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RESEARCH ARTICLE

DUS-based characterization and diversity analysis of French bean (*Phaseolus vulgaris* L.) genotypes from the North-Western Himalaya

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Abstract
French bean (*Phaseolus vulgaris* L.) is an important cool-season legume valued for its nutritional richness and contribution to food and nutritional security in the Himalayan region. The North-Western Himalaya harbours diverse indigenous landraces that remain largely unexplored for their distinctness and breeding potential. The present study aimed to characterize and evaluate 45 French bean genotypes collected from different locations of Uttarakhand using distinctness, uniformity and stability (DUS) descriptors and morpho-phenological traits. The experiment was conducted at the ICAR–Central Institute of Temperate Horticulture (CITH), Mukteshwar, under a randomized Block Design in year 2023-2025. Considerable morphological variability was observed among the genotypes for growth habit, leaf, flower and pod traits. Frequency distribution analysis revealed that 82.2% of the genotypes exhibited indeterminate growth habit, while only 13.3 and 4.5% showed determinate and semi-determinate growth habits, respectively. Medium green leaf colour (51.1%), medium leaflet size (55.6%) and persistent to intermediate leaf retention (88.9%) were predominant among the accessions. Principal component analysis generated 19 principal components, of which six components with eigenvalues greater than one explained 67.8% of the total variation. The first two principal components accounted for 31.25% of the variability, with PC1 and PC2 contributing 18.49 and 12.76%, respectively. Traits such as leaf shape, pod curvature, pod shape, pod colour and standard petal colour contributed most to genotype differentiation. The wide dispersion of genotypes in the PCA biplot confirmed substantial genetic diversity and distinctness among the evaluated landraces. The study underscores the importance of systematic characterization of indigenous French bean germplasm for its effective utilization in crop improvement programmes.

Keywords: French bean, DUS characterization, Landraces, Genetic variability, PCA

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Introduction

French bean (*Phaseolus vulgaris* L.) is an important cool-season legume cultivated worldwide for its tender pods and dry seeds. It is a nutritionally rich crop, providing proteins, dietary fibre, vitamins and minerals, and contributes significantly to food and nutritional security. As a leguminous species, French bean also improves soil fertility through biological nitrogen fixation and plays an important role in sustainable agricultural systems (Awuchi et al., 2020). French bean exhibits considerable morphological diversity in growth habit, leaf morphology, flower colour, pod characteristics and seed traits. Such variability serves as an important genetic resource for crop improvement and adaptation to diverse agro-climatic conditions. The crop is broadly classified into determinate and indeterminate growth types, with considerable variation reported for agronomic and morphological traits among cultivated genotypes (Singh et al., 2014; Geleta et al., 2024; Seth et al., 2026). Morphological characterization of germplasm is therefore essential for identifying unique genotypes and broadening the genetic base available for breeding programmes. Distinctness, uniformity and stability (DUS) testing is a prerequisite for varietal registration under the Protection of Plant Varieties and Farmers' Rights (PPV&FR) Act, 2001. DUS characterization using standardized morphological descriptors facilitates genotype identification, maintenance of reference collections, and protection of plant varieties. Furthermore, DUS descriptors provide valuable information for germplasm conservation and utilization in breeding programmes (Nandedkar et al., 2021; Asati et al., 2023). The North-Western Himalayan region of India possesses a rich repository of indigenous French bean landraces that have evolved under diverse agro-ecological conditions and farmer-led selection. These landraces represent valuable sources of genetic variability for adaptation, quality and productivity traits. However, systematic characterization and documentation of these genetic resources using DUS descriptors remain limited, restricting their effective utilization in breeding and varietal development programmes. Therefore, the present study was undertaken to characterize and evaluate 45 French bean genotypes collected from different locations of Uttarakhand using DUS descriptors and morpho-phenological traits. The study aimed to assess the extent of morphological diversity and identify distinct genotypes for their potential utilization in conservation, varietal registration, and future crop improvement programmes.

Materials and Methods

Plant genetic material

The experimental material comprised 45 French bean (*Phaseolus vulgaris* L.) genotypes, consisting predominantly of indigenous landraces collected from different locations of the North-Western Himalayan region. The genotypes were collected from Paharpani, Chaukhuta, Mukteshwar and Gahna areas of Uttarakhand, along with a few locally adapted selections maintained at ICAR research stations. Additionally, two locally popular cultivars, VL-Bean 01 and Pant Anupama, were included as reference genotypes. All the genotypes used in the present investigation were local landraces or farmer-maintained selections, representing untapped genetic diversity adapted to temperate hill conditions. Detailed information regarding genotype designation, type and source of collection is presented in Table 1.

