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Variability, Character Association and Genetic Divergence Studies on Pole Type French Bean Genotypes

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ABSTRACT

Exploring crop variability can establish an effective selection criterion for genetic improvement and breeding. Although the highlands of Nepal are considered secondary centers of pole bean diversity, limitations on diversity studies have concealed the enormous potential at hand. In this context, 12 pole–type French bean (*Phaseolus vulgaris* L.) genotypes were evaluated for 13 quantitative attributes in Sundarbazar, Lamjung, Nepal, from March to June 2023. This study aimed to investigate the variability and identify the traits to be selected for improvement in future breeding programs. Large variations were observed among the studied genotypes. Yield per plant, yield per plot, days to 50% germination, pod weight, and number of pods per plant had high genotypic and phenotypic coefficients of variation, heritability, and genetic advances, thereby indicating their value in selection for breeding programs. Plant height at the tender pod stage, pods per plant, pod length, pod weight, and yield per plant were found to be highly and positively correlated with yield per plot. Path analysis revealed the direct effects of plant height, days to first flowering, pods per plant, and pod weight on yield per plot and their consideration for selection and improvement. Pod length, yield per plot, and pod weight were found to contribute the most to the genetic divergence. PCA revealed that pods per plant, yield per plant, and pod weight had the highest influence on variability. Cluster analysis grouped the genotypes into three clusters, and choosing genotypes from Cluster I (with eight genotypes) could help improve yield.

Abbreviations: Days to 50% flowering (F50%), Days to 50% germination (G50%), Days to 50% vining (V50%), Days to first flowering (DFF), Days to first harvest (DFH), Harvest duration (HD), Plant height at tender pod stage (PH), Pod diameter (PD), Pod length (PL), Pods per plant (PPP), Pod weight (PW).

Introduction

French bean (*Phaseolus vulgaris L.* 2n=2x=22) is an indigenous leguminous crop of Central America and the Peruvian Andes in South America. It is widely grown in temperate, subtropical, and tropical regions of the world (Dhakal et al., 2020). Approximately 25 million mt of beans are cultivated worldwide annually. China is the major producer of green beans, with an annual production of 19 million mt, while India leads the production of dry beans, producing 62 million mt each year (FAOSTAT, 2020). Pole (indeterminate) and bush (determinate) type French beans are present based on their growth habits (Raggi et al., 2019). Nepal accounts for approximately 0.4% of the global area and production capacity dedicated to growing pulses, as stated by Aryal et al. (2020). Beans are popular as "Poor man's meat" in villages of Nepal because they are a low-cost protein source for impoverished communities (1.7 g protein 100 g^{-1} of green pod, used as vegetable and 21.1 g protein 100 g^{-1} dried seed as pulses) (Luitel et al., 2021). As vegetables, pole beans are cultivated on 4070 ha of land with 42,289 mt production and 10.39 mt ha^{-1} productivity in Nepal (MOALD, 2020). However, only two modern varieties of pole beans are available in the country (Joshi et al., 2017), showing an immense gap in research even though the hills of Nepal are considered secondary centers of its diversity (Pandey et al., 2011). A study by Neupane et al. (2008) highlighted the significant agro-morphological variations observed in bean landraces, indicating the potential for selecting suitable landraces for different production systems.

Yield, a complex quantitative trait, is influenced by multiple yield-associated traits, as stated by Alemu et al. (2017). Among these traits, pod length, diameter, and number of pods per plant play crucial roles in determining pod yield, as highlighted by Stoilova et al. (2005). These traits have also been linked to heritability among different varieties (Nechifor et al., 2011). The genetic makeup of the cultivated plant exerts the greatest impact on any agricultural production initiative and forms the essential foundation upon which all subsequent technological interventions are applied, according to Goutam et al. (2001). Assessing variability is a significant measure of how individual genotypes differ from those of other populations. This is an important parameter for establishing selection criteria for future breeding programs (Sharma et al., 2009).

Progress in breeding for yield and related traits is influenced by polygenic control and environmental factors, which are determined by the magnitude and nature of genetic variability. To comprehend and quantify this diversity, it is imperative to differentiate between inheritable and non-inheritable constituents by employing genetic metrics, such as the genetic coefficient of variation, heritability, and genetic advance. Analyzing correlations between different traits and determining their direct and indirect effects provide valuable insights into the nature and extent of these relationships. The primary objective of this study was to assess pole-type French bean genotypes to investigate their genetic diversity, heritability, character association, and cluster patterns. These findings will subsequently provide insights and recommendations aimed at enhancing cultivar performance in terms of growth, development, and yield within the mid-hill regions of Nepal, considering the country's modest agricultural productivity in this context (Dhakal et al., 2020).

Material and methods

Research site

A field investigation was conducted at the Institute of Agriculture and Animal Science, Sundarbazar, Lamjung, located at coordinates 28.1270° N, 84.4167° E, and 857 meters above sea level. This research was carried out in the Zaid season, specifically from March to June 2023. The soil of the experimental site contained 2.84% organic matter, 0.14% total nitrogen, 281.99 kg ha^{-1} available potassium, and 54.39 kg ha^{-1} available phosphorus. The climatic condition of the research area from March to June (Fig. 1).

