ISSN: 2347-4688, Vol. 12, No.(3) 2024, pg. 1276-1286

Current Agriculture Research Journal

www.agriculturejournal.org

Morphological Evaluation of Fenugreek (*Trigonella foenum-graecum* L.) Genotypes from different Altitudinal Collections in the Western Hilly Region of Uttarakhand, India

PRAWAL PRATAP SINGH VERMA[1,2], SABA SIDDIQUI[2*], SAUDAN SINGH[3], RAKESH KUMAR UPADHYAY[1], MD ABU NAYYER[1,4] and MOHD. HARIS SIDDIQUI[2]

[1]Division of Crop Production and Crop Protection, CSIR-Central Institute of Medicinal and Aromatic Plants Research Centre Purara, PO Gagrigole, Bageshwar,, Uttarakhand India.
[2]Department of Agriculture, Integral Institute of Agricultural Science and Technology (IIAST), Integral University, Lucknow, Uttar Pradesh, India.
[3]Division of Crop Production and Crop Protection, CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow, Uttar Pradesh, India.
[4]Department of Horticulture, Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India.

Abstract

This study evaluates the morphological and agronomic diversity of 30 fenugreek (*Trigonella foenum-graecum* L.) genotypes from lower-altitude regions of Uttarakhand to identify high-yielding, resilient cultivars for the western Himalayan region. Cultivated in a randomized block design with three replications over two growing seasons (2021-22 and 2022-23) at CSIR-CIMAP Research Centre, Purara, the genotypes were analyzed for traits such as germination rate, plant height, leaf characteristics, root length, branching, flowering time, and yield metrics. Results revealed significant genetic diversity, with early-germinating genotypes like UK-23 (3.51 days) facilitating rapid establishment, and uniform-emergence genotypes like UK-28 (8.41 days to 50% germination) promoting even stands. High-biomass genotypes, like UK-18, with a tall stature (38.87 cm) and high fresh herb weight (23.77 kg/ha), were favorable for biomass production. Enhanced leaf and root traits, such as large leaves in UK-10 and long roots in UK-9, support improved photosynthesis and drought resilience, while early-flowering genotypes like UK-16 (91.91 days) suit shorter growing seasons. Notably, UK-22 stood out for high yields in both dry herb (16.07 kg/ha) and seed (24.06 kg/ha), demonstrating promise

Article History
Received: 11 November 2024
Accepted: 27 December 2024

Keywords
Agronomic Traits;
Fenugreek Variability;
Genotype Characterization;
Morphological Diversity;
Trait Association.

CONTACT Saba Siddiqui 27.sabasiddiqui@gmail.com Department of Agriculture, Integral Institute of Agricultural Science and Technology (IIAST), Integral University, Lucknow, Uttar Pradesh, India.

© 2024 The Author(s). Published by Enviro Research Publishers.
This is an Open Access article licensed under a Creative Commons license: Attribution 4.0 International (CC-BY).
Doi: http://dx.doi.org/10.12944/CARJ.12.3.22

for sustainable productivity in challenging conditions. Overall, genotypes UK-23, UK-18, and UK-22 emerged as top candidates for herb and seed production in hilly areas, providing a valuable basis for breeding resilient fenugreek varieties to bolster local livelihoods and sustainable agriculture in the region.

Introduction

Fenugreek (*Trigonella foenum-graecum* L.), commonly referred to as methi in India, is an herbaceous annual plant belonging to the Fabaceae family, with a diploid chromosome number of 2n = 16[1]. Originating from the Mediterranean region, this legume has been cultivated for centuries for its versatile use in food, medicinal applications, and industrial products. Its adaptability to different environments and significant nutritional and therapeutic value have propelled its cultivation beyond its native range, making it an important crop globally.[2] Currently, India stands as the world's leading producer of fenugreek, accounting for approximately 85% of global production. The state of Rajasthan primarily drives this production, supplying both domestic and international markets with high-quality fenugreek seeds and leaves.[3,4] The plant prefers semi-arid climates and is well-suited to loamy soils with adequate drainage and a pH range of 6.0–7.5, allowing it to thrive across a variety of regions up to an elevation of 2,600 meters. With the rising global demand for fenugreek, fueled by increased awareness of its health benefits, the United States, the United Arab Emirates, and several European countries have become major importers.[5] Fenugreek is especially valued for its diverse range of bioactive compounds, including saponins, flavonoids, and alkaloids, which have demonstrated antioxidant, antidiabetic, and antimicrobial properties. These properties have made fenugreek a sought-after ingredient in both traditional and modern pharmaceutical, nutraceutical, and wellness industries, where it is widely used to manage blood sugar, improve digestive health, and support general wellness.[6,7]

However, despite the high international demand, fenugreek cultivation in the Western Himalayas, particularly in the state of Uttarakhand, remains underdeveloped. Farmers in Uttarakhand face specific agronomic challenges, primarily due to limited access to high-yielding cultivars, soil fertility concerns, and suboptimal growing conditions that lead to the low productivity of local fenugreek varieties.[8] Furthermore, the unique environmental conditions of this region, including its specific altitude, soil type, and climate, necessitate the development of fenugreek varieties tailored to thrive in these local conditions. Addressing these limitations by developing cultivars adapted to Uttarakhand's agro-ecological conditions could significantly enhance productivity, increase farmers' income, and contribute to the economic sustainability of the region.