Experimental site, design and crop management

The experiment was conducted during 2023–2025 at the Regional Station, Mukteshwar (Nainital) of the ICAR–Central Institute of Temperate Horticulture (ICAR-CITH), Uttarakhand, India, located at an altitude of approximately 2286 m above mean sea level in the mid-hills of the North-Western Himalaya. The experimental site experiences a temperate climate characterized by cool summers, cold

Table 1: List of genotypes considered for investigation

S.No.	*Genotypes/Variety*	*Type*	*Source of collection*
1.	CITH-M-FB-Selection-1	Local	Paharpani
2.	CITH-M-FB-Selection-2	Local	Paharpani
3.	CITH-M-FB-Selection-3	Local	Paharpani
4.	CITH-M-FB-Selection-5	Local	Chaukhuta
5.	CITH-M-FB-Selection-6	Local	Chaukhuta
6.	CITH-M-FB-Selection-7	Local	Chaukhuta
7.	CITH-M-FB-Selection-8	Local	Chaukhuta
8.	CITH-M-FB-Selection-9	Local	Chaukhuta
9.	CITH-M-FB-Selection-10	Local	Chaukhuta
10.	CITH-M-FB-Selection-11	Local	Chaukhuta
11.	CITH-M-FB-Selection-12	Local	Chaukhuta
12.	CITH-M-FB-Selection-13	Local	Mukteshwar
13.	CITH-M-FB-Selection-14	Local	Mukteshwar
14.	CITH-M-FB-Selection-15	Local	Mukteshwar
15.	CITH-M-FB-Selection-16	Local	Mukteshwar
16.	CITH-M-FB-Selection-17	Local	Mukteshwar
17.	CITH-M-FB-Selection-19	Local	Mukteshwar
18.	CITH-M-FB-Selection-20	Local	Mukteshwar
19.	CITH-M-FB-Selection-21	Local	Mukteshwar
20.	CITH-M-FB-Selection-22	Local	Mukteshwar
21.	CITH-M-FB-Selection-23	Local	Mukteshwar
22.	CITH-M-FB-Selection-24	Local	Mukteshwar
23.	CITH-M-FB-Selection-25	Local	Mukteshwar
24.	CITH-M-FB-Selection-26	Local	Gahna
25.	CITH-M-FB-Selection-27	Local	Gahna
26.	CITH-M-FB-Selection-28	Local	Gahna
27.	CITH-M-FB-Selection-29	Local	Gahna
28.	CITH-M-FB-Selection-30	Local	Mukteshwar
29.	CITH-M-FB-Selection-31	Local	Mukteshwar
30.	CITH-M-FB-Selection-32	Local	Chaukhuta
31.	CITH-M-FB-Selection-33	Local	Mukteshwar
32.	CITH-M-Selection FB-34	Local	Mukteshwar
33.	VL-Bean 01	Local	VPKAS, Almora
34.	Pant Anupama	Local	GB Pantnagar
35.	CITH-M-FB-Selection-37	Local	Gahna
36.	CITH-M-FB-Selection-38	Local	Gahna
37.	CITH-M-FB-Selection-40	Local	Gahna
38.	CITH-M-FB-Selection-41	Local	Gahna
39.	CITH-M-FB-Selection-43	Local	Gahna
40.	CITH-M-FB-Selection-47	Local	Mukteshwar
41.	CITH-M-FB-Selection-49	Local	Mukteshwar
42.	CITH-M-FB-Selection-50	Local	Gahna
43.	CITH-M-FB-Selection-51	Local	Gahna
44.	CITH-M-FB-Selection-52	Local	Gahna
45.	CITH-M-FB-Selection-53	Local	Mukteshwar

winters, occasional frost, mean annual rainfall of 1400 to 1600 mm and temperatures ranging from near freezing during winter to 25 to 28°C during summer. The field trial was laid out in a randomized block design (RBD) with three replications. Each genotype was grown in a single-row plot at a spacing of 45 × 30 cm. Observations were recorded from five randomly selected healthy and competitive plants in each replication, and the mean values were used for further analysis. Uniform agronomic practices were followed throughout the crop-growing period. Fertilizers were applied at the rate of 100:60:40 kg ha^{-1} N:P_2O_5: K_2O, with nitrogen applied in split doses. Standard intercultural operations, irrigation and plant protection measures were adopted as per recommended practices. DUS characterization was carried out following the guidelines prescribed by the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA, 2007), and observations on morphological descriptors were recorded at appropriate growth stages.