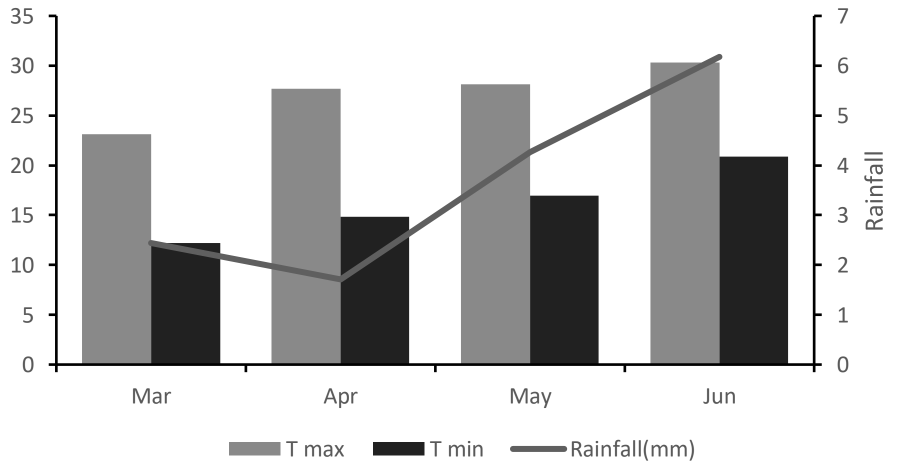

Fig. 1. Monthly weather during the experimental period at Sundarbazar, Lamjung, Nepal.

Experimental design and treatments

The experiment was conducted in a randomized control block design (RCBD) with 12 varieties of pole-type French beans and three replications. Therefore, thirty-six raised plots were present with a 0.5 m gap between the replications and within the replications. A plot of 4.5 m^2 dimension (3m×1.5m) was designed. Each plot had four rows, 75 cm apart, with five plants per row at 30 cm, i.e., each plot had 20 plants. Thus, an entire field area of 252 m^2 (24×10.5 m^2) was managed. The list of pole bean genotypes used in the experiment and their collection sites is shown in Table 1.

Cultural practices

The field was tilled using a tractor-drawn cultivator in March 2023. The plots were then raised. Following the national standard recommended dose of 15 t ha^{-1} FYM and 80:120:60 kg NPK ha^{-1}, 6.75 kg of FYM, 117.2 g DAP, and 45 g MOP were applied to each plot after tillage and then mixed thoroughly. Seed sowing was performed later in the evening time with two seeds per hill. Thinning out and gap-filling were performed 15 d after sowing (DAS). G-Sunami (Chlorpyrifos 50% + Cypermethrin 5% EC) at 2 g L^{-1} water was applied to the field at 19 DAS because of the infestation of white spotted leaf beetle and aphids. 32.4 g urea was later top-dressed at 35 DAS, and hoeing was performed at the same time. Staking with a bamboo stick of about two meters in length was performed on each plant 35 DAS as well. Periodic irrigation and hand-weeding were performed whenever necessary. The lower leaves infested with rust were manually trimmed at regular intervals.

Table 1. List of pole–type French bean genotypes used in the research and their collection site.

Variety	Collection site
Trishuli	National Horticulture Research Center, Khumaltar (Released variety)
Chaumase (Four season)	National Horticulture Research Center, Khumaltar (Popular variety; neither released nor registered)
Semi Light Long	National Horticulture Research Center, Khumaltar (Released variety)
Green Long Bean	National Horticulture Research Center, Khumaltar (Released variety)
LB-31	Directorate of Agriculture Research, Gandaki Province, Lumle, Kaski (Breeding line)
LB-37	Directorate of Agriculture Research, Gandaki Province, Lumle, Kaski (Breeding line)
Madhav	Directorate of Agriculture Research, Gandaki Province, Lumle, Kaski (Breeding line)
Chinese long	Directorate of Agriculture Research, Gandaki Province, Lumle, Kaski (Breeding line)
Rato Makai Simi	Ghanpokhara Seed Bank, Lamjung (Local variety)
Khairo Makai Simi	Ghanpokhara Seed Bank, Lamjung (Local variety)
Kalo Makai Simi	Ghanpokhara Seed Bank, Lamjung (Local variety)
Kalo Simi	Farmer´s field, Sarkegad Gaupalika, Karnali Pradesh, Humla (Local variety)

Data collection and analysis

Thirteen quantitative traits viz. days to 50% germination, days to 50% vining, days to 50% flowering, plant height at tender pod stage, days to first flowering, pod length, pod weight, pod diameter, pods per plant, days to first harvest, harvest duration, yield per plant, and yield per plot were recorded. The data were collected from five sample plants tagged in each experimental plot, excluding the border rows, and then the mean value was calculated for each trait. But for net plot yield (g), the cumulative yield of twenty plants within a specific plot was measured. In detail, the data collection procedure for each trait is explained in Tripathi and Pandey (2024).

The data was analyzed statistically by analysis of variance as per the methods described by Gomez and Gomez (1984). The genotypic coefficient of variation (GCV) and the phenotypic coefficient of variation (PCV) were calculated by equations (1) and (2) respectively, as in Burton and De Vane (1953). Heritability (broad sense) was computed by equation (3), following the methods of Johnson et al. (1955). Similarly, genetic advance (GA) and genetic advance as a percent of the mean (GAM) were determined by equations (4) and (5), as in Johnson et al. (1955) and Falconer and Mackay (1996). The ranges of the parameters are listed in Table 2. Correlation and path coefficient analyses were performed according to Searle (1961) and Dewey and Lu (1959), respectively. The data were statistically analyzed using R version 1.4.1106. Cluster analysis among the genotypes was performed using the complete linkage (farthest-neighbor) method with Euclidean distance using Minitab.

$$GCV\ (\%) = \frac{\sqrt{Vg}}{General\ mean\ of\ population} \times 100 \quad (1)$$

$$PCV\ (\%) = \frac{\sqrt{Vp}}{General\ mean\ of\ population} \times 100 \quad (2)$$

$$Heritability\ (h^2) = \frac{Vg}{Vp} \times 100 \quad (3)$$

Where,

Vg = Genotypic variance

Vp = Phenotypic variance

$$Genetic\ Advance\ (GA) = k.\sigma_p.h^2 \quad (4)$$

Where,
k = selection differential constant (k = 2.056 at 5% selection intensity)
σ_p = phenotypic standard deviation
h^2 = broad sense heritability

$$Genetic\ advances\ as\ per\ mean\ (GAM) = \frac{GA}{X} \times 100 \quad (5)$$

Where,
GA = genetic advances under selection
X = population mean in which selection will be employed

Table 2. Limits used in the calculated genetic parameters.

