally in environments where the climatic conditions are suitable for maize production. The random stress sites were those where chances of mid-season drought were close to 100% during the rainy season and if drought occurred, no supplemental irrigation was given. These sites represented the real conditions to which maize is subjected in the small-scale farming sector, where most of the crop production is done in many countries in Africa.

Soil sampling was done at the beginning of the experiments. Samples were collected using the Horneck et al. (2011) method; from the top 30 cm of the soil profile at all the nine sites. Six soil samples were collected per site, and were bulked. A representative sub-sample from the bulked four samples collected in Angola was taken and submitted for chemical analysis at the Chianga Experimental Station soil laboratory of the Agricultural Research Institute (IIA). Similarly, representative samples from five bulk samples gathered in Zimbabwe were analysed. Samples were analysed for pH and available P, K, Ca and Mg (Table 3).

Table 2. Line × tester crosses developed between the CIMMYT-Zimbabwe white elite lines and the CIMMYT-Colombia ASTDLs

Entry	Hybrid name	Crosses	Entry	Hybrid name	Crosses
1	CH142471	ZW7 × CW1	25	CH142495	ZW5 × CW4
2	CH142472	ZW5 × CW1	26	CH142496	ZW4 × CW4
3	CH142473	ZW4 × CW1	27	CH142497	ZW1 × CW4
4	CH142474	ZW4 × CW8	28	CH142498	ZW2 × CW4
5	CH142475	ZW1 × CW2	29	CH142499	ZW8 × CW4
6	CH142476	ZW2 × CW1	30	CH142500	ZW3 × CW4
7	CH142477	ZW8 × CW2	31	CH142501	ZW6 × CW4
8	CH142478	ZW3 × CW1	32	CH142502	ZW7 × CW5
9	CH142479	ZW6 × CW1	33	CH142503	ZW5 × CW5
10	CH142480	ZW5 × CW3	34	CH142504	ZW4 × CW5
11	CH142481	ZW1 × CW3	35	CH142505	ZW1 × CW5
12	CH142482	ZW2 × CW3	36	CH142506	ZW2 × CW5
13	CH142483	ZW8 × CW3	37	CH142507	ZW8 × CW5
14	CH142484	ZW3 × CW3	38	CH142508	ZW3 × CW5
15	CH142485	ZW6 × CW3	39	CH142509	ZW6 × CW5
16	CH142486	ZW7 × CW7	40	CH142510	ZW7 × CW8
17	CH142487	ZW5 × CW6	41	CH142511	ZW5 × CW8
18	CH142488	ZW4 × CW7	42	CH142474	ZW4 × CW8
19	CH142489	ZW1 × CW7	43	CH142512	ZW1 × CW8
20	CH142490	ZW2 × CW7	44	CH142513	ZW2 × CW8
21	CH142491	ZW8 × CW7	45	CH142514	ZW8 × CW8
22	CH142492	ZW3 × CW6	46	CH142515	ZW3 × CW8
23	CH142493	ZW6 × CW7	47	CH142516	ZW6 × CW8
24	CH142494	ZW7 × CW4			

Table 3. Climatic, geographical and soil chemical characteristics of the top 30 cm of the soil profile at nine sites in Angola and Zimbabwe, used to evaluate 55 white hybrids during the 2014-2016 cropping seasons

Parameter	Angola				Zimbabwe			
	Chianga 1&2	SEDIAC	Chianga	Alto-Kapaka	CIMMYT Harare1	CIMMYT Harare2	Chibero	Marondera
	Low pH	Random stress	Optimal	Random stress	Optimal	Low P	Sandy soil	Sandy soil
Classification	Acid	Non-acid	Non-acid	Non-acid	Non-acid	Acid	Acid	Acid
Geographic Information System (GIS) position	S12º44′27″ E15º49′36″	S11º19′44″ E14º59′21″	S12º44′27″ E15º49′36″	S12º57′15″ E14º25′45″	S17º438′ E31º05′	S17º438′ E31º05′	S18º40′ E30º39′	S18º10′ E31º29′
Altitude (m.a.s.l)	1600	1400	1600	1300	1500	1500	1341	1617
Soil pH (H_2O)	4.75	5.90	6.05	5.76	5.80	5.40	-	5.10
Available P_2O_5 (ppm)	33.14	32.86	61.62	20.30	21.70	10.20	-	45.00
Potassium (ppm)	0.16	0.81	0.66	0.30	0.30	0.30	-	0.10
Calcium ($cmol_{(+)}$ kg^{-1})	0.20	4.42	3.19	1.37	8.10	5.10	-	1.00
Magnesium ($cmol_{(+)}$ kg^{-1})	0.09	0.62	2.36	0.74	3.80	2.50	-	0.50
Organic carbon (%)	1.20	1.99	2.89	1.51	Na	na		Na
Total N	0.07	0.14	0.22	0.09	Na	na		Na

Note. Chianga 1&2 = Chianga 1 and Chianga 2, Soil pH < 5.1; strongly acidic, 5.2-6.0; moderately acidic, 6.1-6.5 slightly acidic (Horneck et al., 2011).

2.3 Experimental Design and Trial Management

The 47 white hybrids (Table A1) were planted using an alpha (0, 1) lattice design (Patterson & Williams, 1996) with two replications at each site. Each replication accommodated a total of 11 incomplete blocks with a block size of five plots each. Randomization was done differently across replications and across sites. Each white hybrid was planted in a single row of 4 m length, having a uniform inter- and intra-row spacing of 0.75 m and

0.25 m, respectively. Two seeds were hand-planted on each hill, and later thinned to one plant on each hill, 3-5 weeks after crop emergence, in order to have an optimum plant population of 53,333 plants per hectare. Border rows were planted to avoid border effects. A total of 400 kg ha^{-1} of Compound D ($N_{12}P_{24}K_{12}$) was applied as basal dressing and 250 kg ha^{-1} of urea (NH_2; N = 46%) was split-applied as top-dressing fertilizer at all sites in Angola. In Zimbabwe, the same quantity of 400 kg ha^{-1} of compound D ($N_7P_{14}K_7$) was applied as basal dressing at most of the sites, except for the low P site. Ammonium nitrate (N = 34.5%) was split-applied as top-dressing at a rate of 400 kg ha^{-1} at the sites used in Zimbabwe.

2.4 Data Collection and Exploitation

Data collection followed the CIMMYT (1985) standard procedures. Grain yield (GY), was measured on a whole plot basis. Shelled grain weight per plot was adjusted to 12.5% grain moisture and converted to ton per hectare using the following formula:

$$\text{GY (t ha}^{-1}\text{)} = [\text{Grain weight (kg plot}^{-1}\text{)} \times 10 \times (100 - \text{MC})/(100 - 15)/(\text{plot area})] \qquad (1)$$

where, MC = grain moisture content; and, plot area = row length × 0.75 (4 × 0.75 = 3 m)

Across-site ANOVA was performed using the ‘aov’ function in the Agricolae R package. The treatments (crosses/hybrids) were considered as fixed. The model for combined ANOVA was:

$$Y_{ij(k)(l)} = b_j(r_k)(E_l) + r_k(E_l) + g_i + E_l + gE_{(il)} + e_{ij(k)} \qquad (2)$$

where, $Y_{ij(k)(l)}$ is the response of the ith genotype in the jth incomplete block nested within the kth replication nested in the lth environment; $b_jr_{(k)}E_{(l)}$ is the effect of the jth incomplete block nested in the kth replication also nested in the lth environment and j = 1, 2, 3, 4; $r_k(E_l)$ is the effect of the kth replication nested in the lth environment and k = 1, 2, 3; g_i is the effect of the ith genotype and I = 1, 2, 3, … 10; E_l is the effect of the lth environment and l = 1, 2, 3,...6; $gE_{(il)}$ is the interaction effect of the ith genotype and the lth environment; and $e_{ij(k)(l)}$ is the random error term.

Broad-sense heritability estimates, best linear unbiased estimators (BLUES), as well as genetic correlations between grain yield and the other agronomic traits were calculated using the Multi-Environment Trial Analysis with R (META-R) version 5.0 (Alvarado et al., 2015). Mean comparisons were performed using Fisher’s Protected Least Significance Difference (LSD) (Little & Hills, 1978) at 5% significance level. L×T crosses with superior grain yield performance, but harbouring other desirable agronomic traits that are of importance in the sub-tropical regions, were visualised on scatter plots using the ‘ggplot’ function in the ggplot2 R package (Wickham, 2016). Stability of the top performing crosses, selected within the A- and B-heterotic groups, was assessed using ranking, and Genotype-Genotype × Environment (GGE) Biplot in the GenStat Software, 17th Edition (Payne et al., 2009).

