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Genetic Studies of Extra Early Maize Genotypes Under Low Nitrogen

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Abstract

Nitrogen (N) is a major limiting factor associated with maize production in sub-Saharan Africa. Low N tolerant hybrids can absorb and utilise N from the soil as well as applied fertilisers, making them efficient users of N. This study focused on identifying inbred lines with desirable GCA for grain yield and other agronomic traits under low N, determining the gene action governing grain yield and other agronomic traits under low N and estimating the genotypic variability for grain yield and other agronomic traits among extra early maize hybrids. Ten extra early white endosperm maize inbred lines were crossed to five testers in a line tester mating design to generate fifty (50) single cross hybrids (SCH) which were evaluated under low N (30 kg N ha^{-1}) and optimum N (90 kg N ha^{-1}). The combined analysis of variance (ANOVA) under low and optimum N showed significant mean squares for the environment and hybrids but non-significant hybrid environment interaction mean squares for grain yield (GY) under low N. General combining ability of line and tester as well as specific combining ability showed significant mean squares for GY under both low and optimum N environments. Non-additive gene action governed GY under low and optimum N. GY had moderate genotypic coefficient of variability and high genetic advance as a percentage of mean under low and optimum N. Lines CRIZEEL-W-242 and CRIZEEL-W-261 were the best inbred lines identified under low and optimum N conditions, hence should be used in recurrent selection or other hybridization programmes.

Keywords: Low nitrogen; Line Tester; Combining Ability; Heritability; Genetic Advance.

Études Génétiques de Génotypes de Maïs Extra-précoces Sous Faible Teneurs en Azote

Résumé

L'azote (N) est un facteur limitant majeur associé à la production de maïs en Afrique subsaharienne. Les hybrides tolérants à l'azote peuvent absorber et utiliser l'azote du sol ainsi que les engrais appliqués, ce qui en fait des utilisateurs efficaces de l'azote. Cette étude s'est concentrée sur l'identification de lignées consanguines avec une ACG souhaitable pour le rendement en grains et d'autres caractéristiques agronomiques sous faible azote, sur la détermination de l'action des gènes régissant le rendement en grains et d'autres caractéristiques agronomiques sous faible azote et sur l'estimation de la variabilité génotypique pour le rendement en grains et d'autres caractéristiques agronomiques parmi les hybrides de maïs extra-précoces.

Dix lignées consanguines de maïs extra-précoce à endosperme blanc ont été croisées avec cinq testeurs dans un plan d'accouplement ligne-testeur pour générer cinquante (50) hybrides simples croisés (SCH) qui ont été évalués sous faible niveau d'azote (30 kg N ha^{-1}) et sous niveau d'azote optimal (90 kg N ha^{-1}). L'analyse de variance combinée (ANOVA) dans des conditions d'azote faible et optimal a montré des carrés moyens significatifs pour l'environnement et les hybrides, mais des carrés moyens d'interaction hybride-environnement non significatifs pour le rendement en grain (GY) dans des conditions d'azote faible. Les lignées CRIZEEL-W-242 et CRIZEEL-W-261 ont été les meilleures lignées consanguines identifiées dans des conditions d'azote faible et optimal, et devraient donc être utilisées dans des programmes de sélection récurrente ou d'autres programmes d'hybridation.

Mots Clés: Faible teneur en azote; ligne x testeur; capacité de combinaison; héritabilité; avance génétique.

Introduction

Maize (*Zea mays*) is one of the major cereal crops cultivated and utilised mainly as a staple crop in sub-Saharan Africa (SSA) (Effa *et al.,* 2012; Okweche *et al.,* 2013; Macauley, 2015). It is consumed across SSA and in 2019, the total maize production recorded in Ghana stood at 2.7 million Mt, corresponding to a 45% increase in production (FAO, 2020). An estimated 85% of the total maize produced in Ghana is used for food, with a per capita consumption of 43.8 kg per head. The remaining 15% is used in feed formulation, mainly in the livestock and poultry industries, where it constitutes about 40 – 75% of their ration (Angelucci, 2012; Abdulai *et al.,* 2017). Despite the economic importance of maize and the efforts made by most researchers to improve the qualities of the crop, the key challenging abiotic constraint in SSA, including Ghana, is low soil fertility (Oyekunle & Badu-Apraku, 2014; Ribeiro *et al.,* 2017). For most soils in Ghana, the total N in the upper portions of the soil after years of cultivating tend to be low (Bationo *et al.,* 2018). Ghana has one of the lowest nitrogen (N) application rates of 34 kg N ha^{-1} in SSA despite efforts to attain a minimum application rate of 50 kg N ha^{-1} (Henao & Baanante, 2006; Bationo *et al.,* 2018). Nitrogen stress not only retards the growth of plants but also markedly affects the photosynthetic rate per unit area by reducing both leaf size and photosynthetic capacity (Su *et al.,* 2020) and, subsequently, the final grain yield, resulting in a range of 10% – 50% yield loss annually (Logrono & Lothrop, 1996).

Current yields of less than 1.5 t ha^{-1} in SSA lag behind the global average of 5.75 t ha^{-1} (Cairns *et al.,* 2013; FAO, 2017). These low yields are attributable to farmers low fertiliser application rates, about 5 – 10 kg N ha^{-1}, compared to the average of 100 kg N ha^{-1} applied worldwide (Ogunniyan *et al.,* 2019). Furthermore, low production capacity locally worsens the issue at hand. The limited supply and the high cost of fertilisers deter farmers from purchasing these fertilisers (Mosier *et al.,* 2005). In addition, the reduced availability of productive land for agricultural purposes and low fertiliser application rates continue to pose a major threat to maize production in Ghana (Ribeiro *et al.,* 2017).

Low N tolerant hybrids can increase maize productivity since they can absorb and utilise N from the soil and from applied fertilisers, thereby making them efficient users of nutrients (Arisede *et al.,* 2020). However, only a few such hybrids have been released in Ghana. Badu-Apraku *et al.* (2015) indicated that genetic improvement of maize germplasm is the most feasible and sustainable choice for mitigating the negative impacts of abiotic stress conditions such as low N in SSA. Genetic approaches to improve yield at reduced N application rates are crucial since fertiliser use in SSA is low (Ogunniyan *et al.,* 2019). In maize breeding programs, knowledge of the general combining ability (GCA) of inbred lines and specific combining ability (SCA) of hybrid combinations are crucial for successful hybrid development. This provides information on the type of gene action controlling yield and its associated traits under stress conditions (Nasser *et al.,* 2020). Successful studies on gene action (combining abilities) are achieved through popular mating schemes such as diallel, Line Tester and North Carolina Design II (NCD II) (Hallauer *et al.,* 2010; Fasahat *et al.,* 2016).

Determination of genotypic variability through the use of parameters such as genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability and genetic advance are vital in every efficient and effective breeding programme (Arunkumar *et al.,* 2018). GCV and PCV usually determine the variation present in a breeding population (Roychowdhury & Randrianotahina, 2011; Bello *et al.,* 2012). PCV and GCV are useful indices as they also act as measuring tools for effective selection in crop improvement (Bello *et al.,* 2012). Effective selection procedures that significantly influence the improvement of a character can be established through the measure of heritability (Samadia, 2005). Heritability deals with the transmissibility of a character from one generation to the other. Though traits with high narrow sense heritability can quickly be fixed using simple selection methods, it requires genetic advance in order to be of practical importance or be more applicable and helpful in formulating selection procedures (Jaiswal *et al.,* 2019). Estimating heritability also assists breeders in allocating resources necessary to select desired traits effectively and to achieve maximum genetic gain faster with limited resources (Smalley *et al.,* 2004). Genetic advance is a useful indicator of the progress that can be expected due to selection (Reddy *et al.,* 2013).

For newly developed inbred lines, the effect of GCA has been reported to be relatively more significant than the SCA effect in tropical maize germplasm (Dhliwayo *et al.,* 2009; Adebayo *et al.,* 2017). There are also inconsistencies in the combining abilities and genetic variability of low N tolerance among inbred lines developed for hybrid maize development. For instance, in the report of Akinwale *et al.* (2014), there was a significant role of GCA in the determination of grain yield of maize inbred lines under varying environmental stress, but Oyekunle *et al.* (2015) reported higher SCA than GCA effect for grain yield when early yellow endosperm maize inbred lines were studied under various stress conditions. Aside the insufficient low N varieties in Ghana, there is limited information on the combining abilities (i.e. general and specific) of newly developed maize inbred lines by the Council for Scientific and Industrial Research (CSIR) – Crops Research Institute (CRI). The objectives of this research were to: identify inbred lines with desirable GCA effect for grain yield and other agronomic traits under low N; assess the gene action governing grain yield and other agronomic traits under low N and; assess the genotypic variability among hybrids for grain yield and other agronomic traits.

Materials and Methods

Germplasm and generation of F_1 hybrids

Ten extra early maturing inbred lines of white endosperm maize were obtained from the CSIR-CRI. These are newly developed inbred lines by the maize breeding programme. Five other inbred lines were used as testers. The ten lines were crossed to the five testers in a line x tester mating design as described by Kempthrone (1957). Each member of the testers was crossed to each member of the lines (i.e. Ti all females; Ti = i^{th} tester) (5 testers x 10 lines), thus giving a total of 50 single cross hybrids (SCH).

