

Genetic Architecture of Fodder Yield in Diverse Yellow Maize Germplasm

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Abstract

Maize (*Zea mays* L.), one of the most widely grown cereal crops in the world, is an essential ingredient in livestock feeding systems because of its high biomass productivity, palatability, and nutritional value. Thus, increasing fodder yield and biomass production in maize has emerged as a primary goal in crop improvement and breeding programs. This study investigated genetic variability and other aspects of the genetic architecture of fodder yield-related traits in yellow maize germplasm.

Seventeen yellow maize germplasm lines were evaluated at the Demonstration Farm Unit-3, Phase-1, Integral University, Lucknow (Uttar Pradesh), India, during the Kharif season of 2025. The experiment was laid out in a randomized complete block design (RCBD) with three replications. 26 observations were recorded, covering phenological and morphological traits, biomass, yield, and quality traits. Data collected were subjected to statistical analysis, analysis of variance (ANOVA), estimation of parameters for genetic variability, heritability, and genetic advance, correlation studies, path coefficient analysis, and cluster analysis.

The results of ANOVA analysis showed highly significant differences among maize genotypes for major traits, including plant height, number of leaves, leaf length, fresh stem weight, green fodder yield, dry matter yield (including grain), and harvest index. The heritability was found to be very high (≥ 90), and the genetic advance was also high for traits like green fodder yield, dry matter yield, fresh stem weight, harvest index, and leaf: stem ratio, which indicates the presence of additive gene action and a good scope of selection. Analysis of correlations among biomass traits indicated a significant positive association, particularly between fresh stem weight, green fodder yield, and dry matter yield ($r \approx 0.99$); however, those for flowering traits were also high, with days to tasseling highly correlated with days to silking ($r = 0.93$). However, cluster analysis grouped these genotypes into three major clusters, which suggests high genetic diversity and their potential for effective breeding programs. The study reveals important traits related to biomass that can be used as efficient selection criteria in enhancing forage productivity and developing dual-purpose maize.

Introduction

Integrated Maize Production in Europe [1], abbreviated as IMPROVE, is a collaborative project that aims to improve maize cultivation across the European continent while addressing environmental sustainability challenges. Maize has become increasingly important in livestock production systems during the past decades due to its high biomass productivity, adaptability, and balanced nutritional composition in terms of constituents. Apart from grain production, maize plants generate considerable vegetative biomass, which can be used for livestock feeding as green fodder, silage, and crop residues. Whole-plant maize silage is one of the most popular forage resources in modern livestock production systems due to its appropriate content of fermentable carbohydrates, moderate protein, and minerals necessary for the growth and productivity of animals [2]. Furthermore, maize silage is highly effective in contributing to high milk production in dairy cattle and growth performance of beef animals due to the high starch concentration ($> 35\%$) available in maize kernels and digestible fiber from vegetative tissues [3].

Thus, maize silage has several advantages over traditional forage crops such as sorghum, millet, and natural grasses. It is more palatable and digestible, which leads to a higher voluntary intake of the animals [4]. The ratio of structural carbohydrates to soluble starch is balanced to enhance fermentation and microbial activity in the rumen, thus optimizing nutrient utilization and feed conversion efficiency [5]. Moreover, through the process of

ensiling, ensiling allows for effective preservation of maize silage, allowing farmers to store large amounts of fodder and feed animals with energy-rich and nutrient-dense provisions throughout the year.

Furthermore, to supporting livestock nutrition, maize is important for sustainable agricultural production systems. The ever-increasing global demand for livestock-derived products like milk, meat, and eggs has led to a pressing need for dependable sources of animal feed. Maize's high biomass yield per unit area makes its silage an attractive option for farmers who want to maximize the fodder produced from limited land areas. Moreover, maize integrates seamlessly into conservation agriculture practices, including crop rotation, retention of residues, and minimal tillage [5], which enhance soil fertility and conserve moisture while minimizing the emission of greenhouse gases.

Maize also acts as an important dual-purpose crop; worldwide, this particular farming system is common, especially in developing nations where maize grain becomes food for humans, and the rest of the plant biomass is used as fodder for livestock. This dual use increases both the economic value of the crop and serves as an integral aspect of integrated crop-livestock farming systems. Yellow maize cultivars are particularly valued for their carotenoid and other nutrient content in the grain, which is beneficial for human and animal nutrition [6].

In India, maize has gained significance as a food as well as a fodder crop, which is driven by increasing diversification towards dairy-based livestock farming. India is among the world's largest milk producers, and the appetite for good-quality livestock feed continues to grow. The use of maize silage technology has greatly enhanced the availability of nutritious fodder year-round and has been promoted under initiatives by the Indian Council of Agricultural Research (ICAR) and other agricultural institutions [7]. Maize is a versatile crop that can be grown as a single or mixed crop due to favorable climatic and soil conditions (such as alluvial soils, including both fertile and reproductive soil) in the Indo-Gangetic Plains Uttar Pradesh region, where it has a dual role for grain and fodder production.

While the significant economic importance of fodder has led to some maize research aimed at improving biomass traits and fodder quality, these traits historically have received less effort than grain yield. Biomass yield is a complex quantitative trait involving multiple genetic and environmental interactions, such as plant height, leaf area, stem girth, and dry matter accumulation. Recent developments, including genome-wide association studies (GWAS) and quantitative trait loci (QTL) mapping, have enhanced the understanding of the genetic basis of these traits [8];[9]. Yet, the assessment of genetic variability and heritability, along with genetic advance, remains a significant factor in selecting superior genotypes and formulating better breeding strategies [10];[11].

Therefore, the current study was conducted to assess yellow maize germplasm under field conditions at the Demonstration Farm Unit of Integral University, Lucknow. The objective of this study was to evaluate the variation in phenological, morphological, biomass, yield, and quality traits and estimate genetic parameters for the abovementioned traits. Furthermore, correlation and path coefficient analysis were performed to reveal the correlated traits. The outcome of the study is expected to help the maize breeding program to develop dual-purpose varieties with greater fodder yield and grain productivity.

Materials and Methods

This study was carried out to assess yellow maize germplasm for variability in phenological, morphological, biomass, yield, and quality traits under field conditions. The experiment was conducted at the Demonstration Farm Unit of Integral University, Lucknow, Uttar Pradesh (India), which is in the Central Plain Zone of the Indo-Gangetic alluvial plains. Seventeen yellow maize germplasm lines were evaluated for growth performance, fodder yield potential, and nutritional quality under field conditions.

Experimental Design

The field experiment was conducted during the Kharif season in 2025 at the Demonstration Farm Unit-3, Phase-1, Integral University, Lucknow, Uttar Pradesh, India. The experimental crop was maize (*Zea mays* L.). Seventeen yellow maize germplasm lines were investigated.

