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Research Article

Yield Performance and Heterosis Analysis of Single-Cross Maize (*Zea mays* L.) Hybrids under Subtropical Winter Environments of Nepal

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Abstract

The present experiment was conducted at Bharatpur-15, Fulbari, Chitwan, Nepal, from 28 November 2017 to 8 May 2018 to evaluate the performance of 27 maize (*Zea mays* L.) hybrids, including pipeline hybrids and commercial checks, under subtropical winter conditions. The experiment was laid out in a randomized alpha-lattice design with three replications. Data were recorded on yield, yield components, and flowering traits, and analyzed using analysis of variance (ANOVA), followed by mean separation using LSD and Duncan's Multiple Range Test (DMRT). The results revealed significant differences among genotypes for all studied traits, indicating substantial genetic variability. Grain yield ranged from 7.08 to 20.99 t ha^{-1}, with K1(A) × Y33 recording the highest yield, followed by K5(A) × Y33 and K2(A) × Y33. These hybrids also exhibited superior performance in biomass yield, harvest index, and kernel weight. Flowering traits, particularly anthesis–silking interval (ASI), showed significant variation, with lower ASI associated with better reproductive efficiency and higher grain yield. Heterosis analysis revealed strong positive heterosis for grain yield, with K1(A) × Y33 showing the highest mid-parent heterosis (80.12%), indicating the importance of non-additive gene action. The study identified K1(A) × Y33, K5(A) × Y33, and K2(A) × Y33 as promising hybrids with high yield potential and desirable agronomic traits. These hybrids can be recommended for further multilocation testing and potential commercialization. Overall, the findings highlight the effectiveness of heterosis breeding in improving maize productivity and provide valuable insights for future hybrid development programs in Nepal and similar agro-ecological regions.

Keywords: Maize (*Zea mays* L.), Heterosis, Hybrid breeding, Grain yield, Anthesis–silking interval (ASI), Harvest index, Genetic variability, Subtropical environment, Nepal.

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, serving as a staple food, livestock feed, and a key raw material for various industrial products. Globally, it ranks among the top three cereal crops alongside wheat and rice and plays a pivotal role in ensuring food and nutritional security, particularly in developing countries (FAO, 2022; Shiferaw *et al.*, 2011). In Nepal, maize is the second most important staple crop after rice and is cultivated across a wide range of agro-ecological zones, from the Terai to the mid-hills. It contributes significantly to household food security, income generation, and the national agricultural economy (MoALD, 2023). Despite its importance, the average productivity of maize in Nepal remains lower than the global average, mainly due to the cultivation of low-yielding varieties, limited adoption of improved hybrids, and exposure to various biotic and abiotic stresses.

To address these challenges, the development and deployment of high-yielding and stress-tolerant maize hybrids is essential. Hybrid breeding has been recognized as one of the most effective approaches for increasing maize productivity, primarily through the exploitation of heterosis or hybrid vigor (Shull, 1948; Duvick, 2005). Heterosis refers to the superior performance of F_1 hybrids over their parental lines in terms of yield and other agronomic traits. Several genetic hypotheses have been proposed to explain the phenomenon, including the dominance hypothesis (Jones, 1917), the overdominance hypothesis (Hull, 1945), and the epistasis hypothesis (Powers, 1944). The magnitude of heterosis largely depends on the genetic divergence of parental lines and their combining ability, which determines the performance of hybrid progenies (Sprague & Tatum, 1942).

Grain yield in maize is a complex and quantitatively inherited trait influenced by multiple components such as biomass accumulation, harvest index, kernel weight, and flowering behavior. Among these, flowering synchronization, particularly the anthesis–silking interval (ASI), plays a crucial role in determining reproductive success and final grain yield. A shorter ASI indicates better synchrony between pollen shedding and silk emergence, resulting in improved fertilization and kernel set, especially under stress conditions (Bolaños & Edmeades, 1996). Likewise, harvest index, which reflects the efficiency of assimilate partitioning from vegetative to reproductive organs, has been identified as a key determinant of yield improvement in cereal crops, including maize (Donald, 1962; Tollenaar & Lee, 2002).

The evaluation of maize hybrids under well-structured experimental conditions is essential for identifying superior genotypes with high yield potential and stability across environments. Advanced experimental designs such as the alpha lattice design are particularly useful for managing a large number of genotypes while improving experimental precision and reducing error variance (Gomez & Gomez, 1984). Moreover, statistical tools such as analysis of variance (ANOVA), least significant difference (LSD), and Duncan's Multiple Range Test (DMRT) are widely employed to determine the significance of differences among genotypes and to facilitate reliable selection decisions.

Considering the importance of hybrid breeding and the need to enhance maize productivity under subtropical conditions, the present study was conducted to evaluate the performance of selected maize hybrids. The specific objectives were to: (i) assess the variability among hybrids for yield and related traits, (ii) estimate heterosis for grain yield and its contributing components, and (iii) identify superior hybrids for potential use in breeding programs and future varietal development.

Materials and Methods

Experimental Site

The field experiment was conducted at Bharatpur-15, Fulbari, Chitwan, Nepal, during the winter season of 2017/18. The experimental site is geographically located at 27.65° N latitude and 84.36° E longitude, with an elevation of 194 meters above sea level. The soil of the experimental field was sandy loam in texture. The climate of the study area is characterized as humid subtropical, with an average annual rainfall of approximately 2000 mm, most of which occurs during the summer months (June–September).

The climatic conditions prevailing during the experimental period are presented in Table 1. The winter season was generally dry, with minimal rainfall and moderate temperature fluctuations, providing suitable conditions for maize growth under irrigated conditions.