DUS characterization and statistical analysis

The French bean genotypes were characterized for distinctness, uniformity and stability (DUS) traits following the guidelines of the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA, 2007) and the International Board for Plant Genetic Resources (IBPGR) descriptors for French bean. Observations were recorded on qualitative, pseudo-qualitative and quantitative morpho-phenological traits related to plant growth habit, stem pubescence, leaf characteristics, flower colour, pod traits and seed attributes at appropriate growth stages to ensure accuracy and repeatability (PPV&FRA, 2007; Pramanik et al., 2023). A total of 38 DUS descriptors were recorded and scored according to the prescribed descriptor states. Frequency distribution analysis was performed to assess the extent of phenotypic variation among the genotypes. Among the recorded descriptors, 19 informative morphological traits were utilized for principal component analysis (PCA) to identify the major contributors to variability and to elucidate patterns of genetic diversity among genotypes. Eigenvalues, correlation coefficients, trait loadings and PCA biplots were generated using GRAPES software (version 1.0.0) following standard multivariate statistical procedures (Pattnaik et al., 2024). Frequency distribution analysis was performed to assess phenotypic variation among genotypes, while PCA was employed to determine the contribution of individual traits towards total variability and genotype differentiation (Pattnaik et al., 2024; Cascante-Yarlequé et al., 2025).

Results and Discussion

Frequency distribution of DUS descriptors

The frequency distribution of major DUS descriptors revealed substantial morphological variability among the 45 French bean genotypes evaluated (Table 2).

Table 2: Frequency distribution of major DUS descriptors among 45 French bean (*Phaseolus vulgaris* L.) genotypes collected from the North-Western Himalayan region

Trait	*Descriptor state*	*Number of genotypes*	*Frequency (%)*
Growth habit	Determinate	5	11.11
Growth habit	Indeterminate	38	84.44
Growth habit	Semi-determinate	2	4.44
Stem pigmentation	Present	34	75.56
Stem pigmentation	Absent	11	24.44
Stem hairiness	Present	44	97.78
Stem hairiness	Absent	1	2.22
Leaf colour	Light green	7	15.56
Leaf colour	Medium green	22	48.89
Leaf colour	Dark green	16	35.56
Leaf shape	Ovate	19	42.22
Leaf shape	Rhomboid	8	17.78
Leaf shape	Cordate	18	40.00
Flower colour	White	15	33.33
Flower colour	Pink	2	4.44
Flower colour	Violet	28	62.22
Pod shape	Flat	43	95.56
Pod shape	Round	2	4.44
Pod pigmentation	Present	4	8.89
Pod pigmentation	Absent	41	91.11

Indeterminate growth habit was predominant, accounting for 84.44% of the accessions, whereas determinate and semi-determinate growth habits were represented by 11.11 and 4.44% of the genotypes, respectively. The predominance of indeterminate growth habit reflects the adaptation of traditional Himalayan landraces to prolonged flowering and harvesting periods under temperate environments (Roy et al., 2023). Representative variation in plant architecture among indeterminate, semi-determinate and determinate genotypes is presented in Figure 1.

Stem pigmentation was present in 75.56% of the genotypes, while stem hairiness was observed in almost all accessions (97.78%), indicating limited variation for this trait. Considerable variation was recorded for leaf-related descriptors. Medium green leaf colour was the most frequent class (48.89%), followed by dark green (35.56%) and light green (15.56%). Similarly, ovate (42.22%) and cordate (40.00%) leaf shapes were well represented, whereas rhomboid leaf shape occurred less frequently (17.78%). Such variation in foliage traits may reflect adaptation to different micro-environments and selection pressures prevailing across the North-Western Himalayan region (He et al., 2021). The frequency distribution of growth, stem and leaf descriptors is presented in Figure 2.

(Indeterminate type) (Semi-Indeterminate type) (Determinate type)

Figure 1: Representative variation in growth habit among French bean genotypes showing indeterminate (CITH-M-FB-Selection-2), semi-determinate (CITH-M-FB-Selection-53) and determinate (CITH-M-FB-Selection-34) plant types.

Flower colour exhibited moderate diversity, with violet flowers predominating (62.22%), followed by white (33.33%) and pink (4.44%) flowered types. Floral pigmentation traits are generally stable and genetically controlled and therefore constitute valuable descriptors for varietal identification and DUS characterization (PPV&FRA, 2007; Pramanik et al., 2023). The distribution of floral and pod descriptor classes among the evaluated genotypes is illustrated in Figure 3.

Pod-related traits displayed the highest degree of polymorphism among the evaluated descriptors. Flat pods were predominant (95.56%), whereas only two genotypes exhibited round pod shape. Pod pigmentation was relatively uncommon and observed in only 8.89% of the genotypes. Variation in pod colour, curvature, pigmentation and stringiness contributed substantially to genotype differentiation and reflects farmer selection for market-preferred pod characteristics. Similar observations have been reported in French bean germplasm collections from diverse agro-ecological regions (García-Fernández et al., 2024).