Components	High	Moderate	Low	Reference
GCV and PCV	>20%	10-20%	<10%	(Deshmukh et al., 1986)
Heritability	>60%	30-60%	<30%	(Robinson et al., 1949)
Genetic advance as percent of mean	>20%	10-20%	<10%	(Johnson et al., 1955)

Results

The analysis of variance for 13 studied traits showed significant differences among the genotypes for all the traits, as shown in Table 3. Most of the traits were found significant at 0.1% level, except days to first harvest and harvest duration, which were significant at 1% and 5% levels, respectively. This suggests sufficient genetic variability among the studied traits in the genotypes, which can be exploited in further crop improvement programs.

Genetic variability

The genetic parameters for 13 traits in 12 pole–type French bean genotypes are shown in Table 4.

Table 3. Analysis of variance for 13 traits observed in 12 pole–type French bean genotypes.

S.N.	Traits	Mean sum of squares		
		Replication (D.F. = 2)	Genotype (D.F. = 11)	Error (D.F. = 22)
1	Days to 50% germination	1.58	10.49***	0.92
2	Plant height at tender pod stage	36.08	597.56***	62.78
3	Days to 50% vining	0.528	36.29***	2.32
4	Days to 50% flowering	6.02	29.05***	2.75
5	Days to first flowering	0.52	27.42***	3.92
6	Pods per plant	2.354	177.33***	27.64
7	Days to first harvest	35.11	25.66**	5.93
8	Pod length (cm)	0.31	6.8***	0.17
9	Pod weight (g)	2.52	3.89***	0.37
10	Pod diameter (mm)	0.84	1.37***	0.25
11	Harvest duration	29.25	17.04*	6.4
12	Yield per plant (g)	4323.3	12014.3***	940.6
13	Yield per plot (g)	1294434	4658329***	371948

D.F. = Degree of freedom; *Significant at 5% level, **significant at 1% level, and ***significant at 0.1% level.

High GCV and PCV values (>20%) were noted for days to 50% germination, pod weight, number of pods per plant, yield per plant, and yield per plot. Conversely, low GCV and PCV values (<10%) were noted for days to 50% flowering, plant height at pod maturity, days to first flowering, pod diameter, and days to first harvest, indicating a narrow range of variation in these traits.

A high broad sense heritability (>60%) was observed for all traits except for days to the first harvest (0.53) and harvest duration (0.36). The highest heritability was recorded for pod length (0.93), followed by days to 50% vining (0.83), yield per plant (0.80), yield per plot (0.79), days to 50% germination (0.78), days to 50% flowering (0.76), pod weight (0.76), plant height at the pod maturity stage (0.74), days to first flowering (0.67), pods per plant (0.64), and pod diameter (0.60). Yield per plant (58.76%), yield per plot (57.52%), pod weight (36.41%), days to 50% germination (35.07%), pod count per plant (33.72%), and pod length (24%) showed high GAM values.

Table 4. Range, GCV (%), PCV (%), h^2_{bs}, GA, and GAM (%) for the 13 traits observed in 12 pole–type French bean genotypes.

Traits	Range	GCV (%)	PCV (%)	h^2	GA	GAM (%)
Days to 50% germination	7–14	19.31	21.91	0.78	3.24	35.07
Days to 50% vining	30–45	9.82	10.78	0.83	6.31	18.43
Days to 50% flowering	46–63	5.31	6.09	0.76	5.32	9.54
Days to first flowering	40–56	5.83	7.15	0.67	4.71	9.81
Plant height at tender pod stage	128.9–193.41	8.25	9.6	0.74	23.65	14.62
Days to first harvest	60–77	3.74	5.16	0.53	3.83	5.59
Pod length (cm)	9-14–24	12.1	12.57	0.93	2.95	24
Pod weight (g)	2.28–7.76	20.31	23.34	0.76	1.94	36.41
Pod Diameter (mm)	7.98–11.09	6.55	8.44	0.6	0.98	10.48
Pods per plant	16–50	20.4	25.44	0.64	11.67	33.72
Harvest duration	6–20	16.03	26.84	0.36	2.32	19.71
Yield per plant (g)	63.45–312.9	31.95	35.79	0.8	111.73	58.76
Yield per plot (g)	1231.25–6200	31.34	35.19	0.79	2193.37	57.52

GCV = Genetic coefficient of variation, PCV = Phenotypic coefficient of variation, h^2 = Broad-sense heritability, GA = Genetic advance and GAM = Genetic advance as a percent of the mean.

Correlation between traits

The correlation coefficients for 13 traits in 12 pole–type French beans are shown in Table 5.