The design of the experiment was a randomized complete block (RCBD) with three replications. The total area for the experiment was about 40 m × 15 m (600 m²). For each genotype, the plots were planted (line sowing) with 78 cm row spacing and 30 cm plant spacing, respectively. Recommended agronomic practices for maize cultivation in the area were followed to ensure proper crop growth and development during the growing period.

For the recording of observations, most of the morphological, biomass, and yield traits were recorded on five randomly selected plants per plot, whereas phenological traits were recorded at a plot level.

Traits Recorded

Observations on phenological, morphological, biomass, yield, and quality traits were recorded during the course of crop growth to obtain information on genetic diversity among maize germplasm lines. Phenological traits included the days to achieve 50% tasseling, days to achieve 50% silking, and days to maturity, reflecting the timing of developmental stages in maize (all expressed as DSS or DM). Vegetative growth and plant structure were measured through morphological traits, including plant height (cm), number of leaves per plant, leaf length (cm), leaf width (cm), stem girth (cm), and ear height. To assess the forage productivity potential of genotypes, biomass and fodder yield traits such as fresh leaf weight, fresh stem weight, leaf-stem ratio, green fodder yield, and dry matter yield were recorded. Furthermore, yield and yield associates like ear length, ear diameter, number of grains per sink point (ear), 100-seed weight, seed productivity per plant, shelling percentage, and harvest index were evaluated to estimate grain productivity with their constituent components. Lastly, the nutritional quality and fodder value of maize biomass were evaluated based on quality traits: crude protein content, neutral detergent fiber (NDF), acid detergent fiber (ADF), and moisture content. Collectively, these measurements offered a thorough assessment of the agronomic performance, yield potential, and nutritional traits of the maize germplasm lines.

Statistical Models and Analysis

The data were analyzed using various statistical techniques to determine genetic variation and the interrelationships of the studied characters. Significant differences between the genotypes were determined by analysis of variance (ANOVA). Genetic variability was expressed as genotypic variance, phenotypic variance, environmental variance, and genotypic (GCV) and phenotypic (PCV) coefficients of variation. To evaluate the potential for genetic improvement by selecting good parents, broad-sense heritability (H^2), genetic advance (GA),

and the ratio of GAM to mean have been determined. Association analysis investigated the relationships among phenological, morphological, biomass, yield, and quality traits, whereas path coefficient analysis was performed to estimate direct as well as indirect effects of component traits contributing toward fodder yield. Statistical analyses were performed using the SARONEX web-based statistical platform.

Results and Discussion

The effect of genotypic differences among maize germplasm on 26 phenological, morphological, biomass, yield, and quality traits was tested using analysis of variance (ANOVA) under a randomized complete block design. Results of ANOVA are summarized in Table 1, and F-value distributions among main traits are presented in Figure 1.

Table 1. Analysis of Variance (ANOVA) for 26 traits in maize germplasm

GENOTYPE	Df (Genotype)	Sum Sq (Genotype)	Mean Sq (Genotype)	F-value	Pr(>F)	Significance
Days to 50% Tasseling	17	66.31	3.90	1.03	0.454	NS
Days to 50% Silking	17	81.87	4.82	0.85	0.628	NS
Plant Height (cm)	17	12807.91	753.41	7.90	1.17e-07	HS
Number of Leaves per Plant	17	80.76	4.75	6.42	1.49e-06	HS
Leaf Length (cm)	17	1750.35	102.96	7.15	4.09e-07	HS
Leaf Width (cm)	17	80.76	4.75	6.42	1.49e-06	HS
Stem Girth (cm)	17	27.51	1.62	3.18	0.0017	S
Fresh Leaf Weight (g)	17	1.04	0.061	2.70	0.0060	S
Fresh Stem Weight (g)	17	34431.51	2025.38	321.87	3.96e-34	HS
Leaf: Stem Ratio	17	271414.93	15965.58	162.97	7.06e-29	HS
Green Fodder Yield (g)	17	0.34	0.020	14.94	1.68e-11	HS
Dry Matter Yield (g)	17	477537.14	28090.42	294.76	1.90e-33	HS
Grain Yield per Plant (g)	17	40956.02	2409.18	72.72	9.68e-23	HS
100-Grain Weight (g)	17	27390.38	1611.20	46.39	2.12e-19	HS
Ear Height (cm)	17	280.93	16.53	22.84	2.43e-14	HS
Number of Cobs per Plant	17	3505.99	206.23	4.73	4.41e-05	S
Days to 50% Brown Husk	17	2.31	0.136	0.53	0.922	NS
Ear Length (cm)	17	136.31	8.02	0.69	0.794	NS
Ear Diameter (cm)	17	176.54	10.38	30.54	2.24e-16	HS
Number of Grain Rows per Ear	17	855.88	50.35	38.60	4.64e-18	HS
Shelling Percentage (%)	17	77.72	4.57	0.93	0.548	NS
Harvest Index	17	1.30	0.076	330.33	2.50e-34	HS

Crude Protein Content (%)	17	8.38	0.493	0.93	0.553	NS
Neutral Detergent Fiber (NDF)	17	138.54	8.15	1.73	0.082	NS
Acid Detergent Fiber (ADF)	17	32.40	1.91	0.56	0.896	NS
Moisture Content (%)	17	86.25	5.07	1.12	0.373	NS

Abbreviation: HS=highly significant, NS=not significant.

As indicated in Table 1, highly significant differences ($p < 0.01$) were observed among genotypes for several traits, including plant height, number of leaves per plant, leaf length, leaf width, fresh stem weight, leaf: stem ratio, green fodder yield, dry matter yield, grain yield per plant, 100-grain weight, ear height, ear diameter, grain rows per ear, and harvest index. Particularly high F-values were recorded for fresh stem weight ($F = 321.87$), dry matter yield ($F = 294.76$), and harvest index ($F = 330.33$), indicating substantial genetic variability among the germplasm lines for biomass and yield-related traits.

A few traits, such as stem girth, fresh leaf weight, and number of cobs per plant, showed significant variation ($p < 0.05$), suggesting moderate genetic variability that may still be useful for selection. In contrast, traits including days to 50% tasseling, days to 50% silking, days to 50% brown husk, ear length, shelling percentage, crude protein content, neutral detergent fiber (NDF), acid detergent fiber (ADF), and moisture content exhibited non-significant differences, indicating either limited genetic variability or stronger environmental influence on these traits.

The pattern of variation is also illustrated in Figure 1, where biomass and yield-related traits exhibit higher F-values compared with phenological and quality traits. The ANOVA results reveal considerable genetic variability among the maize germplasm lines, particularly for biomass and yield traits, indicating good potential for selection and improvement in maize breeding programs.

Genetic Variability, Heritability, and Genetic Advance

Estimates of genetic parameters revealed considerable variation among the studied traits in terms of genetic control and their potential response to selection. Traits exhibiting high heritability along with high genetic advance are generally governed by additive gene action and can therefore be effectively improved through direct selection in breeding programs. The detailed estimates of mean, genotypic variance, phenotypic variance, genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability (H^2), genetic advance (GA), and genetic advance as a percentage of the mean (GAM) are presented in Table 2.