Table 1: Climatic data of the study site during the experiment

Month/Year	Relative Humidity (%)	Maximum Temperature (°C)	Minimum Temperature (°C)	Rainfall (mm)
Dec 2017	94.85	25.49	11.62	0.0
Jan 2018	95.50	20.92	8.52	0.6
Feb 2018	86.84	26.40	12.64	0.0
Mar 2018	70.61	32.62	18.00	26.0
Apr 2018	68.07	34.49	22.27	35.1
May 2018	71.21	34.38	24.32	14.5

Table 2: Name and sources of planting materials used in the study

Entry No.	Maize Hybrid	Source
1	KML-1(A) × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
2	KML-3(B) × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
3	KML-5(A) × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
4	KML-8(A) × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
5	KHUMAL HYBRID-2	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
6	KML-4(A) × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
7	KML-14 × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
8	KML-1(A) × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
9	KML-11(A) × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
10	KML-12 × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
11	KML-4(A) × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
12	KML-5(A) × KYM-86	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
13	LPM-157	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
14	KML-10 × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
15	KML-16 × RML-4	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
16	KML-7 × KYM-86	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
17	KML-2(A) × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
18	KML-8(A) × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
19	KML-5(A) × KYM-33	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
20	SHRESTA	Hamro Agrovet, Narayangarh, Chitwan, Nepal
21	BIOSEED 9782	Hamro Agrovet, Narayangarh, Chitwan, Nepal
22	RAJKUMAR	Hamro Agrovet, Narayangarh, Chitwan, Nepal
23	GANGA KAVERI	Hamro Agrovet, Narayangarh, Chitwan, Nepal
24	RAMPUR HYBRID-6	National Maize research Program, Rampur, Chitwan, Nepal
25	RML-86/RML-96	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal
26	RAMPUR HYBRID-4	National Maize research Program, Rampur, Chitwan, Nepal
27	RML-95/RML-96	Agriculture Botany Division, Khumaltar, Lalitpur, Nepal

Experimental Design and Plant Materials

The experiment was laid out in a randomized alpha lattice design with three replications to improve experimental precision when evaluating a large number of genotypes (Gomez & Gomez, 1984). A total of 27 maize hybrids, including pipeline hybrids and commercial check varieties, were evaluated as treatments. Each replication was divided into three incomplete blocks.

The net plot size was 7.5 m² (2.5 m × 3 m), and the crop was established at a spacing of 0.75 m between rows and 0.25 m between plants. Sowing was carried out manually by placing 1–2 seeds per hill. The experiment was planted on 28 November 2017 and harvested on 8 May 2018.

The experimental materials were collected from the Agriculture Botany Division, Khumaltar, Lalitpur, the National Maize Research Program, Rampur, and local agrovets. Details of the genotypes used in the study are presented in Table 2.

Crop Management

The experimental field was prepared following the harvest of the preceding rice crop on 20 November 2017. Organic manure was applied at the rate of 33 t ha^{-1} during land preparation. The field was finely tilled and leveled using a rotavator two days prior to sowing.

Chemical fertilizers were applied at the rate of 120:60:40 kg $N:P_2O_5:K_2O$ ha^{-1} using urea, diammonium phosphate (DAP), and muriate of potash (MOP), respectively. Half of the nitrogen along with the full doses of phosphorus and potassium were applied as basal during sowing. The remaining nitrogen was top-dressed in two equal splits at 51 and 90 days after sowing (DAS).

Irrigation was provided through a shallow tube well as required to maintain optimal soil moisture. Intercultural operations such as weeding, soil loosening, and earthing-up were carried out manually at 33 and 45 DAS. Each plot consisted of 40 plants, maintaining a plant population density of 53,333 plants ha^{-1}. The crop was harvested at 162 DAS, and threshing was done manually.

Data Collection

Data on key agronomic traits, including plant height, ear height, biomass yield, grain yield, harvest index, and thousand kernel weight, were recorded. Phenological traits such as days to tasseling, days to anthesis, days to silking, and anthesis–silking interval (ASI) were also observed.

All data were recorded following the standard protocols developed by the National Maize Research Program, Rampur, Chitwan, Nepal. Grain yield was adjusted to 15% moisture content and converted to yield per hectare using standard procedures described by Carangal *et al*. (1971) and Shrestha *et al*. (2019).

Standard heterosis was estimated for grain yield and related traits using Rampur Hybrid-6 as the standard check, following the method described by Falconer and Mackay (1996).

Statistical Analysis

The collected data were subjected to analysis of variance (ANOVA) appropriate for an alpha lattice design to determine the significance of genotypic differences. Mean comparisons were performed using the least significant difference (LSD) test at 1% and 5% probability levels and Duncan's Multiple Range Test (DMRT) at the 5% level of significance, as outlined by Gomez and Gomez (1984).

Heterosis (%) was calculated over mid-parent values using standard formulas. All statistical analyses were performed using GENSTAT software (version 14; VSN International, Hemel Hempstead, UK), and preliminary data processing was carried out using Microsoft Excel 2016.

Results and Discussion

Analysis of Variance and Genetic Variability

The analysis of variance (ANOVA) revealed highly significant differences ($p \leq 0.01$ and $p \leq 0.05$) among the maize hybrids for all the studied traits, indicating the presence of substantial genetic variability within the experimental materials. Such variability is essential for effective selection and genetic improvement in breeding programs, as it provides the basis for exploiting heterosis and identifying superior genotypes. Similar findings have been reported by Betrán *et al*. (2003) and Duvick (2005), who emphasized that significant genotypic variation is a prerequisite for successful hybrid development in maize.