Depletion of soil of nitrogen

The experimental sites were depleted of N by cultivating maize at a high population density. The stover (biomass) was entirely removed after each harvest, and soil sampled to a depth of 30 cm for soil total N determination. Nitrogen depletion continued till the residual N reached an acceptable level (<0.2%). The N content was determined using the Kjeldhal method (Bremner & Mulvaney, 1982) at the CSIR - Soil Research Institute (CSIR-SRI), Kwadaso.

Experimental site, field layout and evaluation of single cross hybrids (SCH)

The SCH were evaluated under contrasting environments during the major season of 2022 (April 2022 – August 2022) at three different locations: Fumesua, Kwadaso and Ejura.

The vegetation was cleared using glyphosate herbicide at 200 mL per 15 L of water. Entries, comprising the 50 SCH developed and two commercial hybrids used as checks, were laid in a 413 alpha-lattice designed experiment with three replications. Each plot was two rows and 4 m long. Seeds were sown at a spacing of 0.75 m × 0.40 m at three seeds per hill and thinned to two plants per hill two weeks after sowing (WAS).

The experiment comprised low N and optimum N at all locations except Ejura which had only optimum N trial (low N trial was invaded prior to flowering stage and destroyed by cattle). Phosphorus (triple superphosphate) and potassium (muriate of potash) were each applied at 60 kg ha^{1} to low and optimum N plots at 2 WAS. The low N treatments received 30 kg N ha^{-1} while the optimum N treatments received 90 kg N ha^{-1} applied as urea in two splits: 50% at 2 WAS and the remaining 50% applied at 5 WAS. The low N was selected on the basis of the results from the works of Tetteh *et al.* (2017) and Wongnaa *et al.* (2021) who indicated that about 85% of maize farmers in the Ashanti region do not comply with the CSIR-Savanna Agriculture Research Institute (SARI)/ CSIR-CRI's recommended fertiliser application rate for maize production by Adu *et al.* (2014) and thus apply lower than the average recommended rate (90 kg N ha^{-1}). The optimum N application rate employed in this study is in line with the recommendations made by the CSIR-SARI/CRI and AGRA in the work of Adu *et al.* (2014) stating that, the optimum application rate is selected on the basis of the maturity period and production potential of the maize variety. Since the hybrids developed from this study are extra early and their production potential was not certain, it was advisable to use the optimum/average rate of application of 90 kg N ha^{-1} and not 120 kg N ha^{-1} for depleted soil as recommended by the CSIR-SARI /CRI and AGRA in the work of Adu *et al.* (2014).

Weeds were managed using the post-emergence weedicides (120 mL per 16 L of water) as well as the manual method, whilst fall armyworm larvae were also managed when necessary by applying emamectin benzoate at 30 mL per 15 L of water (knapsack).

Table 1. List of extra early maturing maize germplasm used to generate hybrids

Entry no.	Testers	Agronomic Characteristics	Source
1	Tester 1	52 DTA, Moderately tolerant under low N	CSIR-CRI
2	Tester 2	52 DTA, Tolerant under low N	CSIR-CRI
3	Tester 3	52 DTA, Moderately tolerant under low N	CSIR-CRI
4	Tester 4	51 DTA, Moderately tolerant under low N	CSIR-CRI
5	Tester 5	51 DTA, Moderately tolerant under low N	CSIR-CRI
	Lines		Source
6	CRIZEEL-W-217	49 DTS Moderately tolerant under low N	CSIR-CRI
7	CRIZEEL-W-219	47 DTS Moderately tolerant under low N	CSIR-CRI
8	CRIZEEL-W-222	46 DTS, low N tolerant	CSIR-CRI
9	CRIZEEL-W-261	49 DTS, low N tolerant	CSIR-CRI
10	CRIZEEL-W-232	50 DTS, Moderately tolerant under low N	CSIR-CRI
11	CRIZEEL-W-236	45 DTS, Moderately tolerant under low N	CSIR-CRI
12	CRIZEEL-W-242	49 DTS, low N tolerant	CSIR-CRI
13	CRIZEEL-W-208	47 DTS, Moderately tolerant under low N	CSIR-CRI
14	CRIZEEL-W-263	47 DTS, Moderately tolerant under low N	CSIR-CRI
15	CRIZEEL-W-257	49 DTS Moderately tolerant under low N	CSIR-CRI

DTA = Days to Anthesis, DTS = Days to Silking

Table 2. Description of experimental sites

Features/location	Fumesua	Kwadaso	Ejura
Coordinates	6°41′ N, 1°28′ W	6°43′ N, 1°36′ W	7°23′N, 1°21′W
AEZ	Deciduous Forest	Deciduous Forest	Forest-savannah transition
Soil type	Ferric acrisol (Asuansi series)	Ferric acrisol (Asuansi series)	Ferric lixisol (Ejura series)
Altitude (m)	257	254	254
Rainfall pattern	Bimodal	Bimodal	Bimodal
Major season	April to July	April to July	March to August
Minor season	September to November	September to November	September to November

NB: AEZ = Agro-Ecological Zone, N = North, W = West

Data collection
Data were recorded on days to anthesis (DTA) and silking (DTS), anthesis – silking interval (ASI), chlorophyll content (CC) using the portable CCM-200 plus-opti sciences meter (OptiSciences Inc., Hudson USA), stay green (SG), plant height (PHGT), ear height (EHGT), plant aspect (PASP), ear aspect (EASP), number of ears per plant (EPP) and grain yield (GY). The measurement of all the parameters were carried out according to the method described in the works of Nelimor *et al.* (2020) and Ribeiro *et al.* (2020).

Grain yield (GY) for the low N trials was estimated from the shelled grain weight per plot while assuming a moisture content of 15%. On the other hand, GY for the optimum trials was estimated from the field weight while assuming a shelling percentage of 80% and moisture content of 15%. Grain yield was estimated using the formulae from the works of Mageto *et al.* (2020) and Tandzi & Mutengua (2020).

Statistical analysis
The plot mean values of the 52 entries for grain yield and the other agronomic traits were subjected to analysis of variance (ANOVA). The 50 SCH were further subjected to line tester analysis (Kempthrone, 1957) using R software (R version 4.1.2 (2021-11-01)) where environment and replication served as random effect and genotype as fixed effect. The hybrid component of variation was further partitioned into variations due to tester, line and line tester interaction. The F tests for line, tester and line tester mean squares were computed using the mean squares for their respective interaction with environment. The mean square attributable to line environment and tester environment were tested using the mean square for line tester environment whereas the mean square for line tester environment was tested using the pooled error mean squares. The line and tester main effect served as the GCA-line and GCA-tester, respectively, and the line tester effect served as the SCA. The model for the combined analysis of variance is described below

$$Y_{ijk} = \mu + G_i + E_j + GE_{ij} + L_l + T_m + LT_{lm} + LE_{lj} + TE_{mj} + LTE_{lmj} + R_k : E_j + B_n : R_k : E_j + \varepsilon ijk,$$

where;

$Yijk$ = the response variables
μ = grand mean.
G_i = effect of the ith genotype.
E_j = effect of the jth environment.
GE_{ij} = effect of the interaction between the ith genotype and the jth environment.
L_l = effect of the lth line.
T_m = effect of mth tester.
L_l = effect of the lth line.
T_m = effect of mth tester.
LT_{lm} = effect of the interaction between the lth line and the mth tester.
LE_{lj} = effect of the interaction between the jth environment and the lth line.
TE_{mj} = effect of the interaction between the jth environment and the mth tester.
LTE_{lmj} = effect of the interaction between the lth line, the mth tester and the jth environment.
$R_k{:}E_j$ = effect of replicate nested in environment
$B_n{:}R_k{:}E_j$ = effect of Blocks nested in replicate nested in environment.
$\mathcal{E}_{ijk}$ = error term

General combining ability (GCA) and specific combining ability (SCA) were computed for all characters according to the method described by Kempthrone (1957) and Singh & Chaudhary (1985). Broad sense heritability (H^2b) and narrow sense heritability (h^2n) were estimated under each of the three environments (i.e. low N, optimum N) using the variance component method. The variance components were obtained from a restricted maximum likelihood (REML) analysis using the "lmerTest" and "lme4" packages (Bates *et al*., 2015; Kuznetsova *et al*., 2017) in R software. Heritability was calculated as follows:

$$H^2b = \frac{\sigma^2_g}{\sigma^2_g + \frac{\sigma^2_{gxe}}{e} + \frac{\sigma^2_e}{r \times e}}$$

$$h^2n = \frac{\sigma^2_a}{\sigma^2_g + \frac{\sigma^2_{gxe}}{e} + \frac{\sigma^2_e}{r \times e}}$$

Where:

H^2b = Broad sense heritability

h^2n = narrow sense heritability

σ^2_g= Variance due to genotype

σ^2_a= Variance due to additive gene action

σ^2_{gxe}= Variance due to genotype × environment interaction

σ^2_e= Error variance

e = number of environments and

r = number of replications

Heritability in narrow sense was categorized as: low = 0 – 30 %, intermediate (medium) = 30 – 50 % and high = above 50 %; according to Bhateria *et al.* (2006).

