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Combining Ability for Grain Yield and Popping Expansion in Popcorn (*Zea mays everta*) Hybrids

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ABSTRACT

The poor yield and popping quality underscore the need for indigenous germplasm improvement. This study aimed to find parents with high general combining ability (GCA) and specific combining ability (SCA) for yield and popping traits. A Line × Tester design was used to hybridize 9 inbred lines and 4 testers, resulting in 36 hybrids. These hybrids were tested in field trials across three agro-ecologies of Nigeria in 2019 and 2020. Three replicates of 5 trials were set up in a Randomized Complete Block Design, and an air popper was used for popping tests. The study showed that crosses differed significantly at $\rho \leq 0.01$ for all agronomic traits except ears per plant (EPP) while the line × tester interaction was highly significant for all agronomic traits, except anthesis-silking interval and EPP. Parental lines V7, V9 and M3 had positive and significant GCA effect at $\rho \leq 0.01$ for grain yield, while V8, V9, and M3 were positive and significant at $\rho \leq 0.01$ for popping volume. Ten Hybrids had positive and significant SCA effect for grain yield and popping volume. Non-additive gene effects were more important in the inheritance of most agronomic studied traits, as evidenced by the line × tester interaction contributing a larger proportion (52 – 86%) to hybrid variance compared to the line effects (10.51 - 44.80%) and tester effects (0.20 to 15.24%). The study identified parental lines V7, V9, and M3 as good general combiners, whereas M1×V1, M1×V3, M1×V4, M1×V6, M1×V7, M3×V4, M3×V5, M4×V7, M4×V8 and M4×V9 were considered for their superior specific combining ability across various environments, particularly for grain yield and popping volume.

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Introduction

Combining ability is known as the ability of parental lines to complement together effectively during hybridization to pass advantageous genes to their offspring. It is an important concept in plant breeding that informs the selection of parental lines for hybrid development (Aboderin et al. 2024). Combining ability is typically classified into two components: General Combining Ability (GCA) and Specific Combining Ability (SCA), both of which are essential for population development and inbred line evaluation (Iken and Olakojo 2006; Aboderin et al. 2024). GCA denotes the mean contribution of a genotype to the performance of its hybrids, largely governed by additive gene action across a range of crosses. In contrast, SCA reflects the deviation of certain hybrid combinations from the expected performance based on the parental averages, often influenced by dominant or epistatic gene effects (Sprague and Tatum, 1942). While GCA is important for identifying superior parental lines, SCA provides insight into the performance potential of specific hybrids.

Several studies highlighted the differing genetic bases for key traits in popcorn. Most studies reported a predominance of additive gene effects for grain yield, whereas popping volume was influenced by additive as well as non-additive gene effects (Pereira and Amaral Júnior, 2001; Silva et al., 2010; Schwantes et al., 2018). Iken and Olakojo (2006), in their study of nine popcorn inbreds, reported significant GCA and SCA effects for popcorn yield and shelling percentage. Similarly, Pajic et al. (2008) found significant GCA effects for grain yield and both GCA and SCA effects for popping volume, suggesting that grain yield is primarily controlled by additive effects, while popping volume is influenced by both additive and non-additive gene effects. Silva et al. (2010) further confirmed the significance of GCA for grain yield, whereas the effects of SCA were significant for both grain yield and popping expansion.

Several mating designs are commonly used to estimate GCA and SCA, depending on breeding program's objectives, available resources, and the level of genetic information desired. The most common designs included the diallel mating design, factorial mating design, and Line × Tester mating design, each with unique advantages and limitations (Aboderin et al. 2024). The diallel mating design is widely utilized for evaluating all possible combinations among a set of parental lines, providing comprehensive information on both additive and non-additive gene effects (Griffing 1956). However, it can become impractical with a large number of parents due to the exponential increase in the number of crosses required. The factorial mating design allows for the evaluation of a smaller subset of crosses by grouping parental lines into distinct sets, though it may sacrifice some resolution of genetic effects. The Line × Tester mating design is particularly advantageous for its simplicity and efficiency. It is commonly used for evaluating a large number of parental lines against a few testers, providing valuable insights into the relative contributions of additive and non-additive genetic effects to trait inheritance (Kempthorne, 1957; Ismail et al. 2023; Aboderin et al. 2024). This design is especially useful in early-stage breeding programs to identify parental lines with strong GCA and hybrids with superior SCA for desirable agronomic traits (Aboderin et al. 2024).