The descriptor states recorded for individual genotypes are presented in Table 3. Several accessions exhibited unique combinations of DUS descriptors, particularly for growth habit, floral pigmentation, pod shape, and pod pigmentation. Semi-determinate growth habits were observed only in CITH-M-FB-Selection-20 and CITH-M-FB-Selection-53, while determinate growth habits were recorded in CITH-M-FB-Selection-17, CITH-M-FB-Selection-34, CITH-M-FB-Selection-49, VL-Bean 01 and Pant Anupama. Round pod shape, a relatively rare descriptor class, was observed in CITH-M-FB-Selection-21, VL-Bean 01 and Pant Anupama. Similarly, pod pigmentation was expressed by only a few genotypes, including CITH-M-FB-Selection-27, CITH-M-FB-Selection-47, and CITH-M-FB-Selection-51. The occurrence of these unique descriptor combinations highlights the distinctness of several accessions and their potential utility in varietal identification, registration and future breeding programmes.

Overall, the occurrence of both common and rare descriptor states demonstrates the richness of indigenous French bean diversity and highlights its potential value for conservation, varietal registration and future breeding programmes.

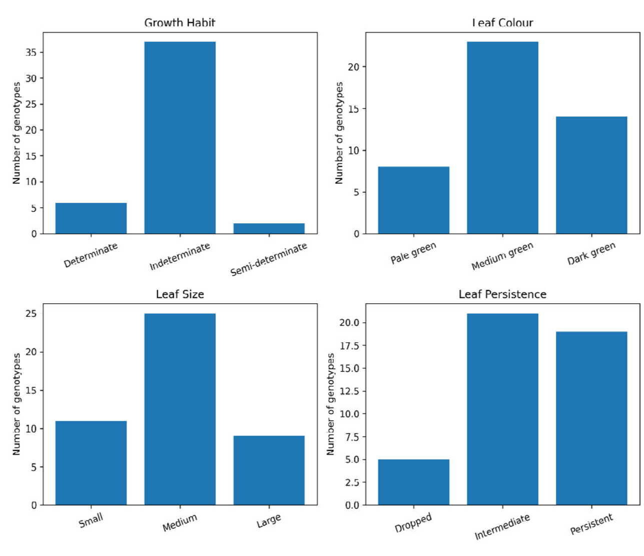

Figure 2: Frequency distribution of growth, stem and leaf descriptors among 45 French bean genotypes

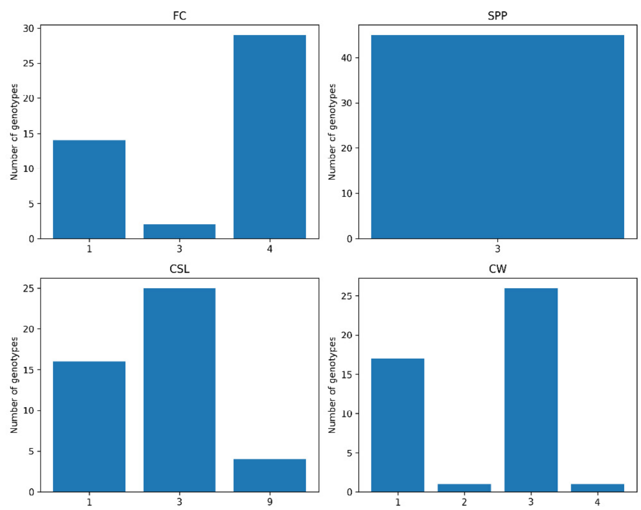

Figure 3: Frequency distribution of flower and pod descriptors among 45 French bean genotypes

Principal Component Analysis

Principal component analysis (PCA) was performed using 19 informative morphological descriptors to identify the major sources of variation among the French bean genotypes. The extracted eigenvalues and loading coefficients for the principal components are presented in Table 4. A total of six principal components with eigenvalues greater than one explained 67.80% of the total variation, indicating that a relatively small number of traits accounted for most of the observed phenotypic diversity. The first two principal components explained 31.25% of the total variability, with PC1 and PC2 contributing 18.49 and 12.76%, respectively.