The observed variability among hybrids in this study is consistent with earlier reports from similar agro-ecological conditions in Nepal, where significant differences among maize genotypes were documented (Kandel *et al*., 2018; Dhakal *et al*., 2018; Shrestha *et al*., 2015; Tripathi *et al*., 2016; Shrestha *et al*., 2016; Prasai *et al*., 2015). This indicates that the tested materials possess adequate genetic diversity, which can be effectively utilized for yield improvement and hybrid breeding.

Mean Performance and Yield Attributes of Maize Hybrids

The mean performance of 27 maize hybrids for yield and yield-related traits is presented in Table 3. Significant variation among hybrids was observed for all traits, reflecting differences in genetic potential and adaptability.

Biomass yield ranged from 20.39 to 41.58 t ha^{-1}, with the highest value recorded in K8(A) × R4, indicating superior vegetative growth and dry matter accumulation. In contrast, lower biomass production in R 86/96 suggests poor adaptation under the given environmental conditions. Similar variability in biomass production among maize hybrids has been reported by Kafle *et al*. (2020), highlighting the influence of genotype and environment interaction.

Ear height varied from 83.60 cm to 145.78 cm, with Khumal hybrid-2 exhibiting the highest ear placement. Lower ear height, as observed in Shrestha, is generally desirable for reducing lodging susceptibility and improving plant stability. Optimal plant architecture, including moderate ear placement, has been identified as a key factor influencing yield stability in maize (Sangoi, 2000).

Harvest index (HI) ranged from 0.29 to 0.62, with higher values recorded in Ganga Kaveri and K5(A) × Y86, indicating efficient partitioning of assimilates toward economic yield. The importance of harvest index in enhancing crop productivity has long been recognized, as improved assimilate allocation contributes significantly to grain yield (Donald, 1962; Tollenaar & Lee, 2002).

Grain yield exhibited wide variation among hybrids, ranging from 7.08 to 20.99 t ha^{-1}. The highest grain yield was recorded in K1(A) × Y33, followed by K5(A) × Y33 and K2(A) × Y33, demonstrating their superior performance. These results align with earlier studies emphasizing the role of hybrid vigor in increasing maize productivity (Hallauer *et al*., 2010).

Thousand kernel weight (TKW) also showed significant variation, with higher values observed in Ganga Kaveri and K5(A) × Y86, suggesting better grain filling and kernel development. Grain weight is considered a stable yield component and plays a crucial role in determining final yield (Fischer & Palmer, 1984).

Table 3: Mean value and DMRT of biomass, ear height (ear-ht), Harvest index (hi), plant height (plant-ht), thousand kernel weight (tkw) and grain yield/ha.

Genotype	biomass	ear-ht	hi	plant-ht	tkw	yield t/ha	tss50	anth50	siini50
01.K1(A) X R4	33.04 cd	117.81 aeg	0.43 bd	249.52 ad	0.51 defg	16.77 b	107.53 def	107.9 eg	107.5 egh
02.K3(B)X R4	30.84 degh	132.93 acd	0.40 de	253.05 abc	0.49 efhj	14.59 cd	107.02 ef	107.6 fgh	106.9 ehi
03.K5(A) X R4	28.97 ghk	128.77 ae	0.39 efg	253.03 abc	0.46 fhl	13.13 ceghi	103.37 ghi	105.9 gj	105.7 gi
04.K8(A)X R4	41.58 a	105.76 ceh	0.29 k	231.11 bde	0.48 efhj	14.11 cef	107.88 cf	108.4 deg	107.0 ehi
05.KH-2	25.90 lmn	145.78 a	0.41 de	245.24 ad	0.55 bcd	12.43 egi	112.27 a	112.7 ab	112.7 a
06.K4(A) X R4	27.47 jklm	126.95 ae	0.43 cd	253.84 abc	0.52 cf	13.86 cfg	104.08 ghi	106.9 gi	106.9 ehi
07.K14X R4	28.46 hl	105.44 ceh	0.30 k	214.69 dg	0.43 ijkl	10.11 j	110.37 ac	111.2 ac	110.7 ac
08.K1(A)X Y33	37.53 b	118.13 aeg	0.48 a	236.17 ade	0.50 defh	20.99 a	105.71 fh	107.1 gi	107.0 ehi
09.K11(A)XY33	28.80 ghk	99.62 eh	0.35 fi	205.04 eg	0.41 kl	12.01 fhij	105.38 fi	106.7 gj	107.0 ehi
10.K12XY33	32.11 cef	102.47 deh	0.32 jk	192.96 fg	0.44 ghl	11.92 gj	108.06 cf	110.4 bce	108.4 cef
11.K4(A)X Y33	32.42 ce	122.94 ae	0.39 ef	243.24 ad	0.55 bcd	14.90 c	103.41 ghi	107.0 gi	107.2 ehi
12.K5(A)X Y86	22.95 o	109.29 bceh	0.44 bc	244.40 ad	0.61 ab	11.97 gj	97.22 j	100.8 k	101.4 j
13.LPM-157	28.03 ijkl	135.77 ac	0.37 fh	243.39 ad	0.52 cf	12.10 fhij	107.21 ef	108.3 deg	106.7 ehi
14.K10 X R4	33.83 c	116.61 aeg	0.29 k	213.80 dg	0.40 kl	11.72 hij	105.88 fg	106.9 gi	106.0 fhi
15.K16X R4	25.92 lmn	89.74 gh	0.37 efh	181.91 g	0.49 defhi	11.35 ij	105.54 fi	106.4 gj	105.8 gi
16.K7X Y86	26.55 klm	89.61 fgh	0.44 abc	204.90 eg	0.57 ac	13.79 cegh	94.75 k	97.7 l	99.2 j
17.K2(A)X Y33	25.07 mo	135.25 ac	0.45 abc	262.37 ab	0.50 defh	13.23 ceghi	108.74 ce	110.0 cef	111.0 ab
18.K8(A)X Y33	31.53 cg	120.95 aeg	0.36 fh	221.82 cdef	0.50 defh	13.33 ceghi	106.90 ef	108.2 eg	107.9 defg
19.K5(A)X Y33	30.26 eghi	125.45 ae	0.35 ghi	268.40 a	0.51 cf	12.58 deghi	107.03 ef	108.4 deg	109.2 bce
20.SHRESTA	23.87 no	83.60 h	0.46 ab	216.45 def	0.53 ce	13.13 ceghi	99.06 j	99.7 kl	100.8 j
21.BIOSEED	31.52 cg	122.95 ae	0.39 ef	246.71 ad	0.49 efhj	14.37 ce	103.04 hi	104.7 ij	106.0 fhi
22.RAJ	30.51 deghi	141.12 ab	0.37 fh	266.80 ab	0.46 efhk	13.19 ceghi	102.74 i	104.3 j	104.8 i
23.GK	27.16 jklm	100.11 eh	0.47 ab	258.51 ab	0.62 a	14.93 c	102.89 hi	105.2 hij	105.1 hi
24.RH-6	30.86 degh	136.47 ac	0.32 ik	236.17 ade	0.44 hl	11.70 hij	112.04 ab	113.1 a	110.7 ac
25.R-86/96	20.39 p	121.42 aef	0.30 k	260.43 ab	0.41 kl	7.08 k	109.59 ace	110.1 ce	110.4 ac
26.RH-4	32.46 ce	98.42 eh	0.35 hij	218.65 cdef	0.39 l	13.28 ceghi	109.40 bce	110.7 acd	110.5 ac
27.R-95/96	29.66 fghj	138.29 ab	0.35 fi	247.07 ad	0.43 jkl	12.41 egi	110.22 acd	111.1 ac	110.0 bc

