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Morphological Characterization and Phenotypic Variability of Common Bean (*Phaseolus vulgaris* L.) Germplasm Lines from Kashmir

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Abstract

Common bean (*Phaseolus vulgaris* L.) is an important legume crop valued for its nutritional richness, versatility, and contribution to sustainable agriculture. However, in Jammu and Kashmir, limited genetic diversity poses challenges to achieving its full yield potential and climatic adaptability. This study characterized 75 common bean germplasm lines, collected from various regions of Kashmir, through Distinctness, Uniformity, and Stability (DUS) testing following the Protection of Plant Varieties and Farmers' Rights Authority guidelines. The evaluation identified promising genotypes, including Alr-37 (early flowering and erect growth habit), Alr-28 (robust growth habit and high pod yield), Kdr-12 (medium flowering time and concave pod sutures), Alr-61 (dark green foliage and pigmented pods), and Ppr-13 (spreading growth and late maturity). These genotypes exhibited desirable traits such as early flowering, high pod count, pigmented seeds, and robust growth habits. The study highlights the commercial potential of these genotypes, aligning with market demands for uniform pod size, seed pigmentation, storability, and high yield, enhancing their suitability for processing and consumer preference. Findings provide a structured framework for breeding efforts targeting high-yielding, stress-tolerant, and market-adapted cultivars, offering valuable resources for sustainable agriculture in Jammu and Kashmir and similar climate-stressed regions.

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Abbreviations

DUS -	Distinctness, Uniformity, and Stability
DARS -	Dryland Agricultural Research Station
PPV & FRA -	Protection of Plant Varieties and Farmers' Rights Authority
UPOV -	International Union for the Protection of New Varieties of Plants
GWAS -	Genome-Wide Association Studies
MAS -	Marker-Assisted Selection
PAR -	Photosynthetically Active Radiation
RCBD -	A Randomized Complete Block Design

Introduction

Common bean (*Phaseolus vulgaris* L.) is one of the most widely consumed legumes globally, valued for its high protein content, dietary fiber, and essential micronutrients like iron and zinc.[1-4] As a staple food in many regions, particularly Africa, Latin America, and Asia, it is crucial in improving food security and addressing malnutrition.[4-6] In addition to its macronutrient richness, common bean exhibits bioactive compounds such as phenolic compounds and antioxidants, which contribute to health benefits, including disease prevention.[1,7,8] Beyond its nutritional importance, the common bean contributes to sustainable agriculture through its ability to fix atmospheric nitrogen, improve soil fertility, and reduce the need for synthetic fertilizers.[9-11] Its adaptability to diverse agro-climatic conditions and its ecological and nutritional significance make it a valuable crop for modern farming systems.[6,11]

In India, common bean holds significant agricultural and cultural importance, particularly in the Himalayan regions, where it exhibits substantial genetic diversity.[12] The country's germplasm, which reflects influences from both Mesoamerican and Andean gene pools, has been shaped by historical trade routes and diverse agro-climatic conditions.[13] Cultivation is primarily concentrated in the north-western Himalayas, where landraces such as 'Chamba Rajmah,' Kinnauree,' and 'Bhaderwah Rajmah' are renowned for their superior agronomic traits and high market value.[14,15] These landraces, adapted to unique microclimates, play a crucial role in traditional farming systems, often intercropped with maize and grain amaranth in rainfed conditions.[16] Despite this rich genetic heritage, modern agricultural practices and single-variety cultivation have led to the gradual displacement of traditional genetic diversity.[12] Efforts to conserve India's common bean germplasm, including over 4,274 accessions stored in the national gene bank, are crucial for sustaining genetic resources and supporting breeding programs for yield improvement, stress tolerance, and disease resistance.[17]

In Jammu and Kashmir, common bean cultivation supports local livelihoods, yet systematic studies on its genetic diversity and phenotypic traits remain limited.[18] The region's agro-climatic diversity provides a unique environment for evaluating germplasm lines, offering the potential for breeding programs to enhance stress tolerance, yield, and nutritional quality.[19-22] Previous research indicates substantial morphological and genetic diversity among local bean varieties (*Phaseolus vulgaris*), which has been shown to enhance yield potential and adaptability in various environments. For instance, studies on *Phaseolus vulgaris* have identified significant variation in traits such as flowering time, seed size, and disease resistance, which are important for breeding programs.[19,21,22] Similarly, studies on cowpea (*Vigna unguiculata*) have also highlighted genetic diversity that improves adaptability to diverse climates, further demonstrating the importance of phenotypic characterization in legumes.[23] However, in Jammu and Kashmir, the genetic diversity of local bean varieties remains limited, hindering their full yield potential. This lack of detailed phenotypic characterization limits their utilization in breeding programs, preventing optimization for higher yield and climate resilience. This study aims to bridge the gap by evaluating the morphological traits of 75 germplasm lines collected from diverse regions of Kashmir using Distinctness, Uniformity, and Stability (DUS) descriptors. Despite the substantial morphological and genetic diversity among local *Phaseolus vulgaris* varieties, DUS characterization is crucial for distinguishing the most promising genotypes that exhibit consistent and stable traits. In the context of Kashmir, where climatic challenges such as temperature fluctuations and drought stress are common, identifying distinct genotypes with specific desirable traits, such as early flowering, robust growth, and stress resilience, is essential.[22,24] Such characterization is crucial for identifying promising germplasm lines suitable for breeding programs targeting yield improvement, stress adaptation, and market preferences.[23,25] DUS characterization not only aids in selecting varieties with superior agronomic potential but also supports the development of crops that meet local market preferences, ensuring both adaptability and commercial viability.[19,25]