The loading matrix (Table 4) indicated that PC1 was primarily associated with pod curvature (0.34), leaf shape (0.32), flower colour (0.27), colour of standard petal (0.27), colour of wing (0.27) and pod shape (0.24). These traits contributed most strongly to genotype differentiation and therefore represent important descriptors for assessing distinctness among French bean accessions. In contrast, leaf pubescence (-0.34), flower bud size (-0.30), pod pigmentation (-0.30), leaflet size (-0.29) and bracteole size (-0.29) exhibited negative loadings, suggesting an inverse association with the first principal axis. The second principal component was mainly influenced by pod colour (0.41), colour of standard petal (0.39), colour of wing (0.39), leaf persistence (0.31) and leaflet size (0.26), indicating that pigmentation and foliage-related traits played an important role in separating genotypes along the second axis. Conversely, pod shape (-0.36), stem pigmentation (-0.26) and pod position (-0.22) showed negative contributions to PC2. The relatively high loading values observed for pod-related descriptors across the first two principal components emphasize their significance in explaining phenotypic divergence among the studied genotypes. The

Table 3: Qualitative traits of different French bean genotype

S.No.	*Genotypes*	*GH*	*SP*	*SH*	*LC*	*LS*	*LP*	*LLS*	*PL*	*FC*	*SPP*	*CSL*	*CW*	*FBS*	*SBL*	*CP*	*PS*	*PC*	*PP*	*POP*
1.	CITH-M-FB-Selection-1	2	+	+	3	1	+	1	5	4	3	3	3	1	3	7	1	5	1	1
2.	CITH-M-FB-Selection-2	2	+	+	7	5	0	1	5	4	3	3	3	1	1	3	1	5	9	1
3.	CITH-M-FB-Selection-3	2	+	+	7	1	+	2	5	1	3	1	1	2	3	7	1	3	1	4
4.	CITH-M-FB-Selection-5	2	+	+	5	3	+	2	5	4	3	3	3	1	5	8	1	3	1	4
5.	CITH-M-FB-Selection-6	2	+	+	7	3	+	2	5	4	3	3	3	1	3	7	1	3	1	1
6.	CITH-M-FB-Selection-7	2	+	+	5	3	0	1	7	3	3	3	3	1	3	8	1	3	1	1
7.	CITH-M-FB-Selection-8	2	+	+	5	1	+	1	5	1	3	1	1	1	3	3	1	5	1	1
8.	CITH-M-FB-Selection-9	2	-	+	7	3	+	2	7	1	3	3	3	1	3	8	1	3	1	1
9.	CITH-M-FB-Selection-10	2	+	+	3	2	+	2	5	4	3	1	1	1	3	7	1	5	1	2
10.	CITH-M-FB-Selection-11	2	-	+	5	1	+	2	5	4	3	3	3	1	3	3	1	5	4	1
11.	CITH-M-FB-Selection-12	2	+	+	3	3	+	3	7	4	3	3	3	2	5	3	1	3	1	1
12.	CITH-M-FB-Selection-13	2	+	+	5	3	+	3	7	1	3	1	4	1	3	8	1	3	1	1
13.	CITH-M-FB-Selection-14	2	+	+	5	3	0	2	7	1	3	1	2	1	3	7	1	3	1	3
14.	CITH-M-FB-Selection-15	2	+	+	3	1	+	3	7	4	3	9	3	2	3	3	1	3	1	1

Cont...