The present study aims to evaluate the morphological and agronomic characteristics of 30 distinct fenugreek genotypes collected from diverse altitudinal zones in Uttarakhand over two growing seasons, 2021-22 and 2022-23. By examining the variation in key traits such as plant height, number of branches, leaf count, pod formation, and seed yield, this study seeks to identify promising genotypes that exhibit superior performance and adaptability to the region's lower altitudes. These insights into genotype-trait relationships will inform breeding programs focused on developing high-yielding, resilient fenugreek varieties specifically suited to the conditions of Uttarakhand. In addition, this study contributes to the conservation and utilization of the genetic diversity of fenugreek, which is crucial for long-term sustainability in cultivation. Enhancing fenugreek's adaptability to new regions not only supports regional agriculture but also aligns with global efforts to conserve valuable genetic resources in agriculture. The findings of this research could potentially increase Uttarakhand's contribution to the fenugreek industry, offering a pathway for local farmers to benefit from both domestic and international markets.

Materials and Methods

Genotype Collection

A total of thirty germplasm samples of fenugreek (*Trigonella foenum-graecum* L.) were collected from diverse hilly regions across Uttarakhand, India. These regions covered a wide altitudinal range, extending from 423 to 2600 meters above mean sea level (Table 1). The collection sites were chosen to represent varied agro-climatic conditions, ensuring a diverse genetic pool. Following the collection, the germplasm samples were carefully authenticated and processed by experts at the Division of Plant Breeding and Genetic Resource Conservation, CSIR-CIMAP, Lucknow. The samples were stored under controlled conditions in the Seed Quality Laboratory at CSIR-CIMAP, Lucknow, to maintain their viability and genetic integrity. For further utilization, the germplasm was transferred to the ex-situ gene bank located at the CSIR-CIMAP Research Centre, Purara, Bageshwar, Uttarakhand.

Table 1: Distribution of fenugreek genotypes collected from various districts in Uttarakhand, India, along with their respective altitude ranges.

Bageshwar (Mean Sea level range from 1500 to 2200 meters)	UK-01, UK-03, UK-04, UK-05, UK-06, UK-07, UK-08, UK-09, UK-10, UK-11, UK-12, UK-14, UK-15, UK-18, UK-19, UK-21, UK-22
Nainital (Mean Sea range from 423 to 2000 meters)	UK-02, UK-16, UK-17
Chamoli (Mean Sea level range from 1850 to 1900 meters)	UK-13, UK-26
Almora (Mean Sea level range from 1800 to 1890 meters)	UK-20, UK-23
Tehri Garhwal (Mean Sea level 2600 meters)	UK-24
Uttarkashi (Mean Sea level 1500 meters)	UK-25
Pithoragarh (Mean Sea level range from 915 to 2200 meters)	UK-27, UK-28, UK-29, UK-30

Experimental Design and Cultivation

The fenugreek germplasm was cultivated over two consecutive growing seasons (2021-22 and 2022-23) with sowing conducted on October 15th each year. The experiment followed a randomized block design (RBD) with three replications to ensure statistical accuracy and minimize variability. Plant spacing was meticulously maintained at 15 cm within rows and 20 cm between rows, allowing for optimal growth conditions. The experimental plots were prepared to meet agronomic standards, with soil properties analyzed beforehand and prevailing weather conditions recorded to assess their impact on crop performance. Throughout the six-month growth cycle, standard agronomic practices such as irrigation, weeding, and nutrient management were applied to sustain crop health and productivity. The cycle commenced with sowing in October, followed by the first harvest in December and the second harvest in February, culminating in seed harvesting in April. This structured approach ensured comprehensive data collection across all growth stages, providing valuable insights into the genetic variability and adaptability of the germplasm.

Soil and Weather Details

The experimental site at the CSIR-CIMAP Research Centre, Purara, Bageshwar, Uttarakhand, was characterized by loamy soil with good drainage properties, ideal for fenugreek cultivation. The soil pH ranged from 6.2 to 7.0, which is optimal for fenugreek growth. The soil's NPK (Nitrogen, Phosphorus, and Potassium) values were as follows: nitrogen content was 0.12%, phosphorus content was 18.5 kg/ha, and potassium content was 120 kg/ha. These nutrient levels were sufficient to support the growth of fenugreek plants. Weather conditions at the site during the experimental period (October to April) were favorable, with average temperatures ranging from 15°C to 28°C. The region experiences a temperate climate with rainfall primarily during the monsoon months (June to September), while the experimental period saw moderate rainfall and clear skies. Average humidity levels ranged from 60% to 80%, providing suitable conditions for plant growth.

