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Boosting Growth and Yield in Fenugreek Using Kinetin: A Study on the Role of Foliar Sprays in Improving Leaf and Seed Quality

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ABSTRACT: Kinetin is a synthetic cytokinin that promotes lateral branch development in leafy vegetables by releasing apical dominance and initiating axillary bud activation. Identifying the optimal concentration of kinetin, correct growth phase for its application and the most effective delivery method is essential to maximize crop performance and productivity. To explore its potential in fenugreek (*Trigonella foenum-graecum* L.), a factorial field experiment was conducted with the primary objective of determining the most effective kinetin dose (25, 50 and 75 ppm) and application timing (45, 60 and 75 DAS) for enhanced crop productivity and seed physiological quality under mid-hill field conditions. Among all treatment combinations, foliar application of 75 ppm kinetin at 45 DAS (D3S1) significantly enhanced vegetative growth, reproductive attributes and seed quality parameters. This treatment also achieved the highest leaf and seed yields, harvest index and biological efficiency. Additionally, superior seed vigour indices and reduced electrical conductivity indicated improved seed membrane integrity. The D3S1 treatment combination thus proved to be agronomically effective and economically viable, though it warrants validation across multiple agro-climatic regions for broader applicability.

Keywords: Cytokinin, Fenugreek, Kinetin, Productivity, Seed quality, *Trigonella foenum-graecum.*

INTRODUCTION

Fenugreek (*Trigonella foenum-graecum* L.), commonly known as 'methi', 'Bird's Foot', or 'Greek Clover', is a leguminous plant widely valued for its multiple uses as a leafy vegetable, spice, condiment, green fodder, and green manure (Giridhar *et al.*, 2023).

It originates from the Mediterranean region and is currently cultivated globally, with India being the leading producer (Alamer, 2025).

India is the world's largest producer. In India, production is mostly centered in Rajasthan, Gujarat, Uttaranchal, Madhya Pradesh, Maharashtra, Haryana and Punjab. Rajasthan is the country's fenugreek bowl, accounting for over 80 per cent of the total production. The present cultivated area for fenugreek in India is 148.01 thousand ha, with a production of 217.57 thousand metric tons and productivity of 1.47 metric tons per hectare (Anonymous, 2024). In Himachal Pradesh, fenugreek is grown over an area of 7.305 thousand hectares, producing approximately 13.830 thousand tonnes (Anonymous, 2021).

It is a hardy, short-duration crop capable of thriving in a variety of soils, including moderately saline ones, and is also known for its drought tolerance and ability to fix atmospheric nitrogen, improving soil fertility (Abdelhameed and Metwally 2024).

Botanically, fenugreek is an annual herb reaching 30–60 cm in height, with trifoliate grey-green leaves, slender stems, and yellow flowers that bloom between March and April. The plant produces long, slender pods containing 10–20 seeds, which are small, brownish-yellow, and rhomboidal in shape. The seeds and leaves are rich in proteins, vitamins (vitamin C), minerals (iron and calcium), and essential amino acids.

Seeds are also known for their medicinal properties due to compounds like trigonelline, which contributes to their slightly bitter taste and is involved in the biosynthesis of cellulose and amino acids (Hanafy and Akladious 2018). They exhibit hypoglycemic, antilipidemic, and anticarcinogenic properties, making them useful in treating diabetes, cancer, and cholesterol-related conditions (Wani and Kumar 2018). Fenugreek's adaptability makes it suitable for various cropping systems, especially as a *Rabi* crop in India. Its growth is influenced by climatic conditions: dry, cold weather favors vegetative growth, while moderately warm and dry conditions enhance seed development and productivity. In order to improve both vegetative growth and seed yield in fenugreek, optimizing plant growth and seed set is essential. One promising approach is the use of Plant Growth Regulators (PGRs), which are organic compounds that influence plant physiological responses at very low concentrations (usually below 10^{-7} M). PGRs such as cytokinins are especially important in regulating plant growth and development by affecting cell division and differentiation, acting in opposition to auxins (Naeem *et al.*, 2004). Every cytokinin variant exerts a broad array of physiological effects across diverse plant species (Ahmad *et al.*, 2022). The response to PGRs is influenced by several factors including concentration, application method, species, environmental conditions, and the plant's physiological status (Ammanullah *et al.*, 2010).

Kinetin (6-benzyladenine or 6-BA), a synthetic cytokinin, is known to play a crucial role in various physiological processes and is effective in stimulating secondary metabolite production, improving source-sink relationships, and enhancing the translocation of photoassimilates toward reproductive organs (Agarwal *et al.*, 2012). This results in improved flowering, fruit, and seed development, ultimately boosting crop yield.

Given the significance of kinetin in influencing plant metabolism and yield, the present investigation was conducted to study the effect of foliar application of kinetin on growth, leaf yield, seed yield and quality attributes in fenugreek and assess the impact of 6-BA on seed yield and quality parameters under field condition and laboratory conditions.