Hybrids with their entries are KML-1(A) X RML-4 (1), KML-3(B)X RML-4 (2), KML-5(A) X RML-4(3), KML-8(A)X RML-4 (4), KHUMAL HYBRID-2 (5), KML-4(A) X RML-4 (6), KML-14X RML-4 (7), KML-1(A)X KYM-33 (8), KML-11(A)XKYM-33 (9), KML-12XKYM-33 (10), KML-4(A)X KYM-33 (11), KML-5(A)X KYM-86 (12), LPM-157 (13), KML-10 X RML-4 (14), KML-16X RML-4 (15), KML-7X KYM-86 (16), KML-2(A)X KYM-33 (17), KML-8(A)X KYM-33 (18), KML-5(A)X KYM-33 (19), SHRESTA (20), BIOSEED 9782 (21), RAJKUMAR (22), GANGA KAVERI (23), RAMPUR HYBRID-6 (24), RML-86/RML-96 (25), RAMPUR HYBRID-4(26) and RML-95/RML-96(27).

Table 4: Heterosis of plant height (plant-ht), ear height, cob length (C-length), cob diameter (C-dia), biomass, grain yield/ha, thousand kernel weight, kernel number, Harvest index, 5 cob weight, days to 50% tasseling, days to 50% anthesis, days to 50%silk initiation and days to silk senescence