The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were calculated according to Burton (1951), Burton & Devane (1953), and Aravind *et al.* (2019) and then ranked as; low = 0 – 10%, intermediate = 10 – 20% and high = greater than 20% (Sivasubramanian & Madhavamenon, 1973; Abebe *et al*., 2017).

The expected genetic advance was calculated as follows;

h^2n = narrow sense heritability,

δp = phenotypic standard deviation,

k = selection differential at 5% selection intensity = 2.06.

Genetic advance as percentage of mean (GAM) was calculated by using the method proposed by Robinson *et al.* (1949); Johnson *et al.* (1955); Jilo *et al*. (2018) and classified as: low = less than 10%, intermediate = 10-20%, and high = more than 20% (Johnson *et al.,* 1955; Abebe *et al*., 2017; Jilo *et al*., 2018).

Results

Combined analysis of variance

The combined ANOVA under low N indicated significant ($p < 0.05$) environment, hybrid, and hybrid environment interaction mean squares for all traits except SG and PASP for environments and DTA, CC, EPP, PASP and GY for hybrid environment interaction. The GCA-line, GCA-tester, and SCA showed significant ($p < 0.05$) mean squares for the measured traits except DTS and DTA for the GCA-tester and SG for SCA. The interaction of GCA-line and GCA-tester with the environment showed significant ($p < 0.05$) mean squares for the measured traits except DTA, CC, EPP, PASP and GY for GCA-line environment and then CC, SG and EPP for GCA-tester environment. In the case of SCA environment, only ASI and EASP showed significant ($p < 0.05$) mean squares (Table 3).

Under optimum N, hybrid, environment and hybrid environment interaction showed significant ($p < 0.05$) mean squares for the measured traits except EPP for the hybrids and CC, EPP and EASP for the hybrid environment interaction. The GCA-line, GCA-tester, and SCA showed significant ($p < 0.05$) mean squares for the measured traits except EPP for GCA-line effect; DTS, DTA and EPP for the GCA-tester effect and finally ASI, CC, EPP and EASP for the SCA effect.

Table 3. Mean squares from combined analysis of variance under low nitrogen environments

Source	Df	DTS (days)	DTA (days)	ASI (days)	CC	PHGT (cm)	EHGT (cm)	SG (1-9)	EPP	PASP (1-9)	EASP (1-9)	GY (kg ha^{-1})
Hybrid	51	16.1**	11.0**	3.7**	268.9**	797.0**	368.7**	0.9**	0.03**	3.3**	2.9**	1012990**
Environment (Env)	1	4092.6**	3759.3**	7.1**	7607.2**	68508.0**	25542.7**	0.2	0.49**	2.5	134.7**	13720313**
Hybrid × Env	51	6.5**	3.8	3.3**	94.2	146.0*	96.8**	0.5*	0.02	0.4	1.6**	387386
Env(Rep)	4	30.1**	28.4**	2.5**	553.3**	489.0**	280.6**	2.2**	0.04*	1.4	2.3**	1466701**
(Env × Rep)Blk	72	4.6	3.8	0.4	120.7*	112.0	50.1	0.6**	0.02*	1.3**	0.8	376562
Residuals	132	3.7	2.9	0.7	75.7	87.0	44.8	0.3	0.01	0.7	0.6	334140
Line	9	49.4**	31.4**	12.6**	723.6**	2112.0**	835.4**	1.6**	0.04**	8.6**	7.6**	2131132**
Tester	4	7.7	3.5	6.2**	338.1**	2509.0**	1501.9**	0.9*	0.05**	7.2**	6.6**	1209950**
Environment (Env)	1	3938.6**	3668.0**	4.8**	7858.1**	64025.0**	24908.6**	0.0	0.53**	2.8	126.8**	12293602**
Line × Tester	36	6.8**	6.0**	1.1**	143.9**	232.0**	132.2**	0.4	0.03**	1.4**	1.4**	720021**
Line × Env	9	13.6**	3.6	11.1**	45.1	215.0*	122.0**	0.7*	0.02	0.2	4.1**	405992
Tester × Env	4	12.6**	13.0**	5.8**	178.7	549.0**	458.3**	0.2	0.02	2.0*	2.3**	1165093*
Line × Tester × Env	36	4.1	2.8	1.1**	94.6	76.0	53.9	0.4	0.01	0.3	1.0*	305056
Env(Rep)	4	29.1**	30.1**	1.3	575.0**	506.0**	258.9**	2.5**	0.04*	1.2	2.2**	1603855**
(Env × Rep)Blk	72	4.2	3.6	0.4	121.3**	104.0	47.4	0.5**	0.02*	1.3**	0.8*	371366
Residuals	124	3.2	2.6	0.6	74.3	88.0	43.5	0.3	0.01	0.7	0.5	342747

Significance codes: $p < 0.001$ = *** $p < 0.01$ = ** $p < 0.05$ = *. DTS = days to silking, DTA = days to anthesis, ASI = anthesis-silking interval, CC = chlorophyll content, PASP = plant aspect, EASP = ear aspect, PHGT = plant height, EHGT = ear height, EPP = ears per plant, SG = stay green, GY = grain yield

Table 4. Mean squares from combined analysis of variance under optimum nitrogen environments

Source	Df	DTS (days)	DTA (days)	ASI (days)	CC	PHGT (cm)	EHGT (cm)	SG (1-9)	EPP	PASP (1-9)	EASP (1-9)	GY (kg ha^{-1})
Hybrid	51	19.6**	18.6**	2.9**	326.4**	1442.4**	561.1**	1.3**	0.05	2.2**	1.6**	3064024**
Environment (Env)	2	1661.4**	2943.3**	188.7**	18056.4**	18482.5**	11761.1**	3.1**	0.18*	5.7**	4.7**	31600091**
Hybrid × Env	102	4.7**	4.4*	2.7**	77.7	207.2*	78.2*	0.7*	0.04	1.0**	0.7	749419*
Env(Rep)	6	21.4**	29.2**	1.8**	493.9**	1371.0**	633.1**	2.2**	0.10*	4.6**	1.4*	6380351**
(Env × Rep)Blk	108	4.7**	4.7**	0.6	87.5	174.3	66.9	0.5	0.04	0.6	0.6	793041*
Residuals	198	3.1	3.0	0.6	80.8	144.7	53.2	0.5	0.04	0.6	0.6	539830
Line	9	61.2**	59.3**	8.8**	1105.6**	3588.9**	1285.5**	3.5**	0.07	5.5**	4.9**	6095803**
Tester	4	3.1	4.7	6.8**	522.6**	4869.5**	2028.3**	1.5*	0.01	1.6*	2.5**	2772400**
Environment (Env)	2	1576.4**	2845.1**	191.5**	16923.2**	17064.9**	11217.5**	2.9**	0.18*	5.9**	4.8**	29662390**
Line × Tester	36	6.8**	7.0**	0.8	119.5	536.4**	243.5**	0.7*	0.06	1.5**	0.7	2059177**
Line × Env	18	6.9**	5.1	7.7**	118.0	169.9	74.1	1.3**	0.03	1.9**	1.2**	725880
Tester × Env	8	8.9**	8.3**	3.5**	113.2	460.4**	131.8**	0.9	0.02	2.0**	1.1	1889152**
Line × Tester × Env	72	3.5	3.9	1.1**	64.3	184.2	68.6*	0.5	0.04	0.7	0.5	661130
Env(Rep)	6	19.8**	26.4**	2.0**	496.6**	1434.3**	599.7**	2.6*	0.12*	4.7**	1.4*	6243772**
(Env × Rep)Blk	108	4.4*	4.6**	0.6	85.5	161.7	59.2	0.5	0.04	0.6	0.6	807712**
Residuals	186	3.2	3.1	0.6	83.0	141.0	49.8	0.5	0.04	0.6	0.6	528542

Significance codes: $p < 0.001$ = *** $p < 0.01$ = ** $p < 0.05$ = *. DTS = days to silking, DTA = days to anthesis, ASI = anthesis-silking interval, CC = chlorophyll content, PASP = plant aspect, EASP = ear aspect, PHGT = plant height, EHGT = ear height, EPP = ears per plant, SG = stay green, GY = grain yield.

The interaction of GCA-line, GCA-tester and SCA with the environment showed significant ($p < 0.05$) mean squares for the measured traits except DTA, CC, PHGT, EHGT, EPP and GY for GCA-line environment and then CC, SG, EPP, and EASP for GCA-tester environment. In the case of SCA environment, only ASI and EHGT showed significant ($p < 0.01$) mean squares (Table 4).

Specific combining ability (SCA) effect of hybrids.

Under low N, none of the cross combinations had a desirable SCA effect for GY. Even though the cross between CRIZEEL-W-261 and Tester 5 was the only combination that had a significant SCA effect it had a negative SCA value (Table 7). Cross combinations CRIZEEL-W-232 Tester 1 and CRIZEEL-W-232 Tester 4 under optimum conditions had significant positive SCA effects ($p < 0.01$) for GY (Table 8).