Accurate morphological characterization provides insights into genetic variability, enabling breeders to select desirable traits for cultivar development.[5] This study employs DUS testing protocols defined by the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA, 2007) and the International Union for the Protection of New Varieties of Plants (UPOV). Evaluations focus on key traits such as flowering time, growth habit, seed shape, and pigmentation, ensuring reliability and comparability for future breeding programs. By systematically assessing phenotypic variability, this study highlights the genetic potential of common beans in Jammu and Kashmir and lays the groundwork for targeted breeding strategies. The findings are expected to contribute to the development of high-yielding, stress-resilient, and nutritionally enriched cultivars adapted to the region's diverse agro-climatic conditions. Field trials and genetic performance studies, which will provide crucial data on the genotypes' adaptability, disease resistance, and stress tolerance, are essential for refining breeding programs and selecting the best-performing varieties for future crop improvement efforts.

Material and Methods

DUS Characterization

Seventy-five common bean germplasm lines, sourced from diverse regions of Kashmir, were evaluated at the Dryland Agricultural Research Station (DARS), SKUAST-K, Budgam (Table 1). The site is located at 74.83°E longitude, 34.08°N latitude, and 1587 m above sea level. The selection criteria ensured a broad representation of genetic variability. The experiment was conducted during the summer months, locally known as the 'Kharif season,' which extends from June to September, in both 2023 and 2024, following the guidelines of the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA, 2007) and the International Union for the Protection of New Varieties of Plants (UPOV) to assess the distinctiveness, uniformity, and stability (DUS).

Experimental Material

The passport data of the germplasm lines of the common bean studied is given in Table 1.

Table 1: Passport data of studied common bean germplasm lines

S. No.	Site of Collection	Code of Germplasm Lines.	No. of Germplasm Lines in Each Location
1	Anantnag	Alr-37, Alr-64, Alr-6, Alr-3, Alr-73, Alr-2, Alr-67, Ppr-1, Ppr-2, Ppr-6, Ppr-7, Ppr-8, Ppr-9, Alr-79, Alr-57, Ang local, Alr-4 , Alr-51, Alr-76, Alr-36, Alr-28, Alr-66, Alr-7	23
2	Bugdam	Alr-24, Alr-25, Ppr-4,Alr-10, Alr-9, Alr-19, Alr-18.	7
3	Ganderbal	Kdr-12, Alr-92, Alr-91, Alr-16, Alr-92, Alr-87, Alr-94, Alr-89, Alr-90, Alr-88, Alr-86, Alr-84, Alr-81, Alr-111	14
4	Shopain	Alr-61, Alr-55, Alr-77, Alr-56, Kdr-36, Alr-63, Alr-62, Ppr-5, Alr-56, Alr-105, Alr-12	11
5	Baramulla	Alr-17, Kdr-45, Kdr-21, Ppr-15, Ppr-14, Kdr-25, Kdr-77, Kdr-12, Kdr-4	9
6	Pulwama	Alr-58, Kdr-46, Alr-15, Alr-326, Alr-20	5
7	Gurez	Gurez local, Ppr-13, Ppr-12, Ppr-11, Ppr-10, Ppr-3	6
Total			75

Experimental Design

A Randomized Complete Block Design (RCBD) with three replications was used to ensure statistical reliability. Each plot consisted of 1.5-meter-long rows, with a plant-to-plant spacing of 15 cm and row-to-row spacing of 40 cm. Standard agronomic practices, such as irrigation, fertilization, and pest control, were uniformly applied to minimize environmental variability.

Data Collection Standards

Observations were recorded from five randomly selected competitive plants per plot, except for traits like days to maturity, which were assessed on a plot basis. Morphological descriptors included observations on time of flowering, stem anthocyanin coloration, leaflet size, plant growth type, plant twining habit, plant habit, leaf intensity of green color, leaflet shape, flower color of standard petal, flower outer surface of standard petal, pod curvature, pod shape of seed section, pod shape in relation to suture, pod shape of distal part, pod color, pod stringiness, pod pigmentation, seed testa color, seed testa variegation, and seed shape. The evaluation adhered strictly to DUS testing procedures to ensure standardization and comparability.

This methodological framework ensured comprehensive characterization of the common bean germplasm, establishing a strong basis for evaluating distinctness, uniformity, and stability in traits.

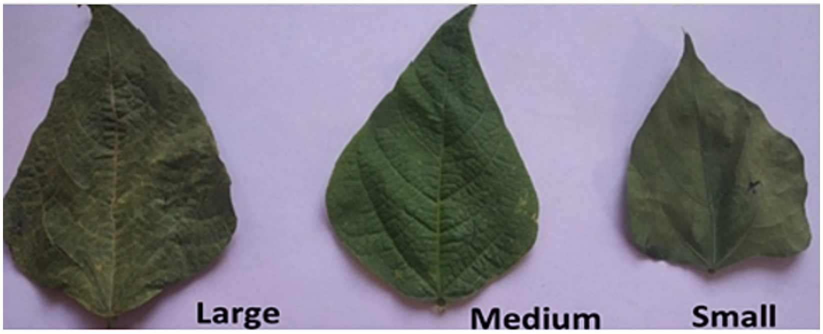
Results

The DUS characterization framework provided a structured assessment of 20 morphological traits, forming the foundation for selecting agronomically viable genotypes suitable for commercial cultivation and market acceptance. The evaluation revealed significant variability across traits, highlighting their potential for breeding programs focused on resilience, yield improvement, and adaptability (Table 2, Figs 1 and Fig 2).