Agronomic Traits Data Collection

To evaluate the performance and variability of the fenugreek germplasm, data on a wide range of agronomic traits were meticulously recorded from ten labeled plants in each plot during every growth stage. Key traits included days to first germination (DFG) and days to 50% germination (D50%G), which captured the time taken for seed emergence and 50% germination, respectively. Plant height (PH) was measured from the base to the highest point, providing insights into overall growth. The number of leaves per plant (NL) and leaf morphology, including measurements of leaf length (LL) and leaf width (LW), were recorded to assess foliage development. Root length (RL) was measured to evaluate root development, while the number of branches per plant (NB) served as an indicator of plant vigor and bushiness. Days to first flowering (DTFF) marked the time from sowing to the appearance of the first flower, highlighting critical developmental milestones. Additionally, fresh herb weight per hectare (FHWH) and dry herb weight per hectare (DHWH) were recorded after each harvest to quantify yield performance. Seed yield per hectare (SYPH) was documented during the final harvest to assess the reproductive success of the plants.

Statistical Analysis

Data on morphological traits and growth yield of fenugreek genotypes were analyzed using analysis of variance (ANOVA) in a randomized block design (RBD) to assess genotype differences. Traits such as plant height, leaf count, root length, number of branches, and yield (fresh and dry herb weight, seed yield) were evaluated for significant variations across two growing seasons (2021-22 and 2022-23) using the R package version 0.1.0.

Results

Findings of morphological and agronomic traits of 30 fenugreek genotypes are described below. Data are summarized in Tables 2 and 3. The analysis revealed considerable genetic variability across various traits, highlighting the adaptability and potential of these genotypes for cultivation in the hilly regions of Uttarakhand.

Germination Traits

Days to first germination (DFG) exhibited considerable variability among the evaluated genotypes, ranging from as low as 3.51 days in UK-23 to as high as 7.00 days in UK-14, with an overall mean of 5.26 days and a coefficient of variation (C.V.) of 5.81%. Genotypes like UK-23 (3.51 days), UK-28 (3.78 days), and UK-16 (4.80 days) showed rapid germination rates, highlighting their potential for quicker crop establishment. These traits are particularly valuable in ensuring early seedling vigor, better competition against weeds, and efficient utilization of available nutrients and moisture. On the other hand, slower germinating genotypes, such as UK-14 (7.00 days), UK-24 (6.71 days), and UK-25 (6.00 days), may require specific management practices to enhance field performance. Days to 50% germination (D50%G) ranged widely, from 8.41 days in UK-28 to 19.17 days in UK-26, with an average of 13.79 days and a relatively high C.V. of 10.94%. Genotypes such as UK-28 (8.41 days), UK-23 (8.87 days), and UK-18 (8.96 days) achieved uniform and fast emergence, which is crucial for achieving a uniform crop stand and optimizing yields. Conversely, genotypes like UK-26 (19.17 days), UK-19 (16.03 days), and UK-4 (15.84 days) displayed delayed germination, which might limit their adaptability to specific agro-climatic conditions, especially in short growing seasons or under high weed pressure. The variability in germination traits underscores the potential for selecting and breeding fenugreek genotypes that align with desired agronomic and environmental requirements. Rapid germination, as observed in UK-23 and UK-28, not only aids in efficient crop establishment but also offers an advantage in regions with unpredictable weather patterns or limited growing windows.

Morphological Traits

The plant height (PH) of the 30 fenugreek genotypes exhibited significant variation, ranging from 7.63 cm in UK-27 to 38.87 cm in UK-18, with an overall average of 20.45 cm and a coefficient of variation (C.V.) of 4.17%. The tallest genotype, UK-18, is particularly suitable for high biomass production, which is advantageous for both foliage yield and medicinal or aromatic applications. Taller plants, such as UK-18, may provide higher volumes of biomass, potentially leading to increased yield in regions where height is correlated with productivity. In contrast, shorter genotypes, such as UK-27 (7.63 cm), offer a more compact structure, making them suitable for dense cropping systems or intercropping, where space efficiency is a priority. This variability in plant height provides opportunities for selecting genotypes according to specific agronomic needs, from high-yielding crops to those adapted to space-limited environments. The number of leaves (NL) also demonstrated considerable variability, with values ranging from 11.21 leaves in UK-26 to 61.31 leaves in UK-4. Genotypes with higher leaf numbers, such as UK-4, exhibit enhanced photosynthetic capacity, a critical factor in biomass production and overall plant health. With a C.V. of 1.88%, the trait showed consistent performance across trials, indicating that genotypes with a high leaf count can be expected to reliably perform well, improving both foliage yield and total biomass. Higher leaf counts are generally associated with better photosynthetic efficiency, which could contribute to enhanced growth rates and higher overall productivity. These genotypes are particularly valuable for farmers aiming to maximize biomass and foliage for use in herbal or medicinal products. In terms of leaf dimensions, there was significant variation in both Leaf Width (LW) and Leaf Length (LL). The leaf width ranged from 0.55 cm in UK-20 to 1.79 cm in UK-10, while leaf length varied from 0.72 cm in UK-29 to 2.34 cm in UK-23. The wide variability in these leaf dimensions indicates a diversity in leaf architecture, which can influence the photosynthetic efficiency of the plant and its potential for biomass production. Larger leaves, such as those seen in UK-10 (1.79 cm width) and UK-23 (2.34 cm length), are expected to contribute to better photosynthetic performance, leading to increased growth and biomass accumulation. Genotypes with larger leaves are also beneficial for their potential use in herbal products, where the quantity and quality of leaves directly affect the production of extracts, oils, or dried herbs. On the other hand, smaller leaves, like those observed in UK-20 and UK-29, may be more suited for specific cultivation practices or regions with space constraints, where a more compact plant architecture is desirable.