Gene action governing grain yield and other agronomic traits

Under low N, most of the traits had higher proportions of GCA than SCA except for EPP (60.58% SCA) and GY (51.90% SCA) which had higher proportion of SCA than GCA. For GY, GCA-line and GCA-tester accounted for about 38.41 % and 9.69%, respectively, of the total gene action. Also, SG characteristic which had a higher proportion of GCA (53.78%), had GCA-line and GCA-tester separately, contributing 43.41% and 10.37%, respectively (Fig. 1). Under optimum N, EPP (74.80%), and GY (52.92%) were the only traits that had higher proportions of SCA than GCA. The proportion of GCA-line and GCA-tester for GY under optimum conditions was 39.16% and 7.92%, respectively, of the total GCA effect (Fig. 2)

Genotypic variability

The hybrids generated from the line tester mating design had different degrees of variability. Under low N, PCV ranged from low (2.80%) for DTA to high (38.59%) for ASI. GCV also ranged from low (2.31%) for DTA to high (20.26%) for PASP. Broad sense heritability ranged from low (12.39%) for ASI to high (80.67%) for PHGT while narrow sense heritability ranged from low (12.39%) for ASI to high (63.77%) for PHGT. The genetic advance as a percentage of the mean (GAM) also ranged from low (3.78 %) for DTS to high (35.51%) for PASP. GY, EHGT, EASP and CC all had high GAM (Table 9).

Under optimum N, PCV ranged from low (2.79%) for DTS to high (25.16%) for ASI. GCV also ranged from low (2.40%) for DTS to intermediate (19.47%) for GY. Broad sense heritability ranged from low (11.31%) for ASI to high (87.94%) for EHGT while narrow sense heritability ranged from low (11.31%) for ASI to high (64.29%) for PHGT. GAM also ranged from low (4.26%) for DTS to high (34.35%) for GY. EHGT, CC and PASP all had high GAM (Table 10)..

Discussion

Combined analysis of variance

The significant hybrid mean squares observed for traits such as ASI, SG, EPP, GY, EASP and PASP under low N implies the hybrids evaluated in this research showed significant differences and expressed varying degrees of tolerance under low N, which could be attributed to the genetic make-up of the lines and testers used. This is in accordance with the findings from the work of Badu-Apraku *et al.* (2011), who further indicated that these traits have a strong correlation with genotype performance under stress conditions such as low N, and that these traits are very vital in maize improvement under stress conditions. Lima *et al.* (2022) also indicated that ASI is very important and directly influences GY. The significant line, tester and line tester effect recorded in this study for traits such as

Table 5. General combining ability effects of extra early maize inbred lines under low nitrogen

INBRED LINES	GY ($kg\ ha^{-1}$)	ASI (days)	CC	DTA (days)	DTS (days)	EASP (1-9)	EHGT (cm)	EPP	PASP (1-9)	PHGT (cm)	SG (1-9)
Lines	GCAl										
CRIZEEL-W-217	-95.65	0.43*	4.34	0.82	1.26**	-0.16	2.18	-0.02	-0.02	6.04*	0.07
CRIZEEL-W-219	52.55	-0.83**	-7.69**	-0.51	-1.34**	-0.33	5.78**	0.01	0.18	8.41**	0.04
CRIZEEL-W-222	-140.78	0.67**	1.56	-0.61	0.06	0.30	-5.76**	-0.04	0.78**	-6.51**	0.01
CRIZEEL-W-261	390.02**	-0.17	5.95**	-0.78	-0.94*	-0.73**	-2.31	0.04	-0.92**	-1.57	-0.56**
CRIZEEL-W-232	-481.89**	-0.50**	2.64	1.92**	1.42**	0.37	-8.03**	-0.08*	0.65*	-12.33**	-0.03
CRIZEEL-W-236	-82.05	0.37*	-1.55	-1.18**	-0.81	-0.16	-5.05**	-0.03	0.08	-7.37**	0.11
CRIZEEL-W-242	445.37**	0.23	3.35	0.52	0.76	-0.33	7.95**	0.02	-0.78**	8.91**	-0.09
CRIZEEL-W-208	72.43	-0.80**	-8.29**	-0.04	-0.84	-0.13	0.52	0.02	0.12	-0.58	-0.06
CRIZEEL-W-263	-71.46	-0.47*	2.29	-1.11	-1.58**	0.07	0.21	0.02	0.08	-7.05**	0.27
CRIZEEL-W-257	-88.52	1.07**	-2.60	0.96*	2.02**	1.10**	4.50**	0.04	-0.18	12.07**	0.24
SE	151.16	0.19	2.23	0.42	0.46	0.19	1.70	0.03	0.22	2.42	0.14
Testers	GCAt										
Tester 1	99.66	0.43**	-2.65	0.04	0.47	0.20	4.54**	-0.02	0.07	5.40**	0.06
Tester 2	-134.52	0.07	0.42	0.223	0.29	0.003	-1.33	-0.02	0.53**	-2.65	0.09
Tester 3	41.70	-0.22	1.31	0.04	-0.18	-0.20	-6.14**	-0.01	-0.30*	-7.58**	0.11
Tester 4	156.07	0.12	-2.11	-0.41	-0.29	0.42**	5.9**	0.05*	-0.32*	7.98**	-0.09
Tester 5	-162.91	-0.40**	3.03	0.11	-0.29	-0.43**	-2.76*	-0.01	0.02	-3.14	-0.16
SE	106.89	0.14	1.57	0.29	0.33	0.13	1.20	0.02	0.15	1.71	0.10

Significance codes: $p < 0.001$ = *** $p < 0.01$ = ** $p < 0.05$ = *. DTS = days to silking, DTA = days to anthesis, ASI = anthesis-silking interval, CC = chlorophyll content, PASP = plant aspect, EASP = ear aspect, PHGT = plant height, EHGT = ear height, EPP = ears per plant, SG = stay green, GY = grain yield, GCAl & GCAt = general combining ability of line and tester parents respectively.

Table 6. General combining ability effects of extra early maize inbred lines under optimum nitrogen

INBRED LINES	GY (kg ha^{-1})	ASI (days)	CC	DTA (days)	DTS (days)	EASP (1-9)	EHGT (cm)	EPP	PASP (1-9)	PHGT (cm)	SG (1-9)
Lines	GCAl										
CRIZEEL-W-217	-217.22	0.46*	2.95	0.76	1.22**	-0.20	2.11	-0.001	0.11	5.41	-0.12
CRIZEEL-W-219	70.54	-0.52**	-9.45**	-0.30	-0.82	-0.14	6.00**	0.006	0.04	8.13**	0.37*
CRIZEEL-W-222	39.34	0.50**	-1.65	-1.02*	-0.51	0.24	-3.62*	-0.072	0.40*	-3.01	0.28
CRIZEEL-W-261	401.03*	0.04	7.71**	-0.19	-0.16	-0.58**	-3.78*	0.053	-0.71**	-0.89	-0.58**
CRIZEEL-W-232	-715.97**	-0.65**	-0.61	2.61**	1.95**	0.55**	-8.35**	-0.034	0.22	-16.49**	0.19
CRIZEEL-W-236	84.27	0.08	0.76	-0.99*	-0.91	-0.11	-5.67**	-0.048	0.15	-8.09**	-0.01
CRIZEEL-W-242	516.67**	0.24	4.38	0.14	0.38	-0.29	8.27**	0.017	-0.51**	9.57**	-0.14
CRIZEEL-W-208	-283.47	-0.39*	-5.64*	-1.02*	-1.40**	0.11	0.72	0.028	0.26	0.32	0.22
CRIZEEL-W-263	-204.63	-0.30	2.74	-0.79	-1.09*	0.09	0.02	0.024	0.09	-6.72*	-0.14
CRIZEEL-W-257	309.44	0.55**	-1.19	0.81	1.35**	0.33	4.30*	0.027	-0.05	11.76**	-0.07
SE	187.71	0.19	2.35	0.45	0.46	0.19	1.82	0.05	0.20	3.07	0.18
Testers	GCAt										
Tester 1	63.64	0.424**	-2.24	-0.28	0.14	-0.16	3.81**	0.003	0.11	4.26*	-0.15
Tester 2	-23.86	-0.18	1.25	-0.04	-0.21	0.03	0.56	-0.009	0.03	0.19	0.16
Tester 3	165.95	-0.13	2.27	-0.06	-0.19	-0.11	-4.47**	0.004	-0.20	-5.95**	-0.11
Tester 4	84.08	0.12	-2.95	0.03	0.15	0.26	5.31**	0.017	-0.06	9.74**	0.03
Tester 5	-289.81*	-0.24	1.67	0.35	0.11	-0.02	-5.21**	-0.014	0.12	-8.23**	0.07
SE	132.73	0.13	1.66	0.32	0.32	0.14	1.29	0.04	0.14	2.16	0.12

Significance codes: $p < 0.001$ = *** $p < 0.01$ = ** $p < 0.05$ = *. DTS = days to silking, DTA = days to anthesis, ASI = anthesis-silking interval, CC = chlorophyll content, PASP = plant aspect, EASP = ear aspect, PHGT = plant height, EHGT = ear height, EPP = ears per plant, SG = stay green, GY = grain yield, GCAl & GCAt = general combining ability of line and tester parents respectively.