Preliminary data checking and individual site ANOVA were performed using CIMMYT Fieldbook software (Bänziger & Vivek, 2007). L×T analysis was performed for grain yield across the acid and non-acid sites, as well as for acid and non-acid sites, separately. The L×T procedures in the R software v3.0.1 (RDevelopmentCoreTeam, 2013), embedded in the CIMMYT Fieldbook software were followed. Briefly, the procedure uses functions in the lme4 (Chang, 2010; Bates et al., 2015, 2019), lattice (Deepayan, 2018) and matrix (Yau, 2016) R packages, to estimate GCA and SCA effects for lines and testers. The model for the combined sites L×T was as follows:

$$Y_{ijkp} = \mu + g_i + g_j + s_{ij} + E_p + r_k(E_p) + (gE)_{ip} + (gE)_{jp} + (sE)_{ijq} + e_{ijkp} \qquad (3)$$

where, i = 1, 2, 3, …10, j = 1, 2, 3,4, k = 1, 2, and Y_{ijkp} represented the value of the progeny of a mating of the ith CIMMYT-Zimbabwe elite white inbred line (*i.e.*, line), the jth CIMMYT-Colombia white acid soil tolerant donor line (*i.e.* tester), in the kth replication, and in the pth environment (site). The μ represents grand mean, g_i is the GCA effect common to all progeny of the ith line, g_j is the GCA effect common to all progeny of the jth tester, s_{ij} is the SCA effect specific to the progeny of mating the ith line and the jth tester, Ep is the average effect of the pth environment, $r_k(E_p)$ is the effect of the kth replication that was nested within the pth environment, $(gE)_{ip}$ and $(gE)_{jp}$ are the interactions between the GCA effects and the environment, $(sE)_{ijq}$ is the interaction between the SCA effect and environment, and e_{ijkp} is the random experimental error. This model was adopted from Lee et al. (2005).

The BLUEs were calculated following the procedures of Puntanen and Styan (2011) and the broad-sense heritability (H^2) estimates were calculated using the Multi-Environment Trial Analysis with R (META-R) software v5.0 (Alvarado et al., 2015). The following model was used to calculate H^2:

$$H^2 = \frac{\sigma^2 g}{\frac{\sigma^2 g}{re} + \frac{\sigma^2 ge}{e} + \sigma^2 p} \times 100 \quad (4)$$

where, $\sigma^2 g$ is genotypic variance, $\sigma^2 ge$ is genotype × environment variance, $\sigma^2 p$ is phenotypic variance, e represents sites and r represents the replications.

Mean comparisons were performed using the Fisher's Protected LSD (Little and Hills, 1978) at 5% significance level. To identify the best yielding, and stable crosses across the acid sites and across the non-acid sites, a stability coefficient method known as superiority performance, which calculates cultivar superiority indices according to Lin and Binns (1988), was performed in GenStat Software, 17th Edition (Payne et al., 2009). GCA and SCA of CIMMYT Zimbabwe and CIMMYT Colombia inbred lines involved in the highest grain yielding crosses under acid, non-acid and across acid and non-acid sites, were visualized using a scatter plot. The most stable, but high yielding L×T crosses under acid and non-acid soil conditions were also visualized using a scatter plot. The scatter plots were graphed using the 'ggplot' function in the ggplot2 R package (Wickham, 2016).

3. Results

3.1 F_1 Yield Performance on Individual Sites and Across Acid and Non-Acid Conditions

Significant ($p < 0.05$) genotype effects for GY were seen at four of the acid soil sites (Chibero, Marondera, Chianga1 and Chianga2) as well as at two non-acid soil sites (Chianga3 and Alto-Kapaca). Most of the acid soil types showed mean grain yields less than 3.5 t ha^{-1}, while the CIMMYT-Zimbabwe low P site, surprisingly had a mean GY of 8.82 t ha^{-1}, which was comparable to yields observed under an optimally managed site (Chinga3), which had a mean of 9.77 t ha^{-1} . Broad sense heritability (H^2) of above 10% was observed at most of the sites, except for SEDIAC (random stress management) and CIMMYT-Harare2 (low P management), which showed heritability of zero (Table 4).

Across acid soil sites; genotypic, GCA_{lines}, $GCA_{testers}$ and SCA effects for GY performance were significant. Similar results were observed for non-acid soils as well as for combined acid and non-acid soils. Significant genotype × site interaction effects were also noted for GY under acid and non-acid soil conditions and the same was seen in the combined trial analysis (Table 4).

Genotypic variance was more important than environmental variance under acid soil conditions and across the acid and non-acid soil conditions, but the opposite was true under non-acid conditions. Additive variances under the acid, non-acid, and combined conditions, were more important than dominance variance. Both H^2 and narrow-sense (h^2) heritability estimates were above 90% under acid soil conditions and across acid and non-acid conditions, but were lower under non-acid conditions (Table 5).

Table 4. Individual site analysis of variance for grain yield performance of the white CIMMYT-Zimbabwe elite lines × CIMMYT-Colombia ASTDLs, evaluated across nine sites in Zimbabwe and Angola during the 2014-16 cropping seasons

Location	**Management**	**Soil type**	**GY (t ha^{-1})**			**Error variance**	**Genotype variance**	**Heritability**	**$LSD_{0.05}$**
			Mean	**Min**	**Max**				
CIMMYT Harare1	Optimal	Non-acid	8.93	0.48	14.19	2.08	3.87	0.79	2.83
CIMMYT Harare2	Low P	Acid	8.53	5.05	14.38	2.80	0.97^{**}	0.41	3.28
Chibero	Sandy soil	Acid	2.47	0.13	7.11	0.70	0.70^{***}	0.67	1.64
Marondera	Sandy soil	Acid	2.82	1.26	5.23	1.95	0.00	0.00	2.74
SEDIAC	Random stress	Non-acid	3.05	1.75	4.45	0.53	0.15	0.36	1.42
Chianga1	Low pH	Acid	4.57	1.64	6.87	1.56	0.36	0.32	2.45
Chianga3	Optimal	Non-acid	6.74	0.51	13.61	8.64	1.80^{***}	0.29	5.76
Alto-Kapaca	Random stress	Non-acid	2.64	1.28	4.52	0.65	0.27^{**}	0.46	1.59
Chianga2	Low pH	Acid	1.86	0.41	3.74	0.41	0.25	0.55	1.25

Note. GY: Grain yield; Min: Minimum; Max: Maximum; LSD: Least significant difference; CV: Coefficient of variation. $^{***}p < 0.001$, $^{**}p < 0.01$.

Table 5. Grain yield L×T analysis of white CIMMYT-Zimbabwe elite lines × CIMMYT-Colombia ASTDLs crosses, evaluated at nine locations during the 2014-16 cropping seasons under acid and non-acid soil conditions in Angola and Zimbabwe

	Acid soil		**Non-acid soil**		**Across**	
	DF	MS	DF	MS	DF	MS
Replication (Site)	6	13.82***	3	0.33	9	9.24****
Site	5	633.81***	2	1110.36***	8	690.87***
Genotype	54	3.02***	45	6.25***	54	4.08***
GCA_{Line}	7	6.03***	7	7.41**	7	9.97***
$\text{GCA}_{\text{Tester}}$	7	4.84***	7	2.81	7	6.66***
$\text{SCA}_{\text{Line xTester}}$	31	2.80***	30	8.19***	31	3.66***
Genotype × Site	209	2.10***	75	4.42**	329	3.03***
GCA_{Line} × Site	35	2.63***	14	3.07	56	2.83***
$\text{GCA}_{\text{Tester}}$ × Site	35	3.42***	14	1.094	56	2.57***
SCA × Site	131	1.672**	45	5.00***	206	3.22***
Residuals	244	1.18	98	2.36	342	1.52
Line variance		5.09**		0.03		6.28**
Tester variance		118.89***		0		138.58***
Line × Tester variance		6.67**		0.17		6.822**
Genotype variance		119.63***		0.23		138.30***
Additive variance		478.51***		0.91		553.19***
Dominance variance		26.50*		0.68		27.29*
Environmental variance		8.06*		0.73		3.38
Broad sense heritability		0.98		0.69		0.99
Narrow sense heritability		0.93		0.39		0.95
Grand mean		3.58		5.02		4.04
LSD		2.01		3.01		2.34
CV		28.64		30.58		29.51

Note. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.5$. GCA: general combining ability; SCA: specific combining ability; LSD: Least significant difference; CV: coefficient of variation; Df: degrees of freedom; MS: mean squares.