Despite its economic potential, popcorn faces significant challenges, including inferior germplasm, poor agronomic traits, and sub-optimal popping characteristics. These limitations have hindered its genetic improvement and reduced its popularity compared to dent corn (Ziegler, 2001). In Nigeria, there is no information regarding popcorn production, which suggests that very little effort has been made so far in production of popcorn. This is as a result of unacceptability of available local cultivars, some of which are low yielding, poor in popping qualities and unacceptable to popcorn consumers across the country, hence the importation of most popcorn consumed in Nigeria. In the same manner, research efforts have largely focused on improving other types of field corn for grain yield and related traits, with no established popcorn breeding programs. Consequently, there is a lack of diverse popcorn germplasm and high-yielding varieties with desirable agronomic and quality traits. Therefore, this study was carried out to address these challenges with the following specific objectives: (i) to determine the dominant gene action in the population; (ii) to identify the best combiners for important economic traits among parental lines and pick up hybrids for further use in subsequent breeding programs.

Materials and Methods

Germplasm Development

Thirty-six (36) hybrids were developed by crossing four testers with nine female inbred lines using a Line × Tester mating design. Two of the testers were high-yielding inbred lines while the other two possessed high-popping quality traits. Details of the genetic materials are presented in Table 1.

Evaluation of Popcorn Hybrids and Their Parents for Grain Yield and Popping Volume

Fifty popcorn genotypes comprising 36 single cross hybrids, 13 parents and a check entry (local unimproved accession commonly cultivated by Nigerian farmers) were evaluated at three locations namely: Ilorin in the southern Guinea savanna (Longitude 8°29'N, Latitude 4°35'E), Orin- Ekiti and Ilora which are located at Rainforest (Longitude 7°49'N, Latitude 5°14'E) and Derived savanna (Longitude 7°45'N, Latitude 3°55'E) agro-ecologies of Nigeria, respectively. The mean annual rainfall at Ilora in 2019 and 2020 were 80.9 mm and 204.4 mm while the annual temperature was 26.95°C and 27.45°C, respectively. Annual rainfall at at Orin-Ekiti in 2019 and 2020 were 98.9 mm and 95.1 mm, while annual temperature were 27.75 and 27.45°C, respectively. At Ilorin in 2020, 119.4 mm of annual rainfall was recorded and an average temperature of 25.3°C (Figure 1 & 2).

The trials were conducted at the three locations in 2019 and 2020 wet season for a duration of four months at each test environment. However, final yield data could not be collected from the trial at Ilorin in 2020 due to abrupt cessation of rainfall in that year.

Table 1. List of Genetic materials and their characters

Code	Pedigree	Characteristics	Colour	Sources
M1	Popcorn 33-1-Y	Round shaped, High yield	Yellow	IAR&T
M2	Popcorn 20-Y	Round shaped, Large popping volume	Yellow	,,
M3	Popcorn 37-Y	Pointed kernel shape, High yield	Yellow	,,
M4	Small pearl shaped	Pointed kernel shape, Large popping volume	Yellow	,,
V1	Popcorn 52-Y	Pointed kernel shape, Average yield and average popping volume	Yellow	,,
V2	Popcorn 2-S_0	Round shaped, Average yield and good popping volume	Yellow	,,
V3	Popcorn 4-Y	Round shaped, Average yield and average popping volume	Yellow	,,
V4	Eruwa local	Pointed kernel shape, Average yield	Yellow	,,
V5	Popcorn 34-Y	Round shaped, Average yield and average popping volume	Yellow	,,
V6	Popcorn 66-Y	Round shaped, Average yield	Yellow	,,
V7	Popcorn 40-Y	Round shaped, Average yield and average popping volume	Yellow	,,
V8	Popcorn 36-Y	Round shaped, Average yield and average popping volume	Yellow	,,
V9	Large pearl shaped	Round shaped, Average yield	Yellow	,,

