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PHENOLOGICAL CHARACTERIZATION AND GENETIC ANALYSIS OF DOUBLE-EAR MAIZE (*ZEA MAYS* L.) CULTIVAR FROM KADATUA ISLAND, INDONESIA

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SUMMARY

Maize (*Zea mays* L.) is vital for global food security, and increasing its yield is a key goal in tropical breeding programs. A unique double-ear maize from Kadatua Island, Indonesia, produces two ears per plant—a promising trait for higher yield if properly developed. However, this germplasm has a low yield, and its phenology and inheritance pattern require further understanding. This study aimed to characterize its phenological development and key genetic parameters for breeding improvement. The recorded vegetative and reproductive growth stages used leaf collar and kernel development benchmarks, respectively. Genetic parameters, as calculated from progeny, utilized North Carolina Design-I. Results showed the vegetative stage was similar to that of commercial hybrids (4–58 days after planting), while the reproductive stage progressed more rapidly (58–83 days after planting). Genetic analysis revealed the dominance variance was greater than the additive variance ($P: 0.00–0.05$) for all traits, except plant height. Broad-sense heritability ranged from moderate to high (0.65–0.83), and narrow-sense heritability was low to moderate (0.01–0.37) for reproductive traits. Strong positive correlations occurred between ear weight, ear length, stem diameter, and grain yield. The study suggests hybrid breeding is a promising approach to improving yield in this double-ear maize.

Keywords: Double-ear maize (*Z. mays* L.), phenological development, genetic parameters, heritability, dominance variance, hybrid breeding

Key findings: The double-ear local maize cultivar exhibited vegetative growth duration comparable to commercial hybrids. Genetic analysis revealed the dominance variance and the high broad-sense heritability play a major role in the expression of reproductive traits. Hybrid breeding strategies hold considerable potential for improving yield in this locally adapted maize population.

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INTRODUCTION

Maize (*Zea mays* L.) represents a major cereal crop of global importance, serving as a foundation for global food security, animal feed, and industrial raw materials (Shiferaw *et al.*, 2011; Chňapek *et al.*, 2024). Its remarkable genetic diversity underpins breeding progress that has enabled yield increases and adaptation to a wide range of environments (Chen *et al.*, 2024). Exploration and utilization of this diversity remain critical to sustaining productivity under pressures of climate change and limited arable lands (Prasanna *et al.*, 2021). Globally, the conservation and genetic characterization of local maize germplasm have gained emphasis, as essential steps proceeded toward identifying unique alleles and traits that can enhance resilience, productivity, and nutritional value (Guzzon *et al.*, 2021).

In Indonesia, local maize landraces represent an invaluable component of this global diversity. Local maize germplasm has reached processing through natural crossbreeding and selection for centuries. They carry unique phenotypic and genetic attributes that can contribute to national breeding programs aimed at achieving self-sufficiency in maize production. Despite Indonesia's substantial maize cultivation area, domestic yields remain below the global average, and imports continue to meet feed industry demands (FAOSTAT, 2023). Therefore, the improvement and utilization of local germplasm are strategic for enhancing both productivity and genetic resilience.

Farming communities in their specific regions, including those in Southeast Sulawesi Province, Indonesia, have cultivated and preserved the germplasm based on adaptability and desirable traits suited to their local environments. Hadini *et al.* (2017) have collected 47 accessions of local maize from Southeast Sulawesi Province, and one genotype from Kadatua Island has two ears with reddish black seeds, a small ear size (5–12 cm long and 2–3 cm in diameter), and low productivity. Double-ear maize has considerable control of genetic factors compared with environmental factors, with the

double-ear trait as confirmed even by growing on infertile and marginal soils. The occurrence of double-ear maize is rare; therefore, it is highly necessary to maintain its existence and increase its potential through various agronomic measures, including breeding.

The double-ear maize from Kadatua Island, Indonesia, has the potential to be developed into a superior national cultivar. Guiding its improvement requires understanding the phenological development and genetic parameters of this germplasm. Together, these two aspects provide a comprehensive basis for developing effective breeding strategies for this unique double-ear maize.