3.2 The Best Grain Yield Performing CIMMYT-Zimbabwe Lines and CIMMYT-Colombia ASTDLs in Hybrid Combinations Under Acid and Non-Acid Soil Conditions

Making comparisons between the highest yielding five crosses (*i.e.*, experimental hybrids) with the five highest grain yielding commercial check hybrids, showed the potential of CIMMYT-Zimbabwe and CIMMYT-Colombia inbred lines in enhancing maize productivity under acid and non-acid soil conditions in Angola (Table 5; Figure 1). The five highest yielding crosses yielded more than the five highest yielding commercial checks under acid (average $\text{GY}_{\text{Experimental}} = 4.43$ t ha^{-1} > average $\text{GY}_{\text{Checks}} = 4.14$ t ha^{-1}); non-acid (average $\text{GY}_{\text{Experimental}} = 8.56$ t ha^{-1} > average $\text{GY}_{\text{Checks}} = 5.816$ t ha^{-1}); and combined acid and non-acid conditions (average $\text{GY}_{\text{Experimental}} = 4.87$ t ha^{-1} > average $\text{GY}_{\text{Checks}} = 4.60$ t ha^{-1}). The highest potential of the crosses was observed under non-acid soils where the two highest yielding crosses, *i.e.*, Entry 30 (CH142500; $\text{BLUE}_{\text{GY}} = 12.69$ t ha^{-1}) and Entry 26 (CH142496; $\text{BLUE}_{\text{GY}} = 9.35$ t ha^{-1}), significantly out yielded all the five highest yielding commercial checks.

To understand the parental contributions for high yields observed in some of the crosses, individual contributions of lines were evaluated (Table 6; Figure 1). It was seen that the CIMMYT-Zimbabwe white inbred lines: ZW1 ($\text{GCA}_{\text{acid}} = 0.421$; $\text{GCA}_{\text{non-acid}} = 0.28$); ZW4 ($\text{GCA}_{\text{acid}} = -0.011$; $\text{GCA}_{\text{non-acid}} = -0.475$); and, ZW5 ($\text{GCA}_{\text{acid}} = 0.071$; $\text{GCA}_{\text{non-acid}} = 0.256$), were involved as parents in the highest yielding experimental hybrids under both acid and non-acid soil conditions. On the other hand, the CIMMYT-Colombia ASTDLs involved as parents in the highest grain yielding genotypes were: CW4 ($\text{GCA}_{\text{acid}} = 0.263$; $\text{GCA}_{\text{non-acid}} = 0.571$) and CW8 ($\text{GCA}_{\text{acid}} = -0.405$; $\text{GCA}_{\text{non-acid}} = -0.059$) (Figure 1; Table 6).

The best CIMMYT-Zimbabwe elite line combiner under acid soil conditions was identified as ZW6 (GCA = 0.578) wheras under non-acid conditions, ZW8 (GCA = 0.49) was observed (Table A2). As for the CIMMYT-Colombia

ASTDLs, CW2 was prominent in hybrids under both soil conditions ($GCA_{acid} = 0.346$; $GCA_{non\text{-}acid} = 1.19$) (Table A3). The best specific cross for acid soil conditions was ZW1xCW8 (SCA = 0.927; $BLUE_{GY} = 4.34$ t ha^{-1}), and for non-acid soil conditions, it was ZW3 × CW4 (SCA = 11.90; $BLUE_{GY} = 12.69$ t ha^{-1}) (Tables A4 and A5).

Table 6. Grain yield performance (t ha^{-1}) of the top five crosses and their respective parental lines compared to the top five commercial check hybrids, under acid and non-acid soils and across the two soil conditions

#	Hybrid		Line	Tester	BLUE Grain yield	GCA		SCA
	Name	**Type**				**Line**	**Tester**	
					t ha^{-1}			
A. Acid soils								
34	CH142464	Experimental	ZY2	CY3	5.51	0.170	0.143	0.343
16	CH142446	Experimental	ZY1	CY1	4.86	0.018	0.170	0.645
24	CH142454	Experimental	ZY3	CY4	4.76	0.626	0.077	0.017
12	CH142442	Experimental	ZY7	CY1	4.74	0.093	0.170	0.456
14	CH142444	Experimental	ZY3	CY1	4.65	0.626	0.170	0.037
Average grain yield					4.81			
41	Check5	Check	-	-	5.85	-	-	-
42	Check6	Check	-	-	4.54	-	-	-
37	Check1	Check	-	-	4.28	-	-	-
38	Check2	Check	-	-	4.19	-	-	-
40	Check4	Check	-	-	4.18	-	-	-
Average grain yield					4.61			
B. Non-acid soils								
17	CH142447	Experimental	ZY2	CY1	7.01	0.636	0.053	1.439*
31	CH142461	Experimental	ZY3	CY3	6.65	0.680	-0.032	0.789
26	CH142456	Experimental	ZY1	CY4	6.53	0.636	0.075	0.532
4	CH142434	Experimental	ZY3	CY2	6.53	0.680	-0.032	0.579
3	CH142433	Experimental	ZY8	CY2	6.30	0.717	-0.032	0.313
Average grain yield					6.61			
39	Check3	Check	-	-	7.15	-	-	-
41	Check5	Check	-	-	6.77	-	-	-
38	Check2	Check	-	-	6.41	-	-	-
42	Check6	Check	-	-	6.40	-	-	-
37	Check1	Check	-	-	5.57	-	-	-
Average grain yield					6.46			
C. Across acid and non-acid soils								
31	CH142461	Experimental	ZY3	CY3	5.54	0.660	0.019	-0.147
17	CH142447	Experimental	ZY2	CY1	5.45	0.398	0.114	0.491
16	CH142446	Experimental	ZY1	CY1	5.41	0.318	0.114	0.383
4	CH142434	Experimental	ZY3	CY2	5.34	0.660	-0.206	0.288
12	CH142442	Experimental	ZY7	CY1	5.27	-0.021	0.114	0.586
Average grain yield					5.40			
Checks								
41	Check5	Check	-	-	6.26	-	-	-
42	Check6	Check	-	-	5.37	-	-	-
38	Check2	Check	-	-	5.19	-	-	-
39	Check3	Check	-	-	4.90	-	-	-
37	Check1	Check	-	-	4.85	-	-	-
Average grain yield					5.31			

Note. * $p < 0.05$. BLUE: best linear unbiased estimates.

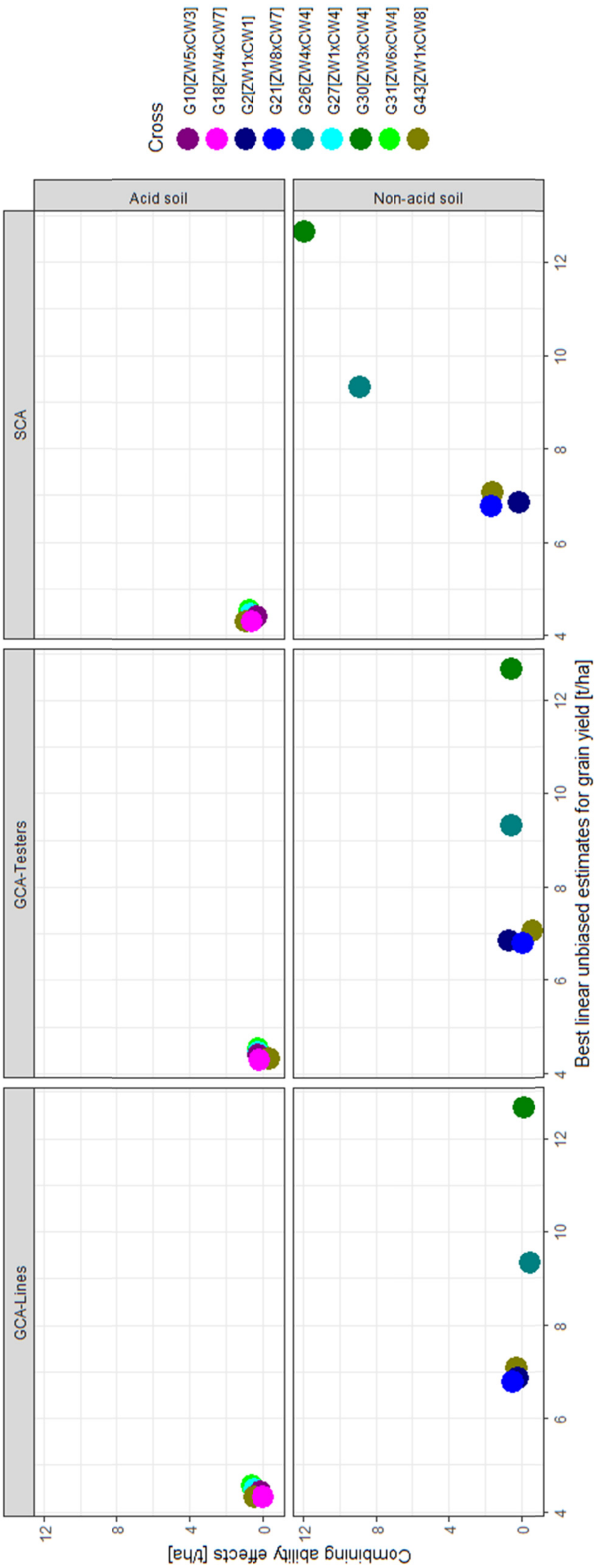

Figure 1. Best linear unbiased estimates for combining ability for grain yield performance (t ha^{-1}) of the top five crosses under acid and non-acid soils and across the two soil conditions (Puntanen & Williams, 2011)