M = Male, V= Female inbreds

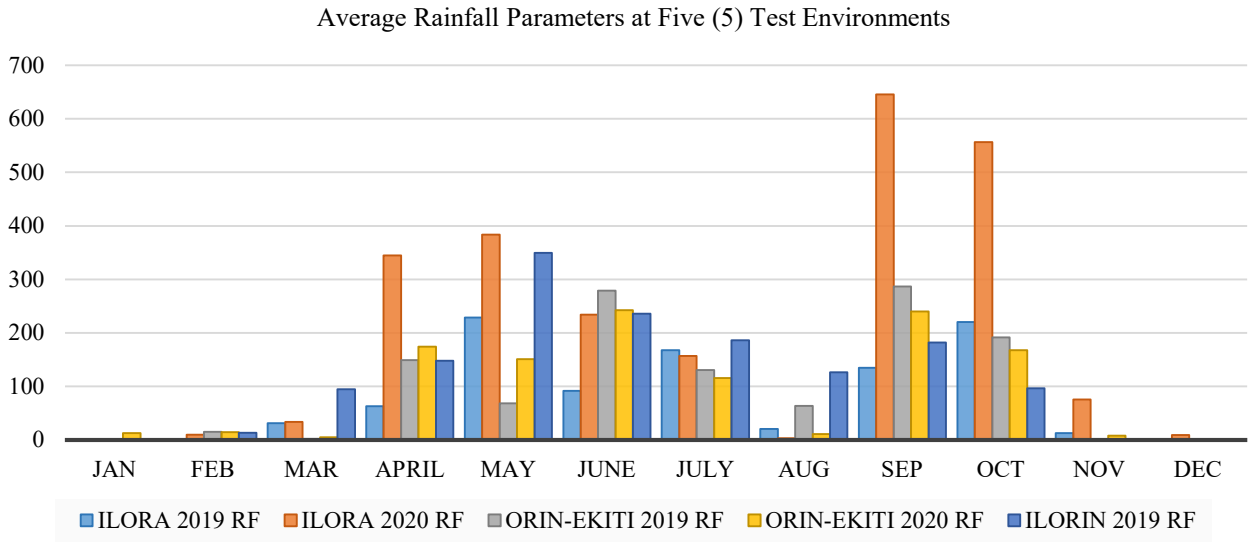

Figure 1. Average rainfall parameters at five (5) test environments

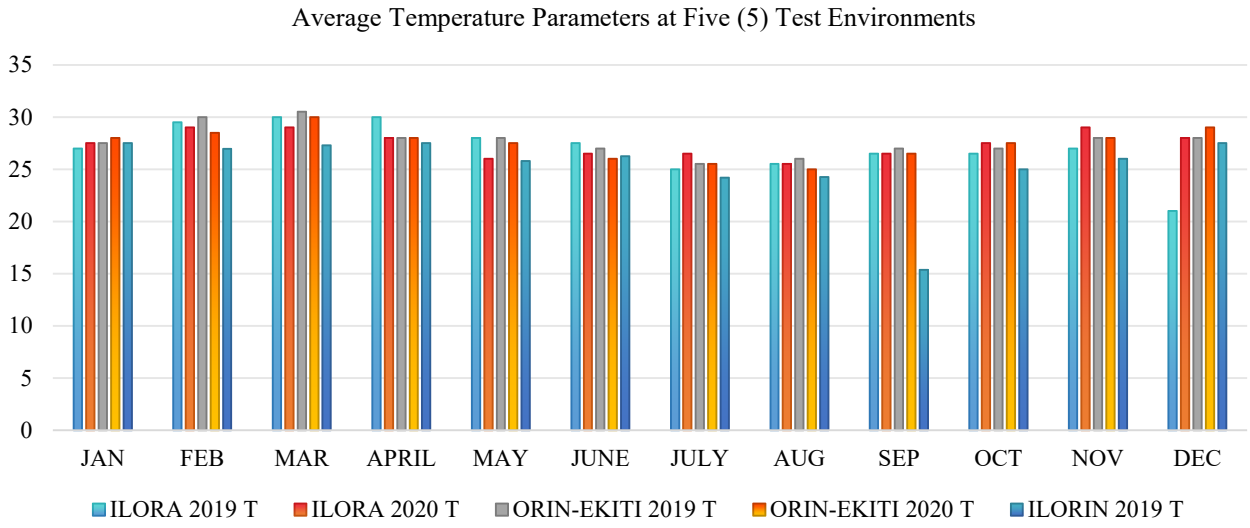

Figure 2. Average temperature parameters at five (5) test environments

Experimental Design and Field Management

The experiments were conducted using a Randomized Complete Block Design (RCBD) with three replication. The plot size consisted of two-rows, five meters in length, and the rows were spaced 0.75 meters apart., and the plants within each row were spaced 0.5 meters apart. To achieve a planting density of 53,333 plants per hectare, three seeds were sown per hole, and the seedlings were later thinned to two plants per hole at two weeks after sowing (WAS). Fertilizer was applied at three weeks after sowing, with the base fertilizer consisting of 80 kg of nitrogen (N), 60 kg of phosphorus (P_2O_5), and 60 kg of potassium (K_2O) per hectare. Six weeks after planting, urea (46-0-0) was applied as a top dressing before flowering. Weed management was achieved through a combination of pre-emergence herbicides, including 250 g/L of Metolachlor and 250 g/L of Atrazine active ingredients (a.i.), followed by post-emergence herbicide application using 276 g/L of Paraquat dichloride. Manual weeding was also carried out as necessary to ensure the field remained free of weeds.

Data Collection

The data were collected on number of days to pollen shed, days to silking, plant height, and ear height. Plant height was measured from the base of the plant to the base of tassel (after milking stage), while ear height was measured from the base of the plant to the node that holds the uppermost ear. These measurements were recorded after the flowering process was completed and were taken from five randomly selected plants per plot to ensure accuracy and representativeness. For plant and ear appearance, a rating scale from 1 to 5 was used, with 1 indicating excellent phenotypic traits, 3 representing an average appearance, and 5 denoting poor appearance. Similarly, husk cover was rated based on how well the husks were closed, with a rating of 1 for tightly arranged husks extending beyond the ear tip, 3 for an average arrangement, and 5 for exposed ear tips. Leaf diseases, such as blight, rust, and streak, were also assessed using a scale from 1 to 5, where 1 represented a slight infection and 5 indicated a very heavy infection. These assessments were performed at the physiological maturity stage, before senescence.