Table 2: Morphological evaluation of 30 fenugreek genotypes (*Trigonella foenum-graecum* L.) for agronomic traits.

Genotype	DFG	D50%G	PH	NL	LW	LL
UK-1	5.12	12.59	26.24	26.30	1.19	1.32
UK-2	3.85	13.36	9.35	59.11	0.81	0.96
UK-3	4.25	13.22	24.21	22.25	0.95	1.32
UK-4	4.50	15.84	8.19	61.31	0.69	1.22
UK-5	4.66	14.06	10.17	52.58	0.80	1.17
UK-6	4.65	13.50	20.89	38.00	1.12	1.44
UK-7	4.84	13.61	22.11	34.33	1.28	1.40
UK-8	4.81	17.20	19.54	21.27	1.30	1.51
UK-9	6.61	12.27	21.40	39.32	1.75	1.54
UK-10	4.50	12.14	15.33	53.68	1.79	1.56
UK-11	4.93	13.59	27.95	24.55	1.69	1.72
UK-12	3.85	10.55	26.45	26.26	1.15	1.47
UK-13	4.88	15.37	24.24	18.13	0.84	1.32
UK-14	7.00	17.13	26.59	26.66	1.35	1.19
UK-15	4.96	11.43	12.06	41.83	0.95	1.36
UK-16	4.80	12.70	32.56	22.23	1.54	1.45
UK-17	5.47	11.15	26.35	33.36	1.30	1.62
UK-18	3.56	8.96	38.87	48.87	1.38	2.10
UK-19	5.50	16.03	10.23	31.15	0.76	1.25
UK-20	5.76	16.95	15.48	17.43	0.55	0.78
UK-21	5.85	18.82	13.45	16.77	0.63	0.80
UK-22	3.95	10.16	33.46	45.82	1.18	1.93
UK-23	3.51	8.87	36.20	18.59	1.51	2.34
UK-24	6.01	18.12	30.24	21.48	0.76	1.09

UK-25	6.00	15.40	11.09	15.13	0.56	0.74
UK-26	5.91	19.17	15.44	11.21	0.78	1.19
UK-27	5.51	13.06	7.63	19.10	0.73	0.87
UK-28	3.98	8.41	9.11	31.79	0.96	0.94
UK-29	5.91	12.40	16.36	24.97	0.62	0.72
UK-30	5.80	12.77	19.44	25.56	0.84	1.39
C.D.	0.48	2.445	1.391	0.953	0.174	0.204
SE(m)	0.169	0.862	0.49	0.336	0.061	0.072
C.V.	5.814	10.945	4.169	1.879	9.989	9.366

DFG - Days to first germination, D50%G - Days to 50% germination, PH - Plant height, NL - Number of leaves per plant, LW - Leaf width (cm), LL - Leaf length (cm); The mean data are presented for the 2021-22 and 2022-23 growing seasons; CD - critical difference; SE - standard error; CV - coefficient of variation.

Root and Branching Traits

Root length (RL) exhibited considerable variability, ranging from 2.57 cm in UK-25 to 7.27 cm in UK-9, indicating significant differences in the rooting ability of the genotypes. Genotypes with longer roots, such as UK-9, are particularly advantageous for cultivation in drought-prone or low-moisture regions, as they can access deeper soil moisture and nutrients. Short-rooted genotypes like UK-25 may be better suited for areas with high soil moisture or irrigated systems, where extensive root systems are less critical. The number of branches (NB) ranged from 2.27 in UK-1 to 5.81 in UK-10, highlighting substantial diversity in branching patterns. High-branching genotypes, such as UK-10, support better plant architecture and increased foliage, leading to higher biomass and seed production. Low-branching genotypes like UK-1 may be utilized for focused studies on compact growth habits or specific uses like intercropping systems. These variations offer valuable traits for selecting genotypes tailored to specific agronomic practices or environmental conditions.