15.	CITH-M-FB-Selection-16	2	+	+	5	3	+	2	5	4	3	3	3	1	3	3	1	5	9	1
16.	CITH-M-FB-Selection-17	1	-	+	5	1	+	2	7	4	3	3	3	2	5	7	1	3	1	1
17.	CITH-M-FB-Selection-19	2	-	+	5	3	+	2	7	4	3	3	3	1	5	8	1	3	1	4
18.	CITH-M-FB-Selection-20	3	+	+	5	3	+	2	7	4	3	3	3	2	5	7	1	3	1	1
19.	CITH-M-FB-Selection-21	2	+	+	7	3	+	2	3	3	3	3	3	3	7	8	2	5	1	1
20.	CITH-M-FB-Selection-22	2	-	+	7	3	+	1	5	4	3	3	3	1	3	7	1	5	1	1
21.	CITH-M-FB-Selection-23	2	-	+	5	3	+	1	5	4	3	1	1	2	3	7	1	3	1	4
22.	CITH-M-FB-Selection-24	2	-	+	7	3	+	2	5	4	3	3	3	1	3	7	1	5	1	1
23.	CITH-M-FB-Selection-25	2	-	+	7	2	+	2	5	1	3	3	1	2	5	7	1	3	1	1
24.	CITH-M-FB-Selection-26	2	-	+	7	3	+	2	5	4	3	1	3	2	5	7	1	3	1	1
25.	CITH-M-FB-Selection-27	2	+	+	7	2	+	2	5	4	3	9	3	2	5	7	1	3	9	1
26.	CITH-M-FB-Selection-28	2	-	+	7	2	+	2	5	4	3	1	1	2	3	7	1	3	1	1
27.	CITH-M-FB-Selection-29	2	+	+	3	1	0	2	7	1	3	1	1	1	3	8	1	3	1	1
28.	CITH-M-FB-Selection-30	2	+	+	5	2	+	2	5	4	3	3	3	2	5	3	1	3	1	1
29.	CITH-M-FB-Selection-31	2	+	+	5	2	+	2	7	1	3	1	1	1	3	8	1	3	1	1
30.	CITH-M-FB-Selection-32	2	+	+	5	3	+	2	5	4	3	3	3	2	3	7	1	5	1	1
31.	CITH-M-FB-Selection-33	2	-	+	5	3	+	2	7	4	3	3	3	1	5	8	1	3	1	4
32.	CITH-M-FB-Selection-34	1	+	+	7	3	0	1	3	1	3	1	1	1	3	7	1	5	1	1
33.	CITH-M-FB-Selection-37	2	+	+	5	1	0	3	7	1	3	1	1	1	3	8	1	5	1	1
34.	CITH-M-FB-Selection-38	2	-	+	5	1	+	1	5	4	3	1	1	2	3	7	1	3	1	4
35.	CITH-M-FB-Selection-40	2	+	+	5	1	+	3	5	4	3	3	3	2	5	3	1	3	1	1
36.	CITH-M-FB-Selection-41	2	+	+	5	2	+	3	7	4	3	9	3	2	3	3	1	3	1	1
37.	CITH-M-FB-Selection-43	2	+	+	5	1	+	2	5	4	3	9	3	2	3	7	1	3	1	1
38.	CITH-M-FB-Selection-47	2	+	+	5	1	+	2	7	4	3	3	1	1	5	5	1	3	9	1
39.	CITH-M-FB-Selection-49	1	+	+	7	1	0	3	7	1	3	1	1	3	7	7	1	5	1	1
40.	CITH-M-FB-Selection-50	2	+	+	3	1	+	2	7	4	3	3	3	2	5	7	1	3	1	1
41.	CITH-M-FB-Selection-51	2	+	+	3	1	+	1	7	4	3	3	1	1	5	5	1	3	9	1
42.	CITH-M-FB-Selection-52	1	+	0	3	1	+	1	7	4	3	3	3	2	5	7	1	3	1	1
43.	CITH-M-FB-Selection-53	3	+	+	7	1	0	1	3	1	3	1	1	3	7	7	1	5	1	1
44.	VL-Bean 01	1	+	+	5	2	0	3	3	1	3	1	1	2	3	3	2	7	1	1
45.	Pant Anupama	1	+	+	5	3	+	3	3	1	3	1	1	2	3	8	2	7	1	1

GH = Growth habit; SP = Stem pigmentation; SH = Stem hairiness; LC = Leaf colour; LS = Leaf shape; LP = Leaf pubescence; LLS = Leaflet size; PL = Leaf persistence; FC = Flower colour; SPP = Standard petal pattern; CSL = Colour of standard petal; CW = Colour of wing; FBS = Flower bud size; SBL = Size of bracteole; CP = Pod colour; PS = Pod shape; PC = Pod curvature; PP = Pod pigmentation; POP = Position of pod.

Table 4: Extracted eigenvalues and correlation (Loading) values for morphological traits

Traits	*PC1*	*PC2*	*PC3*	*PC4*	*PC5*	*PC6*	*PC7*	*PC8*
GH	-0.02	-0.07	0.11	0.08	-0.05	0.03	-0.14	-0.02
SP	0.05	-0.26	0.18	-0.09	0.21	-0.11	-0.46	0.39
SH	-0.01	-0.05	0.07	0.03	-0.02	0.01	-0.05	-0.23
LC	-0.03	0.06	-0.14	0.22	0.11	-0.08	-0.35	0.20
LS	0.32	0.21	-0.18	0.09	0.27	-0.15	-0.00	-0.18
LP	-0.34	-0.00	0.19	-0.12	-0.26	0.14	0.01	0.33
LLS	-0.29	0.26	0.21	-0.17	0.09	0.11	-0.09	0.12
PL	0.03	0.31	-0.22	0.15	-0.18	0.06	0.06	0.56
FC	0.27	0.14	-0.09	0.18	0.24	-0.12	-0.12	0.08
SPP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CSL	0.27	0.39	0.16	-0.05	0.13	0.07	0.12	-0.03
CW	0.27	0.39	0.16	-0.05	0.13	0.07	0.12	-0.03
FBS	-0.30	-0.17	0.22	0.09	-0.21	0.10	0.24	-0.05
SBL	-0.29	0.21	-0.13	0.26	0.08	-0.07	0.04	0.14
CP	-0.20	0.41	0.11	-0.22	0.19	0.05	0.10	0.11
PS	0.24	-0.36	0.17	0.13	-0.09	0.08	0.36	0.27
PC	0.34	-0.14	0.23	-0.08	0.31	-0.11	0.38	0.41
PP	-0.30	0.01	-0.19	0.28	-0.12	0.21	0.52	-0.02
POP	0.12	-0.22	0.09	0.11	-0.07	0.05	0.18	0.09