Table 2: Frequency Distribution of common bean germplasm lines for various DUS- characters.

Characteristics	State of Expression	No. of Germplasm	Percentage (%)
Time of Flowering	Early (<50)	25	33.3%
	Medium (50-75)	32	42.66%
	Late (75-100)	12	16%
	Very Late (>100)	6	8%
Stem Anthocyanin Coloration	Absent	71	94.66%
	Present	4	5.33%
Leaflet Size	Large	21	28%
	Medium	28	37.3%
	Small	26	34.6%
Plant Growth Type	Erect	56	74.6%
	Semi Erect	11	14.6%
	Spreading	8	10.6%
Plant Twining Habit	Viny	17	22.6%
	Non-Viny	58	77%
Plant Habit	Determinate	21	28%
	Indeterminate	54	72%
Leaf Intensity of Green Color	Light	37	49.3%
	Dark	38	50.6%
Leaflet Shape	Cordate	36	48%
	Ovate	32	42.6%
	Rhombohedric	3	4%
	Hastate	4	5.3%
Flower Color of Standard Petal	White	25	33.3%
	Yellow	6	8%

	Pink	37	49.3%
	Violet	7	9.3%
Flower Outer Surface of Standard Petal	Non-Stripped	56	74.6%
	Stripped	19	25.3%
Pod Curvature	Strong	15	20%
	Medium	46	61.3%
	Absent	14	18.6%
Pod Shape of Seed Section	Cordate	44	58.6%
	Circular	18	24%
	Eight-Shaped	0	0%
	Oval	13	17.3%
Pod Shape in Relation to Suture	Concave	75	100%
	Convex	0	0%
Pod Shape of Distal Part	Acute	33	44%
	Acute to Truncate	40	53.3%
	Truncate	2	2.6%
Pod Color	Pale Green	31	41.3%
	Green	44	58.6%
Pod Stringiness	Present	65	86.6%
	Absent	10	13.3%
Pod Pigmentation	Present	5	6.6%
	Absent	70	93.3%
Seed Testa Color	White	2	2.66%
	Red	29	38.6%
	Dark Red	14	18.6%
	Brown	11	14.6%
	Red Cream Strips	6	8%
	Light Red	5	6.6%
	Black	5	6.6%
	Yellow	3	4%
Seed Testa Variegation	Absent	57	76%
	Present	18	24%
Seed Shape	Circular	27	36%
	Kidney	18	24%
	Circular to Elliptic	10	13.33%
	Elliptic	20	26.6%