Table 3: Agronomic traits of 30 fenugreek (*Trigonella foenum-graecum* L.) genotypes evaluated during the 2021-22 and 2022-23 growing seasons.

Genotype	RL	NB	DTFF	FHWH	DHWH	SYPH
UK-1	6.59	2.27	116.25	10.83	5.47	14.84
UK-2	5.47	3.89	118.25	8.62	5.04	15.54
UK-3	4.73	2.51	118.25	14.92	3.14	14.12
UK-4	5.68	4.32	102.25	18.58	3.78	18.68
UK-5	6.46	4.61	101.25	11.67	5.65	15.10
UK-6	4.61	2.67	98.91	14.05	6.79	17.96
UK-7	4.91	3.45	117.08	7.52	4.89	13.95
UK-8	5.00	2.34	96.91	11.72	4.99	13.84
UK-9	7.27	4.41	104.08	12.26	6.99	14.00
UK-10	4.67	5.81	95.58	11.89	7.29	13.88
UK-11	3.79	3.71	107.25	11.09	7.09	14.24
UK-12	4.08	3.54	103.91	15.12	8.88	21.17
UK-13	2.83	2.54	105.58	8.61	4.74	20.52
UK-14	5.04	3.74	97.25	7.89	5.41	13.85
UK-15	4.16	2.49	94.91	8.16	4.98	13.04
UK-16	4.60	3.01	91.91	8.08	6.17	12.97
UK-17	5.09	2.37	93.41	13.83	12.19	15.71
UK-18	5.70	5.19	120.25	23.77	11.57	20.33

UK-19	3.48	2.97	107.25	7.15	4.76	13.88
UK-20	3.86	2.56	108.91	8.74	3.57	12.27
UK-21	5.77	2.97	113.25	7.36	4.03	12.15
UK-22	6.46	4.82	121.41	16.87	16.07	24.06
UK-23	6.35	5.12	120.91	20.50	12.27	21.93
UK-24	4.25	2.52	103.25	12.18	6.46	12.50
UK-25	2.57	2.76	114.25	9.85	3.01	12.48
UK-26	3.28	2.64	113.25	9.51	3.40	13.11
UK-27	4.67	2.26	111.58	7.74	4.83	12.74
UK-28	5.49	2.87	106.58	9.09	7.37	14.16
UK-29	3.41	2.76	111.25	10.53	5.09	17.58
UK-30	3.74	2.61	109.25	7.91	5.67	12.78
C.D.	0.79	0.44	1.631	2.067	0.64	1.28
SE(m)	0.28	0.15	0.575	0.728	0.226	0.452
C.V.	10.103	8.142	0.926	10.93	6.113	5.072

RL - Root length (cm), NB - Number of branches per plant, DTFF - Days to first flowering, FHWPH - Fresh herb weight per hectare (q), DHWH - Dry herb weight per hectare (q), SYPH - Seed yield per hectare (q); The mean data are presented for the 2021-22 and 2022-23 growing seasons; CD - critical difference; SE - standard error; CV - coefficient of variation.

Flowering and Maturation

DTFF showed a relatively narrow range, from 91.91 days in UK-16 to 121.41 days in UK-22. Genotypes like UK-16, which flower early, are particularly suitable for regions with short growing seasons or areas prone to early frost, allowing the crop to complete its lifecycle in a limited timeframe. In contrast, late-flowering genotypes like UK-22 may provide higher yields in regions with longer growing seasons, as prolonged vegetative growth can lead to greater biomass accumulation. The minimal coefficient of variation (C.V.) for DTFF at 0.93% suggests stable flowering behavior across trials. This stability is crucial for synchronized flowering in fenugreek cultivation, aiding in better crop management and harvesting efficiency. Furthermore, the observed variation in flowering time highlights the potential for breeding programs to develop genotypes with adaptable phenological traits, ensuring resilience in diverse agro-climatic zones.

Yield Traits

FHWH exhibited a significant range across the evaluated genotypes, from 7.15 kg in UK-19 to 23.77in UK-18, with an average of 15.46 and a coefficient of variation (C.V.) of 10.93%. High-yielding genotypes such as UK-18 (23.77), UK-20 (20.50), and UK-4 (18.58) demonstrated substantial commercial potential for fresh herb production, particularly in regions with high demand for culinary and medicinal products. On the other hand, lower-yielding genotypes like UK-19 (7.15), UK-25 (9.85), and UK-14 (7.89) may find niche applications in intercropping systems or smaller-scale farming setups. The variation suggests an opportunity for targeted breeding to improve this economically significant trait further. DHWH displayed variability from 3.01in UK-25 to 16.07 in UK-22, with a mean of 10.34and a C.V. of 6.11%. Genotypes such as UK-22 (16.07), UK-23 (12.27), and UK-18 (11.57) stood out for their superior dry matter production, making them ideal candidates for regions with water constraints or for producing value-added products like herbal teas and spices. In contrast, genotypes like UK-25 (3.01), UK-21 (4.63), and UK-14 (5.41) demonstrated limited performance, suggesting the need for improvement in genetic traits or cultivation practices. SYPH, a critical productivity measure, varied notably from 12.15 in UK-21 to 24.06 in UK-22, with an overall mean of 18.26and a low C.V. of 5.07%. High-yielding genotypes, including UK-22 (24.06), UK-18 (20.33), and UK-12 (21.17), showed strong potential for enhancing seed production, critical for meeting market demand and ensuring sustainable cultivation. Lower-yielding genotypes, such as UK-21 (12.15), UK-25 (12.48), and UK-14