For grain yield, the weight of cobs harvested from each plot was recorded in kilograms per plot (kg/plot) and converted to tonnes per hectare (t/ha) using the following formula (Equation 1):

$$\text{Grain yield} = \frac{\text{FWT}(100 - \text{MC}) \times 0.8 \times 10{,}000}{(100 - 12) \times 7.5}$$

Where:

FWT = Field Weight (kg plot^{-1}), which is the total weight of cob harvested per plot;

MC = Moisture Content (%) at harvest, measured using a moisture meter;

0.8 = Shelling coefficient (constant);

7.5 = Area harvested per plot (m²);

1 hectare = 10,000 m²;

12% = Standard moisture content for maize grain at storage (constant).

Popping Expansion of Popcorn Hybrids and Their Parents

All 50 evaluated popcorn genotypes, including the F1 crosses, parents, and check, were subjected to popping using a hot air popper to compare popping characteristics. Approximately 50 g of corn kernels were measured and placed into a domestic hot air popper, which was run until popping ceased. The expansion volume was recorded by measuring the popped corn in a 1000 cm³ measuring cylinder. The expansion volume was calculated as follow (Equation 2):

$$\text{Popping expansion ration} = \frac{\text{Total volume of popped corn}}{\text{Total weight of popcorn}}$$

Data Analyses

SAS version 9.0 was used to perform analyses of variance (ANOVA) on the gathered data. The least significant difference (LSD), as described by Steel and Torrie (1980), was used to differentiate significant means for which variety varied considerably. Additionally, an estimate of combining abilities (GCA and SCA) was performed using a Line x Tester mating design as a tool to select appropriate parents for hybrid combination.

Combining ability effects was estimated using the formulae (Equation 3):

$$\text{GCA effects of lines} = \frac{x_i}{rt} - \frac{x}{rlt}$$

$$\text{GCA effects of testers} = \frac{x_j}{rl} - \frac{x}{rlt}$$

$$\text{SCA effects of hybrids} = \frac{x_{ij}}{r} - \frac{x_i}{rt} - \frac{x_j}{rl} + \frac{x}{rlt}$$

where x… = sum of all hybrids over replications

xi.. =sum of ith line over t testers and r replications

x.j. =sum of jth tester over l lines and r replications

xij, =sum of the hybrid between ith line and jth tester over r replications.