Table 7. Specific combining ability effects for grain yield of extra early maturing maize hybrids under low nitrogen

	Tester 1	Tester 2	Tester 3	Tester 4	Tester 5
CRIZEEL-W-217	-444.55	4.81	348.42	44.71	46.61
CRIZEEL-W-219	-382.20	-25.94	357.38	85.64	-34.88
CRIZEEL-W-222	28.83	-215.60	252.61	-166.08	100.24
CRIZEEL-W-261	638.61	-0.69	-117.45	278.36	-798.82*
CRIZEEL-W-232	513.27	-152.22	-368.63	415.03	-407.45
CRIZEEL-W-236	115.95	-224.78	-78.88	28.65	159.05
CRIZEEL-W-242	50.65	544.87	-228.16	-324.10	-43.27
CRIZEEL-W-208	-448.04	-111.69	-51.53	130.90	480.36
CRIZEEL-W-263	-310.94	-27.40	76.72	37.81	223.82
CRIZEEL-W-257	238.43	208.65	-190.49	-530.92	274.34
SE	338.01	338.01	338.01	338.01	338.01

Significance codes: $p < 0.001$ = *** $p < 0.01$ = ** $p < 0.05$ = *.

ASI, CC, EPP and GY implies that selection of genotypes for these traits will be promising since the genotypes had differences in their combining ability. This finding agrees with Ribeiro *et al*. (2020), who reported significant mean squares for GY, ASI and EPP but disagreed with Amegbor *et al.* (2022), who reported non-significant mean squares for ASI and EPP. The non-significance of line environment and line tester environment mean squares for GY, CC and EPP implies the gene effects for these traits were stable and thus, selecting an inbred line in any of the conditions would not come with an extra cost. This could be attributed to the stage of inbreeding (S6) in the lines used. This finding agrees with Ajala *et al.* (2020), who indicated non-significant line tester environment effect for GY but contradicts the findings of Ribeiro *et al.* (2020), who reported significant line tester environment mean squares for GY.

Combining ability of inbred lines

Inbred lines CRIZEEL-W-261 and CRIZEEL-W-242 was promising under low N since both recorded desirable GCA effect for GY. Furthermore, when used as female parents in hybridization or current selection programme, these two inbred lines would readily pass on favourable genes controlling GY to their offspring. More so, the advantage of a desirable GCA effect for SG, EASP and CC shown by inbred line CRIZEEL-W-261 suggested its high probability of transmitting genes governing these traits to its progenies in a breeding programme. SG is an important agronomic trait that allows plants to maintain their photosynthetic activity and improve the grain-filling process even under stress (Borrell *et al.,* 2014; Zhang *et al.,* 2019). In

Table 8. Specific combining ability effects for grain yield of extra early maturing maize hybrids under optimum nitrogen.

x	Tester 1	Tester 2	Tester 3	Tester 4	Tester 5
CRIZEEL-W-217	-623.59	204.37	179.31	142.00	97.91
CRIZEEL-W-219	-693.39	-112.59	436.43	-268.27	637.81
CRIZEEL-W-222	-47.76	-81.96	79.05	24.36	26.31
CRIZEEL-W-261	340.85	311.60	-384.83	187.5824	-455.21
CRIZEEL-W-232	1039.98*	-311.89	-1028.53*	1117.49*	-817.05
CRIZEEL-W-236	-278.42	-26.47	72.36	128.31	104.22
CRIZEEL-W-242	-107.37	266.38	171.43	-546.25	215.81
CRIZEEL-W-208	139.048	-379.38	345.84	218.25	-323.76
CRIZEEL-W-263	10.20	32.03	-60.37	-390.73	408.87
CRIZEEL-W-257	220.45	97.91	189.30	-612.75	105.08
SE	419.74	419.74	419.74	419.74	419.74

Fsignificance codes: $p < 0.001$ = *** $p < 0.01$ = ** $p < 0.05$ = *.

addition to yield improvement and tolerance against abiotic stress, SG also confers a greater number of grain per ear, enhanced resistance to stem lodging (Luche *et al.,* 2015; Adeyanju *et al.,* 2016) and increased tolerance to diseases and pests (Howard & Smart, 1993). The desirable GCA for GY recorded by inbred line CRIZEEL-W-261 under low and optimum N could be associated with its desirable GCA for most of the traits proposed by Banziger *et al.* (1997), Banziger *et al.* (2000), and Badu-Apraku *et al.* (2011) (i.e. SG, EASP and PASP) for indirect selection and improvement in GY. This further indicates that CRIZEEL-W-261 will be a good source of genes for maize GY improvement.

Gene action

The significant proportions of GCA-line, GCA-tester and SCA variations observed under low N and optimum N suggested both additive and non-additive gene actions played a role in the expression of the traits studied in this research. Under both low and optimum N, the eminence of SCA in the expression of GY and EPP suggest these two traits were under the influence of non-additive gene action and that early generation testing would not be effective. Unsurprisingly, both GY and EPP were under the influence of non-additive gene action because EPP determines the degree of barrenness of a genotype under stress and has direct effect on GY (Badu-Apraku *et al*., 2011). The eminence of non-additive gene

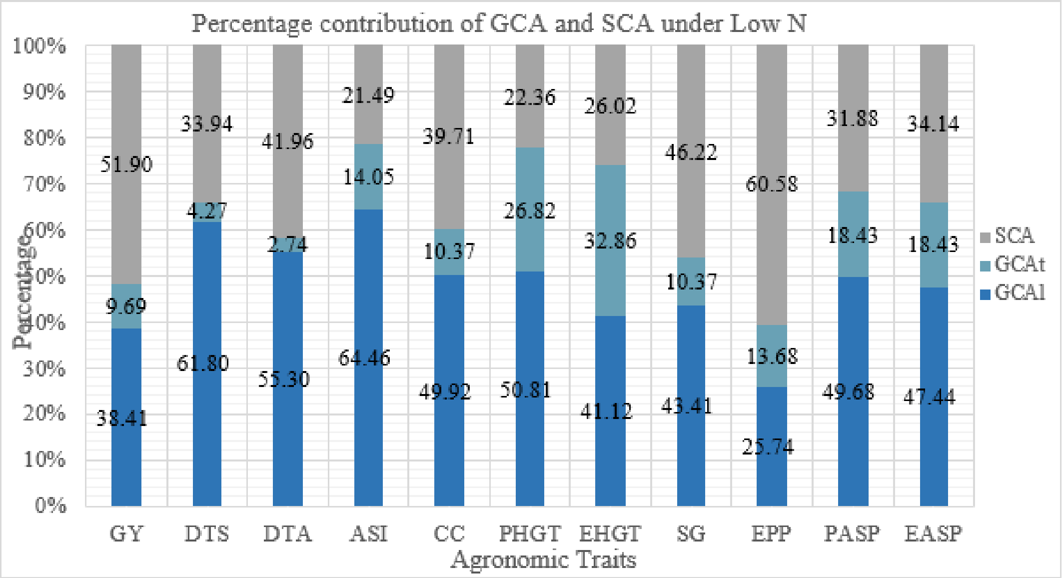

Figure 1. Gene Action for Grain Yield and Other Agronomic Traits Under Low N; DTS = days to silking, DTA = days to anthesis, ASI = anthesis-silking interval, CC = chlorophyll content, PASP = plant aspect, EASP = ear aspect, PHGT = plant height, EHGT = ear height, EPP = ears per plant, SG = stay green, GY = grain yield, GCAl & GCAt = general combining ability of line and tester parents respectively.

action for grain yield under low N in this research is consistent with the report of previous works by Betran *et al.* (2003), Meseka *et al.* (2006), and Mafouasson (2014) who also reported the eminence of non-additive gene action for GY under low N. The additive (GCA) variance under low and optimum N had the effect of GCA-line being more pronounced than the effect of GCA-tester, implying the action of maternal effect in these traits.

Although the preponderance of non-additive gene action for GY under optimum N is consistent with the findings by Wegary *et al.* (2014), who also showed that non-additive gene action in GY were more pronounced under low and optimum N, these findings contradict the results of Mafouasson (2014), Ifie *et al.* (2015), Obeng-Bio *et al.* (2019), and Amegbor *et al.* (2022), all of whom reported additive gene action for GY under optimum N. This contradiction may have resulted from the amount of genes controlling GY in the various germplasms. Again, the significance and eminence of non-additive gene action governing EPP under low N contradicts the findings of Ifie *et al.* (2015) and Obeng-Bio *et al.* (2019), who reported additive gene action for EPP under low N. The significance of GCA-line mean squares, coupled with the higher proportion of GCA-line than GCA-tester in controlling SG implies SG is probably influenced by maternal effect. Hence, female lines with desirable GCA for SG would improve GY.

Genotypic variability

The high PCV and moderate GCV observed for GY, ASI, PASP and EASP under low and optimum N suggests that there is adequate variation within the population to enable improvement under low N. Thus, a good selection or genetic gain could be made from the population used in this study. This finding is consistent with the results from the work of Tesfaye *et al.* (2021), who also reported a moderate GCV among hybrids developed using the same mating design (i.e. line tester). The low difference in magnitude between the GCV and PCV for GY, CC and PASP further supports the claim that, the genotypes used were stable in terms of the performance of these traits. However, the high difference between PCV and GCV observed for ASI implies that the environments greatly influenced this trait and, subsequently, the success of pollination and seed set. These findings contradict the findings of Ige *et al.* (2019) who reported high GCV coupled with low difference between GCV and PCV for GY and ASI under similar contrasting environments. The low GCV and PCV for DTS and DTA under low and optimum N conditions, imply little variation for the two traits. This is very evident from the fact that, all the inbred lines used were in the same maturity group (extra early maturity group).