Phenological characterization provides insights into growth duration, adaptability, and synchronization between vegetative and reproductive phases, which are key determinants of yield potential (Abendroth *et al.*, 2011; Hadini *et al.*, 2023). Genetic analysis quantifies major parameters, such as additive variance, dominance variance, heritability, and correlations among traits, which together determine breeding efficiency (Hallauer *et al.*, 2010). Additive variance reflects heritable effects contributing directly to selection gain, while dominance variance indicates allelic interactions associated with hybrid vigor. Heritability expresses the proportion of genetic control over phenotypic variation, and trait correlations describe the interdependence among characters that affect selection response.

According to Malvar *et al.* (1996), the components of genetic variation can be effective in guiding selection methods. Plant populations with high additive genetic variance are suitable for improvement through intrapopulation selection and development in open-pollinated cultivars. However, populations with high dominance variance are more appropriate for interpopulation selection and hybrid development. Genetic parameters of a population can entail estimation by generating families with defined genetic relationships, employing different mating schemes, including North Carolina Design-I (Hallauer *et al.*, 2010). The translation of the population structure analysis can succeed into genetic parameters

that can further explore future breeding efforts.

Based on the discussed considerations above, it is important to identify the growth and development stages of the local double-ear maize from Kadatua Island, Indonesia, as well as to estimate its genetic parameters. These results will be essential for determining the appropriate breeding direction, whether to develop a superior open-pollinated or hybrid cultivar in double-ear maize.

MATERIALS AND METHODS

Experimental design

The conducted research on double-ear maize ran from January to September 2024, growing it at the experimental field of Halu Oleo University, Kendari, Indonesia (4°0'35.32"S, 122°31'37.47"E). The experiment consisted of two main phases: (1) determination of maize growth stage and (2) conducting the hybridization stage following the North Carolina Design-I mating scheme. The hybrid evaluation phase used a randomized complete block design with three replications.

Plant material and germplasm source

The double-ear maize genotype collection originally came from Kadatua Island, Southeast Sulawesi, Indonesia, during a local germplasm exploration by Hadini *et al.* (2023). This genotype consistently produces two ears per plant, with reddish-black kernels, ear lengths of 5–12 cm, and ear diameters of 2–3 cm. The trait is stable under marginal soil conditions, suggesting a strong genetic basis. Seeds incurred maintenance under isolation for three generations to preserve genetic purity before use. A commercial hybrid variety (Bisi-2) served as a comparison control for phenological parameters.

Environmental conditions and field management

The experimental field classification was ultisol, exhibiting a soil pH of 5.47, organic carbon

content of 2.63%, total nitrogen of 0.33%, available phosphorus of 20.77 ppm, and exchangeable potassium of 22.41 ppm. The research site sits in a humid tropical zone, with a mean temperature of 27.14 °C, mean relative humidity of 82.7%, and cumulative rainfall of 2.199 mm during the study period. Before planting, the land tilling and harrowing twice ensured proper soil structure.

Each planting hole received an initial sowing of two seeds, and after two weeks of planting, thinning the seedlings continued to have a single plant per hole. For the observation of maize growth stages and the implementation of the North Carolina Design-I mating scheme, growing the double-ear maize progressed on five experimental units measuring 7.5 m × 5 m with row and plant spacing of 75 cm and 25 cm, respectively. In contrast, the hybrid evaluation, as carried out, used the one-ear-one-row planting method, consisting of 25 plants per row.

The initial fertilization commenced by spot placement approximately 7 cm from the plant stem, one week after planting, using urea, SP-36, and KCl (at 100, 90, and 60 kg ha⁻¹, respectively). The second round of fertilization was 10 cm from the plant stem at 30 DAP, using urea at 200 kg ha⁻¹. Watering transpired both in the morning and late afternoon when rainfall did not occur, with weed management carried out manually at 20 and 40 DAP. No occurrence of pests or diseases emerged throughout the experiment. Liming implementation had happened in the previous growing season. Harvesting succeeded when the husks had dried and turned brownish, and the kernels had reached physiological maturity, indicated by the appearance of a black layer located at the bottom of the kernels.

Determination of maize growth stages

In determining the double-ear maize growth stages, the study employed the leaf collar method, which involves counting fully emerged leaves with visible collars to assess vegetative development. The reproductive development's assessment depended on silking and grain conditions. The outlines about the main growth

Table 1. Main stages of maize development.