(13.85), indicate the need for strategic interventions to optimize yield potential. In terms of percentage contribution, approximately 40% of the genotypes exhibited above-average yields in FHWH, DHWH, and SYPH, emphasizing their multi-trait superiority. Furthermore, genotypes such as UK-22 and UK-18 consistently ranked among the top performers across all yield traits, making them ideal for high-value commercial applications.

Discussion

The morphological and agronomic traits of the 30 fenugreek genotypes showed significant variability, providing strong evidence of their phenotypic diversity and adaptability to the hilly regions of Uttarakhand. Traits such as plant height (PH), number of leaves (NL), and dry herb weight per hectare (DHWH) exhibited notable variation, which aligns with previous studies that have highlighted genetic variability as a critical factor for the success of breeding programs aimed at enhancing yield and quality[9,10,11] The diversity observed in these traits not only reflects the adaptability of the genotypes but also offers ample opportunities for selective breeding, which can improve both yield and quality in fenugreek cultivation under specific environmental conditions. Plant height, a key trait for biomass production, exhibited substantial variation, ranging from 7.63 cm in UK-27 to 38.87 cm in UK-18. This variability in plant height is consistent with findings from earlier studies that suggested genetic variance in plant stature correlates with environmental adaptability and yield potential in fenugreek.[12,13] In another study observers also found that that variations in plant height could serve as a measure of fenugreek's capacity to adapt to different environments.[14] The current study's results, particularly the genotypes with taller plants, suggest that these may be better suited for regions with higher rainfall and soil fertility, where larger plants can thrive. However, shorter genotypes, such as UK-27, may be more suited to dense cropping systems or areas with limited resources, where their compact structure could offer higher yield per unit area without the need for additional inputs. These observations underline the need to explore the relationship between plant height and other environmental factors like altitude and temperature, which influence plant growth patterns, especially in the Western Himalayan region. Similarly, the number of leaves (NL) exhibited considerable variation among the genotypes, ranging from 11.21 in UK-26 to 61.31 in UK-4. The higher leaf count in specific genotypes is likely indicative of increased photosynthetic capacity, which can lead to enhanced growth and biomass production. This finding is consistent with a similar study, which demonstrated that a higher leaf count correlates with increased plant vigor and overall yield in fenugreek cultivated under similar climatic conditions.[15] Thus, selecting genotypes with a higher number of leaves may prove advantageous in maximizing biomass production, particularly for medicinal and aromatic applications of fenugreek, where high photosynthetic efficiency is essential for achieving the desired quality and quantity of yields. The analysis of dry herb weight per hectare (DHWH) revealed significant variability, ranging from 3.01 in UK-25 to 16.07 in UK-22. High DHWH values are crucial for identifying fenugreek genotypes with the potential for higher yield and biomass production, which is especially important for resource-limited farmers in hilly regions. In the study, researchers emphasized the strong correlation between DHWH and overall yield, which supports the use of this trait as a reliable indicator for selecting high-performing fenugreek varieties.[16] The genotypes with higher DHWH also offer the potential for value-added products, such as herbal teas, which are becoming increasingly popular in global markets. By selecting for high DHWH, farmers can optimize their yields and tap into new market opportunities, particularly in regions where medicinal and aromatic plant products are in demand. Furthermore, the current study highlights the genetic diversity present in fenugreek genotypes from the Western Himalayas, making it an excellent resource for future breeding programs aimed at improving both agricultural and medicinal production goals.[17,18] However, it is important to consider the environmental limitations of the study location. Factors such as soil conditions, water availability, and other site-specific variables likely influenced the expression of traits in the genotypes. These environmental variables may not be uniform across different regions, so the findings from this study may not directly apply to other agro-climatic conditions.[19,20] Therefore, it is essential for future studies to replicate this analysis in diverse environmental settings to validate these results and confirm the adaptability of these genotypes to other areas. Additionally, the exploration of molecular markers associated with the observed phenotypic diversity could provide more precise selection criteria for breeding programs. The use of molecular markers could enhance the efficiency of fenugreek breeding, enabling breeders to select for desirable traits with greater accuracy and speed.[21] Incorporating molecular tools into breeding programs will allow for more targeted improvements in both yield and quality, facilitating the development of fenugreek varieties that are better suited to meet the demands of both farmers and consumers. Future research should focus on the integration of phenotypic and molecular data to optimize breeding strategies for fenugreek cultivation, particularly in the challenging agro-ecological zones of the Western Himalayas.[22-23]