Table 2. Genetic variability parameters (Mean, VG, VP, GCV, PCV, Heritability, GA, GAM)

Trait	Mean	VG (Genetic Var.)	VE (Error Var.)	VP (Phenotypic Var.)	GCV (%)	PCV (%)	H ² (%)	GA	GAM (%)
Days to 50% Tasseling	55.98	0.00	4.00	1.33	0.00	2.06	0.00	0.00	0.00
Days to 50% Silking	59.57	0.00	5.70	1.90	0.00	2.31	0.00	0.00	0.00
Plant Height (cm)	175.54	217.64	100.49	251.14	8.40	9.03	86.66	28.29	16.12
Number of Leaves per Plant	8.20	1.35	0.69	1.58	14.17	15.34	85.38	2.21	26.98
Leaf Length (cm)	59.61	29.41	14.72	34.32	9.10	9.83	85.70	10.34	17.35
Leaf Width (cm)	6.72	0.37	0.52	0.54	9.01	10.93	67.89	1.03	15.29
Stem Girth (cm)	2.55	0.013	0.023	0.020	4.44	5.59	63.07	0.19	7.26
Fresh Leaf Weight (g)	36.53	672.91	6.64	675.13	71.01	71.12	99.67	53.35	146.03
Fresh Stem Weight (g)	124.01	5287.99	101.62	5321.86	58.64	58.83	99.36	149.32	120.41
Leaf:Stem Ratio	0.30	0.006	0.001	0.007	26.38	27.35	92.99	0.16	52.40
Green Fodder Yield (g)	160.55	9330.59	98.66	9363.47	60.17	60.27	99.65	198.64	123.73
Dry Matter Yield (g)	47.68	791.72	34.03	803.06	59.02	59.44	98.59	57.55	120.71
Grain Yield per Plant (g)	110.06	526.06	33.02	537.07	20.84	21.06	97.95	46.76	42.49
100-Grain Weight (g)	26.11	5.28	0.67	5.51	8.81	8.99	95.93	4.64	17.77
Ear Height (cm)	87.33	53.84	44.71	68.74	8.40	9.49	78.32	13.38	15.32
Number of Cobs per Plant	1.31	0.00	0.25	0.08	0.00	22.12	0.00	0.00	0.00
Days to 50% Brown Husk	90.65	0.00	11.71	3.90	0.00	2.18	0.00	0.00	0.00

Ear Length (cm)	15.61	3.34	0.35	3.46	11.71	11.92	96.59	3.70	23.71
Ear Diameter (cm)	3.66	0.12	0.015	0.124	9.42	9.62	95.98	0.70	19.01
Grain Rows per Ear	31.18	16.33	1.35	16.78	12.96	13.14	97.32	8.21	26.34
Shelling Percentage (%)	78.24	0.00	5.14	1.71	0.00	1.67	0.00	0.00	0.00
Harvest Index	0.45	0.025	0.0002	0.025	35.57	35.62	99.73	0.33	73.17
Crude Protein Content (%)	9.80	0.00	0.55	0.18	0.00	4.37	0.00	0.00	0.00
Neutral Detergent Fiber (%)	50.17	1.06	4.98	2.72	2.05	3.29	38.92	1.32	2.63
Acid Detergent Fiber (%)	29.92	0.00	3.38	1.13	0.00	3.55	0.00	0.00	0.00
Moisture Content (%)	70.16	0.28	4.22	1.69	0.76	1.85	16.74	0.45	0.64

The H^2 and GAM analysis, as shown in Table 2, indicated that the heritability of green fodder yield per plant was very high ($H^2 = 99.65\%$), along with a very high genetic advance as a percent of the mean (GAM = 123.73%). Dry matter yield ($H^2 = 98.59\%$, GAM = 120.71%) and fresh stem weight ($H^2 = 99.36\%$, GAM = 120.41%), both of which exhibited very high heritability combined with high genetic advance, suggesting their polygenic nature and substantial potential for improvement by selection. Similarly, harvest index ($H^2 = 99.73\%$, GAM = 73.17%) and leaf: stem ratio ($H^2 = 92.99\%$, GAM = 52.40%), which showed high heritability with high GAM, also indicated that these traits are predominantly controlled by the additive gene effects.

Traits like plant height ($H^2 = 86.66\%$), leaf length ($H^2 = 85.70\%$), number of leaves per plant ($H^2 = 85.38\%$), ear height ($H^2 = 78.32\%$), and leaf width ($H^2 = 67.89\%$) showed moderate heritability values, indicating that both genetic and environmental factors affect the expression of these traits. On the other hand, traits such as days to 50% tasseling, days to 50% silking, days to 50% brown husk, shelling percentage, crude protein content, acid detergent fiber (ADF), and moisture content had low or zero heritability values, indicating more environmental influence on these traits.

The heritability estimates were high for all traits, indicating their usefulness in selection (Table 2) [12]. The reported heritability was highest for green fodder yield, followed by dry matter yield, fresh stem weight, and leaf: stem ratio, all of which are important traits for improvement through selection in maize breeding program.

Correlation Analysis

The correlation analysis among the twenty-six studied traits revealed multiple positive and negative correlations among phenological, morphological, biomass, yield, and quality traits, demonstrating complex relationships between these trait categories. Phenotypic relationship coefficients for these traits are shown in Tables 3a, b, c, d, and e, and all relationship patterns are demonstrated in Figure 2.

Table 3a. Phenotypic correlation matrix among the 26 traits

3a. Phenological Traits Correlation

Trait	D50%T	D50%S	D50%BH
D50%T	1	0.93	0.79
D50%S	0.93	1	0.68
D50%BH	0.79	0.68	1

Abbreviation: D50%T=days to % tasseling, D50%S= days to 50% silking, D50%BH= days to 50% brown husk.

3b. Morphological Traits Correlation

Trait	PH	NL/P	LL	LW	SG	EH
PH	1	0.59	0.87	0.37	0.77	0.97
NL/P	0.59	1	0.66	0.55	0.47	0.61
LL	0.87	0.66	1	0.48	0.63	0.84
LW	0.37	0.55	0.48	1	0.13	0.34
SG	0.77	0.47	0.63	0.13	1	0.75
EH	0.97	0.61	0.84	0.34	0.75	1

Abbreviation: PH=Plant Height, NL/P=Number of Leaves per Plant, LL= Leaf Length, LW=Leaf Width, SG= Stem Girth, EH=Ear Height.