Stage	Visual characteristics	Descriptions
VE	Emergence	The mesocotyl emerges above the soil surface, while the seminal root system is actively growing.
V3	3 Collars	Three leaves have completely unfolded with clearly visible collars. The nodal root system is actively developing, while the growing point remains positioned below the soil surface.
V6	6 collars	The growing point has emerged above the soil surface, marking the initiation of tassel and ear formation.
V12	12 collars	Twelve leaves have completely unfolded, although the lowest two to three leaves might have withered. At this stage, the potential size of the ear, as well as the size and number of kernels, is being established. Any shortages of water or nutrients can lead to reduced yields.
V15	15 collars	The potential number of kernels has been determined. While the top two ears are comparable in size, the ear positioned at the highest node will become the dominant one.
VT	Tassel	The final tassel branch is fully emerged. Total leaf loss can lead to almost complete yield loss. Pollination might take place as the tassel is still emerging.
R1	Silking	One or more silks have emerged from the husk leaves. This is the most critical period for stress. Pollination is underway, and the uptake of nitrogen and phosphorus is rapid. Around 60%, 40%, and 75% of the total nitrogen, phosphorus, and potassium uptake, respectively, occurs during this stage.
R2	Blister	The plant has reached its full height, and the ear has reached its full length. The vegetative weight is also complete. A small maize plant is developing within each fertilized kernel.
R4	Dough	At the beginning of R4, the kernel interior has the consistency of "dough," with the kernel containing approximately 70% moisture.
R5	Dent	Dent formation begins in the upper kernels of the ear. A starch accumulation zone, referred to as the 'milk line,' appears and steadily advances toward the base of the kernel. At the start of R5, the kernels account for about 45% of the total dry weight, reaching nearly 90% of the total dry weight by the time the milk line is halfway down.
R6	Physiological Maturity	The black layer has developed at the base of the kernel, indicating a moisture content of approximately 30% to 35%.

Source: Abendroth *et al.* (2011)

stages along with their brief descriptions are available in Table 1.

North Carolina Design-I implementation

Female flowers with silks that had not yet emerged sustained covering with wax paper envelopes, while enclosing male flowers used kraft paper envelopes. The pollen from each male plant functioned to pollinate three distinct maize plants designated as females. Maize plants totaling 99 served as male parents, requiring 297 female plants for the crosses. At harvest, the three female ears pollinated by the same male plant became a hybrid set. The ears were sun-dried for five days before being shelled individually. The resulting crossed

seeds attained preparations for subsequent evaluation.

Hybrid evaluation and data collection

Ear sets totaling 89 hybrids resulting from previous crosses incurred evaluation. Observations occurred on 10 sample plants per each subplot. The recorded growth components included plant height (cm), stem diameter (cm), and total leaf count per plant at the tasseling stage. However, assessing the yield components continued after harvest. Yield components measurement included ear length (cm), ear diameter (cm), kernel weight per ear (g), and grain yield ($t\ ha^{-1}$).

Table 2. Analysis of variance for half-sib and full-sib families according to the North Carolina Design-I.

Source of variation	Degrees of freedom	Mean squares	Expected mean squares
Among groups in the half-sib family	$m - 1$	MS_m	$\sigma_w^2 + r\sigma_{f/m}^2 + rf\sigma_m^2$
Among full-sib family and half-sib family groups	$m(f - 1)$	$MS_{f/m}$	$\sigma_w^2 + r\sigma_{f/m}^2$
Within full-sib family	$mf(r - 1)$	MS_w	σ_w^2
Total	$mfr - 1$		

The letters m , f , and r represent the number of males, females nested within males, and replications, respectively.

Data analysis

The conduct of variance analysis (ANOVA) for each trait used the generalized linear model (GLM) procedure at the 0.05 and 0.01 probability levels. Variance components' estimation, based on the ANOVA results, followed the method described by Hallauer et al. (2010) (Table 2). Several male parents (m) succeeded in crossing with many female parents (f) to produce progenies for evaluation. The obtained data were dependent on the North Carolina Design-I. The linear model applied described the data as follows.

$$Y_{ijk} = \mu + m_i + f_{ij} + \varepsilon_{ijk}$$

Where y_{ijk} is the k th replication at the $f \times m$ progeny, μ is the experimental mean, m_i represents the effect of the i th male, f_{ij} denotes the effect of the j th female mated with the i th male, and ε_{ijk} was the experimental error.