The low to moderate narrow-sense heritability recorded for majority of the traits under low N except for PHGT, EHGT and PASP suggests that additive gene action played little role in the expression of these traits. The low, narrow sense heritability recorded by GY and EPP supports the earlier findings that non-additive gene action controlled these traits under low N in this study. The relatively higher narrow-sense

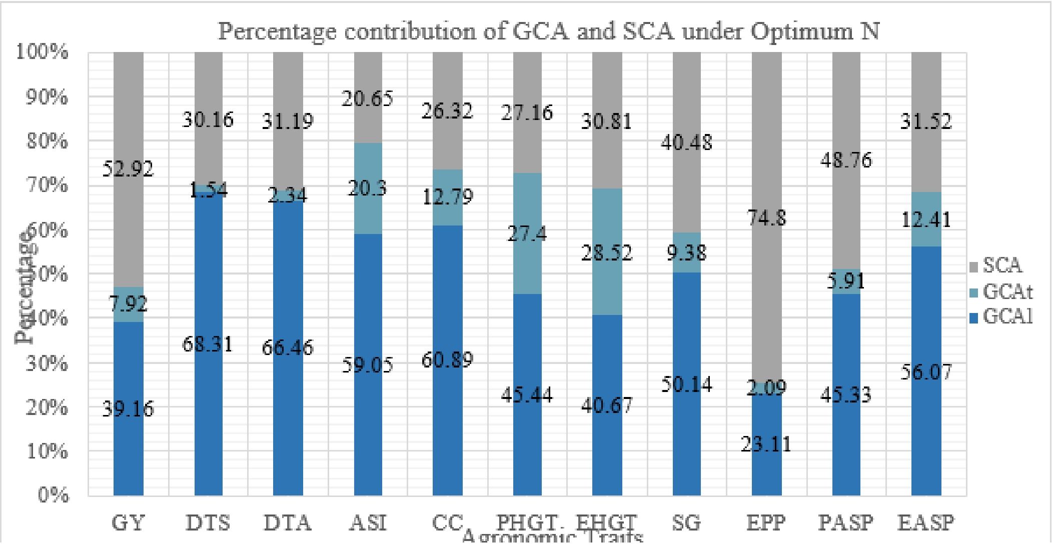

Figure 2. Gene Action for Grain Yield and Other Agronomic Traits Under Optimum N; DTS = days to silking, DTA = days to anthesis, ASI = anthesis-silking interval, CC = chlorophyll content, PASP = plant aspect, EASP = ear aspect, PHGT = plant height, EHGT = ear height, EPP = ears per plant, SG = stay green, GY = grain yield, GCAl & GCAt = general combining ability of line and tester parents respectively.

heritability recorded for a number of the traits under optimum N to that under low N conditions supports the fact that the low N environments had a slightly greater influence on the heritability of these traits, which could be due to the extent of low N stress imposed. This finding agrees with the results of Ige *et al.* (2019), who also reported a low heritability for GY under low N.

The character with high heritability should be accompanied by high genetic advance to arrive at a more reliable conclusion (Arunkumar *et al.,* 2018). Jilo *et al.* (2018), had previously suggested the simultaneous consideration of heritability estimates and GA because high heritability may not always be associated with high GA. The high GAM recorded for GY under both low and optimum N condition shows that GY will respond to selection. This is further supported by the fact that other traits such as CC, EASP and PASP also had high GAM, which may have indirectly improved the GY of maize under low N. This agrees with the findings from the work of Ige *et al.* (2019), who also reported high GAM for GY under low N. Although a high GAM was recorded for GY, the low narrow sense heritability implies that non-additive gene action governed GY. As such, heterosis breeding would be most appropriate for GY in this population.

Table 9. Genotypic variability parameters of extra early maize hybrids under low nitrogen.

Traits	Population Mean	Range Min	Range Max	PCV (%)	GCV (%)	H^2b (%)	h^2n (%)	GA	GAM (%)
ASI	2.08	0.67	3.67	38.59	13.58	12.39	12.39	0.21	9.85
CC	33.51	16.77	46.22	20.36	16.35	64.49	45.31	9.06	27.05
DTA	49.32	46.83	53.17	2.80	2.31	68.02	43.91	1.93	3.92
DTS	51.41	48.83	55.33	3.15	2.40	58.22	42.25	1.94	3.78
EASP	3.12	1.83	5.17	23.13	15.46	44.67	31.78	0.66	21.29
EHGT	59.75	34.93	73.97	13.83	11.87	73.66	54.56	12.54	20.99
EPP	0.89	0.65	1.05	8.31	5.76	48.07	14.31	0.07	8.23
GY	1653.26	630.73	2816.02	25.52	19.75	59.88	25.39	520.47	31.48
PASP	3.17	1.67	4.83	23.81	20.26	72.41	56.03	1.12	35.51
PHGT	137.73	102.40	154.30	8.57	7.70	80.67	63.77	19.62	14.24
SG	2.98	1.83	3.67	11.46	6.76	34.83	31.00	0.25	8.22

DTS = Days to Silking, DTA = Days to Anthesis, ASI = Anthesis-Silking Interval (days), CC = Chlorophyll Content, PASP = Plant Aspect (1-9), EASP = Ear Aspect (1-9), PHGT = Plant Height (cm), EHGT = Ear Height (cm), EPP = Ears per Plant, SG = Stay Green Characteristics (1-9), GY = Grain Yield (kgha^{-1})

Conclusion

CRIZEEL-W-242 and CRIZEEL-W-261 had desirable GCA effect for GY under low N, with CRIZEEL-W-261 being a good genotype for other traits such as SG, CC, EASP and PASP. None of the hybrids had desirable SCA effect for GY under low N in this study. Non-additive gene action controlled GY and EPP under low and optimum N. In contrast, additive gene action controlled the other agronomic traits under low and optimum N. Moderate GCV was observed for GY under low and optimum N whereas high GAM was observed for traits such as GY, EASP, PASP and CC, which assures good genetic gain or improvement from selection. The study provided relevant information on the selected newly developed inbred lines by CSIR-CRI.

Conflict of interest.

The authors declare there are no conflicts of interest.

Table 10. Genotypic variability parameters of extra early maize hybrids under optimum nitrogen

Traits	Population Mean	Range Min	Range Max	PCV (%)	GCV (%)	H^2b (%)	h^2n (%)	GA	GAM (%)
ASI	2.28	1.22	3.78	25.16	8.46	11.31	11.31	0.13	5.86
CC	44.49	31.12	58.69	14.16	12.22	74.53	63.47	9.67	21.73
DTA	48.01	45.78	52.67	2.91	2.51	74.39	58.82	2.14	4.45
DTS	50.30	47.56	54.44	2.79	2.40	74.05	58.06	2.14	4.26
EASP	2.91	2.00	4.00	15.00	11.44	58.09	49.38	0.52	17.96
EHGT	57.46	35.96	69.89	14.56	13.66	87.94	60.20	15.16	26.39
EPP	0.86	0.59	1.31	9.04	4.85	28.74	6.29	0.05	5.35
GY	2525.94	769.34	3446.21	22.73	19.47	73.35	26.92	867.55	34.35
PASP	2.80	1.67	4.22	18.25	13.70	56.34	23.95	0.59	21.18
PHGT	130.02	90.49	150.47	10.19	9.49	86.76	64.29	23.68	18.22
SG	2.27	1.33	3.11	17.05	11.83	48.11	33.11	0.38	16.90

DTS = Days to Silking, DTA = Days to Anthesis, ASI = Anthesis-Silking Interval (days), CC = Chlorophyll Content, PASP = Plant Aspect (1-9), EASP = Ear Aspect (1-9), PHGT = Plant Height (cm), EHGT = Ear Height (cm), EPP = Ears per Plant, SG = Stay Green Characteristics (1-9), GY = Grain Yield (kgha^{-1})

Ethical standards

Not applicable.

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References

Abdulai, S., Nkegbe, P. K. & Donkor, S. A. 2017. Assessing the economic efficiency of maize production in northern Ghana. *Ghana Journal of Development Studies* 14(2): 123 - 145. https://doi.org/10.4314/gjds.v14i2.16

Abebe, T., Alamerew, S. & Tulu, L. 2017. Genetic variability, heritability and genetic advance for yield and its related traits in rainfed lowland rice (Oryza sativa L.) genotypes at Fogera and Pawe, Ethiopia. *Advances in Crop Science and Technology* 5(2): 272.

Acquaah, G. 2012. Principles of Plant Genetics and Breeding (2nd ed., Issue July). WILEY-BLACKWELL.

Adebayo, M. A., Menkir, A., Blay, E., Gracen, V. & Danquah, E. 2017. Combining ability and heterosis of elite drought-tolerant maize inbred lines evaluated in diverse environments of lowland tropics. *Euphytica* 213(43): 1 - 12. https://doi.org/10.1007/s10681-017-1840-5

Adeyanju, A., Yu, J., Little, C., Rooney, W., Klein, P., Burke, J. & Tesso, T. 2016. Sorghum RILs segregating for stay-green QTL and leaf dhurrin content show differential reaction to stalk rot diseases. *Crop Science* 56(6): 2895 - 2903.