3c. Biomass and Fodder Yield Traits Correlation

Trait	FLW/P	FSW/P	L:SR	GFY/P	DMY/P
FLW/P	1	0.89	0.35	0.94	0.94
FSW/P	0.89	1	-0.09	0.99	0.99
L:SR	0.35	-0.09	1	0.03	0.03
GFY/P	0.94	0.99	0.03	1	0.997
DMY/P	0.94	0.99	0.03	0.997	1

Abbreviation: FLW/P= Fresh Leaf Weight per Plant, FSW/P=Fresh Stem Weight per Plant, L:SR= Leaf : Stem Ratio, GFY/P= Green Fodder Yield per Plant, DMY/P= Dry Matter Yield per Plant.

3d. Yield and Yield Component Traits Correlation

Trait	GY/P	100-GW	NC/P	EL	EG/ED	NGR/E	Sh	HI
GY/P	1	0.68	-0.30	0.07	0.39	-0.20	-0.29	0.52
100-GW	0.68	1	-0.23	0.17	0.24	-0.24	-0.45	0.64
NC/P	-0.30	-0.23	1	-0.21	0.11	-0.09	0.01	0.03
EL	0.07	0.17	-0.21	1	0.48	0.70	-0.26	-0.12
EG/ED	0.39	0.24	0.11	0.48	1	0.22	-0.19	0.17
NGR/E	-0.20	-0.24	-0.09	0.70	0.22	1	0.16	-0.27
Sh	-0.29	-0.45	0.01	-0.26	-0.19	0.16	1	-0.39
HI	0.52	0.64	0.03	-0.12	0.17	-0.27	-0.39	1

Abbreviation: GY/P=Grain Yield per Plant, 100-GW=100-Grain Weight, NC/P=Number of Cobs per Plant, EL= Ear Length, EG/ED= Ear Girth / Ear Diameter, NGR/E=Number of Grains per Ear, Sh= Shelling Percentage, HI= Harvest Index.

3e. Quality Traits Correlation

Trait	CPC	NDF	ADF	MC
CPC	1	0.08	-0.20	-0.31
NDF	0.08	1	0.35	0.11
ADF	-0.20	0.35	1	-0.26
MC	-0.31	0.11	-0.26	1

Abbreviation: CPC= Crude Protein Content, NDF= Neutral Detergent Fiber, ADF= Acid Detergent Fiber, MC= Moisture Content.

There were strong positive correlations among days to 50% tasseling, days to 50% silking, and days to 50% brown husk (Table 3) for the phenological traits. Days to 50% tasseling were positively associated with days to both 50% silking ($r = 0.93$) and 50% brown husk ($r = 0.79$). Furthermore, days to 50% silking were also strongly correlated with days to attaining the brown husk ($r = 0.68$), suggesting flowering-maturity coupling behavior between these traits within the evaluated genotypes.

Among the morphological traits, plant height ($r = 0.87$), stem girth ($r = 0.77$), and ear height ($r = 0.97$) were highly positively correlated, as indicated in Table 3, indicating coordinated vegetative growth. The number of leaves per plant was positively correlated with leaf length ($r = 0.66$) and leaf width ($r = 0.55$), suggesting that genotypes possessing a higher number of leaves contributed to large leaf area development.

Traits for biomass and fodder yield had high interrelationships (Table 3). Green fodder yield and dry matter yield showed high correlation with fresh leaf weight and fresh stem weight. Fresh stem weight correlated almost perfectly with green fodder yield ($r = 0.99$) and dry matter yield ($r = 0.99$), suggesting that stem biomass is the primary contributor to total fodder production [13].

For yield and yield component traits, grain yield per plant had a highly significant positive correlation with 100-grain weight ($r = 0.68$) and harvest index ($r = 0.52$), as illustrated in Table 3, indicating that kernel weight and efficient biomass partitioning are critical for grain productivity. In contrast, grain yield showed negative correlations with the number of cobs per plant ($r = -0.30$) and shelling percentage ($r = -0.29$).

Most agronomic characters showed relatively lower associations with quality traits. However, Table 3 revealed a moderate positive correlation between neutral detergent fiber (NDF) and acid detergent fiber (ADF) ($r = 0.35$), which is explained by their interrelated role in defining plant cell wall composition and forage quality.

Indeed, the correlation pattern represented in Figure 2 reinforces a close association between biomass-related traits and fodder yield while identifying kernel weight and harvest index as core drivers of grain yield.

Path Coefficient Analysis

To partition the correlation coefficients into direct and indirect effects of different component traits on fodder yield, path coefficient analysis was therefore performed. Table 4 provides the direct, indirect, and total correlation effects of studied traits, and Figure 3 shows major relationships among traits affecting fodder yield.

Table 4. Direct and indirect effects of component traits on fodder yield

Predictor	Direct Effect	Total Correlation	Indirect Effect
Days to 50% Tasseling	0.469773801	5.21E-18	-0.469773801
Days to 50% Silking	-0.449125534	-0.15790328	0.291222254
Plant Height(cm)	1.172581331	0.019355566	-1.153225765
Number of Leaves per Plant	0.22224895	0.096493788	-0.125755161
Leaf Length(cm)	-1.001344953	-0.060846678	0.940498275
Leaf Width(cm)	-0.13256152	-0.089100061	0.043461459
Stem girth(cm)	0.144892222	0.150535198	0.005642976
Fresh Leaf Weight per Plant(g)	-1.167775633	-0.00277529	1.165000343
Fresh Stem Weight per Plant(g)	-1.495375944	-0.015088558	1.480287386
Leaf : Stem Ratio	0.467489149	0.009582073	-0.457907076
Dry Matter Yield per Plant(g)	2.898724765	0.028892451	-2.869832314
Grain Yield per Plant(g)	0.453162307	0.041559419	-0.411602887
100-Grain Weight(g)	-0.492408612	-0.060309776	0.432098835
Ear Height(cm)	-0.174728254	0.019721244	0.194449498
Number of Cobs per Plant	-0.015986777	-0.146501328	-0.130514551
Days to 50% Brown Husk	-0.493066773	-0.197854744	0.295212029
Ear Length(cm)	0.218139116	0.023047183	-0.195091933
Ear girth / Ear Diameter(cm)	-0.121979248	-0.037154689	0.084824559
Number of grain Rows per Ear	-0.108775954	-0.033225575	0.075550379
Shelling Percentage (%)	-0.255714914	0.034886165	0.290601079
Harvest Index	0.259827751	0.027848437	-0.231979314
Crude Protein Content (%)	0.164695184	0.100973448	-0.063721736
Neutral Detergent Fibre (NDF, %)	0.139551908	-0.013861385	-0.153413294
Acid Detergent Fibre (ADF, %)	0.168729557	0.131896773	-0.036832784
Moisture Content (%)	-0.111346171	-0.276073444	-0.164727273

The dry matter yield per plant had the highest positive direct effect on fodder in terms of its contribution to overall biomass production (Table 4) (direct effect = 2.899). The plant height showed a high positive direct effect (1.173), which indicates its contribution to improving fodder productivity and is considered an important trait. Grain yield per plant (0.453) and leaf: stem ratio (0.467) also showed moderate positive direct effects on fodder yield.