The assumptions to meet were as follows.

$$m_i \approx NID(0, \frac{1}{4}\sigma_A^2 + \frac{1}{4}\sigma_D^2); f_{ij} \approx NID(0, \frac{1}{4}\sigma_A^2 + \frac{1}{4}\sigma_D^2); \varepsilon_{ijk} \approx NID(0, \sigma_\varepsilon^2)$$

, where $\hat{\sigma}_A^2$ is additive genetic variance, and $\hat{\sigma}_D^2$ is dominance genetic variance.

The genetic parameters for estimation were as follows:

$$\begin{aligned} \hat{\sigma}_m^2 &= CovHS = \frac{1}{4}\hat{\sigma}_A^2 \\ &= \frac{MS_m - MS_{f/m}}{rf} \end{aligned}$$

Therefore,

$$\begin{aligned} \hat{\sigma}_A^2 &= \frac{4(MS_m - MS_{f/m})}{rf} \\ &= 4\sigma_m^2 \end{aligned}$$

$$\begin{aligned} \hat{\sigma}_{f/m}^2 &= CovFS - CovHS = \frac{1}{4}(\hat{\sigma}_A^2 + \hat{\sigma}_D^2) \\ &= \frac{MS_{f/m} - MS_w}{r} \end{aligned}$$

Therefore,

$$\hat{\sigma}_D^2 = \frac{4(MS_{f/m} - MS_w)}{r} - \hat{\sigma}_A^2$$

Genetic variance of the population, as calculated, used the following equation.

$$\hat{\sigma}_G^2 = \hat{\sigma}_A^2 + \hat{\sigma}_D^2 = 4\hat{\sigma}_{f/m}^2$$

The H^2 (broad-sense heritability) and h^2 (narrow-sense heritability) determination employed the following equations.

$$\hat{H}^2 = \frac{4\hat{\sigma}_{f/m}^2}{\hat{\sigma}_w^2 / r + 4\hat{\sigma}_{f/m}^2}$$

$$\hat{h}^2 = \frac{4\hat{\sigma}_m^2}{\hat{\sigma}_w^2 / r + 4\hat{\sigma}_{f/m}^2}$$

Based on the guidelines of Stanfield (1991), traits with heritability estimates below 0.20 obtained the grouping as low, while those between 0.20 and 0.50 as medium, and those exceeding 0.50 as high.

Phenotypic correlations (r_p) calculations among traits assessed the magnitude and direction of relationships between growth and yield traits using the following formula (Pearson correlation):

$$r_p = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \times \sum (y_i - \bar{y})^2}}$$

Where r_p represents the phenotypic correlation coefficient between traits x and y , x_i and y_i are individual observations, and \bar{x} and \bar{y} denote the average values of the corresponding traits. Positive r_p indicates that the traits increase together, while a negative r_p signifies an inverse relationship.

RESULTS AND DISCUSSION

Vegetative and reproductive stages

In the double-ear local maize cultivar, the developmental stages from emergence (VE) to physiological maturity (R6) achieved documentation as follows. Emergence (VE) occurred at 4–6 days after planting (DAP), the first leaf stage (V1) at 7–8 DAP, V2 at 10–11 DAP, V3 at 11–14 DAP, V4 at 14–19 DAP, V5 at 17–24 DAP, and V6 at 22–29 DAP. Meanwhile, the appearance of V7 was at 27–39 DAP, V8 at 31–45 DAP, V9 at 33–48 DAP, V10 at 42–53 DAP, V11 at 45–53 DAP, V12 at 48–55 DAP, and V13 at 50–56 DAP. Tasseling (VT) was evident between 50 and 58 DAP, followed by silking (R1) at 57–65 DAP, R2 at 65–70

DAP, R3 at 69–74 DAP, R4 at 72–77 DAP, R5 at 74–80 DAP, and physiological maturity (R6) at 80–83 DAP.