Genotype	plant-ht	ear-ht	C-length	C-dia	biomass	GYTN	tkw15%	knl no	HI	5cobwt	TS50	AN50	SIIN50	SISEN100
01.K1(A) X R4	7.86	-15.48	-2.38	9.38	5.45	43.81	14.85	25.33	36.47	31.36	-4.17	-4.72	-3.01	-2.70
02.K3(B)X R4	7.14	-8.33	0.00	3.13	-0.64	27.56	13.85	12.02	28.36	28.77	-4.76	-4.72	-3.31	-2.70
03.K5(A) X R4	10.71	-7.14	4.76	9.38	-6.70	12.62	5.70	6.61	20.74	56.07	-8.33	-6.78	-4.82	-3.51
04.K8(A)X R4	-1.43	-25.00	0.00	0.00	33.83	22.25	9.94	13.73	-8.53	5.90	-3.87	-4.13	-3.31	-3.24
05.KH-2	3.57	5.95	-4.76	6.25	-15.50	8.30	31.58	-17.56	28.15	8.12	0.89	0.00	2.11	-25.68
06.K4(A) X R4	6.43	-10.24	4.76	3.13	-10.35	21.78	23.46	-1.35	35.92	40.58	-6.55	-5.01	-3.01	-3.51
07.K14X R4	-5.71	-23.81	-4.76	6.25	-8.35	-13.37	-0.13	-13.09	-5.41	13.28	-2.08	-2.06	-0.30	-1.35
08.K1(A)X Y33	0.00	-13.10	2.38	15.63	21.47	80.12	16.53	56.08	48.30	60.50	-5.65	-5.31	-3.31	-1.62
09.K11(A)XY33	-9.29	-27.38	-9.52	9.38	-8.48	0.65	-6.89	8.19	9.96	12.54	-6.25	-5.90	-3.61	-3.51
10.K12XY33	-16.43	-27.38	-14.29	6.25	4.51	7.37	-0.73	8.02	2.42	35.78	-3.57	-2.95	-2.11	-0.81
11.K4(A)X Y33	4.29	-13.10	7.14	6.25	5.17	32.02	24.58	6.01	25.36	73.78	-7.44	-5.31	-3.01	-1.35
12.K5(A)X Y86	2.43	-21.90	14.29	0.00	-26.95	0.15	43.40	-30.20	37.08	29.51	-12.80	-10.32	-8.13	-4.32
13.LPM-157	1.43	-3.57	2.38	6.25	-9.35	3.65	22.20	-15.12	14.50	38.36	-4.17	-3.83	-3.31	0.00
14.K10 X R4	-8.29	-16.67	-2.38	9.38	7.65	-0.72	-9.25	9.37	-7.79	39.10	-5.36	-5.31	-4.22	-4.05
15.K16X R4	-21.43	-38.10	-19.05	6.25	-16.77	-2.56	13.44	-13.45	17.14	6.64	-6.25	-5.90	-4.52	-3.24
16.K7X Y86	-12.14	-36.90	7.14	9.38	-13.75	22.52	32.28	-7.27	42.21	66.40	-15.18	-13.57	-10.24	-5.41
17.K2(A)X Y33	13.57	-5.95	9.52	6.25	-18.71	16.61	13.76	2.48	43.46	30.99	-2.98	-2.65	0.30	0.81
18.K8(A)X Y33	-2.14	-13.10	-4.76	6.25	2.33	17.38	16.89	0.30	14.71	30.25	-4.76	-4.72	-2.71	-1.89
19.K5(A)X Y33	14.29	-13.10	14.29	12.50	-3.74	7.84	23.21	-11.27	11.88	70.09	-4.46	-3.83	-1.20	0.81
20.SHRESTA	-9.29	-38.10	0.00	6.25	-22.84	11.36	17.92	-5.57	44.38	37.63	-11.31	-11.50	-8.73	-5.68
21.BIOSEED	8.57	-10.71	4.76	9.38	0.28	21.02	15.72	4.63	20.69	73.04	-8.33	-7.67	-4.52	-5.14
22.RAJ	12.86	3.57	7.14	3.13	-2.71	9.53	1.69	7.62	12.70	32.46	-7.74	-7.37	-5.12	-2.70
23.GK	10.00	-32.14	0.00	3.13	-11.69	33.48	46.53	-8.93	51.26	11.80	-8.04	-6.78	-4.82	-1.35
25.R-86/96	13.57	-13.10	-19.05	-9.38	-33.84	-37.48	-11.37	-29.47	-5.59	-19.92	-2.08	-2.65	-0.30	-1.62
26.RH-4	-4.29	-28.57	-16.67	-3.13	2.95	10.62	-6.71	19.08	7.45	-21.40	-2.38	-2.06	-0.30	-0.27
27.R-95/96	3.57	-1.19	-7.14	12.50	-5.33	3.95	1.60	2.20	9.74	-1.84	-1.19	-1.18	-0.30	-1.35

Hybrids with their entries are KML-1(A) X RML-4 (1), KML-3(B)X RML-4 (2), KML-5(A) X RML-4(3), KML-8(A)X RML-4 (4), KHUMAL HYBRID-2 (5), KML-4(A) X RML-4 (6), KML-14X RML-4 (7), KML-1(A)X KYM-33 (8), KML-11(A)XKYM-33 (9), KML-12XKYM-33 (10), KML-4(A)X KYM-33 (11), KML-5(A)X KYM-86 (12), LPM-157 (13), KML-10 X RML-4 (14), KML-16X RML-4 (15), KML-7X KYM-86 (16), KML-2(A)X KYM-33 (17), KML-8(A)X KYM-33 (18), KML-5(A)X KYM-33 (19), SHRESTA (20), BIOSEED 9782 (21), RAJKUMAR (22), GANGA KAVERI (23), RAMPUR HYBRID-6 (24), RML-86/RML-96 (25), RAMPUR HYBRID-4(26) and RML-95/RML-96(27).

Table 5: Mean value and DMRT of Flowering and Reproductive traits of the Maize hybrids:

Genotype	tss25	tss50	tss75	tss100	anth25	anth50	anth75	anth100	ant-ts50	ant-ts100	gyn
01.K1(A) X R4	106.5 cef	107.5 def	107.5 dfh	108.9 eg	107.9 dfh	107.9 eg	109.1 defg	109.6 dfh	0.4 f	0.7 dh	16.77 b
02.K3(B)X R4	106.0 cef	107.0 ef	107.2 fh	108.4 eh	106.6 fj	107.6 fgh	107.9 fh	108.9 efj	0.6 ef	0.5 dh	14.59 cd
03.K5(A) X R4	102.3 g	103.4 ghi	104.2 jk	105.3 j	105.1 ijl	105.9 gj	106.6 hi	107.7 hij	2.5 acd	2.4 ab	13.13 ceghi
04.K8(A)X R4	106.8 cef	107.9 cf	108.5 cfg	108.9 eg	108.1 dfh	108.4 deg	109.3 cf	110.0 dfg	0.5 ef	1.1 adfh	14.11 cef
05.KH-2	111.6 a	112.3 a	112.9 a	112.9 ab	112.2 ab	112.7 ab	113.1 a	113.1 ab	0.4 f	0.2 fh	12.43 egi
06.K4(A) X R4	103.5 fg	104.1 ghi	105.6 hk	106.4 hj	105.8 hjl	106.9 gi	107.4 fi	107.7 ghij	2.8 ac	1.4 adf	13.86 cfg
07.K14X R4	109.3 ac	110.4 ac	110.5 bc	111.6 acd	110.7 ac	111.2 ac	112.3 ab	112.3 abc	0.8 df	0.7 dh	10.11 j
08.K1(A)X Y33	104.7 eg	105.7 fh	106.9 fhi	107.6 fghi	106.9 fhi	107.1 gi	108.1 efh	108.7 fj	1.4 bcef	1.1 adfh	20.99 a
09.K11(A)XY33	104.4 eg	105.4 fi	106.3 ghj	107.8 fghi	105.5 hjl	106.7 gj	107.6 fi	108.6 fj	1.4 bcef	0.9 cfh	12.01 fhij
10.K12XY33	106.7 cef	108.1 cf	109.2 cf	110.2 ce	108.6 cdfg	110.4 bce	110.3 bce	110.0 dfg	2.3 ade	-0.3 h	11.92 gj
11.K4(A)X Y33	102.4 g	103.4 ghi	104.6 ijk	106.3 hj	106.2 ghjk	107.0 gi	107.4 fi	108.6 fj	3.6 a	2.3 ac	14.90 c
12.K5(A)X Y86	95.9 hi	97.2 j	98.5 l	102.4 k	99.7 m	100.8 k	102.6 j	104.4 k	3.6 a	2.0 acd	11.97 gj
13.LPM-157	105.9 def	107.2 ef	107.7 efh	108.3 eh	107.3 efhi	108.3 deg	108.3 defh	109.4 dfi	1.1 cef	1.1 adfh	12.10 fhij
14.K10 X R4	104.5 eg	105.9 fg	106.6 ghj	107.7 fghi	106.5 fj	106.9 gi	107.6 fi	108.6 fj	1.0 cef	0.9 bcdfh	11.72 hij
15.K16X R4	104.5 eg	105.5 fi	106.3 ghj	107.2 ghj	105.5 hjl	106.4 gj	106.8 ghi	108.3 fj	0.8 df	1.1 adfh	11.35 ij
16.K7X Y86	93.4 i	94.7 k	96.3 m	100.0 l	96.5 n	97.7 l	98.4 k	101.0 l	2.9 ab	1.0 adfh	13.79 cegh
17.K2(A)X Y33	108.4 bcd	108.7 ce	109.8 cde	109.7 def	109.0 cdf	110.0 cef	110.3 bce	111.0 bde	1.2 bcef	1.3 adf	13.23 ceghi
18.K8(A)X Y33	106.3 cef	106.9 ef	107.3 fh	108.8 eg	107.9 dfh	108.2 eg	109.1 defg	110.0 df	1.3 bcef	1.3 adfg	13.33 ceghi
19.K5(A)X Y33	106.0 cef	107.0 ef	107.3 fh	108.2 eh	108.4 cdfg	108.4 deg	109.6 cf	110.6 cdf	1.4 bcef	2.4 a	12.58 deghi
20.SHRESTA	97.7 h	99.1 j	100.0 l	102.1 k	98.8 mn	99.7 kl	101.3 j	103.1 k	0.7 df	1.0 adfh	13.13 ceghi
21.BIOSEED	102.1 g	103.0 hi	104.3 jk	106.1 hj	103.9 kl	104.7 ij	106.3 hi	107.6 hij	1.7 bcef	1.6 adf	14.37 ce
22.RAJ	101.8 g	102.7 i	103.8 k	105.9 ij	103.2 l	104.3 j	105.3 i	107.1 j	1.5 bcef	1.2 adfg	13.19 ceghi
23.GK	101.6 g	102.9 hi	104.3 jk	105.5 ij	104.1 jl	105.2 hij	106.4 hi	107.3 ij	2.3 ade	1.8 acde	14.93 c
24.RH-6	111.0 ab	112.0 ab	112.2 ab	113.6 a	112.5 a	113.1 a	113.5 a	114.1 a	1.1 cef	0.4 efh	11.70 hij
25.R-86/96	107.6 ce	109.6 ace	109.8 ce	111.5 acd	109.8 bcde	110.1 ce	110.6 bcd	111.4 bd	0.5 ef	-0.1 gh	7.08 k
26.RH-4	108.4 bcd	109.4 bce	110.4 bc	112.2 ac	110.1 ad	110.7 acd	111.4 ac	113.0 ab	1.3 bcef	0.8 dh	13.28 ceghi
27.R-95/96	109.3 ac	110.2 acd	110.8 ac	111.4 bcd	110.4 ad	111.1 ac	111.9 ab	112.4 abc	0.9 df	1.0 adfh	12.41 egi

Hybrids with their entries are KML-1(A) X RML-4 (1), KML-3(B)X RML-4 (2), KML-5(A) X RML-4(3), KML-8(A)X RML-4 (4), KHUMAL HYBRID-2 (5), KML-4(A) X RML-4 (6), KML-14X RML-4 (7), KML-1(A)X KYM-33 (8), KML-11(A)XKYM-33 (9), KML-12XKYM-33 (10), KML-4(A)X KYM-33 (11), KML-5(A)X KYM-86 (12), LPM-157 (13), KML-10 X RML-4 (14), KML-16X RML-4 (15), KML-7X KYM-86 (16), KML-2(A)X KYM-33 (17), KML-8(A)X KYM-33 (18), KML-5(A)X KYM-33 (19), SHRESTA (20), BIOSEED 9782 (21), RAJKUMAR (22), GANGA KAVERI (23), RAMPUR HYBRID-6 (24), RML-86/RML-96 (25), RAMPUR HYBRID-4(26) and RML-95/RML-96(27).