Conversely, negative direct effects were observed for some traits that had positive influences through their other correlated traits. Fresh stem weight per plant ($\beta = -1.495$) and fresh leaf weight per plant ($\beta = -1.168$), for example, also showed direct negative effects but strong indirect positive effects through other traits, resulting in small overall correlation coefficients (Table 4). The traits such as leaf length (-1.001), 100-grain weight (-0.492), and days to 50% brown husk (-0.493) also negatively impacted fodder yield directly.

Figure 3 provides a graphical representation of the major relationships between these traits that affect fodder yield. Positive contributions of certain characters, such as dry matter yield, plant height, grain yield per plant, and leaf: stem ratio for fodder yield, were observed either directly or through other associated characters.

The results in Table 4 and Figure 3 show that different traits had complex effects through direct and indirect relationships on fodder yield. Consequently, dry matter yield (DMI) and its associated traits, such as plant height (PH), grain yield per plant (GYP), and leaf: stem ratio (L:S), can be very useful as selection criteria for improvement of fodder productivity in maize breeding programs.

Cluster Analysis and Germplasm Diversity

The cluster analysis segregated 17 maize genotypes into 3 distinct clusters, indicating considerable genetic diversity among the evaluated genotypes. The tables below show that the clustering pattern is representative of the diversities in phenological, morphological, biomass, yield, and quality traits.

Table 5a: Extent of phenological and morphological traits by cluster.

Trait	Cluster I	Cluster II	Cluster III
Days to 50% Tasseling	54.66 – 57.33	53.66 – 56.00	56.33 – 58.66
Days to 50% Silking	57.66 – 61.33	57.33 – 59.66	60.33 – 62.00
Plant Height (cm)	160.6 – 182.8	161.86 – 173.13	175.27 – 228.47
Leaves per Plant	6.53 – 10.06	6.60 – 8.00	8.20 – 10.20
Leaf Length (cm)	54.10 – 62.65	52.58 – 59.74	58.65 – 79.80
Leaf Width (cm)	5.38 – 7.63	5.36 – 7.20	6.72 – 7.22
Stem Girth (cm)	2.40 – 2.65	2.28 – 2.59	2.48 – 2.93

Table 5b: Biomass and fodder yield traits by cluster

Trait	Cluster I	Cluster II	Cluster III
Fresh Leaf Weight (g)	12.87 – 35.92	30.18 – 111.24	17.19 – 59.14
Fresh Stem Weight (g)	38.04 – 164.46	91.99 – 298.51	56.32 – 173.58
Leaf: Stem Ratio	0.13 – 0.39	0.24 – 0.44	0.20 – 0.40
Green Fodder Yield (g)	50.91 – 185.89	122.17 – 409.76	73.52 – 208.52
Dry Matter Yield (g)	14.70 – 56.07	34.90 – 123.06	22.40 – 64.32

Table 5c: Yield and yield-related traits by cluster

Trait	Cluster I	Cluster II	Cluster III
Grain Yield per Plant (g)	97.64 – 175.80	84.37 – 118.44	75.44 – 108.32
100 Grain Weight (g)	24.03 – 30.52	22.91 – 27.10	21.98 – 26.06
Ear Height (cm)	79.36 – 90.23	81.24 – 84.75	89.62 – 114.18
Number of Cobs per Plant	1 – 1.66	1 – 1.66	1 – 1.33
Ear Length (cm)	11.60 – 18.44	15.11 – 20.23	13.70 – 15.90

Table 5d: Quality traits by cluster

Trait	Cluster I	Cluster II	Cluster III
Crude Protein (%)	9.16 – 10.36	9.18 – 10.67	9.47 – 10.01
NDF (%)	47.98 – 52.24	46.97 – 51.66	48.06 – 52.30
ADF (%)	29.35 – 31.52	28.56 – 31.17	29.34 – 30.00
Moisture Content (%)	67.80 – 71.16	70.01 – 71.79	69.16 – 72.90

Biplot or cluster scatter plot of PCA (**Figure 5**).

Table 5a summarizes the phenological and morphological trait ranges for each cluster. Cluster III had relatively taller plants (175.27 - 228.47 cm) and longer leaves (58.65 - 79.80 cm), which indicated vigorous vegetative growth, whereas the overall plant height and leaf length in Clusters I and II were relatively moderate.

Biomass and fodder yield trait variation details are highlighted in Table 5b. Cluster II exhibited significantly higher ranges for fresh stem weight (91.99–298.51 g), green fodder yield (122.17–409.76 g), and dry matter yield (34.90–123.06 g) as compared to the other clusters, indicating greater potential for biomass production. Clusters I and III showed moderate values

Yields and related traits are presented in Table 5c. Cluster I had considerably higher grain yield per plant (97.64–175.80 g) and 100-grain weight (24.03–30.52 g), indicating improved grain productivity, while Cluster III showed greater ear height (89.62–114.18 cm) ($p < 0.01$). The quality traits, summarized in Table 5d, exhibited comparatively less variation among clusters.

The clustering of genotypes is also portrayed in Figure 4, which shows a dendrogram with derivative classifications confirming the associations shown in the PCA biplot (Figure 5), and which revealed extended divergences among clusters revealed by multiple traits.

Cluster I included nine genotypes with balanced agronomic performance and relatively good grain yield. Cluster II genotypes contained superior potential for biomass and fodder yield. Cluster III included four genotypes with taller plants and longer leaves, showing vigorous vegetative growth.

The clustering pattern of maize germplasm lines (Tables 5a-d and Figures 4-5) showed appreciable genetic divergence among the genotypes. This divergence can be utilized to identify potential parents for hybridization programs focused on both fodder yield and grain productivity.

Conclusion

A total of 17 yellow maize germplasms were evaluated for phenological, morphological, biomass, yield, and quality traits in the current study to estimate genetic variability and assess the determinants of fodder productivity. The results of ANOVA indicated significant differences among genotypes for plant height, leaf traits, fresh stem weight, green fodder yield, dry matter yield, grain yield, and harvest index, showing the presence of considerable genetic diversity among the germplasm accessions studied.

Estimates of genetic parameters revealed that markedly high heritability, along with high genetic advance, were recorded for green fodder yield, dry matter yield, fresh stem weight, and leaf: stem ratio, indicating that the preponderance of additive gene action is amenable to improvement by direct selection. Based on correlation analysis, high and positive relationships were observed among biomass-related traits, including fresh stem weight, green fodder yield, and dry matter yield, indicating that incoming energy allocated to stem biomass was vital in determining fodder productivity.

A path coefficient analysis also revealed that fodder yield received strong positive direct effects from dry matter yield and plant height. The germplasm was grouped into three major clusters using cluster analysis, indicating high genetic diversity among the assessed genotypes.