3.3 Grain Yield Stability of the Five Highest Grain Yielding Crosses and Commercial Checks Under Acid and Non-Acid Soils

Cultivar superiority indices also revealed encouraging results. First, four experimental genotypes [Crosses: CH142480, entry 10 (Rank = 1); CH142497, entry 27 (Rank = 3); CH142501, entry 31 (Rank = 6); and, CH142512, entry 43 (Rank = 8)], out of the five selected as the best grain yielding genotypes under acid soil conditions (Table 5), were all ranked in the top 10 most stable genotypes. Similar results were observed under non-acid soil conditions, where crosses: CH142472, entry 2 (Rank = 10); CH142491, entry 21 (Rank = 7); CH142500, entry 30 (Rank = 1.5); and, CH142512, entry 43 (Rank = 9), all appeared in the top 10 most stable genotypes group. It was interesting to note that only one check (Check5, entry 52; GY_BLUE = 4.54 t ha^{-1}; Rank = 4) ranked amongst the top 10 most stable genotypes under acid soils. On the other hand, under non-acid soils, only two check genotypes, entry 49 (GY_BLUE = 6.24 t ha^{-1}; Rank = 3) and entry 51 (GY_BLUE = 6.23 t ha^{-1}; Rank = 8), ranked in the top 10 most stable genotypes (Figure 2; Table 7).

Table 7. Mean grain yield and cultivar superiority indices for the top five crosses and commercial checks under acid and non-acid soils

#	Genotype			GY_BLUE	Cultivar superiority indices (CSI)	Rank
	Name	Cross	Type			
				t ha^{-1}		
A. Acid soils						
10	CH142480	ZW5 × CW3	Experimental	4.43	1.944	1
18	CH142488	ZW4 × CW7	Experimental	4.33	2.873	14
27	CH142497	ZW1 × CW4	Experimental	4.49	2.055	3
31	CH142501	ZW6 × CW4	Experimental	4.57	2.241	6
43	CH142512	ZW1 × CW8	Experimental	4.34	2.469	8
48	Check1	Check1	Check	3.95	3.506	19
49	Check2	Check2	Check	4.50	3.034	15
52	Check5	Check5	Check	4.54	2.067	4
53	Check6	Check6	Check	3.73	3.204	16
55	Check8	Check8	Check	3.92	2.667	11
B. Non-acid soils						
2	CH142472	ZW5 × CW1	Experimental	6.88	2.67	10
21	CH142491	ZW8 × CW7	Experimental	6.81	1.72	7
26	CH142496	ZW4 × CW4	Experimental	9.35	7.2	17
30	CH142500	ZW3 × CW4	Experimental	12.69	0.00	1.5
43	CH142512	ZW1 × CW8	Experimental	7.09	2.57	9
48	Check1	Check1	Check	5.24	10.74	27
49	Check2	Check2	Check	6.24	0.00	3
51	Check4	Check4	Check	6.23	2.38	8
52	Check5	Check5	Check	6.13	4.1	13
54	Check7	Check7	Check	5.24	7.45	19

Note. GY: Grain yield; BLUE: Best line unbiased estimates; CSI: Cultivar stability indices.

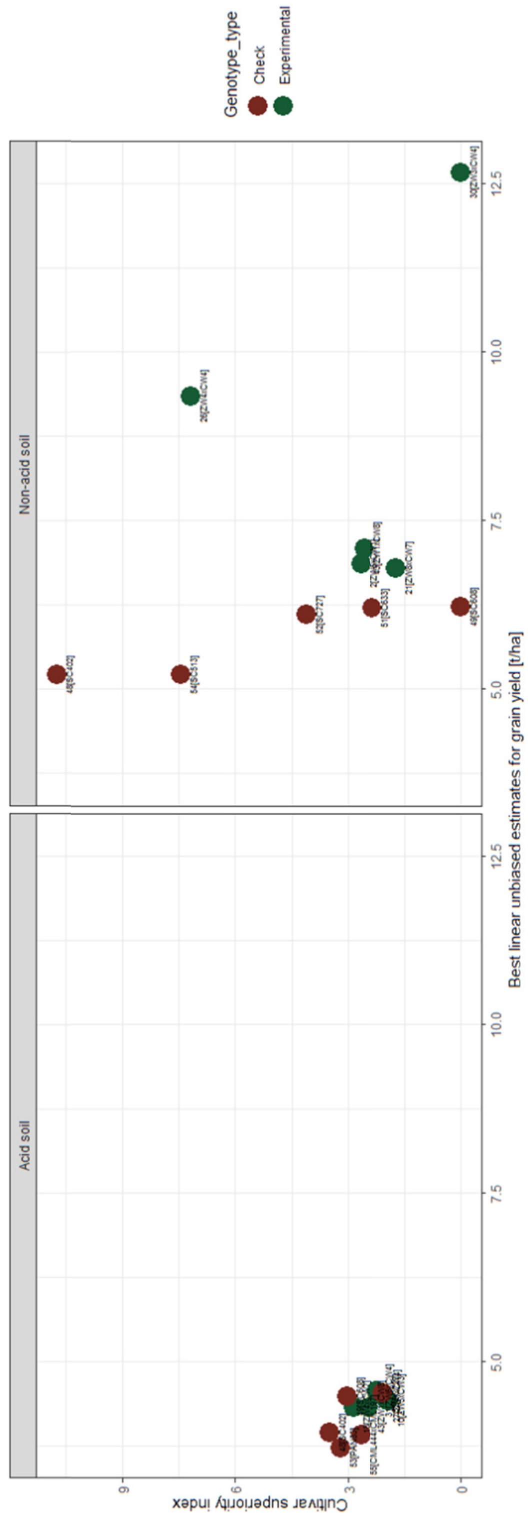

Figure 2. Best linear unbiased estimates (BLUEs) for grain yield and cultivar superiority indices of the top five crosses (*i.e.*, experimental hybrids) and commercial check hybrids under acid and non-acid soils

4. Discussion

Low pH in soils is attributed as the main contributor to the low yields characteristic in maize production regions of Angola, were both yellow and white maize is essential for food and nutritional security. Here, eight white-kernel acid soil tolerant donor lines (ASTDLs) sourced from CIMMYT-Colombia (testers) were crossed with eight white elite lines adapted to the mid-altitude climatic conditions from CIMMYT-Zimbabwe (lines), in order to identify donor lines, which can be potential sources of acid tolerance genes in breeding programmes in Angola and within the mid-altitude climatic zones. L×T analysis revealed significant ($p < 0.001$) genotype effect for grain yield performance across all environments. Under acid soil conditions, the effects of the genotype, general combining ability (GCA) and specific combining ability (SCA) on grain yield were also significant ($p < 0.05$). From the CIMMYT-Zimbabwe breeding programme, the inbred lines identified as ZW1, ZW4 and ZW5, together with the CIMMYT-Colombia ASTDLs noted as CW4 and CW8 seemed to be ideal parents for crosses that can do well under both the acid and non-acid soils. The best specific cross for acid soils was identified as ZW1 × CW8 (CH142512), whereas for non-acid soils, ZW3 × CW4 (CH142500) was identified. Interestingly, the cross ZW1 × CW8 was also observed as stable under both acid and non-acid soil conditions.

To begin with, combined ANOVA showed highly significant differences among the nine test sites for grain yield, indicating the presence of considerable variation among sites for genotype performance. This result is in agreement with Apala Mafouasson et al. (2018) who, in their study on genotype × environment interaction of maize single cross hybrids developed from tropical inbred lines, found that environment contributed more to variation than genotype and genotype × environment interaction. Similarly, Badu-Apraku et al. (2012) reported that the contribution of the test environments were much greater than from the other sources of variation in most multi-environmental trials. The effects of genotype were highly significant for grain yield under acid and non-acid soil conditions and in combined analysis, which could be explained by the inherent genetic variation in the germplasm studied. Desired genes from this germplasm can effectively be utilized to develop high performing and adapted hybrids to the local conditions in Angola.

The significant site effect on GY performance (Table 4) was evident as seen in most breeding results. In a recent study by Apala Mafouasson et al. (2018), the variation of the test environments was due to the greater variation contributed by environment than those from genotype and genotype × environment interaction. Similarly, Badu-Apraku et al. (2012) reported that the contribution of the test environments is much greater than the other sources of variation in most multi-environmental trials. The highly significant genotypic, GCA of lines and testers effects on GY under acid and non-acid soil conditions can point to high inherent genetic variation among the germplasm studied.