Results and Discussion

The analyses of variance (ANOVA) for grain yield and other agronomic traits of the popcorn genotypes revealed that environments (E) were highly significant ($\rho \leq 0.01$) for all traits (Table 2). These differences are likely influenced by climatic variables such as rainfall, temperature, biotic and edaphic factors peculiar to each test environment. This finding highlights the uniqueness of each testing site and their role in discriminating among the popcorn genotypes. Significant differences ($\rho \leq 0.01$ or $\rho \leq 0.05$) were observed among genotypes (crosses) for all studied traits except ears per plant (EPP), suggesting wide genetic differences among the crosses. This variation can thus be exploited to enhance popcorn performance for these traits through selection. The lines (L) varied substantially ($\rho \leq 0.01$) from each other for every character except EPP and streak, while the testers (T) differed significantly ($\rho \leq 0.01$) for plant and ear height, popping volume, and grain yield (GY). These results suggest sufficient genetic diversity among the lines for these traits, while differences among testers indicate their potential to transfer desirable traits to progenies when crossed with appropriate parental lines. These findings align with previous studies by Shushay et al. (2013), Patil et al. (2016) and Aboderin et al. (2024b), which reported significant genetic variability in grain yield and other agronomic traits across testcrosses.

Significant Line × Tester interaction obtained for all traits except ASI and EPP indicates high SCA effect among the hybrids and the divergence in performance of the lines and testers across the test environments. This provides evidence of variability and the potential for exploiting heterotic effects in hybrid development. Moreover, the larger mean squares for lines compared to testers for all traits except ear height (EH) and EPP suggest greater genetic variability among the lines. This observation aligns with the findings of Abuali et al. (2012) and Dar et al. (2018), who also reported greater contributions from lines than testers to total variability in popcorn traits.

Interactions between environment, line, and tester (E × L × T) were highly significant ($\rho \leq 0.01$) for all traits except EPP, while genotype (crosses) × environment (E) interactions were significant for all traits (Table 2). These findings demonstrate the differential responses of popcorn hybrids across the contrasting environments. Significant mean squares for Environment × Line (E × L), Environment × Tester (E × T), and E × L × T for most traits further emphasize the variability in parental line and tester performance across locations. These interactions may be attributed to differences in environmental conditions, including non-uniformity in the distribution of rainfall from one test environment to the other, which underscores the necessity to evaluate new genotypes across several environments within the available resources in the ecologies where they are intended for cultivation. Such a step will help in the accurate determination of the genetic potentials of the materials under varying environmental conditions, ascertain their stability and adaptation to proposed ecologies of cultivation and thus enable the breeder to identify location-specific popcorn hybrids during the release process.

Table 2. Mean squares from combined ANOVA of agronomic and yield traits of popcorn genotypes evaluated across five environments in a line × tester trial

Source of variation	df	GY	PV	DP	DS	ASI	PH	EH	RL
Environment (Env.)	4	7.65**	138.33**	1156.54**	808.30**	88.30**	67052.47**	28105.10**	200.98**
Replicate (Env.)	10	1.00	23.06	25.65	33.51	3.55	2655.44	1208.69	65.54
Genotype (crosses)	35	3.42**	346.88**	56.70**	69.60**	2.18*	2313.38**	423.71**	19.15**
Env × Crosses	140	0.40**	19.09**	11.81**	14.50**	2.26**	515.96**	270.41**	9.85**
Line (L)	8	2.43**	222.41**	111.17**	125.69**	3.75**	1042.19**	403.47**	28.60**
Tester (T)	3	1.26**	138.65**	1.18	6.23	2.30	925.02**	753.40**	5.41
Env × Line	32	0.36*	22.78**	14.84**	15.52**	1.62	550.92**	320.33**	12.63**
Env × Tester	12	0.17	13.03*	19.46**	20.93**	2.91**	611.21**	288.01**	10.75*
Line × Tester	24	4.02**	414.40**	45.48**	58.82**	1.64	2910.65**	389.24**	17.71**
Env × Line × Tester	96	0.44**	18.62**	9.85**	13.36**	2.39**	492.39**	251.57**	8.81**
Error	350	0.23	7.14	3.49	4.95	1.33	247.02	120.44	5.84