Days to 50% germination correlated with days to 50% vining, pod length, pod weight, yield per plant, and yield per plot. Similarly, plant height at tender pod stage was correlated to pods per plant, pod length, pod weight, yield per plant, and yield per plot; days to 50% vining with days to first flowering, days to 50% flowering, days to first harvest, pods per plant, pod length, pod weight, yield per plant, and yield per plot, days to 50% flowering with days to first flowering, days to first harvest, pods per plant, pod diameter, and harvest duration; days to first flowering with days to first harvest, pod diameter, and harvest duration, pods per plant with pod length, pod weight, harvest duration, days to first harvest, yield per plant, and yield per plot; days to first harvest with pod weight, pod diameter, harvest duration, yield per plant, and yield per plot; pod length with pod weight, yield per plant, and yield per plot, pod weight with yield per plant, and yield per plot, pod diameter with harvest duration, harvest duration with yield per plant and yield per plot, yield per plant with yield per plot.

Path analysis

The path coefficient analysis of the studied traits on yield per plot (g) for 12 pole–type French bean genotypes is shown in Table 6.

A direct effect of pods per plant, pod weight, plant height at tender pod stage, days to 50% flowering, and days to first flowering was obtained on yield per plot. However, pod weight, pods per plant, plant height at the tender pod stage, and days to first flowering showed a greater correlation with yield per plot because they influenced other traits under study. Days to 50% germination, days to 50% vining, first harvest and pod length were the traits having a negative direct effect on yield per plot. The low value of residual effect showed that the traits under study accounted for most of the variation present in yield per plot.

Table 5. Phenotypic correlation between 13 traits observed in 12 pole–type French bean genotypes.

Characters	G50%	PH	V50%	F50%	DFF	PPP	DFH	PL	PW	PD	HD	Yield per plant	Yield per plot
G50%	1												
PH	-0.24^{ns}	1											
V50%	0.66**	-0.27^{ns}	1										
F50%	0.06^{ns}	-0.15^{ns}	0.47**	1									
DFF	-0.02^{ns}	-0.09^{ns}	0.44**	0.73 **	1								
PPP	-0.41*	0.38*	-0.58**	-0.41 *	-0.27^{ns}	1							
DFH	0.27^{ns}	-0.07^{ns}	0.62**	0.64**	0.56**	-0.45**	1						
PL	-0.75**	0.55**	-0.59 **	0.06^{ns}	0.17^{ns}	0.36 *	-0.14^{ns}	1					
PW	-0.68**	0.56**	-0.7 **	-0.16^{ns}	-0.02^{ns}	0.43 **	-0.38*	0.91 **	1				
PD	0.27^{ns}	0.06^{ns}	-0.15^{ns}	-0.51**	-0.70**	-0.02^{ns}	-0.42*	-0.32^{ns}	-0.06^{ns}	1			
HD	-0.18^{ns}	0.13^{ns}	-0.50**	-0.61**	-0.52**	0.36*	-0.96**	0.01^{ns}	0.36*	0.47**	1		
Yield per plant	-0.66**	0.55 **	-0.75**	-0.32^{ns}	-0.14^{ns}	0.84 **	-0.5 **	0.74 **	0.82**	-0.07^{ns}	0.43**	1	
Yield per plot	-0.66**	0.57 **	-0.76**	-0.31^{ns}	-0.15^{ns}	0.83 **	-0.51 **	0.75**	0.84**	-0.06^{ns}	0.44**	0.99 **	1

G50% = Days to 50% germination, PH = Plant height at tender pod stage, V50% = Days to 50% vining, F50% = Days to 50% flowering, DFF = Days to first flowering, DFH = Days to first harvest, PPP = Pods per plant, PL = Pod Length, PW = Pod weight, PD = Pod diameter, HD = Harvest duration, ** = highly significant (P<0.01), * = significant (P<0.05), ^{ns} = non-significant.

Table 6. Phenotypic Path coefficient: Direct (diagonal) and Indirect (non-diagonal) effect of the traits on yield per plot (g) in twelve pole–type French bean genotypes.

Characters	G50%	PH	V50%	F50%	DFF	PPP	DFH	PL	PW	PD	HD
G50%	**-0.06**	-0.02	-0.05	0.00	-0.00	-0.22	-0.01	0.07	-0.35	0.00	-0.00
PH	0.01	**0.09**	0.02	-0.01	-0.00	0.2	0.00	-0.05	0.29	0.00	0.00
V50%	-0.04	-0.02	**-0.08**	0.03	0.03	-0.31	-0.03	0.05	-0.36	-0.00	-0.01
F50%	-0.00	-0.01	-0.03	**0.06**	0.05	-0.22	-0.03	-0.00	-0.08	-0.00	-0.01
DFF	0.00	-0.00	-0.03	0.04	**0.06**	-0.15	-0.03	-0.01	-0.01	-0.00	-0.01
PPP	0.02	0.03	0.04	-0.02	-0.01	**0.54**	0.02	-0.03	0.22	-0.00	0.00
DFH	-0.01	-0.00	-0.04	0.04	0.03	-0.24	**-0.06**	0.01	-0.20	-0.00	-0.01
PL	0.04	0.05	0.04	0.00	0.01	0.19	0.00	**-0.09**	0.47	-0.00	0.00
PW	0.04	0.05	0.05	-0.01	-0.00	0.23	0.02	-0.08	**0.52**	-0.00	0.00
PD	-0.01	0.00	0.01	-0.03	-0.04	-0.01	0.02	0.03	-0.03	**0.00**	0.00
HD	0.01	0.01	0.04	-0.04	-0.03	0.19	0.05	-0.00	0.18	0.00	**0.01**
Correlation with Yield per plant	0.00	0.18	-0.03	0.06	0.10	0.2	-0.05	-0.1	0.65	0.00	-0.03

G50% = Days to 50% germination, PH = Plant height at tender pod stage, V50% = Days to 50% vining, F50% = Days to 50% flowering, DFF = Days to first flowering, PPP = Pods per plant, DFH = Days to first harvest, PL= Pod length, PW = Pod weight, PD = Pod diameter, HD = Harvest duration.