Traits related to biomass, namely fresh stem weight, dry matter yield, and green fodder yield, can be pivotal selection criteria for enhancing fodder productivity and developing dual-purpose maize varieties for sustainable crop-livestock production systems.

Declarations

Author's contributions

Conceptualization and study design were carried out by Ali Mohammed Jidda, Prof. Saba Siddiqui, and Dr. Akshay Kumar Singh, while overall supervision and academic guidance were provided by Prof. Saba Siddiqui

(Adviser) and Dr. Akshay Kumar Singh (Co-adviser). Methodology development was undertaken by Ali Mohammed Jidda, Manasi Singh, and Yusuf Abba Asheikh. Field experimentation and data collection were performed by Ali Mohammed Jidda, Umar Musa, Arshi Fatima, Alok Dubey, and Dev Tyagi.

Formal analysis and data interpretation were conducted by Ali Mohammed Jidda, Muhammad Goni, Abdullahi Usman Largema, and Rohimat Mustapha, whereas software support, tools, and visualization were handled by Yusuf Abba Asheikh and Manasi Singh. The original draft of the manuscript was prepared by Ali Mohammed Jidda, and review and editing were carried out by Saba Siddiqui, Akshay Kumar Singh, and all co-authors. All authors read and approved the final manuscript.

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Clinical Trial Number

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Ethics Approval and Consent to Participate

Not applicable. This study did not involve human participants, animal experimentation, or clinical trials requiring ethical approval or informed consent.

Consent for Publication

Not applicable.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests.

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Figures

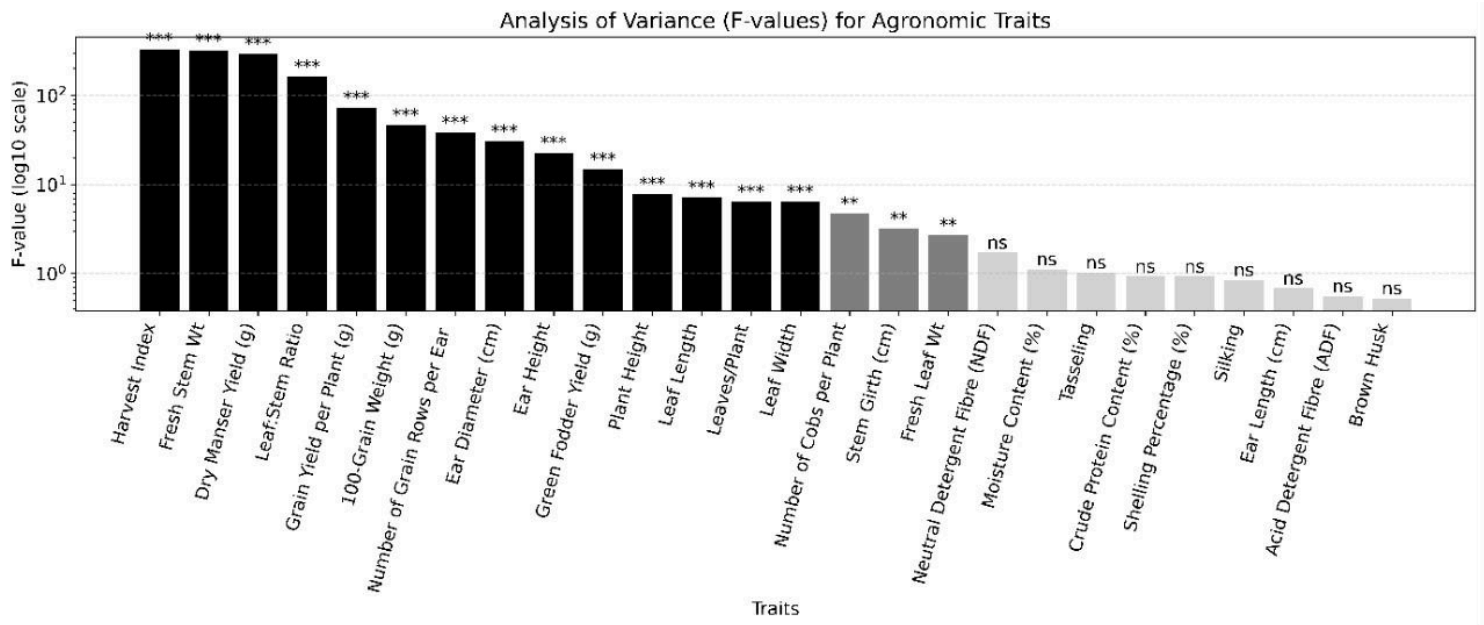


Figure 1

Log-scale bar chart of ANOVA F-values for 26 maize traits. Asterisks indicate significance levels (*** $p < 0.01$, ** $p < 0.05$, ns = non-significant). Higher F-values reflect greater genetic variability among genotypes.