Source of variation	df	SL	HC	PA	EA	EPP	Strk	Rust	Blight
Environment (Env.)	4	527.65**	49.38**	35.94**	40.54**	1.41**	4.89**	21.56**	9.54**
Replicate (Env.)	10	92.56	1.23	2.60	1.55	0.30	1.36	0.80	2.17
Genotype (crosses)	35	19.53**	0.52**	2.11**	1.84**	0.03	0.43*	0.98**	1.22**
Env × Crosses	140	14.76**	0.54**	0.71**	0.73**	0.05*	0.41**	0.43**	0.41**
Line (L)	8	20.16*	0.67**	3.43**	1.07**	0.02	0.39	1.08**	1.43**
Tester (T)	3	10.34	0.31	0.53	0.26	0.03	0.16	0.09	0.29
Env × Line	32	10.02	0.81**	0.77**	0.53*	0.06**	0.57**	0.49**	0.31
Env × Tester	12	12.75	0.83**	1.18**	1.75**	0.05	0.45	0.29	0.25
Line × Tester	24	20.47**	0.50**	1.86**	2.29**	0.04	0.48*	1.05**	1.28**
Env × Line × Tester	96	16.59**	0.41**	0.63**	0.67**	0.04	0.35	0.43**	0.47**
Error	350	9.32	0.24	0.29	0.34	0.04	0.28	0.23	0.30

*, ** Significantly different at 0.05 and 0.01 levels of probability, respectively;N.B: Env: Environment, df: Degree of freedom, DP: Days to pollen shed, DS: Days to silking, ASI: Anthesis-silking interval, PH: Plant height, EH: Ear height, RL: Root lodging, SL: Stem lodging, HC: Husk cover, PA: Plant aspect, EA: Ear aspect, EPP: Ears per plant, PV: Popping volume, GY: Grain yield, Strk: Streak

Table 3. Proportional contribution of lines, testers and their interaction to total hybrid variance for popcorn characters

Traits	Line	Tester	Line × Tester
Grain yield	15.9	3.10	81.00
Popping volume	14.59	3.41	81.92
Days to Pollen shed	44.80	0.20	55.00
Days to silking	41.20	0.77	58.00
Anthesis-Silking-Interval	39.03	8.97	52.00
Plant Height	10.51	3.50	86.00
Ear Height	21.78	15.24	63.00
Root Lodging	34.55	2.46	63.00
Stem lodging	23.48	4.50	72.00
Husk cover	28.9	5.10	66.00
Plant aspect	36.88	2.12	60.56
Ear aspect	13.75	1.25	85.41
Ears per plant	15.11	8.89	75.68

Given their apparent genetic diversity for grain production, the popcorn genotypes used in this study suggested that their innate genetic potentials affected the notable variations in yield and yield component characters seen among them. However, based on the data from all five environments, environmental variables also significantly influenced how grain yield was expressed. The implication of this is that high-yielding potential alone is not sufficient in commercial popcorn production; growing environments must also be favourable for farmers and popcorn processors to break even in the popcorn business.

The study of combining ability is important in understanding the genetic basis of traits and guiding the development of superior hybrids (Aboderin et al. 2024b). GCA reflects the additive genetic effects associated with the parental lines, while SCA captures the non-additive effects arising from specific line × tester interactions. In this study, the line × tester interactions, which represent SCA effects, accounted for over 80% of the total hybrid variance across traits, particularly for grain yield, popping volume, plant height, and ear aspect (Table 3). The predominance of non-additive gene action implies that popcorn hybrid breeding programs can achieve significant gains by exploiting heterosis through careful selection of parental lines and testers with complementary traits. These findings align with those of Moterle et al. (2012), who reported that non-additive gene effects were crucial in determining popping expansion and seed quality in popcorn. On the other hand, Pajic et al. (2008) and Silva et al. (2010), reported a dominance of additive gene action in the inheritance of grain yield in popcorn. This discrepancy might be due to variation in genetic materials used for the studies and the experimental conditions under which the materials were evaluated.

In addition, the interest in obtaining estimates of the GCA of parents in crosses is usually to determine their genetic potential for use in the development of superior progenies for grain yield and/or trait(s) of interest (Aboderin et al. 2024b). High GCA values indicate strong heritability, less environmental influences, minimal gene interactions and higher prospects for successful selection