Table 6: Mean value and DMRT of Flowering and Reproductive traits of the Maize hybrids:

Genotype	siini25	siini50	siini75	siini100	sisen25	sisen50	sisen75	sisen100	actanth	actsiini	acttss
01.K1(A) X R4	106.9 defg	107.5 egh	108.0 deg	108.5 eg	113.3 ghi	116.1 defi	117.8 defh	120.1 a	1.6 ac	1.6 ac	2.4 bc
02.K3(B)X R4	105.8 fhik	106.9 ehi	107.7 eh	107.9 fg	113.9 fghi	116.1 defi	118.0 defh	119.8 a	2.3 ac	2.1 ac	2.4 bc
03.K5(A) X R4	104.6 hik	105.7 gi	106.7 gh	107.7 fg	111.7 hjk	114.5 ghik	116.9 fi	119.5 a	2.6 ac	3.1 ac	3.0 bc
04.K8(A)X R4	106.0 eij	107.0 ehi	107.7 eh	108.0 fg	111.3 hjl	113.3 ik	116.5 ghij	117.8 a	1.9 ac	2.0 ac	2.1 bc
05.KH-2	111.6 a	112.7 a	112.6 a	113.0 a	120.2 a	122.0 a	123.4 a	91.6 b	0.9 c	1.4 ac	1.2 c
06.K4(A) X R4	105.8 fhik	106.9 ehi	107.5 eh	108.0 fg	112.1 hj	114.1 hik	116.2 ghij	120.3 a	2.0 ac	2.2 ac	2.9 bc
07.K14X R4	109.9 abc	110.7 ac	111.1 ab	111.7 ac	117.4 abe	119.2 abd	120.2 bd	122.2 a	1.6 ac	1.8 ac	2.3 bc
08.K1(A)X Y33	106.7 deh	107.0 ehi	108.0 eg	108.3 eg	116.6 bef	118.0 bfg	119.7 bf	119.4 a	1.9 ac	1.5 ac	2.9 bc
09.K11(A)XY33	106.2 ei	107.0 ehi	107.4 eh	108.4 eg	113.3 ghi	115.3 efij	117.3 efi	119.3 a	3.1 ac	2.2 ac	3.4 bc
10.K12XY33	108.1 be	108.4 cef	109.2 be	110.1 ce	118.1 abd	120.0 abc	121.1 abc	126.3 a	1.4 bc	2.0 ac	3.5 bc
11.K4(A)X Y33	106.2 ei	107.2 ehi	107.6 eh	108.6 eg	115.6 cdeg	118.3 af	119.9 be	123.8 a	2.4 ac	2.4 ac	3.9 b
12.K5(A)X Y86	100.2 l	101.4 j	103.0 i	105.0 h	109.6 jl	112.2 jk	114.9 ik	115.4 a	4.6 a	4.8 ac	6.4 a
13.LPM-157	105.3 ghik	106.7 ehi	107.4 eh	108.7 eg	116.7 bef	119.8 abd	121.2 abc	120.9 a	2.1 ac	3.4 ac	2.4 bc
14.K10 X R4	105.0 ghik	106.0 fhi	106.7 gh	107.3 g	110.9 ijl	113.4 ik	115.9 hij	116.6 a	2.1 ac	2.3 a	3.1 bc
15.K16X R4	103.8 jk	105.8 gi	106.4 gh	108.2 eg	112.5 ghj	114.9 efij	117.1 efi	119.4 a	2.8 ac	4.4 ac	2.7 bc
16.K7X Y86	98.2 m	99.2 j	100.6 j	101.9 i	108.3 l	110.9 k	113.9 jk	118.8 a	4.4 ab	3.7 ac	6.6 a
17.K2(A)X Y33	110.3 ab	111.0 ab	110.9 abc	111.4 acd	119.2 ab	117.6 bfh	122.2 ab	128.0 a	2.0 ac	1.1 ac	1.3 c
18.K8(A)X Y33	107.8 cef	107.9 defg	108.9 cef	109.7 def	115.4 deg	116.8 cdefi	118.9 cdefg	125.1 a	2.2 ac	1.9 ac	2.5 bc
19.K5(A)X Y33	108.1 be	109.2 bce	110.0 bcd	110.6 bcd	118.8 abc	120.9 ab	122.0 ab	123.9 a	2.2 ac	2.5 bc	2.1 bc
20.SHRESTA	99.8 lm	100.8 j	102.1 ij	103.7 h	108.8 kl	111.0 k	113.1 k	112.6 a	4.3 ab	4.0 ac	4.4 b
21.BIOSEED	105.2 ghik	106.0 fhi	107.0 fgh	107.7 fg	108.3 l	110.9 k	113.9 jk	117.3 a	3.8 ac	2.5 ac	4.0 b
22.RAJ	103.7 k	104.8 i	105.7 h	107.1 g	112.1 hj	114.7 fij	117.1 efi	116.0 a	3.8 ac	3.3 ac	4.1 b
23.GK	104.0 ik	105.1 hi	106.5 gh	107.5 g	114.2 eh	117.8 bfh	119.7 bf	125.1 a	3.2 ac	3.5 c	3.9 b
24.RH-6	110.1 ab	110.7 ac	111.0 ab	112.3 ab	119.3 ab	120.7 ab	122.0 ab	121.4 a	1.6 ac	2.2 ac	2.6 bc
25.R-86/96	109.8 abc	110.4 ac	111.0 ab	111.5 acd	117.3 abe	118.4 af	120.4 bd	123.7 a	1.6 ac	1.7 ac	3.9 b
26.RH-4	109.6 abc	110.5 ac	110.8 abc	111.5 acd	117.9 abd	119.9 abc	122.0 ab	121.4 a	2.9 ac	2.0 ab	3.8 b
27.R-95/96	108.9 bcd	110.0 bcd	111.0 ab	111.0 bcd	116.6 bef	118.6 abe	119.6 bf	119.1 a	1.9 ac	2.1 ab	2.1 bc

Hybrids with their entries are KML-1(A) X RML-4 (1), KML-3(B)X RML-4 (2), KML-5(A) X RML-4(3), KML-8(A)X RML-4 (4), KHUMAL HYBRID-2 (5), KML-4(A) X RML-4 (6), KML-14X RML-4 (7), KML-1(A)X KYM-33 (8), KML-11(A)XKYM-33 (9), KML-12XKYM-33 (10), KML-4(A)X KYM-33 (11), KML-5(A)X KYM-86 (12), LPM-157 (13), KML-10 X RML-4 (14), KML-16X RML-4 (15), KML-7X KYM-86 (16), KML-2(A)X KYM-33 (17), KML-8(A)X KYM-33 (18), KML-5(A)X KYM-33 (19), SHRESTA (20), BIOSEED 9782 (21), RAJKUMAR (22), GANGA KAVERI (23), RAMPUR HYBRID-6 (24), RML-86/RML-96 (25), RAMPUR HYBRID-4(26) and RML-95/RML-96(27).