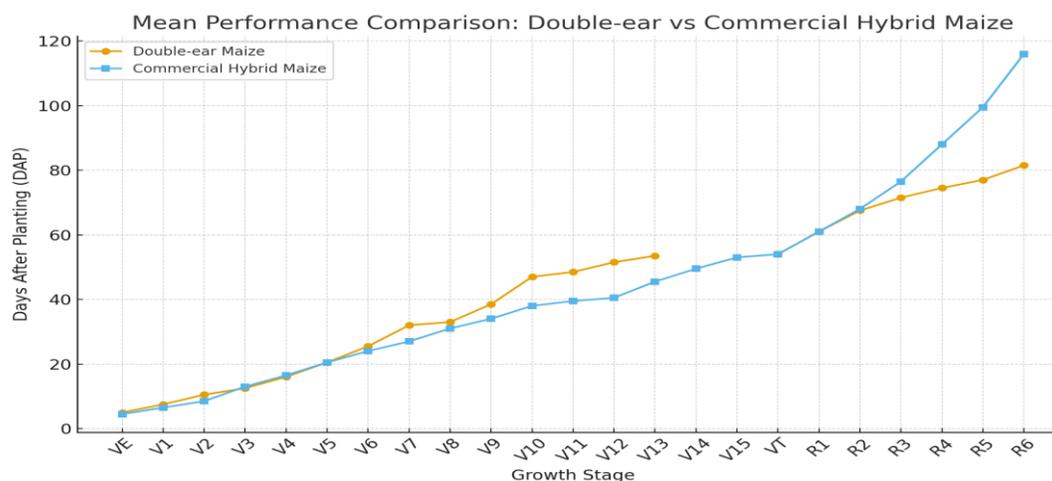
Comparative mean performance between double-ear maize and a commercial hybrid maize (Bisi 2) across both vegetative and reproductive stages appears in Table 3 and Figure 1. The double-ear maize exhibited a slightly slower early growth (VE–V2) than the commercial hybrid but showed a faster progression through the middle vegetative stages (V6–V9). However, the commercial hybrid completed many more vegetative stages (up to V15) before tasseling (VT), indicating a longer vegetative growth phase. During the reproductive phase, both maize types reached tasseling (VT) and silking (R1) at similar times (around 54–61 DAP). Nevertheless, the commercial hybrid required substantially more time to reach physiological maturity (R6, 116 DAP) than the double-ear maize (R6, 81.5 DAP). This indicates the commercial hybrid had a prolonged grain-filling period, which commonly has an association with a larger ear size and higher yield potential. In contrast, the double-ear maize completed its development cycle earlier, reflecting its adaptation toward early maturity and possibly lower yield potential per ear.

In maize, the duration required for seed germination remains relatively long (4–6 DAP), indicating the need for specific pre-sowing treatment to enhance the early seedling emergence. Suggestions on several biological approaches have emerged in various studies to accelerate maize development and early germination. These included hydropriming (Chimdi, 2023; Dawadi *et al.*, 2023), hormonal treatment with salicylic acid (Rehman *et al.*, 2011), and the strategic application of nitrogen and phosphorus starter fertilizers near the seed row at the sowing time (Ujvári *et al.*, 2023).

In this local double-ear maize genotype, the vegetative stages (V1 to VT) were generally comparable to that observed in commercial maize hybrids. For instance, Jan *et al.* (2018) reported the widely cultivated

Table 3. Mean performance comparison between double-ear maize and commercial hybrid maize.

	Vegetative stage (days after planting)															
	VE	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15
Double-ear maize	5	7.5	10.5	12.5	16	20.5	25.5	32	33	38.5	47	48.5	51.5	53.5		
Commercial hybrid	4.5	6.5	8.5	13	16.5	20.5	24	27	31	34	38	39.5	40.5	45.5	49.5	53
	Reproductive stage (days after planting)															
	VT	R1	R2	R3	R4	R5	R6									
Double-ear maize	54	61	67.5	71.5	74.5	77	81.5									
Commercial hybrid	54	61	68	76.5	88	99.5	116									

**Figure 1.** Growth and developmental progression of the double-ear maize and the commercial hybrid maize.

hybrids, such as DK-Garanon, WS-666, Pioneer-3025, and Pioneer-3164, typically reached the tasseling stage between 53 and 57 DAP. In the current study, tasseling also occurred between 50 and 58 DAP, indicating a similar duration for vegetative growth. The results suggested that, although the said maize cultivar is locally adapted and possesses a distinct double-ear trait, its vegetative growth rate aligns closely with the high-performing hybrids. Despite these factors, the overall similarity in the timing of vegetative stages compared to commercial hybrids supports the idea that this local maize cultivar holds valuable adaptive traits. Its phenological consistency, combined with its unique reproductive and ear formation, may offer potential in breeding efforts aimed at enhancing yield stability under diverse environmental conditions.