It was also interesting to note from the results that both additive and non-additive gene actions were important in expression of grain yield under acid soil conditions (Table 5). A study by Martin et al. (2017) also reported on the importance of both additive and non-additive gene actions for the expression of grain yield under stressed environments. In addition, the high broad and narrow heritability estimates observed under the acid and the non-acid soil conditions indicates the possibility of effective selection for genetic improvement of GY for the maize production environments in Angola. High heritability estimates for maize grain yield are not surprising, as they were reported elsewhere by Kashiani et al. (2008), Rafique et al. (2004), and Wannow et al. (2010). The results also provide the evidence that a large proportion of phenotypic variance was attributed to genotypic variance, and reliable selection could be made for these traits on the basis of phenotypic expression (Salani et al., 2007).

Selection was done for the five top grain yielding crosses (*i.e.*, experimental hybrids) and their grain yield potential was compared against the commercial check hybrids. It was so encouraging to note that the crosses showed GY superiority over the commercial checks under acid and the non-acid soil environments (Table 6). For instance, under non-acid soils, the crosses, ZW3 × CW4 (12.69 t ha^{-1}) and ZW4 × CW4 (9.35 t ha^{-1}) significantly out yielded the five highest grain yielding commercial checks. On the other hand, the crosses, ZW6 × CW4 (4.57 t ha^{-1}) and ZW1 × CW4 (4.49 t ha^{-1}) also outperformed commercial checks under acid soils. Most of these superior crosses (such as ZW4 × CW4) were formed by parents residing within the same heterotic group (*see* Table 1), hence are good targets for pedigree start populations for development of new lines adapted to conditions in Angola. A cross such as ZW3 (heterotic group B) × CW4 (heterotic group A), can be subjected to further testing for yield stability and can be targeted for release.

The search to really understand parental contributions to the high yields observed in some of the experimental hybrids did not disappoint, as it revealed that the CIMMYT-Zimbabwe elite lines as well as the CIMMYT-Colombia ASTDLs could potentially be useful in breeding programmes for acid tolerance adaptation and wide adaption of maize in Angola. From the CIMMYT-Zimbabwe breeding programme, the inbred lines identified as ZW1, ZW4 and ZW5, together with the CIMMYT-Colombia ASTDLs noted as CW4 and CW8 seemed to be ideal parents for crosses that can do well under both the acid and non-acid soil conditions in Angola (Figure 1). This finding was not surprising, since in previous genetic studies, inbred lines with highly positive

GCA effects for GY were found to have contributed to high GY performance in maize hybrids (Egesel et al., 2003; Bhatnagar et al., 2004; Fan et al., 2007; Bello & Olaoye, 2009).

Breeders should also consider those lines that do well in specific combinations, as these can be potential single-cross testers or potential targets for pedigree start populations, or can be potential targets for commercial release. In this study, the best specific combination was identified as ZW1 × CW8 and for the non-acid conditions, the cross, ZW3 × CW4 was noted. Results met expectations, as the parents making up these two specific crosses lie in opposite heterotic groups where heterosis is always expected to be high. Therefore, if, after further evaluation, mainly for GY stability, these hybrids continue to show GY superiority, they can be key targets for commercialization in Angola.

Lastly, some of the new crosses need to be recommended for production in different environments of Angola. However, before commercialization, assessment of yield stability and adaptability is an important factor, particularly for recommendation purposes (Liu et al., 2011, Eberhart & Russell, 1966). Cultivar superiority indices were used to determine grain yield stability and adaptability of the five highest grain yielding white kernel experimental hybrids and checks under acid and non-acid soil conditions. The hybrids: CH142480, CH142497, CH142501 and CH142512 were selected as the most stable among the 10 top highest grain yielding under acid soil condition. Under non-acid soil conditions, the most stable hybrids among the 10 top highest grain yielding were CH142472, CH142500, CH142512 and CH142491. The hybrid CH142512 (ZW1 × CW8) seemed to be stable in both conditions (acid and non-acid soil conditions) and could be immediately be further evaluated and recommended for commercial release in Angola.

5. Conclusion

Data demonstrated potential of tropically-adapted exotic white maize acid tolerance donor line for use in sub-tropical breeding programs for low-pH adaptation as most of the crosses outperformed the commercial check hybrids and showed stable performance under both acid and non-acid soils.

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Appendix

Table A1. The 47 crosses evaluated together with eight commercial check hybrids under acid and non-acid soils, during the 2015-16 cropping seasons in Angola and Zimbabwe

Entry	Hybrid name	Crosses	Entry	Hybrid name	Crosses
1	CH142471	ZW7 × CW1	29	CH142499	ZW8 × CW4
2	CH142472	ZW5 × CW1	30	CH142500	ZW3 × CW4
3	CH142473	ZW4 × CW1	31	CH142501	ZW6 × CW4
4	CH142474	ZW4 × CW8	32	CH142502	ZW7 × CW5
5	CH142475	ZW1 × CW2	33	CH142503	ZW5 × CW5
6	CH142476	ZW2 × CW1	34	CH142504	ZW4 × CW5
7	CH142477	ZW8 × CW2	35	CH142505	ZW1 × CW5
8	CH142478	ZW3 × CW1	36	CH142506	ZW2 × CW5
9	CH142479	ZW6 × CW1	37	CH142507	ZW8 × CW5
10	CH142480	ZW5 × CW3	38	CH142508	ZW3 × CW5
11	CH142481	ZW1 × CW3	39	CH142509	ZW6 × CW5
12	CH142482	ZW2 × CW3	40	CH142510	ZW7 × CW8
13	CH142483	ZW8 × CW3	41	CH142511	ZW5 × CW8
14	CH142484	ZW3 × CW3	42	CH142474	ZW4 × CW8
15	CH142485	ZW6 × CW3	43	CH142512	ZW1 × CW8
16	CH142486	ZW7 × CW7	44	CH142513	ZW2 × CW8
17	CH142487	ZW5 × CW6	45	CH142514	ZW8 × CW8
18	CH142488	ZW4 × CW7	46	CH142515	ZW3 × CW8
19	CH142489	ZW1 × CW7	47	CH142516	ZW6 × CW8
20	CH142490	ZW2 × CW7	48	Check1	Check1
21	CH142491	ZW8 × CW7	49	Check2	Check2
22	CH142492	ZW3 × CW6	50	Check3	Check3
23	CH142493	ZW6 × CW7	51	Check4	Check4
24	CH142494	ZW7 × CW4	52	Check5	Check5
25	CH142495	ZW5 × CW4	53	Check6	Check6
26	CH142496	ZW4 × CW4	54	Check7	Check7
27	CH142497	ZW1 × CW4	55	Check8	Check8
28	CH142498	ZW2 × CW4			

Table A2. Mean grain yield (t ha^{-1}) estimates and general combining ability effects for the CIMMYT-Zimbabwe elite lines (*i.e.*, lines) under acid, non-acid and across acid and non-acid soils

Line	**Mean**	**GCA**	**T_value_GCA_line**	**Prob_t_GCA_line**	**Rank**
A. Acid soils					
ZW1	4.141	0.421	1.781	0.0813	2
ZW2	3.189	-0.531	-2.243	0.0295	8
ZW3	3.496	-0.224	-0.946	0.3490	7
ZW4	3.709	-0.011	-0.048	0.9623	4
ZW5	3.791	0.071	0.299	0.7659	3
ZW6	4.298	0.578	2.444	0.0183	1
ZW7	3.588	-0.132	-0.557	0.5798	6
ZW8	3.625	-0.095	-0.400	0.6912	5
B. Non-acid soils					
ZW1	4.946	0.280	0.762	0.4534	2
ZW2	4.473	-0.193	-0.524	0.6054	6
ZW3	4.536	-0.130	-0.353	0.7275	5
ZW4	4.190	-0.475	-1.293	0.2084	8
ZW5	4.921	0.256	0.695	0.4936	3
ZW6	4.541	-0.125	-0.339	0.7376	4
ZW7	4.346	-0.319	-0.868	0.3942	7
ZW8	5.156	0.490	1.333	0.1951	1
C. Across acid & non-acid soils					
ZW1	4.391	0.382	1.540	0.1279	1
ZW2	3.613	-0.396	-1.598	0.1143	8
ZW3	3.816	-0.193	-0.778	0.4392	7
ZW4	3.856	-0.154	-0.619	0.5379	5
ZW5	4.139	0.130	0.523	0.6029	3
ZW6	4.352	0.343	1.384	0.1707	2
ZW7	3.832	-0.177	-0.713	0.4781	6
ZW8	4.116	0.107	0.432	0.6668	4

Note. GCA: General combining ability.