Adu, G. B., Abdulai, M. S., Alidu, H., Nustugah, S. K., Buah, S. S., Kombiok, J. M., Obeng-Antwi, K., Abudulai, M. & Etwire, P. M. 2014. Recommended production practices for maize in Ghana. Accra: AGRA/CSIR.

Ajala, S. O., Olayiwola, M. O., Job, A. O., Olaniyan, A. B. & Gedil, M. 2020. Assessment of heterotic patterns of tropical low-nitrogentolerant maize (*Zea mays* L.) inbred lines using testcross performance, morphological traits and SNP markers. *Plant Breeding* 139(6): 1113-1124. https://doi.org/10.1111/pbr.12866

Akinwale, R. O., Badu-Apraku, B., Fakorede, M. A. B. & Vroh-Bi, I. 2014. Heterotic grouping of tropical early-maturing maize inbred lines based on combining ability in Striga-infested and Striga-free environments and the use of SSR markers for genotyping. *Field Crops Research* 156: 48 - 62. https://doi.org/10.1016/j.fcr.2013.10.015

Amegbor, I. K., Abe, A., Adjebeng-Danquah, J. & Adu, G. B. 2022. Genetic analysis and yield assessment of maize hybrids under low and optimal nitrogen environments. *Heliyon* 8(3): e09052. https://doi.org/10.1016/j.heliyon.2022.e09052

Angelucci, F. 2012. Analysis of incentive and disincentive for maize in Ghana. Draft Version. In Technical notes series, MAFAP, FAO (Issue October).

Aravind, K., Banumathy, S., Vanniarajan, C., Arunachalam, P., Ilamaran, M. & Kalpana, K. 2019. DUS characterization and genetic variability studies of rice mutants. *Electronic Journal of Plant Breeding* 10(2): 451 - 461.

Arisede, C., Mainassara, Z. A., Jill, C., Amsal, T., Cosmos, M., Bish, D., Benhildah, M., Mike, O. & Maruthi, P. B. 2020. Low-N stress tolerant maize hybrids have higher fertiliser N recovery efficiency and reduced N-dilution in the grain compared to susceptible hybrids under low N conditions. *Plant Production Science* 23(4):417 - 426. https://doi.org/10.1080/1343943X.2020.1746188

Arunkumar, B., Gangapp, E., Rames, S., Savithramma, D. L., Nagaraju, N. & Lokesha, R. 2018. Genetic potential, variability, heritability and genetic advance of grain yield and its component traits in maize (*Zea mays* L.) inbreds. *International Journal of Chemical Studies* 6(6): 2015 - 2018.

Awata, L. A. O., Tongoona, P., Danquah, E., Ifie, B. E. & Marchelo-Dragga, P. W. 2018. Common mating designs in agricultural research and their reliability in estimation of genetic parameters. IOSR *Journal of Agriculture and Veterinary Science* 11(7): 16 - 36. https://doi.org/10.9790/2380-1107021636

Badu-Apraku, B., Akinwale, R. O., Ajala, S. O., Menkir, A., Fakorede, M. A. B. & Oyekunle, M. 2011. Relationships among traits of tropical early maize cultivars in contrasting environments. *Agronomy Journal.* 103(3): 717 - 729. https://doi.org/10.2134/agronj2010.0484

Badu-Apraku, B., Fakorede, M. A., Oyekunle, M., Yallou, G. C., Obeng-Antwi, K., Haruna, A., Usman, I. S. & Akinwale, R. O. 2015. Gains in grain yield of early maize cultivars developed during three breeding eras under multiple environments. *Crop Science* 55(2): 527 - 539. https://doi.org/10.2135/cropsci2013.11.0783

Badu-Apraku, B., Oyekunle, M., Akinwale, R. O. & Lum, F. A. 2011. Combining ability of early-maturing white maize inbreds under stress and nonstress environments. *Agronomy Journal* 103(2): 544 - 557. https://doi.org/10.2134/agronj2010.0345

Bänziger, M., Betrán, F. J. & Lafitte, H. R. 1997. Efficiency of high-nitrogen selection environments for improving maize for low-nitrogen target environments. *Crop Science* 37(4): 1103 - 1109.

Bationo, A., Joseph, O. F. & Kwaw, A. 2018. Assessment of soil fertility status and integrated soil fertility management in Ghana. In *Improving the Profitability, Sustainability and Efficiency ofNutrients Through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems* (Vol. 1, pp. 13 - 39). Springer International Publishing. https://doi.org/10. 1007/978-3-319-58789-9_7

Bates D., Maechler, M., Bolker, B. & Walker, S. 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 67(1): 1 - 48. doi:10.18637/jss.v067.i01.

Bello, B. O., Ige, S. A., Azeez, M. A., Afolabi, M. S., Abdulmaliq, S. Y. & Mahamood, J. 2012. Heritability and genetic advance for grain yield and its component characters in maize (*Zea mays* L.). *International Journal of Plant Research* 2(5): 138 - 145. https://doi.org/10.5923/j.plant.20120205.01

Betrán, F. J., Beck, D., Bänziger, M. & Edmeades, G. O. 2003. Genetic analysis of inbred and hybrid grain yield under stress and nonstress environments in tropical maize. *Crop Science* 43(3): 807 - 817. https://doi.org/10.2135/cropsci2003.8070

Bhateria, S., Sood, S. P. & Pathania, A. 2006.

Genetic analysis of quantitative traits across environments in linseed (*Linum usitatissimum* L.). *Euphytica* 150(1): 185 - 194.

Bolaños, J. & Edmeades, G. O. 1996. The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. *Field Crops Research* 48(1): 65 - 80.

Borrell, A. K., Mullet, J. E., George-Jaeggli, B., van Oosterom, E. J., Hammer, G. L., Klein, P. E. & Jordan, D. R. 2014. Drought adaptation of stay-green sorghum is associated with canopy development, leaf anatomy, root growth, and water uptake. *Journal of Experimental Botany* 65(21): 6251 - 6263.

Bremner, J.M. & Mulvaney, C.S. 1982. Nitrogen-total. In: Page AL *et al.* (eds) Methods of soil analysis. Part 2. 2nd ed. Agronomy Monograph 9. ASA and SSSA, Madison, pp 595 - 624

Burton, G. W. 1951. Quantitative inheritance in pearl millet *(Pennisetum glaucum)* 1. *Agronomy Journal* 43(9): 409 - 417.

Burton, G. W. & Devane, de E. H. 1953. Estimating heritability in tall fescue *(Festuca arundinacea)* from replicated clonal material 1. *Agronomy Journal* 45(10): 478 - 481.

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C. & Prasanna, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security* 5(3): 345 - 360. https://doi.org/10.1007/ s12571-013-0256-x

Comstock, R. E. & Robinson, H. F. 1952. Estimation of the average dominance of genes (Issue 1, pp. 494 - 516).

Dhliwayo T., Pixley, K., Menkir, A. & Warburton, M. 2009. Combining ability, genetic distances, and heterosis among elite CIMMYT and IITA tropical maize inbred lines. *Crop Science* 49(4): 1201 - 1210. https://doi.org/10.2135/cropsci2008.06.0354

Effa, E. B., Uwah, D. F., Iwo, G. A., Obok, E. E. & Ukoha, G. O. 2012. Yield performance of popcorn (*Zea mays* L. everta) under lime and nitrogen fertilisation on an acid soil. *Journal of Agricultural Science* 4(10): 1 - 12.

FAO. 2020. Food and agriculture organization of the United Nations. Rome, URL: Http://Faostat. Fao. Org.

FAO 2017. The future of food and agriculture: trends and challenges. Retrieved from http://www.fao.org/publications%0fao.org/3/a-i6583e.pdf%0. Accessed on 7th August, 2021.

Fasahat, P., Rajabi, A., Rad, M. J. & Derera, J. 2016. Principles and utilisation of combining ability in plant breeding. *Biometrics and Biostatistics International Journal* 4(1): 1 - 24. https://doi.org/10.15406/bbij.2016.04.00085

Hallauer, A. R., Carena, M. J. & Miranda F. J. B. 2010. Quantitative genetics in maize breeding. In *Quantitative Genetics in Maize Breeding* https://doi.org/10.1007/978-1-4419-0766-0

Henao, J. & Baanante, C. 2006. Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development.Howard, T. & Smart, C. M. 1993. Crops that stay green 1. *Annals of Applied Biology* 123(1): 193 - 219.

Ifie, B. E., Badu-Apraku, B., Gracen, V. & Danquah, E. Y. 2015. Genetic analysis of grain yield of IITA and CIMMYT early-maturing maize inbreds under Striga-infested and low soil-nitrogen environments. *Crop Science* 55(2): 610 - 623. https://doi.org/10.2135/cropsci2014.07.047

OIge, S. A., Bello, O., Charity, A., &

Stephen, A. 2019. Estimation of genetic variation, heritability and genetic advance for yield and agronomic traits correlation of some low nitrogen tolerance maize *(Zea mays)* varieties in the tropics. *Research on Crops* 21(3): 595 - 603. https://doi.org/10.31830/2348-7542.2020.093

Jaiswal, P., Banshidhar, S. R. A. & Singh, R. 2019. Estimation of genetic parameters for yield related traits and grain zinc concentration in biofortified inbred lines of maize (*Zea mays* L.). *The Pharma Innovation Journal* 8(3): 87 - 91.