For the local double-ear maize, the reproductive stage began with tasseling (VT) at 50–58 DAP, followed by silking (R1) at 57–65 DAP and subsequent kernel development stages until physiological maturity (R6) at 80–83 DAP. The extended interval between VT and R1 revealed an unsynchronized flowering pattern, which can hinder effective pollination and reduce kernel setting (Cárcova and Otegui, 2001). By comparing with various commercial maize hybrids, which often reached physiological maturity by 100–110 DAP (Pradeep and Patil, 2018), this local double-ear maize cultivar demonstrates a relatively shorter reproductive stage.

The silking occurrence after tasseling within seven days disclosed low synchrony between pollen shedding and silk emergence, which is a crucial determinant of yield potential, especially under marginal and stress-

prone soil conditions. According to Edmeades *et al.* (2017), synchrony between tasseling and silking is essential for successful fertilization. Anthesis-silk interval (ASI) has a considerable genetic linkage to grain yield, and delayed silking emergence may adversely affect grain production. The ideal scenario for maximal grain yield occurs when silking happens within a few days of tasseling. A prolonged ASI, resulting from delayed silk emergence, desiccates the silks and impairs fertilization, causing kernel abortion and, ultimately, reducing the total kernels produced per ear and grain yield (Bakhtavar *et al.*, 2015; Li and Howell, 2021).

Anthesis-silk interval emerged as an indicator of environmental stress, as it tends to lengthen under conditions such as drought and heat, as well as weed competition. Compared with the non-drought-tolerant hybrid, the drought-tolerant hybrid exhibited a reduced ASI, produced fewer kernels, and had a greater kernel weight (Reid *et al.*, 2014). However, if it persists for an extended period, a prolonged ASI may occur as an adaptive mechanism of maize in response to environmental stress conditions. A prolonged ASI is also a characteristic often observed in early-maturing maize genotypes. Previous research has shown particular maize varieties with a shorter growth period may display lower synchrony because of the faster transition from tasseling to silking (Wang *et al.*, 2024).

A relatively short duration between the growth stages R2 (blister) and R5 (dent) may indicate a compressed grain-filling period, which can adversely affect kernel development and grain yield. Kernel filling is a critical phase during which the transfer of assimilates from the source (leaves and stem) to the sink (developing kernels) occurs. However, when the R2–R5 interval becomes shorter, the time available for dry matter accumulation in the kernels declines, resulting in lower kernel weight and grain yield. Modern maize hybrids typically benefit from extended grain-filling phases, supporting higher yield potential through prolonged dry matter translocation (Borrás *et al.*, 2021). These physiological differences underscore the need to consider

ASI and grain-filling duration as selection criteria in breeding programs aimed at improving stress resilience and yield performance of the double-ear maize cultivar.

ANOVA, variance components, and heritability

The analysis of variance revealed significant differences among genotypes for most measured traits, indicating the presence of genetic variability within the double-ear maize population (Table 4). Significant mean square values were evident for plant height, stem diameter, ear length, ear diameter, ear weight, and grain yield, both among male parents and their respective female progenies. These results demonstrate that genotypic factors contributed substantially to phenotypic variation in these traits, suggesting their potential for improvement through selection. In contrast, leaf number per plant (LP^{-1}) showed a nonsignificant effect across all sources of variation, signifying a narrow genetic base or high environmental influence on this trait. This finding corresponds with its low correlation values, implying limited importance in yield determination (Table 5). Similar results, as documented by Genievsckaya *et al.* (2025), stated that traits with nonsignificant variance components generally have low heritability and weak association with yield performance.

The results expressed that the dominance variance (σ_D^2) was greater than the additive variance (σ_A^2) (P-value: 0.000–0.050), which authenticated the involvement of non-additive genetic effects, particularly dominance. It plays a more considerable role in the expression of evaluated traits (Table 6). In quantitative genetics, the additive variance is often heritable and transmitted from parents to offspring, while the dominance variance arises from allelic interactions at a locus and typically has an association with heterozygosity (Falconer and Mackay, 1996). Hadini *et al.* (2015) also reported the genetic contribution from dominance effects was larger than that from additive effects for kernel weight per ear in maize. Higher dominance variance may

Table 4. Analysis of variance (mean square) for all traits in double-ear maize populations.