Table A3. Mean grain yield (t ha^{-1}) estimates and general combining ability effects for CIMMYT-Colombia ASTDLs (*i.e.*, testers) under acid, non-acid and across acid and non-acid soils

Tester	**Mean**	**GCA**	**T_value_GCA**	**Prob_t_GCA**	**Rank**
A. Acid soils					
CW1	4.048	0.328	1.574	0.1221	2
CW2	4.066	0.346	1.658	0.1038	1
CW3	3.986	0.266	1.275	0.2085	3
CW4	3.984	0.263	1.264	0.2122	4
CW5	3.309	-0.411	-1.973	0.0543	8
CW6	3.936	0.215	1.034	0.3063	5
CW7	3.861	0.141	0.678	0.5013	6
CW8	3.315	-0.405	-1.943	0.0579	7
B. Non-acid soils					
CW1	5.364	0.698	3.080	0.0051	2
CW2	5.856	1.190	5.248	0.0000	1
CW3	4.324	-0.342	-1.508	0.1447	7
CW4	5.237	0.571	2.518	0.0189	3
CW5	4.427	-0.239	-1.053	0.3029	6
CW6	5.027	0.362	1.595	0.1238	4
CW7	4.606	-0.059	-0.262	0.7955	5
CW8	4.081	-0.585	-2.578	0.0165	8
C. Across acid & non-acid soils					
CW1	4.414	0.404	2.030	0.0460	2
CW2	4.662	0.653	3.279	0.0016	1
CW3	4.088	0.079	0.395	0.6940	5
CW4	4.335	0.326	1.637	0.1060	3
CW5	3.687	-0.322	-1.617	0.1104	7
CW6	4.286	0.277	1.392	0.1682	4
CW7	4.082	0.073	0.364	0.7166	6
CW8	3.551	-0.458	-2.300	0.0243	8

Note. GCA: General combining ability.

Table A4. Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the crosses under acid, non-acid and across acid and non-acid soils

Line	Tester	Mean			SCA_L×T	SCA_SE L×T	T_Value L×T	Prob_T L×T	SCA_L×T RANK
		L×T	Tester	Line					
A. Acid soils									
ZW1	CW1	-	4.048	4.141	-	0.423	-	-	47
ZW1	CW2	4.924	4.066	4.141	0.437	0.423	1.034	0.302	11
ZW1	CW3	4.708	3.986	4.141	0.301	0.423	0.711	0.477	16
ZW1	CW4	4.423	3.984	4.141	0.018	0.423	0.044	0.965	26
ZW1	CW5	3.103	3.309	4.141	-0.627	0.423	-1.483	0.139	43
ZW1	CW6	-	3.936	4.141	-	0.423	-	-	48
ZW1	CW7	3.476	3.861	4.141	-0.806	0.423	-1.906	0.057	45
ZW1	CW8	4.664	3.315	4.141	0.927	0.423	2.193	0.029	1
ZW2	CW1	4.296	4.048	3.189	0.779	0.423	1.842	0.066	4
ZW2	CW2	-	4.066	3.189	-	0.423	-	-	49
ZW2	CW3	3.195	3.986	3.189	-0.260	0.423	-0.615	0.539	32
ZW2	CW4	3.161	3.984	3.189	-0.292	0.423	-0.689	0.491	34
ZW2	CW5	3.209	3.309	3.189	0.431	0.423	1.018	0.309	12
ZW2	CW6	-	3.936	3.189	-	0.423	-	-	50
ZW2	CW7	3.585	3.861	3.189	0.255	0.423	0.602	0.548	18
ZW2	CW8	2.429	3.315	3.189	-0.355	0.423	-0.840	0.402	36
ZW3	CW1	3.872	4.048	3.496	0.048	0.423	0.113	0.910	25
ZW3	CW2	-	4.066	3.496	-	0.423	-	-	51
ZW3	CW3	3.467	3.986	3.496	-0.295	0.423	-0.698	0.485	35
ZW3	CW4	4.447	3.984	3.496	0.687	0.423	1.624	0.105	6
ZW3	CW5	2.703	3.309	3.496	-0.382	0.423	-0.904	0.367	37
ZW3	CW6	4.135	3.936	3.496	0.423	0.423	1.000	0.318	13
ZW3	CW7	-	3.861	3.496	-	0.423	-	-	52
ZW3	CW8	2.829	3.315	3.496	-0.263	0.423	-0.621	0.535	33
ZW4	CW1	4.952	4.048	3.709	0.915	0.423	2.164	0.031	2
ZW4	CW2	-	4.066	3.709	-	0.423	-	-	53
ZW4	CW3	-	3.986	3.709	-	0.423	-	-	54
ZW4	CW4	3.865	3.984	3.709	-0.107	0.423	-0.253	0.800	27
ZW4	CW5	3.368	3.309	3.709	0.070	0.423	0.167	0.868	24
ZW4	CW6	-	3.936	3.709	-	0.423	-	-	55
ZW4	CW7	4.447	3.861	3.709	0.597	0.423	1.412	0.159	8
ZW4	CW8	3.162	3.315	3.709	-0.142	0.423	-0.335	0.738	28
ZW5	CW1	3.550	4.048	3.791	-0.569	0.423	-1.344	0.180	41
ZW5	CW2	-	4.066	3.791	-	0.423	-	-	57
ZW5	CW3	4.366	3.986	3.791	0.310	0.423	0.733	0.464	14
ZW5	CW4	4.231	3.984	3.791	0.177	0.423	0.418	0.676	22
ZW5	CW5	3.208	3.309	3.791	-0.172	0.423	-0.407	0.684	29
ZW5	CW6	3.791	3.936	3.791	-0.216	0.423	-0.510	0.611	30
ZW5	CW7	-	3.861	3.791	-	0.423	-	-	56
ZW5	CW8	3.614	3.315	3.791	0.228	0.423	0.539	0.590	20
ZW6	CW1	5.459	4.048	4.298	0.833	0.423	1.969	0.050	3
ZW6	CW2	-	4.066	4.298	-	0.423	-	-	58
ZW6	CW3	4.014	3.986	4.298	-0.550	0.423	-1.301	0.194	40
ZW6	CW4	5.285	3.984	4.298	0.723	0.423	1.709	0.088	5
ZW6	CW5	4.029	3.309	4.298	0.142	0.423	0.335	0.738	23
ZW6	CW6	-	3.936	4.298	-	0.423	-	-	59
ZW6	CW7	4.744	3.861	4.298	0.305	0.423	0.721	0.471	15

ZW6	CW8	2.859	3.315	4.298	-1.034	0.423	-2.445	0.015	46
ZW7	CW1	3.481	4.048	3.588	-0.435	0.423	-1.028	0.304	38
ZW7	CW2	-	4.066	3.588	-	0.423	-	-	62
ZW7	CW3	-	3.986	3.588	-	0.423	-	-	60
ZW7	CW4	3.354	3.984	3.588	-0.498	0.423	-1.176	0.240	39
ZW7	CW5	3.354	3.309	3.588	0.177	0.423	0.419	0.676	21
ZW7	CW6	-	3.936	3.588	-	0.423	-	-	61
ZW7	CW7	3.976	3.861	3.588	0.247	0.423	0.584	0.559	19
ZW7	CW8	3.792	3.315	3.588	0.609	0.423	1.439	0.151	7
ZW8	CW1	-	4.048	3.625	-	0.423	-	-	64
ZW8	CW2	3.350	4.066	3.625	-0.621	0.423	-1.469	0.143	42
ZW8	CW3	4.408	3.986	3.625	0.517	0.423	1.222	0.223	10
ZW8	CW4	3.631	3.984	3.625	-0.258	0.423	-0.610	0.543	31
ZW8	CW5	3.483	3.309	3.625	0.268	0.423	0.635	0.526	17
ZW8	CW6	-	3.936	3.625	-	0.423	-	-	63
ZW8	CW7	3.134	3.861	3.625	-0.633	0.423	-1.496	0.135	44
ZW8	CW8	3.747	3.315	3.625	0.527	0.423	1.245	0.214	9
B. Non-acid soils									
ZW1	CW1	-	5.364	4.946	-	1.022	-	-	46
ZW1	CW2	5.665	5.856	4.946	-0.471	1.022	-0.461	0.646	30
ZW1	CW3	5.181	4.324	4.946	0.577	1.022	0.564	0.573	13
ZW1	CW4	2.509	5.237	4.946	-3.008	1.022	-2.943	0.004	45
ZW1	CW5	5.038	4.427	4.946	0.331	1.022	0.324	0.746	18
ZW1	CW6	-	5.027	4.946	-	1.022	-	-	47
ZW1	CW7	5.249	4.606	4.946	0.363	1.022	0.355	0.723	17
ZW1	CW8	5.993	4.081	4.946	1.632	1.022	1.597	0.112	4
ZW2	CW1	6.039	5.364	4.473	0.868	1.022	0.849	0.397	10
ZW2	CW2	-	5.856	4.473	-	1.022	-	-	48
ZW2	CW3	4.634	4.324	4.473	0.503	1.022	0.493	0.623	15
ZW2	CW4	4.998	5.237	4.473	-0.046	1.022	-0.045	0.964	23
ZW2	CW5	3.835	4.427	4.473	-0.400	1.022	-0.391	0.696	28
ZW2	CW6	-	5.027	4.473	-	1.022	-	-	49
ZW2	CW7	3.116	4.606	4.473	-1.298	1.022	-1.270	0.206	40
ZW2	CW8	4.799	4.081	4.473	0.911	1.022	0.891	0.374	8
ZW3	CW1	5.291	5.364	4.536	0.057	1.022	0.055	0.956	22
ZW3	CW2	-	5.856	4.536	-	1.022	-	-	50
ZW3	CW3	3.750	4.324	4.536	-0.444	1.022	-0.434	0.665	29
ZW3	CW4	17.006	5.237	4.536	11.899	1.022	11.642	0.000	1
ZW3	CW5	3.569	4.427	4.536	-0.728	1.022	-0.712	0.477	34
ZW3	CW6	5.416	5.027	4.536	0.518	1.022	0.507	0.613	14
ZW3	CW7	-	4.606	4.536	-	1.022	-	-	51
ZW3	CW8	2.535	4.081	4.536	-1.416	1.022	-1.386	0.168	41
ZW4	CW1	5.173	5.364	4.190	0.284	1.022	0.278	0.781	19
ZW4	CW2	-	5.856	4.190	-	1.022	-	-	52
ZW4	CW3	-	4.324	4.190	-	1.022	-	-	53
ZW4	CW4	13.668	5.237	4.190	8.907	1.022	8.715	0.000	2
ZW4	CW5	2.869	4.427	4.190	-1.083	1.022	-1.059	0.291	38
ZW4	CW6	-	5.027	4.190	-	1.022	-	-	54
ZW4	CW7	3.907	4.606	4.190	-0.224	1.022	-0.219	0.827	24
ZW4	CW8	4.097	4.081	4.190	0.492	1.022	0.481	0.631	16
ZW5	CW1	5.780	5.364	4.921	0.161	1.022	0.157	0.875	20
ZW5	CW2	-	5.856	4.921	-	1.022	-	-	56