Leaflet Size

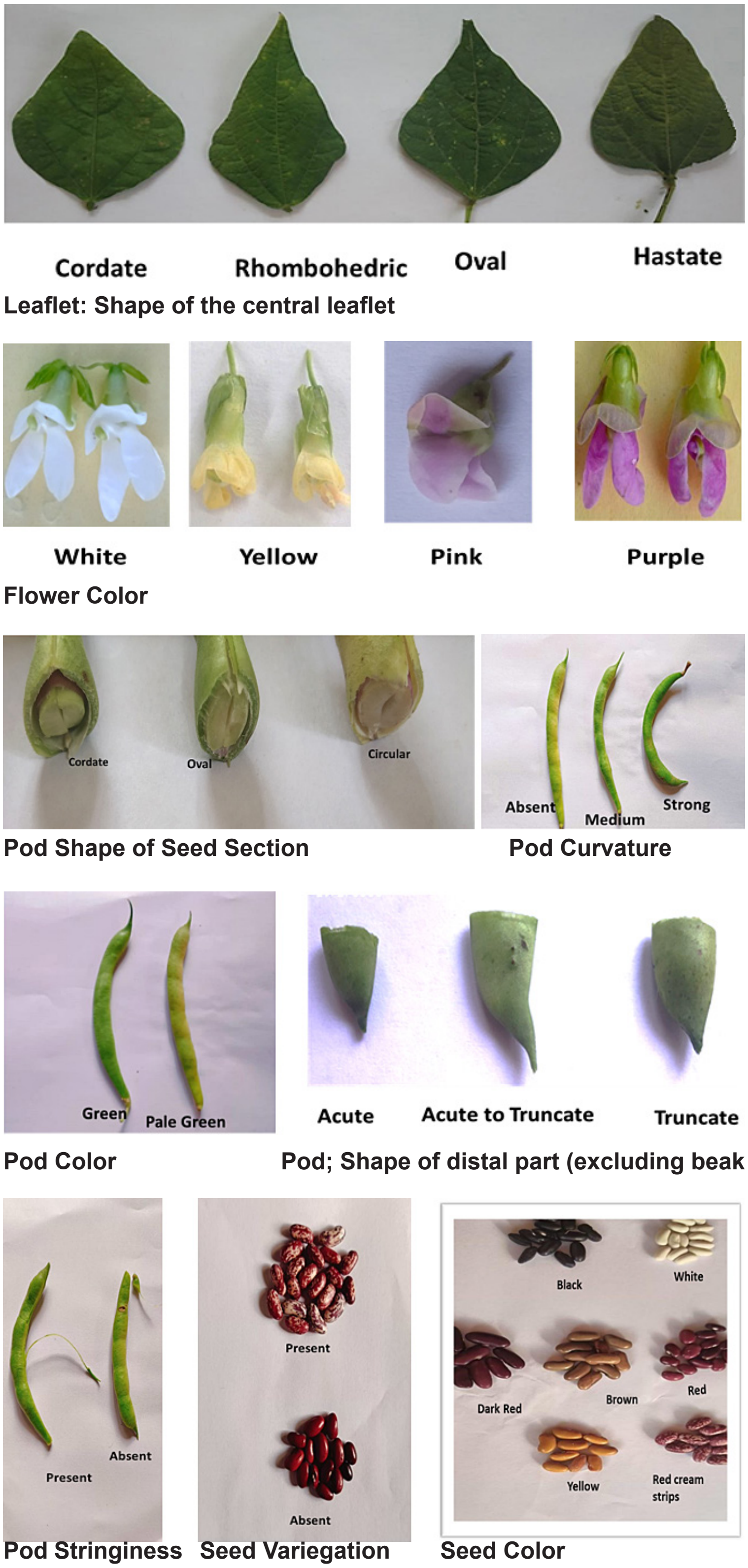


Fig. 1: Pattern of variation in some of the DUS traits in germplasm lines of common beans

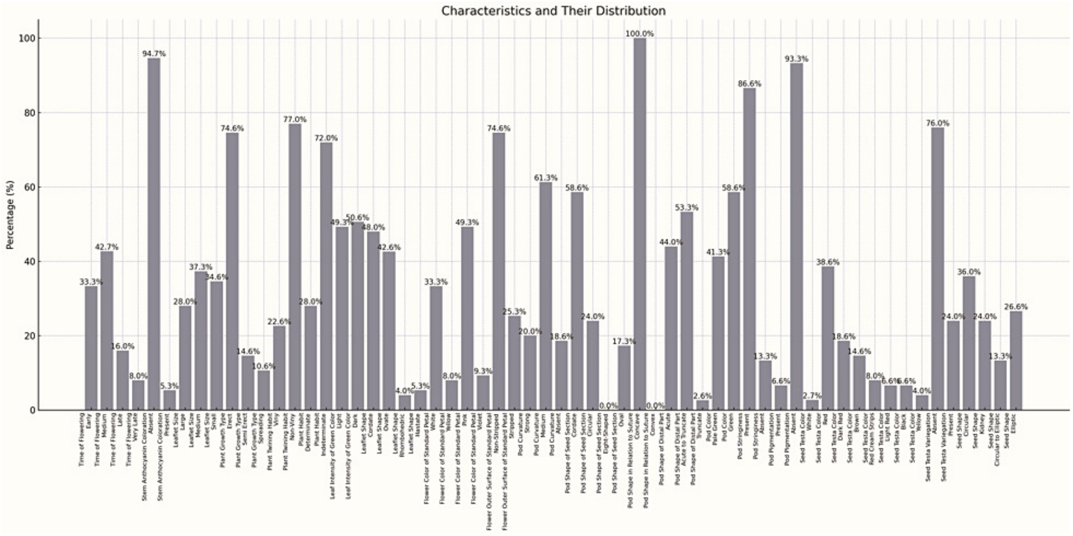


Fig. 2: Frequency Distribution of common bean germplasm lines for various DUS- characters

For time of flowering, the majority of lines exhibited medium flowering (42.66%), followed by early flowering (33.3%). A smaller proportion showed late flowering (16%) and very late flowering (8%), allowing flexibility in harvest schedules. Regarding plant growth type, most lines displayed an erect growth habit (74.6%), which is beneficial for mechanical harvesting and high-density planting systems, while semi-erect (14.6%) and spreading types (10.6%) were also present. In terms of plant twining habit, 77% of the lines exhibited a non-viny growth habit, ideal for row planting and mechanized operations, whereas 22.6% had a viny growth habit, suitable for intercropping systems. For plant habit, most exhibited indeterminate growth (72%), providing extended vegetative and reproductive phases that contribute to higher yield potential in favorable conditions.

Regarding vegetative characteristics, the distribution of leaf intensity of green color was almost equal, with light green (49.3%) and dark green (50.6%) foliage being present. The most common leaflet shape was cordate (48%), followed by ovate (42.6%), and leaflet size showed a predominance of medium-sized leaflets (37.3%), with small (34.6%) and large (28%) leaflets also present. Most lines (94.66%) exhibited no anthocyanin coloration in their stems, suggesting reduced antioxidant content, with only a small percentage (5.33%) showing the presence of anthocyanin.

As for flower traits, pink (49.3%) and white (33.3%) were the most common flower colors, followed by violet (9.3%) and yellow (8%). Regarding the flower outer surface of the standard petal, non-stripped petals (74.6%) were the most predominant, with stripped petals found in 25.3% of lines. For pod traits, medium pod curvature was the most common (61.3%), while strong curvature and absent curvature were observed in 20% and 18.6% of the lines, respectively. The pod shape of the seed section showed a dominance of cordate (58.6%) and circular (24%) shapes, while oval shapes were seen in 17.3% of the lines. Green pods (58.6%) and pale green pods (41.3%) were the most common, aligning with market preferences for fresh produce. Most pods (53.3%) had an acute to truncate shape at the distal part, while 86.6% of the lines exhibited pod stringiness, which may present challenges in processing. All lines (100%) exhibited concave pod sutures, ensuring structural integrity during harvest. Regarding pod pigmentation, 93.3% of the lines showed no pigmentation, while only 6.6% exhibited pigmentation, which could offer benefits like pest resistance. For seed traits, red seeds (38.7%) and dark red seeds (18.6%) were the most common, with smaller proportions of brown (14.6%), light red (6.6%), black (6.6%), and yellow (4%) seeds. Seed testa variegation was present in 24% of the lines, adding visual appeal, while 76% had a uniform testa. The most common seed shapes were circular (36%)

and elliptic (26.6%), followed by kidney-shaped (24%) and circular to elliptic (13.33%) shapes.