MATERIALS AND METHODS

The present research on fenugreeek was conducted in *Pandah* research farm of Dr Yashwant Singh Parmar University of Horticulture from October 2021- April 2022. The research farm was located at elevation of 1250 meter above mean sea level with latitude 35.5° N and longitude of 77.8° E in mid hill zone of Himachal Pradesh. The average relative humidity and rainfall of area is presented in Fig. 1. Soil texture of area is characterised by loam to clay loam with average pH of 6.85 -7.05.

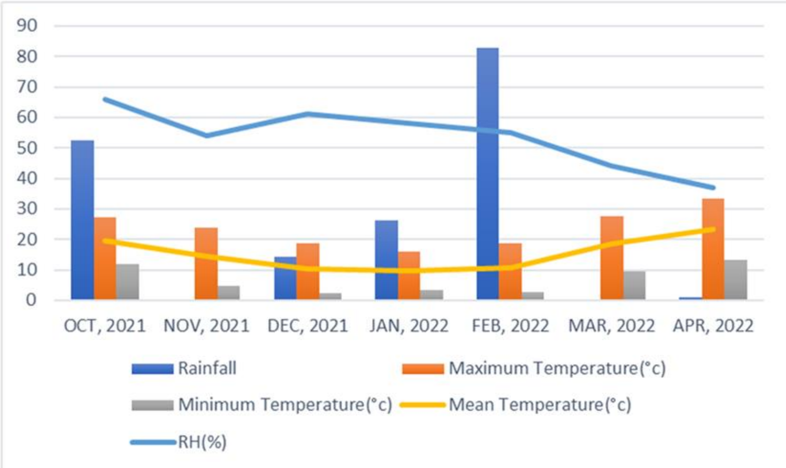

Fig. 1. Graphical representation of meterological data from October 2021- April 2022.

The field experiment was conducted using a Randomized Block Design (RBD), while laboratory studies followed a Completely Randomized Design (CRD). The study comprised 10 treatments, each replicated three times. Fenugreek seeds were sown directly in lines according to the respective treatments, with each plot measuring 1.8 × 1.8 m and a spacing of 30 cm between rows and 10 cm between plants within rows.

The experiment was conducted using fenugreek cultivar 'Pusa Early Bunching (PEB)', a dwarf, quick-growing variety with bold seeds and late bolting habit, developed at Indian agriculture research institute, New Delhi. Healthy seeds were sourced from the Department of Seed Science and Technology, UHF, Nauni. The field was prepared with FYM @ 20 t/ha, and fertilizers were applied as per recommended practices. The trial, comprising 10 treatments with 3 replications in a Factorial Randomized Complete Block Design, was sown on 29th October 2021 with spacing of 30 × 10 cm. Standard cultural practices, including weeding and irrigation, were followed. Kinetin (benzyl adenine) spray solutions of 25, 50, and 75 ppm were prepared and applied uniformly using a knapsack sprayer on sunny days. The layout details are provided below in Table 1.

Table 1: Details of field and laboratory experiment.

Crop and Variety	**Fenugreek and Pusa early bunching**
Number of treatments	10
Number of replications	3
Plot size	1.8 × 1.8m
Design	RCBD factorial with one extra treatment in Field CRD in laboratory
Spacing	30 × 10 cm

Experiment consists two factors *i.e.* Factor A- stages of foliar application days after sowing (S) which include 45 Days after sowing (S1), 60 days after sowing (S2), 75 days after sowing (S3) and factor B Kinetin doses at 25 ppm (D1), 50 ppm (D2), 75 ppm (D3). Treatment details were given in Table 2.

Table 2: Details of treatment used in research.

Treatment	Treatment Code	Stages of application
Trt1	6-BA @ 25ppm	45 DAS
Trt2	6-BA @ 50 ppm	45 DAS
Trtt3	6-BA @ 75 ppm	45 DAS
Trt4	6-BA @ 25ppm	60 DAS
Trt5	6-BA @50 ppm	60 DAS
Trt6	6-BA @ 75 ppm	60 DAS
Trt7	6-BA @25ppm	75 DAS
Trt8	6-BA @50 ppm	75 DAS
Trt9	6-BA @75 ppm	75 DAS
Trt10	Control	

Each plot under every treatment was divided into two equal sections. One half of the area (1.62 m²), consisting of three rows, was designated for recording green leaf yield, while the remaining half was used for assessing seed yield and associated parameters.

Observation recorded

Field and Seed Quality Parameters. Growth and leaf yield observations were recorded from 25 randomly selected plants, while seed quality parameters were assessed from another set of 25 plants per plot per replication. The study evaluated various growth, yield, and physiological parameters of fenugreek. Days to first leaf cut were recorded from germination to the first harvest, and green leaf yield was measured per plot after the first and second cuts. Number of branches per plant and days to 50% flowering were recorded using randomly selected samples. Yield components such as number of pods per plant, pod length, and weight of 25 pods were also measured. Plant height at harvest and number of root nodules after pod harvest were noted. Post-harvest observations included dry matter accumulation, seed yield per plot and per hectare, and number of seeds per pod. Additionally, test weight (1000-seed weight), biological yield, and harvest index were calculated to assess overall crop performance (Donal and Hamblin 1976).