ZW5	CW3	4.235	4.324	4.921	-0.344	1.022	-0.336	0.737	26
ZW5	CW4	4.761	5.237	4.921	-0.731	1.022	-0.715	0.476	35
ZW5	CW5	6.218	4.427	4.921	1.536	1.022	1.503	0.135	5
ZW5	CW6	4.716	5.027	4.921	-0.566	1.022	-0.554	0.580	33
ZW5	CW7	-	4.606	4.921	-	1.022	-	-	55
ZW5	CW8	3.588	4.081	4.921	-0.749	1.022	-0.733	0.465	36
ZW6	CW1	-	5.364	4.541	-	1.022	-	-	57
ZW6	CW2	-	5.856	4.541	-	1.022	-	-	58
ZW6	CW3	4.866	4.324	4.541	0.667	1.022	0.653	0.515	12
ZW6	CW4	6.164	5.237	4.541	1.052	1.022	1.029	0.305	6
ZW6	CW5	5.182	4.427	4.541	0.880	1.022	0.861	0.390	9
ZW6	CW6	-	5.027	4.541	-	1.022	-	-	59
ZW6	CW7	2.545	4.606	4.541	-1.936	1.022	-1.894	0.060	44
ZW6	CW8	2.340	4.081	4.541	-1.616	1.022	-1.581	0.115	43
ZW7	CW1	4.668	5.364	4.346	-0.376	1.022	-0.368	0.713	27
ZW7	CW2	-	5.856	4.346	-	1.022	-	-	62
ZW7	CW3	-	4.324	4.346	-	1.022	-	-	60
ZW7	CW4	4.112	5.237	4.346	-0.805	1.022	-0.788	0.432	37
ZW7	CW5	5.156	4.427	4.346	1.048	1.022	1.025	0.307	7
ZW7	CW6	-	5.027	4.346	-	1.022	-	-	61
ZW7	CW7	4.415	4.606	4.346	0.128	1.022	0.125	0.900	21
ZW7	CW8	3.252	4.081	4.346	-0.510	1.022	-0.499	0.618	31
ZW8	CW1	-	5.364	5.156	-	1.022	-	-	64
ZW8	CW2	6.015	5.856	5.156	-0.331	1.022	-0.324	0.746	25
ZW8	CW3	3.669	4.324	5.156	-1.144	1.022	-1.120	0.264	39
ZW8	CW4	5.216	5.237	5.156	-0.510	1.022	-0.499	0.618	32
ZW8	CW5	3.372	4.427	5.156	-1.545	1.022	-1.511	0.132	42
ZW8	CW6	-	5.027	5.156	-	1.022	-	-	63
ZW8	CW7	6.773	4.606	5.156	1.676	1.022	1.640	0.103	3
ZW8	CW8	5.344	4.081	5.156	0.773	1.022	0.756	0.450	11
C. Acid-non-acid soils									
ZW1	CW1	-	4.414	4.391	-	0.394	-	-	47
ZW1	CW2	5.171	4.662	4.391	0.127	0.394	0.322	0.748	19
ZW1	CW3	4.866	4.088	4.391	0.396	0.394	1.003	0.316	11
ZW1	CW4	3.945	4.335	4.391	-0.773	0.394	-1.959	0.051	45
ZW1	CW5	3.786	3.687	4.391	-0.283	0.394	-0.718	0.473	33
ZW1	CW6	-	4.286	4.391	-	0.394	-	-	48
ZW1	CW7	3.998	4.082	4.391	-0.466	0.394	-1.181	0.238	40
ZW1	CW8	5.063	3.551	4.391	1.130	0.394	2.865	0.004	2
ZW2	CW1	5.043	4.414	3.613	1.026	0.394	2.602	0.010	4
ZW2	CW2	-	4.662	3.613	-	0.394	-	-	49
ZW2	CW3	3.618	4.088	3.613	-0.073	0.394	-0.185	0.853	27
ZW2	CW4	3.773	4.335	3.613	-0.165	0.394	-0.419	0.675	29
ZW2	CW5	3.430	3.687	3.613	0.139	0.394	0.353	0.724	18
ZW2	CW6	-	4.286	3.613	-	0.394	-	-	50
ZW2	CW7	3.447	4.082	3.613	-0.238	0.394	-0.604	0.546	31
ZW2	CW8	3.219	3.551	3.613	0.065	0.394	0.165	0.869	23
ZW3	CW1	4.345	4.414	3.816	0.124	0.394	0.316	0.752	20
ZW3	CW2	-	4.662	3.816	-	0.394	-	-	51
ZW3	CW3	3.561	4.088	3.816	-0.334	0.394	-0.846	0.398	34
ZW3	CW4	5.842	4.335	3.816	1.700	0.394	4.309	0.000	1
ZW3	CW5	2.992	3.687	3.816	-0.503	0.394	-1.274	0.203	41

ZW3	CW6	4.562	4.286	3.816	0.468	0.394	1.187	0.236	9
ZW3	CW7	-	4.082	3.816	-	0.394	-	-	52
ZW3	CW8	2.737	3.551	3.816	-0.621	0.394	-1.574	0.116	44
ZW4	CW1	4.984	4.414	3.856	0.724	0.394	1.835	0.067	6
ZW4	CW2	-	4.662	3.856	-	0.394	-	-	53
ZW4	CW3	-	4.088	3.856	-	0.394	-	-	54
ZW4	CW4	5.266	4.335	3.856	1.084	0.394	2.748	0.006	3
ZW4	CW5	3.181	3.687	3.856	-0.353	0.394	-0.894	0.372	38
ZW4	CW6	-	4.286	3.856	-	0.394	-	-	55
ZW4	CW7	4.278	4.082	3.856	0.350	0.394	0.888	0.375	14
ZW4	CW8	3.474	3.551	3.856	0.077	0.394	0.194	0.846	22
ZW5	CW1	4.206	4.414	4.139	-0.337	0.394	-0.855	0.393	36
ZW5	CW2	-	4.662	4.139	-	0.394	-	-	57
ZW5	CW3	4.328	4.088	4.139	0.110	0.394	0.280	0.780	21
ZW5	CW4	4.408	4.335	4.139	-0.057	0.394	-0.145	0.885	26
ZW5	CW5	4.211	3.687	4.139	0.395	0.394	1.001	0.317	12
ZW5	CW6	4.080	4.286	4.139	-0.336	0.394	-0.852	0.395	35
ZW5	CW7	-	4.082	4.139	-	0.394	-	-	56
ZW5	CW8	3.607	3.551	4.139	-0.074	0.394	-0.187	0.852	28
ZW6	CW1	5.459	4.414	4.352	0.703	0.394	1.781	0.075	7
ZW6	CW2	-	4.662	4.352	-	0.394	-	-	58
ZW6	CW3	4.241	4.088	4.352	-0.190	0.394	-0.481	0.630	30
ZW6	CW4	5.460	4.335	4.352	0.782	0.394	1.982	0.048	5
ZW6	CW5	4.413	3.687	4.352	0.383	0.394	0.971	0.332	13
ZW6	CW6	-	4.286	4.352	-	0.394	-	-	59
ZW6	CW7	4.378	4.082	4.352	-0.047	0.394	-0.119	0.905	25
ZW6	CW8	2.765	3.551	4.352	-1.129	0.394	-2.863	0.004	46
ZW7	CW1	3.830	4.414	3.832	-0.406	0.394	-1.030	0.303	39
ZW7	CW2	-	4.662	3.832	-	0.394	-	-	62
ZW7	CW3	-	4.088	3.832	-	0.394	-	-	60
ZW7	CW4	3.607	4.335	3.832	-0.552	0.394	-1.398	0.163	43
ZW7	CW5	3.955	3.687	3.832	0.445	0.394	1.127	0.260	10
ZW7	CW6	-	4.286	3.832	-	0.394	-	-	61
ZW7	CW7	4.123	4.082	3.832	0.218	0.394	0.553	0.581	16
ZW7	CW8	3.623	3.551	3.832	0.249	0.394	0.632	0.528	15
ZW8	CW1	-	4.414	4.116	-	0.394	-	-	64
ZW8	CW2	4.238	4.662	4.116	-0.531	0.394	-1.347	0.178	42
ZW8	CW3	4.191	4.088	4.116	-0.004	0.394	-0.011	0.991	24
ZW8	CW4	4.160	4.335	4.116	-0.283	0.394	-0.717	0.474	32
ZW8	CW5	3.450	3.687	4.116	-0.344	0.394	-0.872	0.384	37
ZW8	CW6	-	4.286	4.116	-	0.394	-	-	63
ZW8	CW7	4.347	4.082	4.116	0.158	0.394	0.400	0.689	17
ZW8	CW8	4.280	3.551	4.116	0.621	0.394	1.576	0.116	8