Discussion

The DUS characterization of common bean germplasm lines revealed significant morphological diversity, which offers great potential for breeding programs aimed at enhancing resilience, yield, and market adaptability. Key traits, such as early flowering, dark green foliage, and erect growth habits, emerged as highly valuable for improving crop productivity and adapting to varying environmental conditions. This diversity provides a strong foundation for breeding climate-resilient cultivars that can thrive in diverse agro-climatic conditions, particularly in Jammu and Kashmir.

However, while the morphological DUS characterization revealed valuable insights into the diversity of common bean germplasm, it is important to recognize that the assessment of morphological traits can be influenced by environmental conditions. The subjective nature of visual evaluations may also lead to inconsistencies. Moreover, certain traits related to stress tolerance or disease resistance may not be fully captured through DUS evaluation, underlining the need for complementary molecular or biochemical analyses in breeding programs.

Growth and Development Characteristics

Plant Growth Type

Most germplasm lines exhibited an erect growth habit, which is advantageous for mechanical harvesting and high-density planting systems. This growth type's predominance highlights its potential for yield improvement and adaptability across diverse environments. Like the BRS Cometa cultivar, which combines erect growth habit with lodging and disease resistance,[26] these lines could serve as candidates for breeding programs focused on improving harvest efficiency, stress resilience, and adaptability in diverse agro-climatic conditions.[21] Semi-erect growth was observed in fewer lines, providing flexibility for mixed cropping systems. The spreading type was also observed, which is more suited for low-input farming systems, offering natural weed suppression through canopy coverage and competition with weeds. Previous studies have demonstrated that strategic cropping arrangements, such as narrow rows and mechanical weed treatments, can significantly reduce weed infestation and maintain grain yields comparable to chemically treated plots.[27] Such approaches highlight the relevance of spreading growth types for sustainable, low-input agricultural systems where herbicide dependence can be minimized. Erect types, in particular, demonstrate greater lodging resistance, making them ideal for high-density planting systems, whereas spreading types may better suit low-input, smallholder farming systems.[21,28]

Plant Twining Habit

The majority of germplasm lines exhibited a non-viny growth habit, which is well-suited for row planting and mechanical operations due to its open canopy that improves air circulation and reduces the risk of diseases like anthracnose and leaf spots.[29] These types align with high-density planting systems, supporting efficient weed control and fertilizer application to further lower disease severity. In contrast, viny types may perform better in low-input systems and intercropping, offering natural weed suppression but requiring optimized spacing or support systems to mitigate disease vulnerability.[29] The observed diversity in growth habits highlights the importance of matching plant architecture with cropping practices to improve disease resistance and yield stability, providing a foundation for targeted breeding programs focused on adaptability and sustainability. Also, morphological characterization of Rajmash (*Phaseolus vulgaris* L.) genotypes has revealed significant diversity in plant architecture, highlighting its role in breeding programs aimed at optimizing growth habits for different cropping systems.[30]

Non-viny growth types, with their suitability for high-density planting, complement intensive farming systems, while viny types may be advantageous in intercropping systems due to their ability to suppress weeds naturally. Studies have shown that intercropping bushy varieties of common bean with maize can improve land-use efficiency and yield performance across agro-ecological zones.[32] Morphological characterization of Rajmash (*Phaseolus vulgaris* L.) genotypes has revealed significant diversity in growth habit, with accessions displaying both non-viny and viny types.[12,33] This variation underscores the importance of selecting optimal plant architectures suited for different farming systems. Non-viny types, which are typically more compact and upright, align well with mechanical harvesting and high-density planting, whereas viny types offer advantages in traditional low-input systems by utilizing vertical space and reducing weed pressure. The observed diversity in growth habit provides valuable genetic resources for breeding programs aimed at optimizing plant structure for sustainable agricultural systems.[34]

Plant Habit

The dominance of indeterminate growth habit indicates extended vegetative and reproductive phases, which may benefit yield in favorable conditions. Similar findings were reported, where indeterminate growth habits (Types II and III) demonstrated higher yields than determinate types (Type I).[35,36] In contrast, determinate growth types, which accounted for 28%, could be preferred for synchronized flowering and harvesting, particularly in short-season environments, as observed in studies evaluating growth habits under different spacing and support systems. These results emphasize the importance of selecting indeterminate types for breeding programs focused on maximizing yield and adaptability.[35,36]

Time of Flowering

The dominance of early flowering (33.3%) and medium flowering (42.6%) types indicates a strong adaptability to staggered harvesting and the ability to adapt to varying climatic conditions. This observation is consistent with earlier research indicating that phenological plasticity in common beans is an adaptive mechanism to cope with variable rainfall patterns and growing seasons in rainfed environments.[37] Similarly, morphological characterization of 300 Rajmash genotypes revealed substantial variation in flowering traits, further reinforcing the adaptability of common bean genotypes. Significant differences were observed in days to flowering and days to maturity, demonstrating the genetic diversity available for optimizing flowering time in breeding programs aimed at improving resilience under varying environmental conditions.[12] The observed variation provides opportunities to develop cultivars with flowering durations tailored for specific agro-climatic zones and cropping systems.