GH = Growth habit; SP = Stem pigmentation; SH = Stem hairiness; LC = Leaf colour; LS = Leaf shape; LP = Leaf pubescence; LLS = Leaflet size; PL = Leaf persistence; FC = Flower colour; SPP = Standard petal pattern; CSL = Colour of standard petal; CW = Colour of wing; FBS = Flower bud size; SBL = Size of bracteole; CP = Pod colour; PS = Pod shape; PC = Pod curvature; PP = Pod pigmentation; POP = Position of pod.

PCA biplot revealed a wide dispersion of genotypes across different quadrants, confirming the presence of substantial morphological diversity within the germplasm (Figure 4). Genotypes positioned farther from the origin were more divergent and may therefore serve as potential parental lines for breeding programmes aimed at broadening the genetic base. In contrast, closely clustered genotypes exhibited greater phenotypic similarity and may share common ancestry or adaptation patterns. The distribution of traits in the biplot further indicated positive associations among descriptors located in close proximity, whereas traits separated by wider angles exhibited weaker or negative relationships.

Overall, the PCA results identified pod curvature, leaf shape, pod colour, floral pigmentation and pod shape as the principal contributors to variability among the evaluated genotypes. These descriptors may therefore be considered key traits for DUS characterization, germplasm management and future French bean improvement programmes. Similar findings highlighting the usefulness of PCA in identifying major diversity-contributing traits have been reported in French bean and other leguminous crops (Zayed et al., 2022; Pramanik et al., 2023).

Implications for DUS characterization and germplasm utilization

The substantial variability observed for growth habit, foliage characteristics, floral pigmentation and pod-related traits confirms the existence of a broad genetic base within the indigenous French bean germplasm of the North-Western Himalayan region. Several genotypes possessed unique combinations of DUS descriptors, particularly for growth habit, pod pigmentation, pod shape and flower colour, indicating their potential utility for varietal registration and protection under the PPV&FR framework. The predominance of indeterminate growth habit reflects adaptation to local production systems, whereas the occurrence of rare descriptor classes such as semi-determinate growth habit, round pod shape and pigmented pods provides valuable opportunities for broadening breeding populations. The identified diversity can therefore be effectively utilized in conservation programmes, parental selection and the development of improved cultivars adapted to temperate hill environments (Dias et al., 2024; Parker et al., 2022).

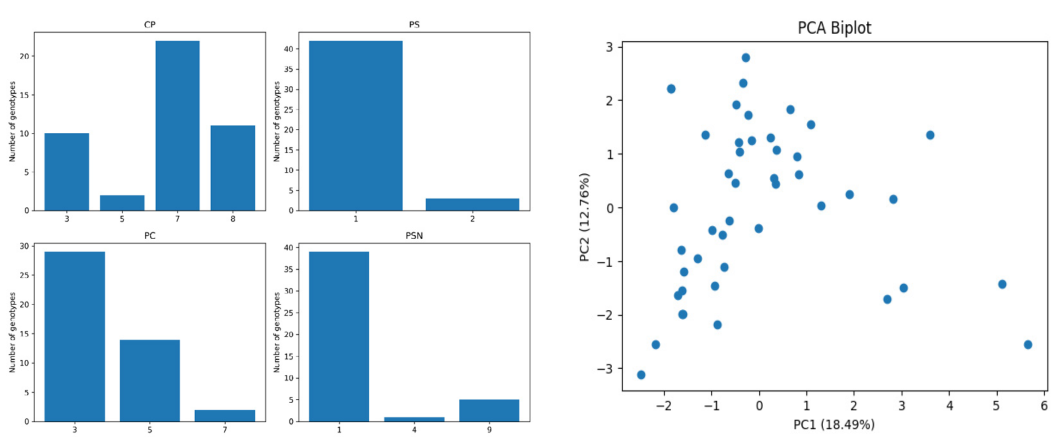

Figure 4: PCA biplot showing distribution of French bean genotypes based on first two principal components (PC1 and PC2).