Jilo, T., Tulu, L., Birhan, T. & Beksisa, L. 2018. Genetic variability, heritability and genetic advance of maize (*Zea mays* L.) inbred lines for yield and yield related traits in southwestern Ethiopia. *Journal of Plant Breeding and Crop Science* 10(10): 281 - 289.

Johnson, H. W., Robinson, H. F. & Comstock, R. E. 1955. Estimates of genetic and environmental variability in soybeans 1. *Agronomy Journal* 47(7): 314 - 318.

Kempthrone, O. 1957. An introduction to genetic statistics. John Willey and Sons., New York.Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. 2017. Lmertest package: tests in linear mixed effects models. *Journal of Statistical Software* 82(13): 1 - 26.

Lima, D. C., Leon1, N. de. & Kaeppler Shawn M. 2022. Utility of anthesis-silking interval information to predict grain yield under water and nitrogen limited conditions. https://doi.org/10.1002/csc2.20854.Logrono,

M. L. & Lothrop, J. E. 1996. Impact of drought and low nitrogen on maize production in Asia. Developing drought-and Low N-tolerant maize. Proceedings of a Symposium, (pp. 3943).

Luche, H. de S., Silva, J. A. G. da, Maia, L. C. da, & Oliveira, A. C. de. 2015. Stay-green: a potentiality in plant breeding. *Ciência Rural* 45: 1755 - 1760.

Macauley, H. 2015. Cereal Crops: Rice, Maize, Millet, Sorghum, Wheat; Background paper. Conference on Feeding Africa, 2123 October 2015. An Action Plan for African Agricultural Transformation, 136.

Mafouasson, A. H. N. 2014. Genetic analysis of tolerance to low soil nitrogen in intermediate maturing maize (*Zea mays* L.) inbred lines. PhD Thesis, University of Ghana Legon, West Africa Centre for Crop Improvement/School of Agriculture/ College of Agriculture and Consumer Scienc. UG Space, pp 64-82.

Mageto, E. K., Lee, M., Dhliwayo, T., Palacios-Rojas, N., Vicente, F. S., Burgueño, J. & Hallauer, A. R. 2020. An evaluation of kernel zinc in hybrids of elite Quality Protein Maize (QPM) and Non-QPM inbred lines adapted to the tropics based on a mating design. *Agronomy* 10(695): 118. https://doi.org/10.3390/agronomy10050695

Meseka, S. K., Menkir, A., Ibrahim, A. E. S. & Ajala, S. O. 2006. Genetic analysis of performance of maize inbred lines selected for tolerance to drought under low nitrogen. *Maydica* 51(3): 487 - 495.

Mosier, A. R., Syers, J. K. & Freney, J. R. 2005. Global assessment of nitrogen fertiliser: The SCOPE/IGBP nitrogen fertiliser rapid assessment project. Science in China Series C: *Life Sciences* 48(2): 759 - 766.

Nasser, L. M., Badu-Apraku, B., Gracen, V. E. & Mafouasson, H. N. A. 2020. Combining ability of early-maturing yellow maize inbreds under combined drought and heat stress and well-watered environments. *Agronomy* 10(10): 1558. https://doi.org/10.3390/agronomy10101585

Nelimor, C., Badu-Apraku, B. & Tetteh, A. Y. 2020. Assessing the potential of extra-early maturing landraces for improving tolerance to drought, heat, and both combined stresses in maize. *Agronomy* 10(318): 1 - 23.

Obeng-Bio, E., Badu-Apraku, B., Ifie, B. E., Danquah, A., Blay, E. T. & Annor, B. 2019. Genetic analysis of grain yield and agronomic traits of early provitamin A quality protein maize inbred lines in contrasting environments. *Journal of Agricultural Science* 157(5): 413 - 433. https://doi.org/10.1017/S0021859619000753

Ogunniyan, D. J., Ojo, D. K., Olakojo, S. A. & Talabi, O. A. 2019. Diallel analysis of maize inbred lines for agronomic traits in nitrogen stress and optimal conditions. *Ghana Journal of Agricultural Science* 54(1): 10 - 23. https://doi.org/10.4314/gjas.v54i1.2

Okweche, S. I., Ogunwolu, E. O. & Adeyemo, M. O. 2013. Parameters, interrelationships with yield and use of carbofuran to control stem borers in maize (*Zea mays* L.) at Makurdi in the Nigerian Southern Guinea Savanna. *Greener Journal of Agricultural Sciences* 3(10): 702 - 708. https://doi.org/10.15580/gjas.2013.3.170913845

Oyekunle, M. & Badu-Apraku, B. 2014. Genetic analysis of grain yield and other traits of early-maturing maize inbreds under drought and well-watered conditions. *Journal of Agronomy and Crop Science* 200(2): 92 - 107. https://doi.org/10.1111/jac.12049

Oyekunle, M., Badu-Apraku, B., Hearne, S. & Franco, J. 2015. Genetic diversity of tropical early-maturing maize inbreds and their performance in hybrid combinations under drought and optimum growing conditions. *Field Crops Research* 170: 55 - 65. https://doi.org/10.1016/j.fcr.2014.10.005

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Reddy, B. R., Reddy, D. S., Reddaiah, K. & Sunil, N. 2013. Studies on genetic variability, heritability and genetic advance for yield and quality traits in tomato (*Solanum lycopersicum* L.). *International Journal of Current Microbiology and Applied Sciences* 2(9): 238 - 244.

Ribeiro, P. F., Badu Apraku, B., Gracen, V., Danquah, E. Y., Afriyie-Debrah, C., Obeng-Dankwa, K. & Toyinbo, J. O. 2020. Combining ability and testcross performance of low N tolerant intermediate maize inbred lines under low soil nitrogen and optimal environments. *Journal of Agricultural Science* 158(5): 351 - 370. https://doi.org/10.1017/S0021859620000702

Ribeiro, P. F., Badu-Apraku, B., Gracen, V. E., Danquah, E. Y., Ewool, M. B., Afriyie-Debrah, C. & Frimpong, B. N. 2017. Farmers Perception of Low Soil Fertility and Hybrid Maize and the Implications in *Plant Breeding. Sustainable Agriculture Research* 6(2): 1 - 6. https://doi.org/10.5539/sar.v6n2p1

Robinson, H. F., Comstock, R. E. & Harvey, P. H. 1949. Estimates of heritability and the degree of dominance in corn. *Agronomy Journal* 49(8): 353 - 359. doi.org//10.2134//agronj1949.00021962004100080005x

Roychowdhury, R. & Randrianotahina, J. 2011. Evaluation of genetic parameters for agro-metrical characters in carnation genotypes. *African Crop Science Journal* 19(3): 183 - 188.

Samadia, D. K. (2005). Genetic variability studies in Lasora (Cordia myxa Roxb.). *Indian Journal of Plant Genetic Resources* 18(3): 236 - 240.

Singh, R. K. & Chaudhary, B. D. 1985. Biometrical methods in quantitative genetic analysis.

Sivasubramanian, S. & Madhavamenon, P. 1973. Genotypic and phenotypic variability in rice. *Madras Agriculture Journal* 60(913): 1093 - 1096.

Smalley, M. D., Daub, J. L. & Hallauer, A. R. 2004. Estimation of heritability in maize by parent-offspring regression. *Maydica* 49(3): 221 - 229.

Su, W., Ahmad, S., Ahmad, I. & Han, Q. 2020. Nitrogen fertilisation affects maize grain yield through regulating nitrogen uptake, radiation and water use efficiency, photosynthesis and root distribution. *PeerJ* 8(e10291): 1 - 21. https://doi.org/10.7717/peerj.10291

Tandzi, L. N., & Mutengua, C. S. 2020. Agronomy estimation of maize (*Zea mays* L.) yield per harvest area : appropriate methods. *Agronomy* 10(29): 118.

Tesfaye, D., Abakemal, D. & Habte, E. 2021. Genetic variability, heritability and genetic advance estimation of highland adapted maize (*Zea mays* L.) genotypes in Ethiopia. *Journal of Current Opinion in Crop Science* 2(2): 184 - 191.

Tetteh, F. M., Quansah, G. W., Frempong, S. O., Nurudeen, A. R., Atakora, W. K. & Opoku, G. 2017. Optimizing fertiliser use within the context of integrated soil fertility management in Ghana. In Fertilizer use optimization in sub-Saharan Africa (pp. 6781). CABI

GB.Wegary, D., Vivek, B. S. & Labuschagne, M. T. 2014. Combining ability of certain agronomic traits in quality protein maize under stress and nonstress environments in Eastern and *Southern Africa. Crop Science* 54(3): 1004 - 1014.

Wongnaa, C. A., Bakang, J.-E. A., Asiamah, M., Appiah, P. & Asibey, J. K. 2021). Adoption and compliance with Council for Scientific and Industrial Research recommended maize production practices in Ashanti region, Ghana. *World Journal of Science, Technology and Sustainable Development* 18(4): 438 - 456. https://doi.org/10.1108/wjstsd-03-2021-0035

Zhang, J., Fengler, K. A., Van Hemert, J. L., Gupta, R., Mongar, N., Sun, J., Allen, W. B., Wang, Y., Weers, B. & Mo, H. 2019. Identification and characterization of a novel stay-green QTL that increases yield in maize. *Plant Biotechnology Journal* 17(12): 2272 - 2285.