Vegetative Characteristics

Leaf Intensity of Green Color

The nearly balanced distribution between light green (49.3%) and dark green (50.6%) foliage highlights a significant variation in leaf intensity, which can affect photosynthetic efficiency and productivity. Dark green leaves are often associated with higher chlorophyll content, which may contribute to improved photosynthetic efficiency and productivity. Chlorophyll and other pigments, such as carotenoids, influence leaf color, affecting light absorption, photosynthesis, and market preferences.[38,39] Studies have shown that leaf and pod color variations in common beans can be quantitatively assessed using tools like colorimeters and standard color scales, enabling better characterization and selection in breeding programs.[40] In common beans, leaf color variation is not only important for agronomic traits but also holds relevance in DUS (Distinctness, Uniformity, and Stability) evaluations, where distinctness and uniformity of traits such as leaf color play a crucial role.[12,33]

Leaflet Shape

The cordate (48%) and ovate (42.6%) leaflet shapes are predominant in the germplasm lines, with these shapes being associated with improved light interception, which may enhance photosynthetic performance. Studies on *Phaseolus vulgaris* have demonstrated that variations in leaf area development and canopy architecture influence light interception and photosynthetic efficiency, with taller, indeterminate types intercepting more photosynthetically active radiation (PAR) than shorter, determinate types.[41] These variations offer opportunities for developing varieties with optimized light capture and productivity. Furthermore, the diversity of common bean genotypes in the region, as noted in the study (Jammu and Kashmir region), highlights the potential for selecting genotypes with distinct leaflet shapes that enhance canopy structure and overall productivity in diverse environmental conditions.[21] This diversity could be instrumental in breeding programs aimed at optimizing light capture and yield potential in varying agro-ecological zones.[42]

Leaflet Size

The predominant presence of medium-sized leaflets (37.3%) suggests that this leaf size may be favorable for photosynthetic surfaces, contributing to improved growth and productivity. Medium and large leaflets are advantageous as they can capture more sunlight, enhancing the plant's ability to perform photosynthesis and thus supporting overall plant development. Small leaflets could be advantageous in drought-prone areas, reducing water loss and increasing adaptability. Studies on *Phaseolus vulgaris* have shown that leaflet size can be effectively estimated using non-destructive methods based on linear models, enabling accurate predictions of leaflet area under field and greenhouse conditions during both vegetative and reproductive stages.[43] This diversity supports breeding efforts targeting specific environmental and agronomic conditions.

Stem Anthocyanin Coloration

The absence of anthocyanin coloration in most of the germplasm lines (94.6%) suggests a reduced antioxidant content in these plants. This could make them more vulnerable to environmental stresses such as UV radiation, pests, and other abiotic factors. Anthocyanin, a pigment associated with antioxidant properties, can protect against oxidative stress, UV damage, and various pests. Therefore, the lines without anthocyanin might exhibit reduced resilience to these environmental challenges. Conversely, the presence of anthocyanin could enhance stress tolerance and pest resistance, providing breeding opportunities for resilience-focused programs. Studies on *Phaseolus vulgaris* germplasm have revealed significant morphological diversity, including leaf color, size, and shape variations, which may serve as essential selection criteria in breeding programs targeting stress adaptation and genetic improvement.[21]

Flower Traits

Flower Color of Standard Petal

The observed variation in flower color, with pink and white being the most common, suggests a potential influence on pollinator attraction. Different flower colors can attract specific pollinators, which may enhance natural cross-pollination rates and contribute to greater genetic diversity. This variability in flower color is consistent with studies on *Phaseolus vulgaris*, which have shown significant morphological diversity across genotypes from different regions.[21] The study conducted in Jammu and Kashmir, India, highlighted the vast genetic diversity of common bean genotypes, including variations in flower traits, and provided valuable insights into the different types of phaseolin, which may correlate with distinct flower colors and pollination behaviors.[18] Such variability underscores the potential for genetic improvement programs targeting traits for enhanced pollination, visual appeal, and overall productivity.

Flower Outer Surface of Standard Petal

The dominance of non-stripped petals suggests that visual uniformity is a key characteristic that may be desirable for ornamental purposes or for meeting market preferences where uniform appearance is valued. In contrast, though less common, stripped petals can offer distinct market appeal by providing variety in visual aesthetics, potentially catering to niche markets that favor unique crop traits. The variation in flower traits, such as petal striping, highlights the importance of visual markers in cultivar selection.[21] This underscores the role of flower trait variation in breeding programs, where selecting specific flower characteristics can enhance both marketability and the adaptability of varieties to different consumer preferences.

Pod Traits

Pod Curvature

The predominance of medium curvature in the pods suggests that this trait may contribute to mechanical strength, reducing the risk of breakage during handling and storage, which is essential for commercial cultivation. This aligns with the morphological variation observed in *Phaseolus vulgaris* across different genotypes, where pod shape, including curvature and cross-section, showed significant diversity.[21] The study on common bean genotypes from the Western Himalayas also highlighted the importance of pod shape in determining desirable traits for handling and storage, indicating that curvature could play a role in improving post-harvest performance and reducing damage during transportation and storage.[21] Recent genome-wide association studies (GWAS) in *Phaseolus vulgaris* have identified QTL regions associated with pod length and cross-sectional shape, indicating a genetic basis for these variations.[31] These findings reinforce the role of morphological traits in genetic improvement and breeding programs targeting pod quality and structural efficiency.