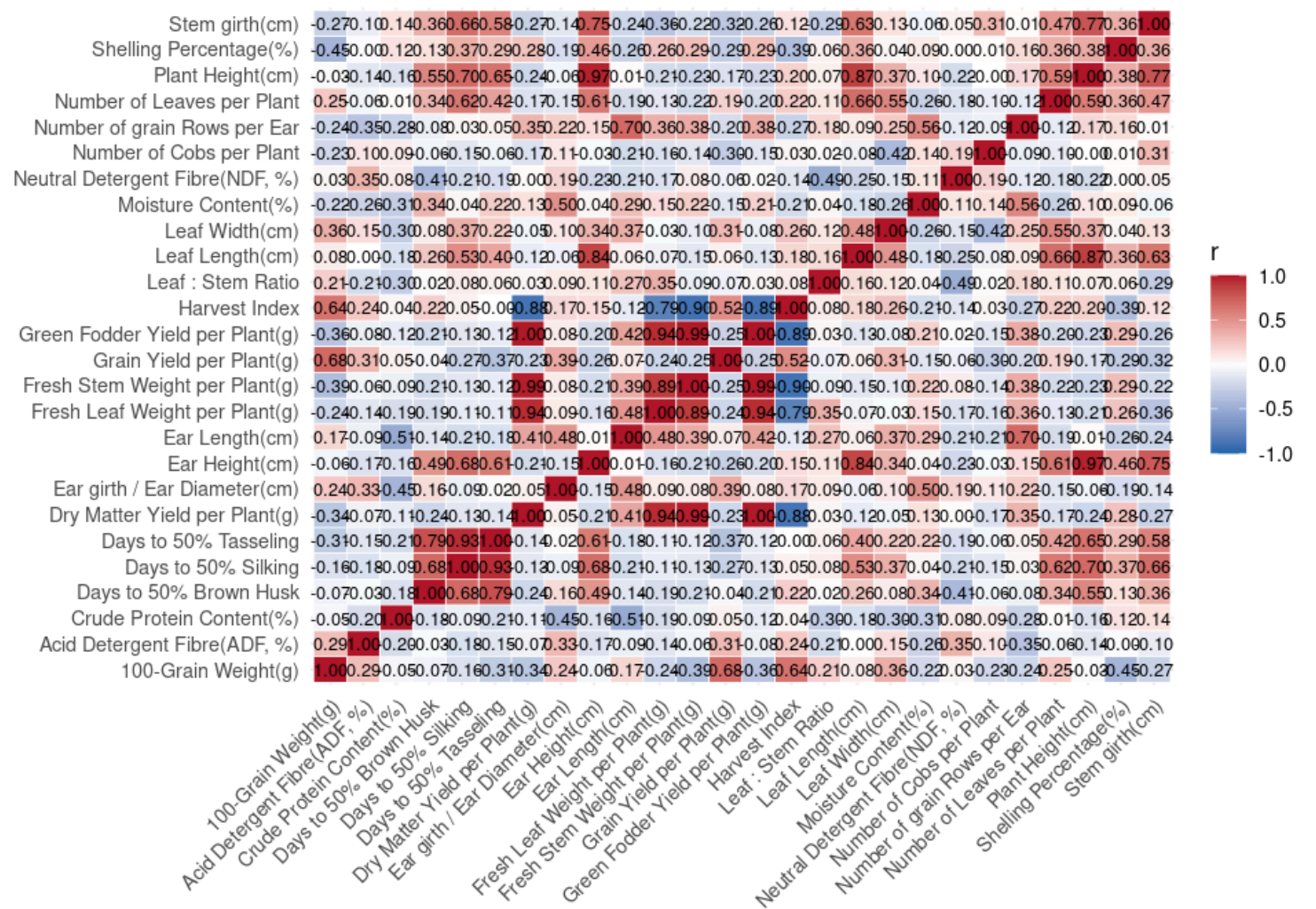


Figure 2

Traits correlation heatmap.

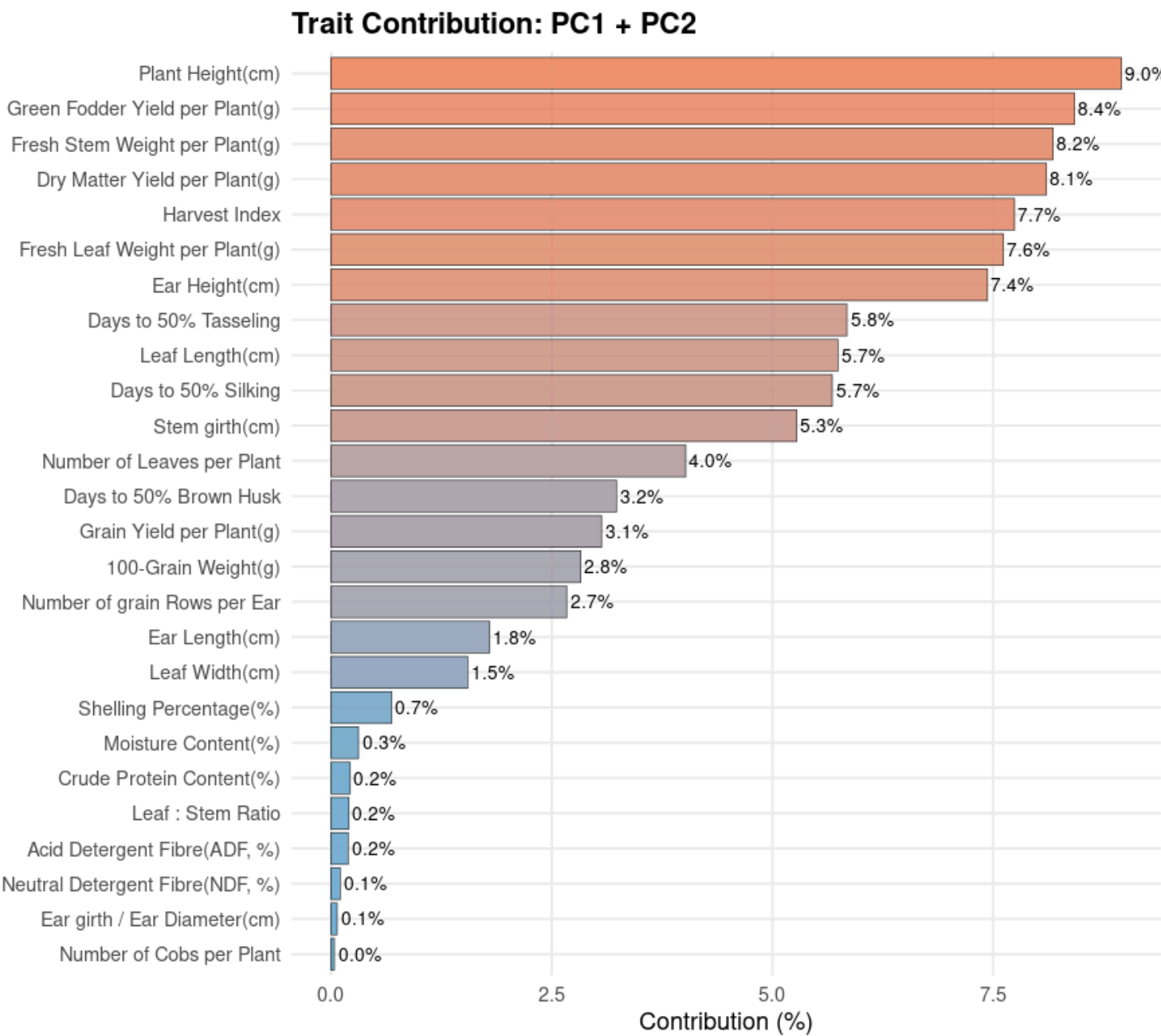


Figure 3

Path diagram of the direct contribution of the main factors to fodder yield.