Conclusion

The present study revealed substantial morphological diversity among 45 French bean (*Phaseolus vulgaris* L.) genotypes from the North-Western Himalayan region. Frequency distribution and principal component analysis confirmed the existence of wide phenotypic variation, with pod curvature, pod colour, pod shape, leaf shape and floral pigmentation contributing most to genotype differentiation. Genotypes CITH-M-FB-Selection-20 and CITH-M-FB-Selection-53 (semi-determinate growth habit), CITH-M-FB-Selection-17, CITH-M-FB-Selection-34 and CITH-M-FB-Selection-49 (determinate growth habit), and CITH-M-FB-Selection-27, CITH-M-FB-Selection-47 and CITH-M-FB-Selection-51 (distinct pigmentation traits) were identified as valuable genetic resources. The occurrence of rare descriptor classes, including round pod shape and absence of stem hairiness, further highlighted the distinctness of the evaluated germplasm. These genotypes may serve as potential candidates for varietal registration and as parental lines in future breeding programmes aimed at improving adaptation, pod quality and productivity under temperate hill conditions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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सारांश

फ्रेंच बीन (*Phaseolus vulgaris* L.) एक महत्वपूर्ण शीतकालीन दलहनी फसल है, जो अपने उच्च पोषण मूल्य तथा हिमालयी क्षेत्र में खाद्य एवं पोषण सुरक्षा में महत्वपूर्ण योगदान के लिए जानी जाती है। उत्तर-पश्चिमी हिमालय क्षेत्र में फ्रेंच बीन की अनेक स्थानीय देशी किस्में पाई जाती हैं, जिनका विशिष्टता तथा पादप प्रजनन में उपयोग की दृष्टि से अभी तक पर्याप्त वैज्ञानिक अध्ययन नहीं किया गया है। प्रस्तुत अध्ययन का उद्देश्य उत्तराखण्ड के विभिन्न क्षेत्रों से संकलित 45 फ्रेंच बीन प्ररूपों का विशिष्टता, एकरूपता एवं स्थायित्व (डीयूएस) लक्षणों तथा आकारिक एवं वृद्धि-विकास संबंधी लक्षणों के आधार पर वर्णन एवं मूल्यांकन करना था। यह प्रयोग वर्ष 2023–2025 के दौरान आईसीएआर–केन्द्रीय शीतोष्ण बागवानी संस्थान, मुक्तेश्वर में यादृच्छिक पूर्ण खण्ड विन्यास के अंतर्गत संचालित किया गया। अध्ययन में वृद्धि प्रकार, पत्ती, पुष्प तथा फली से संबंधित विभिन्न लक्षणों में पर्याप्त आकारिक विविधता पाई गई। आवृत्ति वितरण विश्लेषण से ज्ञात हुआ कि 82.2% प्ररूपों में अनिश्चित वृद्धि प्रकार, 13.3% में निश्चित वृद्धि प्रकार तथा केवल 4.5% में अर्ध-निश्चित वृद्धि प्रकार पाया गया। अधिकांश प्ररूपों में मध्यम हरे रंग की पत्तियाँ (51.1%), मध्यम आकार की पत्रिकाएँ (55.6%) तथा पत्तियों का लंबे समय तक पौधे पर बने रहना अथवा मध्यम अवधि तक बने रहना (88.9%) प्रमुख विशेषताएँ थीं। प्रधान घटक विश्लेषण से कुल 19 प्रधान घटक प्राप्त हुए, जिनमें से एक से अधिक स्वमान वाले छह प्रधान घटकों ने कुल 67.8% परिवर्तनशीलता की व्याख्या की। प्रथम दो प्रधान घटकों ने संयुक्त रूप से 31.25% परिवर्तनशीलता को स्पष्ट किया, जिनमें प्रथम प्रधान घटक का योगदान 18.49% तथा द्वितीय प्रधान घटक का योगदान 12.76% रहा। पत्ती का आकार, फली की वक्रता, फली का आकार, फली का रंग तथा पुष्प की ऊपरी पंखुड़ी का रंग ऐसे प्रमुख लक्षण रहे, जिन्होंने विभिन्न प्ररूपों के मध्य विभेदन में सर्वाधिक योगदान दिया। प्रधान घटक विश्लेषण के द्वि-आयामी चित्र में प्ररूपों का व्यापक बिखराव उनके मध्य पर्याप्त आनुवंशिक विविधता एवं स्पष्ट विशिष्टता को दर्शाता है। यह अध्ययन स्थानीय फ्रेंच बीन जननद्रव्य के व्यवस्थित लक्षण-वर्णन के महत्व को रेखांकित करता है तथा भविष्य में इनके प्रभावी उपयोग द्वारा उन्नत किस्मों के विकास की दिशा में उपयोगी आधार प्रदान करता है।