Pod Shape of Seed Section

The dominance of cordate and circular pod shapes of seed section suggests that these shapes may be optimized for seed packing efficiency, potentially enhancing yield and ease of storage. In a similar study, the substantial variation observed pod shape among the 93 common bean accessions, ranging in pod length and seed arrangement, supports the notion that these traits are key for improving seed packing and storage efficiency.[33] GWAS studies on common bean identified several QTL influencing pod shape, seed arrangement, and morphological development, providing insights into the inheritance patterns and genetic mechanisms underlying pod traits.[31]

Pod Color

The dominance of green and pale green pods aligns well with market preferences for fresh produce, as these colors are often associated with visual appeal and perceived freshness, enhancing market value. Similar results have been found in other study, in which green pods were found predominant among the 93 accessions supporting this preference, while the presence of other colors such as purple, red, and golden highlights the substantial variation in pod color within the germplasm.[33] GWAS analyses identified QTL linked to pigment synthesis genes, explaining variations in pod color and providing tools for marker-assisted selection in breeding programs.[31] Such genetic insights complement phenotypic evaluations used in DUS testing.

Pod Shape of Distal Part

The predominance of acute to truncate pod shapes suggests that this trait may play a significant role in harvesting efficiency and seed retention. The acute and truncate shapes are likely to offer better structural integrity, which can reduce the likelihood of seed loss during harvesting and handling. These variations in distal pod shape may also influence how seeds are dispersed, potentially affecting overall yield and seed quality. The diversity of pod shapes observed in the 109 common bean genotypes collected from different hotspots in the Western Himalayas, including differences in pod shape in relation to the suture and cross-section, further supports the idea that pod morphology plays a significant role in seed retention and dispersal mechanisms. Such diversity in pod characteristics is vital for breeding programs aimed at improving pod structure and seed retention.[21] Research has suggested that pod valve composition and structural integrity play a key role in pod morphology and may influence seed retention and dispersal mechanisms.[44]

Pod Stringiness

The presence of stringiness in most germplasm lines (86.6%) may pose challenges in processing and consumer acceptance, as stringy pods can be difficult to handle and may reduce the quality of the product. The absence of stringiness in 13.3% of lines suggests the potential for breeding stringless varieties to meet market demands. This observation is in line with the wide variation observed in pod characteristics across 109 common bean genotypes in the study, where pod quality traits, including stringiness, were evaluated.[21] Investigations into pod-shattering mechanisms have shown that lignin concentration in pod valves affects fiber development, contributing to stringiness and structural rigidity, which can be selectively modified through breeding programs.[44]

Pod Shape in Relation to Suture

Consistent concave pod sutures across all germplasm lines suggest that this trait enhances structural integrity, which can help reduce splitting during maturation and handling. This trait is particularly advantageous for mechanized harvesting and post-harvest processing. Pod shape factors and moisture content have shown that internal stresses in sclerenchyma increase as pods dry, influencing convexity and the force required for opening. In a similar study, characterization of pod traits in 109 common bean genotypes, including the shape in relation to the suture, revealed substantial variation in these morphological traits, highlighting their importance in determining pod durability and mechanical strength.[21] Studies on snap bean pod development have demonstrated that treatments affecting pod fiber content and moisture levels can influence pod mechanical properties, including bending resistance and humidity percentage.[45] More convex pods require less force to open, suggesting that structural curvature can act as a natural mechanism for splitting resistance and seed retention. These findings reinforce the role of suture morphology and pod structure in improving mechanical strength and breeding efficiency for durability traits.

Pod Pigmentation

The presence of pigmentation in 6.6% of the germplasm lines suggests that this trait may be associated with anthocyanin content, which is known to offer several potential benefits, including pest resistance, UV protection, and enhanced aesthetic appeal. Genome-wide association studies (GWAS) on *Phaseolus vulgaris* have identified 18 QTL and 8 candidate genes involved in pigment synthesis, particularly related to flavonoid and anthocyanin pathways.[31] These findings highlight the dual role of pigmentation as a functional trait for environmental resilience and a visual marker for market preferences. Marker-assisted selection for pigmentation genes may support breeding programs targeting pest resistance and improved marketability.

Seed Traits

Seed Testa Color

The observed diversity in seed testa color, including red, dark red, brown, white, black, and yellow, reflects significant genetic diversity within the germplasm. These variations highlight genetic diversity and adaptability to different culinary uses and market preferences, providing avenues for diversification. Studies have shown that seed coat color is associated with nutritional quality, including higher mineral accumulation (e.g., cadmium (Cd) and molybdenum (Mo)) in black-colored seeds and distinct mineral profiles in green-colored seeds.[46] Similarly, a study conducted on 109 common bean genotypes from Jammu and Kashmir revealed significant variation in seed color among different genotypes.[21] This aligns with the notion that seed color diversity can be linked to functional traits, including the nutritional composition of seeds. The study also demonstrated substantial variation in seed micronutrients and macronutrients, highlighting the role of pigmentation traits in influencing both marketability and nutritional value.[21] These findings suggest that pigmentation traits influence market preferences and nutritional value, making them valuable targets for breeding programs focused on functional improvements.