Genotype Dendrogram

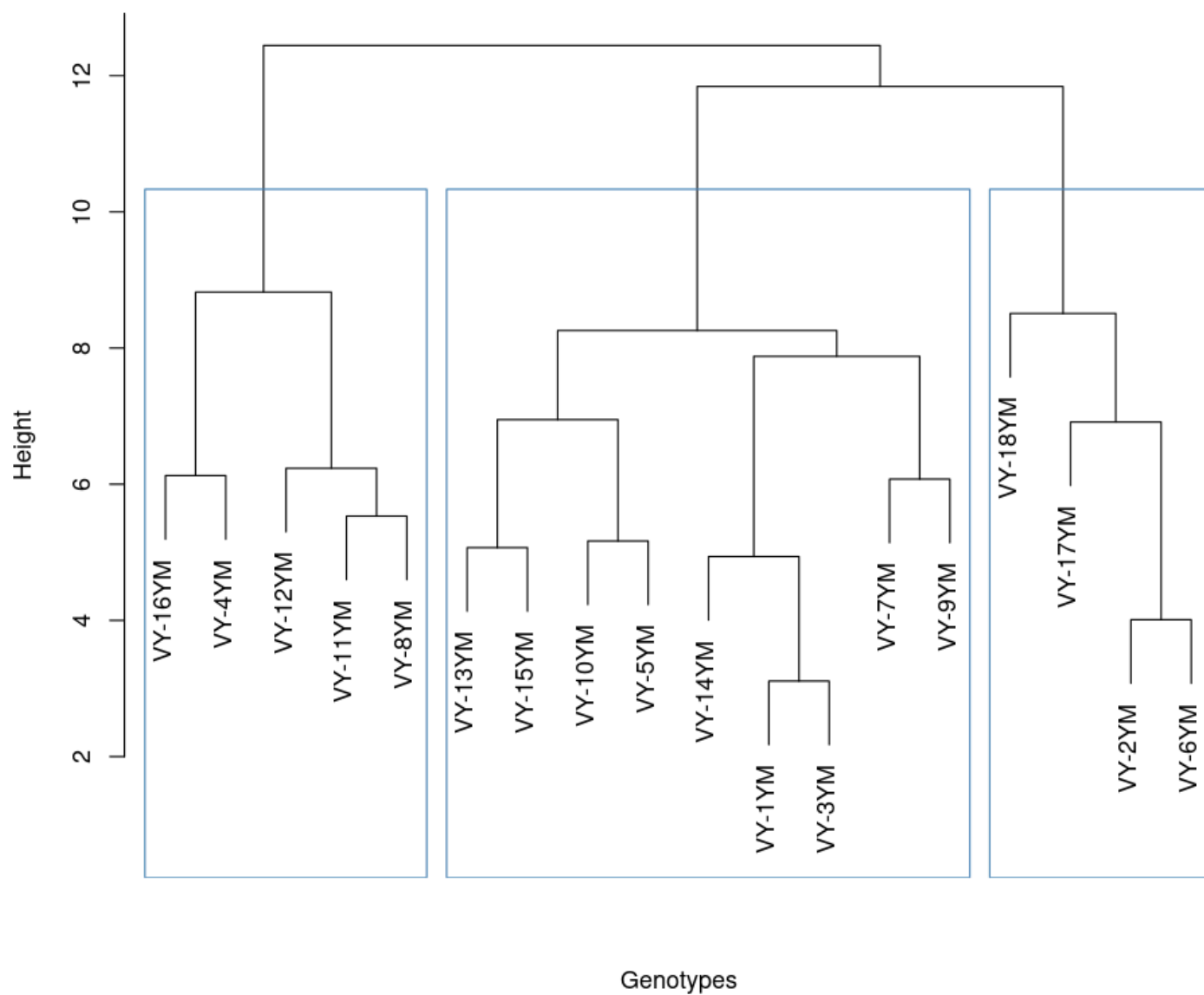


Figure 4

Dendrogram showing cluster grouping of maize germplasm

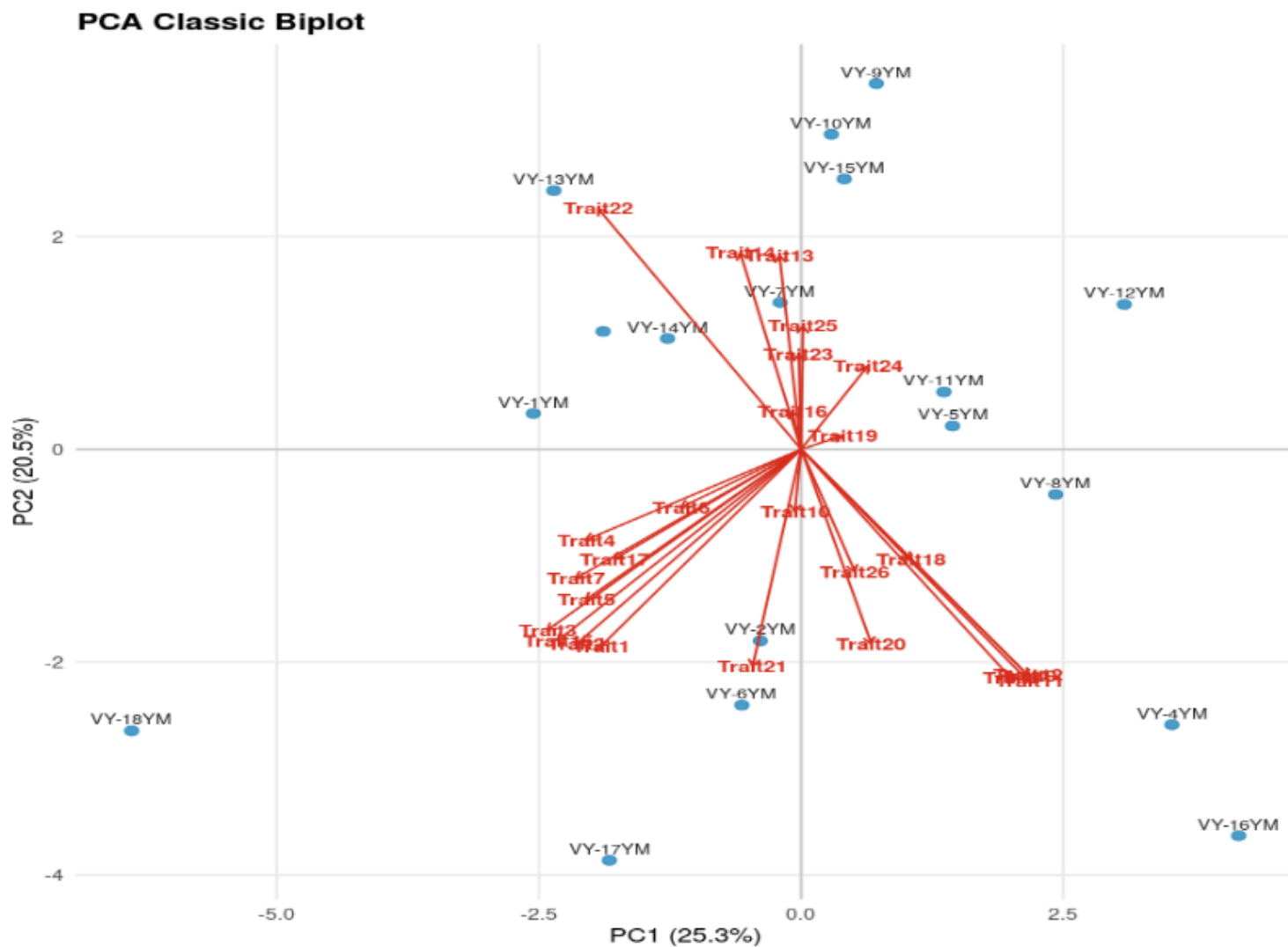


Figure 5

Biplot or cluster scatter plot of PCA