Residual effect = 0.016.

Cluster analysis

Following the complete linkage method, cluster analysis grouped the 12 pole–type French bean genotypes into three clusters, as shown in Figure 2. The maximum number of genotypes (eight) was aggregated in cluster I, whereas the minimum number of genotypes (one) was aggregated in cluster II. Cluster III included three genotypes. The distribution of French bean genotypes in various clusters is shown in Table 7, with intra- and inter-cluster distances shown in Table 8. The cluster means for different traits are included and shown in Table 9.

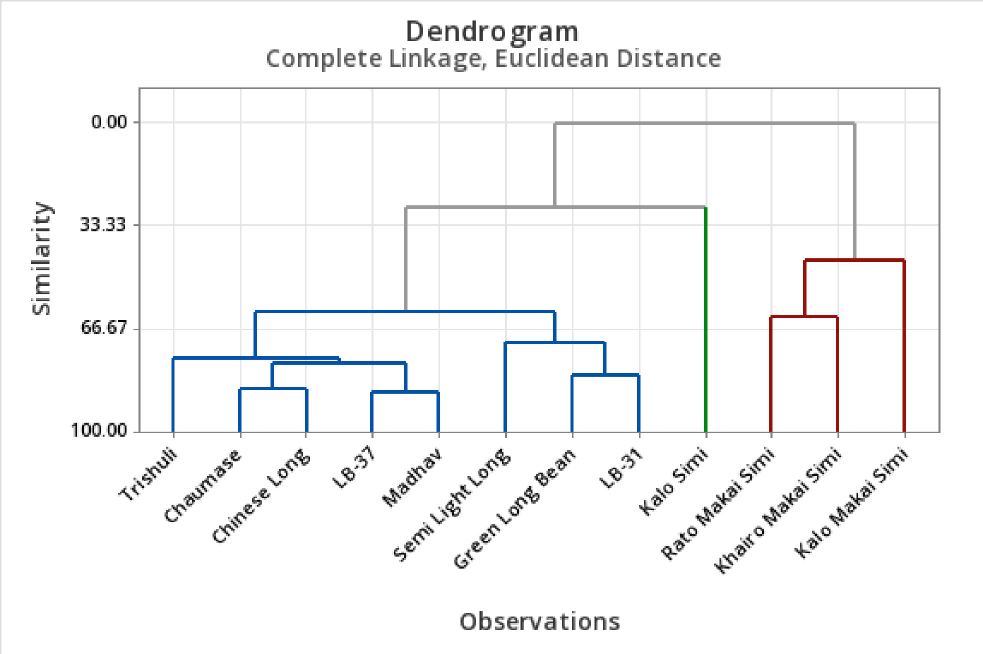

Fig. 2. Dendrogram of twelve pole–type French bean genotypes for thirteen traits.

Table 7. Grouping of 12 pole–type French bean genotypes into three clusters.

Cluster	Number of genotypes	Name of genotypes
I	8	Trishuli, Chaumase, Semi Light Long, Green Long Bean, LB-31, LB-37, Madhav, Chinese Long
II	1	Kalo Simi
III	3	Rato Makai Simi, Khairo Makai Simi, Kalo Makai Simi

Table 8. Average intra– and inter-cluster distance between the three observed clusters.

Cluster	I	II	III
I	103.4694	439.8254	507.3911
II		265.1379	565.0455
III			0.00

The mean performance of the traits showed that cluster I had the earliest days to 50% germination, days to first harvest, and highest plant height at the tender pod stage, pod length, pod weight, yield per plant, and yield per plot. Similarly, cluster II had the earliest days to 50% vining, days to 50% flowering, days to first flowering, the greatest pods per plant, pod diameter and harvest duration.

The intra-cluster distance ranged from 0 to 265.14. The maximum intra-cluster distance was noted for Cluster II (265.14), followed by Cluster I (103.47). The minimum intra-cluster distance was for cluster III (0). The maximum intercluster distance was noted between clusters II and III (565.04), followed by clusters I and III (507.39). The minimum intercluster distance was noted between clusters I and II (439.82).

As shown in Figure 3, pod length (26.8%), yield per plot (16.9%), and pod weight (13.4%) were the main contributors to the genetic divergence.

Table 9. Cluster mean for the 13 traits observed in 12 pole–type French bean genotypes.

Traits	Cluster means		
	Cluster 1	Cluster 2	Cluster 3
Days to 50% germination	8.17	11.67	11.33
Plant height at tender pod stage	166.0	163.13	150.16
Days to 50% vining	32.67	31.67	39.44
Days to 50% flowering	55.92	49.0	57.57
Days to first flowering	48.54	41.0	48.78
Pods per plant	36.89	39.8	26.94
Days to first harvest	68.20	69.33	71.11
Pod length (cm)	13.27	10.13	10.38
Pod weight (g)	6.04	4.62	3.66
Pod diameter (mm)	9.10	11.06	9.43
Harvest duration	11.87	16.66	9.78
Yield per plant (g)	223.32	186.43	102.9
Yield per plot (g)	4477.72	3786.65	2049.76