(Topal et al., 2004; Chigeza et al., 2014; Aboderin et al. 2024b). In this study, parental lines V7, V9, and tester M3 demonstrated significant positive GCA effects for grain yield (Table 4), highlighting their potential as good combiner lines for developing high-yield popcorn composites or synthetics. Similarly, lines V1, V7, V8, and V9, exhibited significant positive GCA effects for popping volume (Table 4), indicating their suitability for developing open- pollinated varieties (OPVs) with superior popping traits. Meanwhile, lines V2 and V6, with significant negative GCA effects for both days to anthesis and silking, emerged as promising candidates for developing early-maturing varieties, advantageous for drought-prone regions and short growing seasons (Estakhr and Heidari, 2012; Aboderin et al. 2024; Ismail et al. 2024). Notably, line V6 not only showed significant negative GCA effects for both days to anthesis and silking but also emerged as the best combiner for ASI, demonstrating its potential for improving flowering synchrony. The dual role of line V6 as a donor for early maturity and improved ASI underscores its value in hybrid combinations, which could result in progenies with improved stress tolerance, early flowering, and consistent performance across diverse environments (Aboderin et al. 2024).

SCA effects, indicative of non-additive genetic influences, were highly significant for several traits (Table 5). Eight crosses (M1 × V1, M1 × V3, M1 × V4, M3 × V4, M1 × V6, M4 × V7, M4 × V8, M4 × V9, M1 × V7, and M3 × V5) showed significant positive SCA effects for grain yield, making them strong candidates for the development of stable, high-yielding commercial hybrids across diverse environments. Thirteen crosses, including M1 × V1, M2 × V2, M1 × V3, M1 × V4, M2 × V5, M3 × V5, M1 × V6, M1 × V7, M4 × V7, M4 × V8, M2 × V9, M4 × V9, and M3 × V4, demonstrated significant SCA effects for popping expansion in the positive direction, indicating their suitability for exploiting heterosis in popping volume traits.

For early maturity, negative SCA effects with respect to silking are advantageous. Hybrids M1 × V4, M4 × V7, and M4 × V8 exhibited significant negative SCA effects for this trait, making them suitable for developing early-maturing commercial popcorn hybrids. Notably, hybrids M1 × V4 and M4 × V8 with favorable SCA effects across multiple traits (days to pollen shed, days to silking, popping volume, and grain yield) stand out as exceptional combiners. Their adoption in breeding programs could greatly benefit the Nigerian popcorn industry by offering a combination traits that align with the needs of both farmers and popcorn processors, including early maturity, synchronous flowering, high yield, and superior popping volume.

Conclusion

This study revealed that non-additive gene action predominated in the inheritance of the traits assessed. Parental lines V7, V9, and M3 were identified as excellent general combiners for grain yield, highlighting their potential for developing open-pollinated varieties (OPVs) and synthetic popcorn varieties. Hybrids M1 × V1, M1 × V3, M1 × V4, M1 × V6, M1 × V7, M3 × V4, M3 × V5, M4 × V7, M4 × V8, and M4 × V9 were identified as strong specific combiners for grain yield and popping volume across diverse environments. These hybrids represent promising candidates for the development of commercial popcorn hybrids with improved yield and popping expansion.

Declarations

Author Contribution Statement

O.O. Olakojo: Conceptualization of study, Data analyses and Report writing.

D.J. Ogunniyan: Methodology and Experimentation.

A.T. Akintunde: Data analyses and Interpretation.

S.A. Olakojo: Supervision and review

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this research.

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Table 4. General Combining Ability effects of popcorn parents for Grain yield, Popping volume and other agronomic traits across five environments

Parents	GCA						
	DP	DS	ASI	PH	EH	PV	GY
LINES							
V1	0.36	0.62	0.27	-5.19	-0.53	1.47*	-0.11
V2	-1.86**	-1.84**	0.02	-5.64*	0.68	-1.71**	-0.28**
V3	1.02*	0.78	-0.23	2.80	1.40	0.16	-0.06
V4	1.44**	1.56**	0.12	1.59	5.10*	-2.98**	0.13
V5	-1.08*	-0.90	0.18	-2.97	-2.92	-0.78	-0.26**
V6	-2.19**	-2.61**	-0.42**	0.86	-3.18	-1.85**	0.08
V7	0.31	0.31	0.00	6.28*	0.95	1.28*	0.32**
V8	0.90	1.21*	0.31*	-1.88	-2.24	2.57**	-0.02
V9	1.12*	0.87	-0.24	4.16	0.73	1.85**	0.19**
Testers							
M1	0.63	0.74	0.11	3.17	2.02	-0.95**	0.01
M2	-1.53**	-1.65**	-0.12	-8.62**	-2.01	1.96**	-0.10
M3	-0.54	-0.59	-0.04	9.41**	-0.37	14.52**	0.24**
M4	1.45**	1.50**	0.06	-3.96*	0.36	14.52**	-0.15*