Flowering Behavior and Reproductive Traits

The mean performance for flowering and reproductive traits is presented in Table 4 and Table 5. Significant differences among hybrids were observed for days to tasseling, anthesis, and silking, indicating variation in maturity groups.

Early flowering hybrids such as K7 × Y86 and K5(A) × Y86 may be advantageous in environments with shorter growing seasons or terminal stress conditions. Similar findings have been reported by Bolaños and Edmeades (1996), who highlighted the importance of early maturity in stress-prone environments.

Anthesis–silking interval (ASI), a key indicator of reproductive efficiency, varied significantly among the hybrids. Lower ASI values observed in KHUMAL HYBRID-2 and K1(A) × R4 indicate better synchronization between pollen shedding and silk emergence, which enhances fertilization success and kernel set. Reduced ASI has been strongly associated with improved grain yield under both stress and non-stress conditions (Edmeades *et al*., 1993).

Silk senescence also showed significant variation among hybrids. Hybrids such as KHUMAL HYBRID-2 and RAMPUR HYBRID-6 exhibited delayed silk senescence, suggesting a longer grain filling duration. Extended grain filling has been reported to positively influence kernel development and final yield (Bänziger *et al*., 1999).

Heterosis Analysis

Heterosis (%) over the mid-parent is presented in Table 6. The results revealed substantial heterosis among hybrids for all studied traits, indicating strong hybrid vigor.

Positive heterosis for grain yield was highest in K1(A) × Y33 (80.12%), followed by GANGA KAVERI (33.48%) and K3(B) × R4 (27.56%), demonstrating the superiority of these hybrid combinations. The concept of heterosis, first described by Shull (1908), remains fundamental to hybrid maize breeding and has been widely exploited for yield enhancement.

Significant positive heterosis was also observed for biomass yield, harvest index, and thousand kernel weight, suggesting the importance of non-additive gene action in controlling these traits. These findings support the dominance and overdominance hypotheses proposed by Jones (1917) and Hull (1945), respectively.

Hybrids such as K1(A) × Y33 and K4(A) × Y33 exhibited consistent positive heterosis across multiple traits, indicating their potential as promising hybrid combinations. Similar results have been reported by Sprague and Tatum (1942), emphasizing the importance of combining ability in hybrid performance. Conversely, negative heterosis observed in some hybrids, such as R 86/96, indicates poor parental combinations and limited breeding value.

Relationship Between Traits and Yield

Grain yield showed a positive association with biomass yield, harvest index, and thousand kernel weight. Hybrids with higher biomass production and efficient assimilate partitioning produced superior grain yields. Additionally, shorter ASI contributed to improved fertilization efficiency and higher productivity.

These findings are consistent with previous studies that highlighted the importance of physiological efficiency and source–sink relationships in determining maize yield (Tollenaar & Wu, 1999). The integration of these traits is essential for developing high-yielding and stable maize hybrids.

Overall Performance and Breeding Implications

Among the evaluated hybrids, K1(A) × Y33, K5(A) × Y33, and K2(A) × Y33 emerged as the most promising genotypes based on their superior performance in grain yield, heterosis, and yield components. These hybrids demonstrated strong adaptability and can be recommended for further multilocation trials and potential release.

The results of this study confirm that heterosis breeding remains an effective strategy for enhancing maize productivity. The presence of significant genetic variability and strong hybrid vigor indicates excellent prospects for developing high-yielding maize hybrids adapted to diverse agro-ecological conditions. These findings are in agreement with Duvick (2005), who emphasized the continued importance of hybrid breeding in sustaining maize yield improvement.

Conclusion

The present study demonstrated the existence of substantial genetic variability among the evaluated maize hybrids for yield, yield components, and flowering traits under subtropical winter conditions of Nepal. The significant differences observed among genotypes confirm the potential for effective selection and genetic improvement through hybrid breeding.

High levels of heterosis were recorded for grain yield and its contributing traits, indicating the importance of non-additive gene action in the expression of these traits. Among the tested hybrids, K1(A) × Y33, K5(A) × Y33, and K2(A) × Y33 consistently exhibited superior performance in terms of grain yield, biomass production, harvest index, and favorable flowering behavior, particularly shorter anthesis–silking interval (ASI), which contributed to improved reproductive efficiency.

The positive association of grain yield with biomass yield, harvest index, and kernel weight further emphasizes the importance of these traits in maize improvement programs. The identification of high-performing hybrids with stable and desirable agronomic characteristics highlights their potential for advancement to multilocation trials and eventual release as commercial hybrids.

Overall, the findings of this study reaffirm that heterosis breeding remains a powerful and reliable strategy for enhancing maize productivity. The superior hybrids identified can serve as valuable genetic resources for future breeding programs aimed at developing high-yielding and climate-resilient maize varieties suitable for diverse agro-ecological conditions of Nepal and similar environments.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this work.

Author's Contribution

All authors contributed equally at all stages of research and preparation of the manuscript. Final form of manuscript was approved by all authors.

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