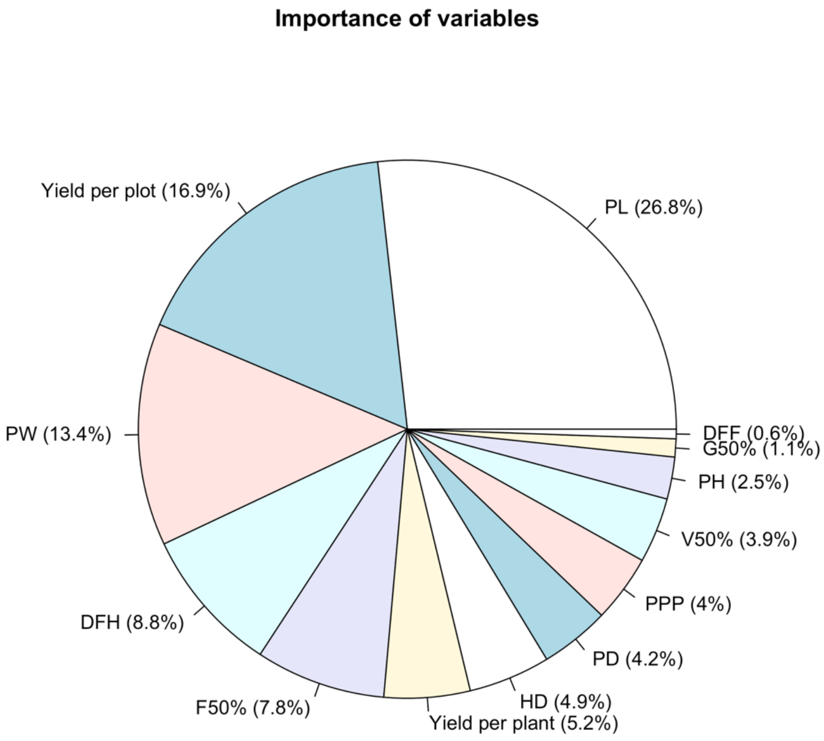

Fig. 3. Contribution of Thirteen Traits to Genetic Divergence in Twelve Pole-Type French Bean Genotypes.

Principal component analysis (PCA)

PCA helps in understanding how genotypes of similar categories group together when compared to dissimilar ones. Thus, it was performed to visualize the relationships between French bean genotypes and their quantitative traits, as shown in Table 10 and Figure 4.

PCA showed three principal components to be significant (eigenvalue>1) which contributed 90.4% of the variance. PC1 accounted for the greatest variance (53.3%), followed by PC2 (29.2%) and PC3 (7.9%), as shown in Table 10. PC1 is dominated by yield-contributing variables, including pods per plant (0.834), pod length (0.666), pod weight (0.818), harvest duration (0.686), and yield per plant (0.942).

Genotypes with high PC1 scores are closely connected with productivity and yield performance. PC2 reflects phenological and structural features, specifically days to first flowering (0.841) and pod diameter (-0.869). PC3 represents features such as plant height (0.755) and days to 50% germination (0.326). Although PC3 adds little variance, it does highlight the structural and early development characteristics that distinguish various genotypes.

Table 10. Average mean value of 13 traits observed in 12 pole–type French bean genotypes in three principal components (PC).

Traits	PC1	PC2	PC3
Days to 50% germination	-0.706	-0.451	0.326
Plant height at tender pod stage	0.592	0.247	0.755
Days to 50% vining	-0.943	0.048	0.208
Days to 50% flowering	-0.610	0.711	-0.053
Days to first flowering	-0.419	0.841	-0.122
Pods per plant	0.834	-0.043	-0.001
Days to first harvest	-0.740	0.575	0.302
Pod Length	0.666	0.690	0.079
Pod Weight	0.818	0.471	0.091
Pod Diameter	0.079	-0.869	0.377
Harvest Duration	0.686	-0.628	-0.194
Yield per plant	0.942	0.260	0.049
Yield per plot	0.954	0.250	0.051
Eigenvalue	6.9248	3.7953	1.0302
Proportion	0.533	0.292	0.079
Cumulative	0.533	0.825	0.904