Source of variation	D.f.	PH	LP ⁻¹	SD	EL	ED	EWP ⁻¹	GY
Replication	2	6054.0**	123.090**	1.751**	13.372*	0.358*	1081.08**	3.512**
Male	88	864.0*	4.104 ^{ns}	0.046**	17.286**	0.604**	313.01**	1.017**
Female (Male)	178	602.1 ^{ns}	3.789 ^{ns}	0.021**	14.952**	0.242**	302.35**	0.982**
Error	532	577.7	3.482	0.016	3.454	0.153	91.01	0.296
Total	800							

DF = Degrees of freedom, PH = Plant height, LP⁻¹ = Leaves plant⁻¹, SD = Stem diameter, EL = Ear length, ED = Ear diameter, EWP⁻¹ = Ear weight plant⁻¹, GY = Grain yield

*, **: indicates significance level at 5% and 1% probability, respectively; ns = non-significant.

Table 5. Phenotypic correlation among agronomic traits in the double-ear maize.

	EWP ⁻¹	ED	EL	SD	LP ⁻¹	PH
ED	0.166*					
EL	0.310**	0.067 ^{ns}				
SD	0.295**	0.071 ^{ns}	0.110*			
LP ⁻¹	0.150**	0.054 ^{ns}	0.006 ^{ns}	0.101*		
PH	0.173**	0.023 ^{ns}	0.155**	0.256**	0.071 ^{ns}	
GY	0.288**	0.068 ^{ns}	0.068 ^{ns}	0.129**	0.021 ^{ns}	0.010 ^{ns}

EWP⁻¹ = Ear weight plant⁻¹, ED = Ear diameter, EL = Ear length, SD = Stem diameter, LP⁻¹ = Leaves plant⁻¹, PH = Plant height, GY = Grain yield

*, **: indicates significance level at 5% and 1% probability, respectively; ns = non-significant effect.

Table 6. Estimated values of genetic variance ($\hat{\sigma}_G^2$), additive variance ($\hat{\sigma}_A^2$), dominance variance ($\hat{\sigma}_D^2$), as well as broad-sense (\hat{H}^2) and narrow-sense (\hat{h}^2) heritabilities for all traits in double-ear maize populations.

No.	Traits	$\hat{\sigma}_G^2$	$\hat{\sigma}_A^2$	$\hat{\sigma}_D^2$	\hat{H}^2	\hat{h}^2
1	Plant height	148.933	116.400	32.533	0.205	0.160
2	Leaves plant ⁻¹	0.549	0.140	0.409	0.136	0.035
3	Stem diameter	0.018	0.007	0.011	0.524	0.328
4	Ear length	16.368	1.037	15.331	0.826	0.052
5	Ear diameter	0.161	0.119	0.280	0.647	0.372
6	Ear weight plant ⁻¹	286.524	4.738	281.787	0.759	0.013
7	Grain yield	0.902	0.015	0.900	0.760	0.012

result from several factors, such as the highest level of heterozygosity in the population, especially in cross-pollinated species like maize, which naturally maintain the high levels of genetic diversity (Hallauer *et al.*, 2010). Furthermore, some traits, particularly grain yield and plant vigor, are frequently under the control of loci showing overdominance or pseudo-overdominance effects (Bernardo, 2020). The heterozygous individuals with these effects perform better than either homozygote,

increasing the influence of dominance effects on total genetic variability.

The predominance of the dominance variance (σ_D^2) over the additive variance (σ_A^2) has a significant implication in maize breeding. Traditional selection methods that primarily exploit an additive genetic variance may be less effective where governing the traits expression was largely by non-additive genetic influences. In such cases, hybrid

breeding is more appropriate, as its design is to capture the non-additive effects and maximize heterosis. Recent studies have also emphasized the importance of incorporating non-additive genetic effects into breeding programs. For instance, Roth *et al.*'s (2022) findings demonstrated that accounting for dominance and incorporating inbreeding effects into genomic prediction models led to greater accuracy in forecasting maize hybrids' performance. Similarly, Fritsche-Neto *et al.* (2021) highlighted that including dominance and epistatic effects in genomic selection models can significantly enhance the prediction accuracy for complex traits in maize hybrids. Furthermore, Ghazy *et al.* (2024) reported the non-additive genetic factors, including dominance and epistasis, could play a crucial role in hybrid vigor in key traits such as grain yield and disease resistance.