Conclusion

This study highlights the significant genetic diversity and adaptability among fenugreek genotypes collected from different altitudes in Uttarakhand's hilly regions. The observed variability in traits such as germination rate, plant height, leaf characteristics, root length, branching, flowering time, and yield potential demonstrates the potential for selecting and breeding high-yielding, resilient cultivars suited for the region's unique environmental conditions. Genotypes like UK-23, UK-18, and UK-22 stand out for their rapid germination, substantial biomass, and high seed yield, indicating their suitability for both herb and seed production under lower altitude of western Himalayan region of Uttarakhand. The early-flowering genotypes and those with robust root systems further support the potential for cultivation in diverse and water-scarce areas, enhancing resilience against environmental stress. This study thus provides a foundation for breeding programs focused on improving fenugreek productivity and economic sustainability, with broader implications for meeting the rising demand for fenugreek in medicinal and culinary markets, supporting local livelihoods, and promoting sustainable agriculture in hilly areas of Uttarakhand.

Acknowledgment

This research was part of the PhD study of the first author. The authors sincerely thank the Director of CIMAP, Lucknow, for providing the necessary facilities that made this study possible. The authors also express their heartfelt gratitude to the co-author and supervisor from Integral University, Lucknow, as well as the co-supervisor from CIMAP, Lucknow, for their exceptional guidance and support throughout the study, which helped achieve its objectives.

Funding Sources

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

All data pertinent to the current study are presented within the manuscript.

Ethics Statement

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

Author Contributions

- **Prawal Pratap Singh Verma:** Conceptualization, Writing-Original Draft, Investigation, Formal analysis.
- **Saba Siddiqui:** Conceptualization, Methodology, Investigation, Supervision.
- **Saudan Singh:** Supervision, Writing-Review & Editing, Visualization.
- **Rakesh Kumar Upadhyay:** Investigation, Supervision.
- **Md Abu Nayyer:** Data Curation, Validation.
- Mohd. Haris Siddiqui: Visualization.

Reference

1. Verma, P. P. S., Nayyer, M. A., Singh, S., Siddiqui. S., Kumar, D., Agri, B., Padalia, R. C. Exploring genetic and morphological diversity of fenugreek (*Trigonella foenum-graecum* L.) in Uttarakhand: A Review. J. Ayurvedic herb. med. 2023;9(3):133–137. https://doi.org/10.31254/jahm.2023.9307.
2. Wani, S. A., Kumar, P. Fenugreek: A review

on its nutraceutical properties and utilization in various food products. *J. Saudi Soc. Agric.* Sci. 2018;17:97-106 https://doi.org/10.1016/j.jssas.2016.01.007.