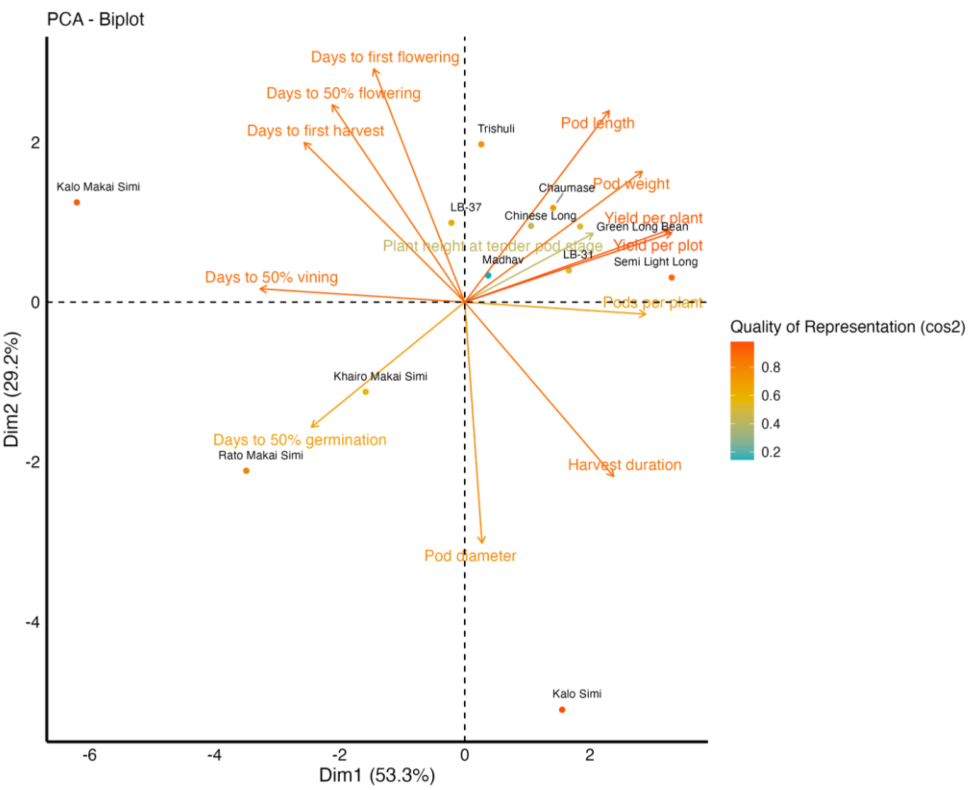

Fig. 4. Biplot of twelve pole–type French bean genotypes for first and second principal components.

Here, the genotypes are represented by points, and the traits are represented by vectors. The length of the arrow shows the variable's contribution to the principal components (PCs). The direction of the arrow indicates a positive or negative correlation with the PC. Longer arrows indicate a stronger influence on the corresponding PC and vice versa. Arrows pointing in the same direction indicate a positive correlation between those studied parameters and vice versa. Arrows close together imply that the variables contribute similarly to a PC. To increase yield potential, breeding programs should target genotypes with high positive PC1 scores. Kalo Simi and Semi Light Long are good for breeding programs that aim to increase production under favourable conditions. Madhav and Trishuli have strong phenological characteristics (indicating early-flowering genotypes), making them suited for short-duration cropping systems or regions with early harvests. LB-31, LB-37 and Green Long Bean have stable and balanced profiles, making them suitable for a variety of environmental conditions. Rato Makai Simi and Khairo Makai Simi could be sources of stress resistance or specialized characteristics that warrant further exploration.

Discussion

Significant variability was observed among the genotypes tested, represented by a wide variation in the range of values observed for different traits. This suggests that there is ample opportunity to improve these characteristics through direct selection, as concluded by Muthuramu et al. (2015) and Panda et al. (2016) in the French bean. PCV represents the effect of both the heritable and nonheritable components, whereas GCV accounts only for the heritable component. Johnson et al. (1955) pointed out that GCV is more suitable than PCV. The value of GCV followed PCV in all the traits observed, similar to Haralayya et al. (2015), indicating the influence of environmental factors on the expression of these traits (Prakash et al., 2015); however, the differences between PCV and GCV were less, showing fewer environmental effects on these traits and thus, stable (Prakash et al., 2015). The greater the difference, the greater the environmental influence.

Heritability predicts the reliability of phenotypic values to account for its breeding value (Falconer and Mackay, 1996). The magnitude of heritability represents the response of genetic constituents to selection; the higher the value, the lesser the influence of the environment and the more desirable for selection (Panse et al., 1957). High broad sense heritability (>60%) was observed for all the traits, indicating less environmental influence upon their expression; thus, selection based on these traits is more reliable.

Heritability along with genetic advancement is better than heritability alone in selecting a better genotype because they consider the additive effects (Johnson et al., 1955). Genetic advances depend on genetic variability and mask the effects of the environment on gene expression and selection intensity. Combined analysis and interpretation of GCV, heritability, and genetic advancement would best depict the advances that can be gained via selection (Prakash et al., 2015). High heritability and substantial genetic advancement may be influenced by both additive and non-additive genetic components but primarily by additive factors; thus, direct selection would be beneficial for improvement (Langat et al., 2019). Traits with high heritability and moderate genetic advancement indicate the equal importance of both additive and non-additive gene actions, as well as the significant influence of the environment on trait expression. Reciprocal recurrent selection can be employed to improve this trait (Singh and Singh, 2013). Low genetic advancement and high heritability indicate the regulation of non-additive genes and can be exploited via heterosis breeding.

In our study, high GCV, broad-sense heritability, and GAM were observed for yield per plant, yield per plot, days to 50% germination, pod weight, and number of pods per plant. These traits could be effective selection tools for bean improvement programs to develop stable genotypes with better yield and quality characteristics. This finding is consistent with Singh et al. (2014) and Jhanavi et al. (2018) in French beans, except for days to 50% germination. Studies by Verma et al. (2014) and Singh et al. (2018) showed the greatest heritability and genetic advancement for the number of pods per plant, which contradicts our findings. Correlation indicates the mutual relationship among the traits and identifies the trait to be selected for the improvement program. Plant height at the tender pod stage, pods per plant, pod length, pod weight, and yield per plant were found to be highly and positively correlated with yield per plot, in line with the results of Singh et al. (2018), Muthal et al. (2018), and Subedi et al. (2022). Gonçalves et al. (2017) stated that desirable traits with significant positive correlations are essential for selecting plants for breeding. Therefore, these traits can be an effective basis for selecting plants. In our study, no significant correlation was found between days to first flowering and days to 50% flowering with green pod yield, in contrast with the results reported by Kumar et al. (2014), Haralayya et al. (2015), and Akladee (2018). Also, no significant association was found between pod diameter and yield per plot, in contrast to the findings of Rai et al. (2010). Here, path analysis can provide a clearer picture of their effect. Days to 50% germination, days to 50% vining, and days to first harvest were, however, negatively correlated with