Seed Testa Variegation

Variegation in 24% of the germplasm lines adds visual appeal and offers the potential to cater to niche markets that value unique and aesthetically attractive seed traits. This variation in seed appearance can be leveraged to meet specific consumer preferences, especially in markets where distinctive seed patterns are desired. Research has shown that pigment patterns can be linked to seed composition and mineral accumulation variations, reinforcing their role in market preferences and nutritional quality.[46] In line with these findings, a study on 109 common bean genotypes from Jammu and Kashmir also highlighted significant diversity in seed color and composition, with variations in seed micronutrients such as Fe, Zn, and Cu.[21] This supports the idea that variegation in seed testa could be indicative of broader genetic and nutritional variations, making it an important trait for breeding nutrient-rich cultivars.[21] Marker-assisted selection based on these findings offers opportunities for breeding nutrient-rich cultivars.

Seed Shape

The predominant circular and elliptic seed shapes and the presence of kidney-shaped and circular-to-elliptic seeds reflect the diversity in seed morphology within the germplasm. These variations have important implications for cooking and processing qualities, as different shapes can affect how the seeds are handled, prepared, and used in various culinary applications. Studies evaluating French bean varieties have demonstrated similar diversity in seed shapes, with most varieties exhibiting elliptic or kidney shapes and none showing round seeds.[47] In alignment with these findings, a study on 109 common bean genotypes collected from the Western Himalayas also observed a wide range of morphological traits, including seed shape variations, which support the idea of significant genetic diversity within the germplasm.[21] Such variations in seed morphology highlight genetic distinctness and can aid in selecting reference varieties for breeding programs and DUS testing, as demonstrated in the current study's characterization of different seed shapes and other morphological traits.[30]

Implications for Breeding Programs and Future Research

The comprehensive DUS characterization of common bean germplasm lines in this study highlights key traits with potential applications in breeding programs aimed at improving yield, stress resilience, and market adaptability. Traits such as early flowering, dark green foliage, erect growth habits, concave pod sutures, and pigmented seeds provide a strong genetic foundation for developing climate-resilient cultivars and high-yielding varieties tailored for the agro-climatic conditions of Jammu and Kashmir. Future research should focus on evaluating untested traits, including disease resistance, drought tolerance, and nutritional profiling, through multi-environment trials to validate genotype stability and performance under climate variability. Integrating marker-assisted selection (MAS) and genome-wide association studies (GWAS) can further enhance the efficiency of breeding programs by identifying candidate genes responsible for specific phenotypic traits.

Promising Germplasm Lines for Breeding

Based on the morphological diversity revealed through DUS testing, several promising genotypes were identified for targeted breeding programs across different agro-climatic zones. Alr-37 (Anantnag) exhibits early flowering and an erect growth habit, making it suitable for short-season cropping and mechanized harvesting. Similarly, Alr-28 (Anantnag) demonstrates a robust growth habit and high pod yield, which is ideal for stress-prone environments. In Ganderbal, Kdr-12 features medium flowering time and concave pod sutures, ensuring structural integrity for mechanized harvesting and post-harvest processing.

Alr-61 (Shopain) displays dark green foliage and pigmented pods, providing pest resistance and visual appeal, which enhances its market potential. Likewise, Alr-57 (Anantnag) is notable for its erect growth type and medium-sized seeds, making it suitable for high-density planting and mechanical operations. In Gurez, Ppr-13 combines a spreading growth habit with late maturity, offering advantages in drought-prone areas by retaining moisture and suppressing weeds. Further, Alr-25 (Budgam) demonstrates high seed testa color diversity, including variegated patterns, which make it ideal for niche markets and culinary applications. Alr-20 (Pulwama) exhibits large leaflet size and a high seed count per pod, ensuring yield stability in variable climates. Kdr-45 (Baramulla) is known for its semi-erect growth and moderate flowering time, making it highly adaptable for intercropping systems and sustainable agriculture. Lastly, Alr-92 (Ganderbal) features dark red seed color, which could be of interest for future breeding programs focusing on seed color and visual appeal. These genotypes demonstrate distinct morphological and agronomic traits that make them valuable resources for breeding programs aimed at improving yield stability, stress tolerance, and market preferences across diverse agro-climatic regions.

Conclusion

This DUS characterization of common bean germplasm provides a structured foundation for breeding programs aimed at improving yield stability, resilience, and market adaptability across diverse agro-climatic conditions, particularly in Jammu and Kashmir. Distinct genetic diversity was observed in key traits such as growth habits, leaflet size, flower color, pod characteristics, and seed pigmentation, offering valuable opportunities for targeted breeding programs. Breeders are encouraged to focus on promising genotypes such as Alr-37, Alr-28, Kdr-12, Alr-61, Alr-57, Ppr-13, Alr-25, Alr-20, Kdr-45, and Alr-92, as these lines exhibit traits beneficial for high productivity and regional adaptability. Traits such as early flowering, erect growth habits, concave pod sutures, and pigmented seeds should be prioritized to enhance stress tolerance, mechanized harvesting potential, and market acceptance. Policymakers can support these efforts by facilitating access to quality seeds, providing training for farmers, and ensuring that agricultural policies align with the goal of improving crop resilience and productivity. Additionally, breeders should focus on enhancing drought and disease resistance based on the genetic diversity observed, thus addressing climate variability and improving food security. This foundational characterization supports breeding efforts focused on developing regionally adapted, commercially viable cultivars. The identified genotypes, with their unique morphological and agronomic features, provide a promising base for addressing climatic challenges and promoting sustainable agriculture. These findings emphasize the potential of genetic improvement programs to drive economic growth and long-term food security for farmers in Jammu and Kashmir and beyond.

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Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Author Contributions

- **Muneeb Ahmad Rather:** Data collection, analysis, and Writing the Original Draft.
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- **Zahoor Ahmad Dar:** Visualization, Review, and Editing.
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