M: Male, V: Variety, DP: Days to Pollen shed, DS: Days to Silking, ASI: Anthesis-Silking Interval, PH: Plant Height, EH: Ear Height, PV: Popping Volume, GY: Grain Yield

Table 5. Specific Combining Ability effects of popcorn hybrids for Grain yield, Popping volume and other agronomic traits across five environments

Hybrid	GY	PV	DP	DS	ASI	PH	EH
M1 × V1	0.35**	6.13**	-0.38	-0.67	-0.29	6.96	5.04
M2 × V1	0.13	0.59	0.79	1.06	0.27	-1.58	0.39
M3 × V1	-0.19	-1.91*	-0.73	-0.54	0.19	1.29	-0.85
M4 × V1	-0.28*	-4.81**	0.32	0.15	-0.17	-6.66	-4.58
M1 × V2	-0.24	-1.82*	0.14	0.16	0.02	-5.36	01.4
M2 × V2	0.24	2.74**	-0.60	-0.67	-0.08	2.48	3.62
M3 × V2	0.15	1.08	-0.65	-0.74	-0.09	4.99	-0.31
M4 × V2	-0.15	-2.00*	1.10	1.25	0.14	-2.11	-3.45
M1 × V3	0.31**	4.88**	-0.17	-0.43	-0.26	7.84	5.65
M2 × V3	-0.02	-1.47	0.40	0.57	0.17	2.28	-0.01
M3 × V3	0.12	0.89	-0.26	-0.50	-0.24	-0.15	-0.99
M4 × V3	-0.41**	-4.30**	0.03	0.35	0.33	-9.97*	-4.66
M1 × V4	0.57**	3.28**	-1.86**	-2.40**	-0.54	10.62*	2.49
M2 × V4	-0.59**	-5.43**	1.47*	1.83*	0.36	-19.82**	-11.21
M3 × V4	0.50**	1.95*	-0.15	-0.21	-0.06	14.20**	10.92
M4 × V4	-0.49**	0.20	0.54	0.78	0.24	-4.99	-2.20
M1 × V5	-0.29*	-4.26**	1.00	1.42	0.42	-5.20	-1.78
M2 × V5	0.14	3.41**	-0.71	-0.88	-0.18	6.60	3.08
M3 × V5	0.27*	3.54**	-0.82	-1.28	-0.46	-0.22	-2.46
M4 × V5	-0.12	-2.70**	0.53	0.74	0.21	-1.18	1.15
M1 × V6	0.36**	3.79**	-0.69	-0.97	-0.28	2.21	0.24
M2 × V6	-0.04	-1.79*	-0.60	-0.91	-0.31	0.79	4.77
M3 × V6	0.17	-0.03	0.09	0.49	0.41	9.13	1.03
M4 × V6	-0.49**	-1.97*	1.20	1.38	0.18	-12.12**	-6.04
M1 × V7	0.30*	3.91**	0.14	0.18	0.04	5.82	-2.01
M2 × V7	0.18	-1.30	-0.70	-0.89	-0.19	7.98	1.57
M3 × V7	-1.02**	-8.38**	2.29**	2.54**	0.26	-30.31**	-2.99
M4 × V7	0.54**	5.77**	-1.73**	-1.84*	-0.11	16.52**	3.44
M1 × V8	-0.59**	-8.52**	1.22	1.51*	0.30	-10.28*	-5.84
M2 × V8	0.02	1.01	0.05	0.08	0.03	-1.19	-1.82
M3 × V8	-0.19	1.67	-0.01	0.14	0.15	-0.43	0.07
M4 × V8	0.76**	5.85**	-1.26	-1.74*	-0.48	11.89**	7.59*
M1 × V9	-0.77**	-7.39**	0.60	1.18	0.58	-12.61**	-3.93
M2 × V9	-0.05	2.25**	-0.11	-0.19	-0.08	2.48	-0.40
M3 × V9	0.19	1.18	0.24	0.08	-0.17	1.50	-4.43
M4 × V9	0.63**	3.95**	-0.74	-1.07	-0.33	8.63	8.76**

M: Male, V: Variety, DP: Days to Pollen shed, DS: Days to Silking, ASI: Anthesis-Silking Interval, PH: Plant Height, EH: Ear Height, PV: Popping Volume, GY: Grain Yield.

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