the yield per plot, signifying their less importance during selection.
Plant height at the tender pod stage showed a positive and direct effect on pod yield per plot, as per the findings of Aklade et al. (2018). Similarly, Days to 50% flowering also exhibited a positive and direct impact on pod yield per plot, as previously reported by Kumar et al. (2014) and Aklade et al. (2018). However, days to first flowering were identified to have a positive and direct effect on pod yield per plot, contrasting the findings of Haralayya et al. (2015). The number of pods per plant displayed a positive and direct influence on pod yield per plot in line with the findings of Sodagar et al. (2020). Like the findings of Kumar et al. (2014) and Aklade et al. (2018), pod weight exhibited a positive and direct impact on pod yield per plot. Pod diameter indicates a positive and direct effect on pod yield per plot like Singh et al. (2018) but differs from Rai et al. (2010). However, pod length showed a negative direct effect in contrast to Sodagar et al. (2020) and Aklade et al. (2018). Despite the direct positive effect on yield per plot via days to 50% flowering, it had indirect negative effects on plant height, pods per plant, pod weight, and harvest duration. Similarly, days to 50% germination and 50% vining had a negative direct effect on yield per plot, but it had a significant positive indirect effect on the dependent variable via pods per plant, pod length, pod weight, and plant height. Thus, both direct and indirect effects should be considered during selection (Singh et al., 2018). The correlation between yield per plot and a trait via its direct effect shows what a true relationship they have; therefore, these traits can be selected for improvement. In the case of indirect effects through another trait, selection should be performed based on the trait through which the indirect effect is exerted (Verma et al., 2014). Based on these findings, plant height, days to first flowering, pods per plant, and pod weight should be considered for selection and improvement. Genotypes of clusters with high mean values for a character can be directly adopted or used in hybridization programs for selection and improvement (Dalsaniya et al., 2009; Gangadhara et al., 2014). Cluster I included the earliest days to first harvest, highest pod length, pod weight, yield per plant, and yield per plot. Cluster II had the earliest days to first flowering, days to 50% flowering, highest pod count per plant, pod diameter, and harvest duration. These two clusters are thus beneficial for direct adoption by farmers in different regions or useful to breeders for use in future improvement programs. The genotypes of the same cluster have little genetic divergence between them for the aggregate effect of 13 traits under study, but the diversity is greater among genotypes of different clusters (Pushpavalli et al., 2017; Singh et al., 2018). Thus, it is found that the eight genotypes in cluster I and three genotypes in cluster III are similar. With the minimum inter-cluster distance noted between clusters I and II, they should be genetically similar to the remaining inter-cluster genotypes.
The concentration of heterosis and transgressive segregation potential depends on the magnitude of genetic diversity in the parental lines (Mackay et al., 2021). This reveals that the parents for the hybridization program should be selected from the clusters with greater inter-cluster distances (Singh et al., 2018). In this case, the cross between Kalo Simi included in cluster III with either Trishuli, Chaumase, Semi Light Long, Green Long Bean, LB-31, LB-37, Madhav, and Chinese Long from cluster I or Rato Makai Simi, Khairo Makai Simi, and Kalo Makai Simi from cluster II is to be done. This results in transgressive genetic variation among segregants (Ahmed et al., 2015). Together, pod length, yield per plot, and pod weight contributed to 57.1% of the total divergence studied among the 12 pole–type French bean genotypes. Similar divergence studies in French beans have previously been conducted by Panchbhaiya et al. (2017) and Singh et al. (2018). These traits should be the primary focus of future divergence studies among French bean genotypes and serve as key traits for selection.

Conclusion

The present study showed significant genetic variability among the tested varieties of pole-type French bean genotypes. GCV was found to be greater than PCV in all traits, indicating the influence of environmental factors on the expression of these traits. However, the difference between them was less, signifying a rather stable expression. Traits with high GCV, PCV, broad-sense heritability, and GAM, viz., yield per plant, yield per plot, days to 50% germination, pod weight, and number of pods per plant, suggest significant variability in them, providing ample opportunity for selection. Correlation and path analysis revealed that traits such as plant height at the tender pod stage, pods per plant, pod weight, and yield per plant would directly affect green pod yield; thus, their selection would determine the success of the breeding program. Finally, a framework for selection is given by PCA that identified yield-related traits such as pods per plant, pod weight, and yield per plant as key contributors to genetic variability. The dendrogram grouped the 12 bean genotypes into three clusters. Cluster I had the highest number of genotypes (eight: Trishuli, Chaumase, Semi Light Long, Green Long Bean, LB-31, LB-37, Madhav, and Chinese Long), followed by cluster III (three: Rato Makai Simi, Khairo Makai Simi, and Kalo Makai Simi), and cluster II (one: Kalo Simi). The mean performance revealed that cluster I had the earliest days to 50% germination, days to first harvest, highest plant height at the tender pod stage, pod length, pod weight, yield per plant, and yield per plot. Similarly, cluster II had the earliest days to 50% vining, days to 50% flowering, days to first flowering, the greatest pods per plant, pod diameter and harvest duration. Crosses between genotypes in cluster III with either I or II can result in the greatest transgressive segregation. Pod length, yield per plot, and pod weight were found to contribute the most to genetic divergence. Such genetic variability observed among the tested pole French bean genotypes can offer exclusive opportunities for future breeding programs.

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Author contributions
AT: designed and conducted experiments, data collection, analysis, and manuscript writing, MP: conducted the experiment, data collection, and manuscript writing, BPK: Data analysis, manuscript review and editing.

Data availability
Data will be made available upon request via the corresponding email address.

Conflict of Interest
The authors indicate no conflict of interest in this work.

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