The results detailed that for vegetative traits in maize, the broad-sense heritability (H^2) estimates ranged from moderate to high (0.136–0.524; 95% CI: 0.75–1.33), whereas the reproductive traits exhibited consistently high heritability values (0.647–0.826; 95% CI: 0.75–1.33). This pattern suggested a differential genetic control between the vegetative and reproductive traits. Specifically, the vegetative traits observed with the lower heritability indicate a greater environmental influence on their expression. However, the higher heritability in reproductive traits points to a predominant genetic control. For instance, Magar *et al.* (2021) reported that grain yield and 1000-grain weight in maize displayed the highest heritability estimates (0.93 and 0.99, respectively), indicating considerable genetic influence. In contrast, traits like leaf length and leaf width showed lower heritability estimates (0.50 and 0.39, respectively), implying a significant environmental impact on these vegetative traits.

Furthermore, the reproductive traits with high heritability imply these traits showed more reliable transmission from parent to offspring and thus appeared more responsive to selection. This is particularly advantageous in breeding programs aiming for genetic improvement, as the selection based on these traits is likely to result in significant genetic

gains. According to Falconer and Mackay (1996), traits with high heritability, especially those under considerable additive genetic control, respond more effectively to direct selection, enabling more efficient accumulation of favorable alleles in breeding populations. Similarly, Bernardo (2020) emphasized that reproductive traits, such as yield-related traits, often exhibited higher heritability, and after selection, can substantially increase the genetic gain in maize breeding.

The outcomes further showed that narrow-sense heritability (h^2) values were in the low to moderate range (0.012–0.372), which suggested that the additive genetic variance contributes partially to the total phenotypic variation observed for both vegetative and reproductive traits in maize. These findings explored that trait expression incurred large influences from non-additive genetic factors, including dominance and epistasis, along with environmental interaction. According to Bernardo (2020), the traits with low to moderate narrow-sense heritability more often received influences from complex genetic factors and environmental variability, which can obscure the response to selection based solely on phenotypic values. Falconer and Mackay (1996) also emphasized that narrow-sense heritability is critical for predicting the response to selection; its lower value does not necessarily imply poor genetic control, and it may instead highlight the non-additive gene action. Magar *et al.* (2021) declared that even though some agronomic traits in maize showed a high broad-sense heritability, and the narrow-sense heritability values were significantly lower, they reflect the effect of dominance and epistatic variances. Similarly, Belay (2018) shared that plant height exhibited moderate narrow-sense heritability values, reinforcing the role of non-additive genetic variance in their inheritance.

Correlation analysis between traits

Phenotypic correlation analysis revealed significant positive associations among several yield-related traits (Table 5). Ear weight per plant (EWP^{-1}) exhibited strong correlations with ear length ($r = 0.310^{**}$), stem diameter ($r =$

0.295**), plant height ($r = 0.173^{**}$), and grain yield ($r = 0.288^{**}$), suggesting that these traits contribute directly to yield formation. Grain yield (GY) expressed the strongest connection with ear weight per plant, confirming ear weight and ear length as primary indicators of yield performance. Similar relationships between yield and ear components have successful reports from Olawamide and Fayeun (2020), Reddy *et al.* (2022), and Maulana *et al.* (2023). Therefore, simultaneous selection for ear weight, ear length, stem diameter, and plant height will improve maize yield potential effectively. In contrast, ear diameter (ED) showed weak and mostly nonsignificant correlations, implying limited importance in determining total productivity in this population.

Stem diameter (SD) demonstrated a positive association with ear weight, plant height, and grain yield, indicating that thicker stems may facilitate better nutrient translocation and ear filling, enhancing yield stability (Chukwudi *et al.*, 2022). Leaf number per plant (LP^{-1}) showed low and mostly nonsignificant correlations with other traits. This weak association likely has linkages to the nonsignificant ANOVA result for leaf number (Table 4), reflecting low genetic variability and a stronger influence of environmental conditions. Consequently, leaf number appears less suitable as a selection index for yield improvement.

CONCLUSIONS

The study demonstrated that the local double-ear maize exhibited earlier maturity and a shorter grain-filling period than the commercial hybrid (Bisi 2), indicating its adaptation to early-maturing environments. Significant genetic variability was evident among genotypes. Genetic analysis showed the dominance variance exceeded the additive variance, revealing the importance of non-additive gene action. For reproductive traits, broad-sense heritability was moderate to high, whereas narrow-sense heritability remained low to moderate. The results suggested that hybrid breeding strategies leveraging heterosis

would be more effective than selection based solely on additive genetic variance. Strong positive correlations among ear weight, ear length, stem diameter, and grain yield indicate that these traits can serve as effective selection indices to improve yield potential in double-ear maize breeding programs.

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