3. Kumari, S., Meena, A. K., Singh, J., Kumar, R., Kumar, V., Singh, J. 2023. Management of Charcoal Rot (*Macrophomina phaseolina*) of Fenugreek in Rajasthan. https://doi.org/10.18805/lr-5114.
4. Shekhawat, N., Meena, V. S., Singh, K., Rani, K., Gupta, V. Studies on Genetic Variability, Heritability and Genetic Advance for Morphological Traits in Fenugreek (*Trigonella foenum-graecum* L.) for Arid Climate of Rajasthan. Legume Research. 2023;46(3):312–315. https://doi.org/10.18805/LR-5046.
5. Pavlista, A. D., Santra, D. K. Planting and harvest dates, and irrigation on fenugreek in the semi-arid high plains of the USA. Ind. Crop. Prod. 2016;94:65-71. https://doi.org/10.1016/j.indcrop.2016.07.052.
6. Bitarafan, Z., Asghari, H. R., Hasanloo, T., Gholami, A., Moradi, F., Khakimov, B., Liu, F., Andreasen, C. The effect of charcoal on medicinal compounds of seeds of fenugreek (*Trigonella foenum-graecum* L.) exposed to drought stress. Ind. Crop. Prod. 2019;131:323-329. https://doi.org/10.1016/j.indcrop.2019.02.003.
7. Krishnaveni, B., Vethamoni, P. I., S., Selvi, B., Raveendran, M. Studies on genetic variability, correlation, and path coefficient analysis in fenugreek (*Trigonella foenum-graecum* L.) genotypes. Electron. *J. Plant Breed.* 2021;12(3),835–840. https://www.ejplantbreeding.org/index.php/EJPB/article/view/3907.
8. Tariyal, Y. S., Bisht, S. S., Pant, S. C., Chauhan, R. S., Variability studies in fenugreek (*Trigonella foenum-graecum* L.) under mid-hill conditions of Bharsar, Uttarakhand. *J. Stress Physiol. Biochem*. 2021;17(3);127-133.
9. Maurya, H. K., Mishra, D. P., Singh, H., Singh, A. V., Maurya B. K. An Experimental Study of Genetic Divergence in Fenugreek (*Trigonella foenum-graecum* L.). *International Journal of Plant and Soil Science*. 2023;35(17):23–30. https://doi.org/10.9734/ijpss/2023/v35i173177.
10. Roba, R., Mohammed, W. Genetic variability of fenugreek (*Trigonella foenum-graecum* L.) accessions from agroecological and morphoagronomic traits, Ethiopia. Beverage Plant Res. 2024;4, e014. https://doi.org/10.48130/bpr-0024-0003.
11. Chaya, Y., Meena, K., Soni, N., Naruka, I., Kachouli, B., Singh, O. Studies on genetic variability, heritability and genetic advance in fenugreek (*Trigonella foenum-graecum* L.) germplasms grown under the Malwa region of Madhya Pradesh, *India. IJSS.* 2024;12(1), 39-47. https://doi.org/10.56093/IJSS.v12i1.4.
12. Singh, P. P., Gujar, M., Naruka, I. S. Association and path analysis in fenugreek (Trigonella foenum graecum). *Indian J. Agric. Sci*. 2016;86(7):951–955. https://doi.org/10.56093/ijas.v86i7.59854.
13. Prakash, S., Pandey, V. P., Bhargava, A. K. Assessment of correlation and path analysis in fenugreek (*Trigonella foenum-graecum* L.) germplasms. *Int. J. Chem. Stud*. 2021;9(1):3432–3434. https://doi.org/10.22271/chemi.2021.v9.i1av.11767.
14. Riasat, M., Heidari, B., Pakniyat, H., Jafari, A. A. Assessment of variability in secondary metabolites and expected response to genotype selection in fenugreek (Trigonella spp.). Ind. Crop. Prod. 2018;123:221–231. https://doi.org/10.1016/j.indcrop.2018.06.068.
15. Syed, P. M., Singh, M., Yadav, M. P., Himanshu, Yadav, R., Yadav, Y. Studies on genetic variability in fenugreek (*Trigonella foenum-graecum* L.) germplasms grown under Bundelkhand region, Uttar Pradesh, India. *J. Exp. Agric. Int.* 2024;46(9): 702-707. https://doi.org/10.9734/jeai/2024/v46i92867.
16. Gurjar, M., Naruka, I. S., Shaktawat, R. P. S. Variability and correlation analysis in fenugreek (*Trigonella foenum-graecum* L.). *Legume Research*. 2016;39(3):459-465. https://doi.org/10.18805/lr.v0iOF.9286.
17. Choudhary, M., Gothwal, D. K., Jakhar, M. L., Singh, D., Kumawat, K. R., Kumawat, R. Genetic variability, character association and path analysis in fenugreek (*Trigonella foenum-graecum* L.) under normal and staggered irrigation regimes. *Electron. J. Plant Breed.* 2022;13(2):465–475. https://doi.org/10.37992/2022.1302.046.

18. Bianchi, M. C., Bruzi, A. T., Soares, I. O., Ribeiro, F. D. O., Gesteira, G. D. S. Heritability and the genotype × environment interaction in soybean. Agrosystems Geosci. *Environ.* 2020;3(1):1-10. https://doi.org/10.1002/agg2.20020.
19. Kumar, D., Ram, C. N., Singh, V., Singh, N., Kumar, P. Genetic variability, GCV, PCV, heritability and genetic advance analysis in fenugreek (*Trigonella foenum-graecum* L.). *Int. J. Plant Sci.* 2022; 34(21):282–286. https://doi.org/10.9734/ijpss/2022/v34i2131263.
20. Prakash, S., Pandey, V. P., Bhargava, A. K. Assessment of correlation and path analysis in fenugreek (*Trigonella foenum-graecum* L.) germplasms. *International Journal of Chemical Studies.* 2021;9(1):3432–3434. https://doi.org/10.22271/chemi.2021.v9.i1av.11767.
21. Upadhyay, K., Adhikari, N., C., G. B. K., Sharma, S. Genetic variability and cluster analysis of wheat (Triticum aestivum L.) genotypes in the foothills of Nepal. *Archives of Agriculture and Environmental Science.* 2019;9(1):350-355. https://doi.org/10.26832/24566632.2019.0403013.
22. Upadhyay, R., Naidu, A., Dhakhariya, T. Studies on genetic variability among yield-attributing traits of fenugreek genotypes. *International Journal of Chemical Studies.* 2020;8(4):1821–1825. https://doi.org/10.22271/chemi.2020.v8.i4s.9891.
23. Yaldiz, G., Camlica, M. Performance of fenugreek (*Trigonella foenum-graecum* L.) genotypes towards growth, yield and UPOV properties. *Legume Research.* 2022;45(1):10–17. https://doi.org/10.18805/LR-639.