Note. L × T: Line by tester; SCA: Specific combining ability; SE: Square error.

Table A5. BLUEs and BLUPs for grain yield of 47 crosses and the eight (8) commercial check hybrids under acid, non-acid and across acid and non-acid soils

Entry	Cross	Line	Tester	Acid		Non-acid		Across Acid & Non-acid	
				BLUP_GY	BLUE_GY	BLUP_GY	BLUE_GY	BLUP_GY	BLUE_GY
1	ZW7 × CW1	ZW7	CW1	3.406	2.988	5.057	5.689	3.999	3.936
2	ZW5 × CW1	ZW5	CW1	3.519	3.42	5.285	6.880	4.249	4.571
3	ZW4 × CW1	ZW4	CW1	3.529	3.372	4.685	0.422	3.812	3.234
4	ZW4 × CW8	ZW4	CW8	3.561	3.543	4.685	3.794	3.850	3.613
5	ZW1 × CW2	ZW1	CW2	3.841	4.315	4.991	5.330	4.295	4.662
6	ZW2 × CW1	ZW2	CW1	3.264	2.022	4.757	3.578	3.631	2.528
7	ZW8 × CW2	ZW8	CW2	3.45	3.194	5.138	6.032	4.081	4.137
8	ZW3 × CW1	ZW3	CW1	3.638	3.756	4.945	4.790	4.082	4.146
9	ZW6 × CW1	ZW6	CW1	3.744	4.295	.	.	4.179	4.731
10	ZW5 × CW3	ZW5	CW3	3.865	4.433	4.957	5.332	4.290	4.699
11	ZW1 × CW3	ZW1	CW3	3.808	4.269	4.808	4.203	4.139	4.307
12	ZW2 × CW3	ZW2	CW3	3.403	3.056	5.132	6.311	4.053	4.090
13	ZW8 × CW3	ZW8	CW3	3.835	4.326	4.814	4.184	4.158	4.352
14	ZW3 × CW3	ZW3	CW3	3.543	3.497	4.698	3.913	3.850	3.615
15	ZW6 × CW3	ZW6	CW3	3.649	3.794	5.081	6.058	4.218	4.502
16	ZW7 × CW7	ZW7	ZW7	3.523	3.398	4.794	4.154	3.895	3.688
17	ZW5 × CW6	ZW5	CW6	3.618	3.676	5.072	5.802	4.176	4.391
18	ZW4 × CW7	ZW4	CW7	3.816	4.328	4.857	4.762	4.161	4.362
19	ZW1 × CW7	ZW1	CW7	3.5	3.355	4.877	4.576	3.935	3.784
20	ZW2 × CW7	ZW2	CW7	3.474	3.276	4.783	4.248	3.856	3.615
21	ZW8 × CW7	ZW8	CW7	3.456	3.237	5.29	6.809	4.200	4.472
22	ZW3 × CW6	ZW3	CW6	3.51	3.339	4.873	4.627	3.946	3.774
23	ZW6 × CW7	ZW6	CW7	3.788	4.161	4.934	5.283	4.224	4.563
24	ZW7 × CW4	ZW7	CW4	3.544	3.481	4.745	4.146	3.878	3.663
25	ZW5 × CW4	ZW5	CW4	3.751	4.041	4.905	4.779	4.167	4.351
26	ZW4 × CW4	ZW4	CW4	3.44	3.085	5.132	9.351	4.071	4.210
27	ZW1 × CW4	ZW1	CW4	3.869	4.493	4.907	4.863	4.265	4.675
28	ZW2 × CW4	ZW2	CW4	3.299	2.769	4.911	4.837	3.799	3.473
29	ZW8 × CW4	ZW8	CW4	3.681	3.885	4.996	5.387	4.167	4.367
30	ZW3 × CW4	ZW3	CW4	3.653	3.8	5.304	12.685	4.375	5.115
31	ZW6 × CW4	ZW6	CW4	3.871	4.571	4.872	4.426	4.241	4.679
32	ZW7 × CW5	ZW7	CW5	3.445	3.216	4.969	5.134	3.964	3.894
33	ZW5 × CW5	ZW5	CW5	3.499	3.349	5.16	6.002	4.132	4.278
34	ZW4 × CW5	ZW4	CW5	3.61	3.679	4.541	3.289	3.783	3.414
35	ZW1 × CW5	ZW1	CW5	3.348	2.903	4.904	5.003	3.833	3.582
36	ZW2 × CW5	ZW2	CW5	3.482	3.262	4.727	3.980	3.823	3.502
37	ZW8 × CW5	ZW8	CW5	3.455	3.202	4.789	4.161	3.838	3.554
38	ZW3 × CW5	ZW3	CW5	3.304	2.856	4.639	3.670	3.619	3.111
39	ZW6 × CW5	ZW6	CW5	3.759	4.072	4.989	5.265	4.224	4.475
40	ZW7 × CW8	ZW7	CW8	3.674	3.886	4.777	4.386	4.008	4.011
41	ZW5 × CW8	ZW5	CW8	3.588	3.63	4.812	4.183	3.964	3.891
42	ZW4 × CW8	ZW4	CW8	3.328	2.861	4.802	4.239	3.749	3.355
43	ZW1 × CW8	ZW1	CW8	3.798	4.336	5.154	7.094	4.402	5.126
44	ZW2 × CW8	ZW2	CW8	3.149	2.394	4.919	5.009	3.692	3.240
45	ZW8 × CW8	ZW8	CW8	3.642	3.784	4.977	5.130	4.112	4.224
46	ZW3 × CW8	ZW3	CW8	3.321	2.853	4.622	3.192	3.614	3.025
47	ZW6 × CW8	ZW6	CW8	3.302	2.698	4.584	1.730	3.558	2.665
48	Check1	Check1	Check1	3.7	3.953	4.951	5.235	4.144	4.322

49	Check2	Check2	Check2	3.898	4.495	5.046	6.242	4.397	5.016
50	Check3	Check3	Check3	3.447	3.189	4.745	4.351	3.807	3.494
51	Check4	Check4	Check4	3.595	3.632	5.156	6.226	4.203	4.447
52	Check5	Check5	Check5	3.906	4.537	5.145	6.125	4.451	5.071
53	Check6	Check6	Check6	3.63	3.726	4.951	4.909	4.087	4.147
54	Check7	Check7	Check7	3.431	3.165	4.96	5.241	3.946	3.834
55	Check8	Check8	Check8	3.701	3.921	4.777	4.114	4.019	4.000

Note. BLUP: Best linear unbiased predicts; BLUE: Best linear unbias estimates; GY: Grain yield.

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Authors Contributions

Dr. D. Nginamau carried out field work, analyzed the data and drafted the first draft of the manuscript. Dr. Cosmos Magorokosho conceived the research study and supervised research work. Prof. Maryke Labuschagne supervised the PhD study of the first author. Mr. João Constâncio Saraiva assisted in mobilizing resources for research activities in Angola. Dr. Angeline van Biljon co-supervised the PhD study. Dr. Casper N. Kamutando co-supervised the PhD study, analyzed the data and co-wrote the manuscript.

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Competing Interests

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