Seed quality analysis of harvested seeds was conducted under laboratory conditions as per ISTA rules (Anonymous, 1985) Germination percentage was assessed using the paper towel method at 25 ± 2°C and 80% RH, with four replications of 100 seeds per treatment. Seedling length and dry weight were measured from ten randomly selected normal seedlings. Seedling length was recorded from apex to root tip, and dry weight was determined after oven-drying at 50°C for 48 hours. Seed Vigour Index-I was calculated by multiplying germination percentage with seedling length, while Seed Vigour Index-II was computed using seedling dry weight. For electrical conductivity (EC) testing, 2 g of seed was surface-sterilized using 0.1% $HgCl_2$ for 5–10 minutes and thoroughly washed with water. The seeds were then soaked in 100 ml of distilled water at room temperature for 24 hours. After soaking, the seeds were removed and the remaining solution was termed as leachate. EC of both distilled water and leachate was measured. The seed leachate EC was calculated by subtracting the EC of distilled water from that of the leachate.

Statistical Analysis. The statistical analysis was carried out for each recorded character under study using MS-Excel and OP-STAT packages. The mean values of data were subjected to analysis of variance as described by Gomez and Gomez (1984). Randomized Complete Block Design (RCBD factorial) was used for all the parameters studied in field experiments whereas Completely Randomized Design (CRD) was used for analysis of data generated in the laboratory studies to test the significance of treatments.

RESULTS AND DISCUSSION

Leaf Yield Parameters. The data in Table 3 revealed that both stages of foliar application and kinetin (6-BA) doses significantly affected days to first leaf cut in fenugreek. The earliest leaf cut (84.22 days) was observed with foliar application at 45 DAS (S1), while the latest (87.22 days) occurred at 75 DAS (S3), possibly due to unfavorable temperatures at later stages. Among kinetin doses, 75 ppm (D3) resulted in the minimum days to first cut (85.00), showing superiority over other doses. The interaction between kinetin (6-BA) doses and application stages significantly influenced days to first leaf cut. The earliest leaf cut (82.00 days) was recorded with 75 ppm kinetin applied at 45 DAS (D3S1), while the latest (88.00 days) occurred with 25 ppm at 75 DAS (D1S3). Control plots without any growth regulator showed the highest days to first cut (90.33), indicating delayed response.

Kinetin promoted better vegetative growth through enhanced cell division and elongation. Plants treated with 6-BA showed improved nutrient uptake and chlorophyll content. These findings align with previous studies in black cumin by Shah *et al.* (2007). The analysis of variance indicated a significant effect of application stages, kinetin (6-BA) doses, and their interaction on leaf yield at the first cutting. The highest yield (0.761 kg $plot^{-1}$) was observed at 45 DAS (S1), while the lowest (0.686 kg $plot^{-1}$) was at 75 DAS (S3), likely due to unfavorable conditions at later stages. Among kinetin doses, 75 ppm (D3) produced the maximum leaf yield (0.749 kg $plot^{-1}$), while 25 ppm (D1) yielded the least (0.677 kg $plot^{-1}$). The interaction D3S1 (75 ppm at 45 DAS) resulted in the highest yield (0.807 kg $plot^{-1}$). All kinetin treatments significantly outperformed the control (0.510 kg $plot^{-1}$), confirming the growth-promoting effect of kinetin. These results closely align with the observations reported by Ailenokhuria and Orimadegun (2020) in pigeon pea.

A significant influence of foliar application stages, kinetin (6-BA) concentrations, and their interaction on total leaf yield (kg plot^{-1}) was observed. Application at 45 DAS (S1) produced the highest yield (1.60 kg), significantly surpassing later stages, with the lowest yield at 75 DAS (S3; 1.43 kg). Among kinetin levels, 75 ppm (D3) recorded the maximum yield (1.64 kg), while 25 ppm (D1) resulted in the lowest (1.44 kg). The treatment combination D3S1 (75 ppm at 45 DAS) showed the highest total leaf yield (1.71 kg), whereas D1S3 (25 ppm at 75 DAS) had the minimum (1.37 kg). Control plots without kinetin produced significantly lower yield (1.26 kg) than most treatments. Cytokinins regulate various plant developmental processes, including the formation of root and shoot meristems, promotion of lateral shoot branching, enhancement of chlorophyll production, and increase in leaf number, primarily due to their role in accelerating the rate of mitosis (Dodd, 2005). The present findings align with those reported by El-Shaarwi *et al.* (2009); El-Metwally *et al.* (2021) in soybean.

Table 3: Impact of Kinetin foliar application on leaf and pod yield parameters.

Parameters	Stages of application (S)	Kinetin Doses (D)			Mean	$CD_{0.05}$
		D_1 (25 ppm)	D_2 (50 ppm)	D_3 (75 ppm)		
Leaf cut	S_1 (45 DAS)	85.33	85.33	82.00	84.22	S: 0.32 D: 0.32 S × D: 0.56 S × D × C : 1.60
	S_2 (60 DAS)	86.00	87.00	85.33	86.11	
	S_3 (75 DAS)	88.00	86.00	87.67	87.22	
	Mean	86.44	86.11	85.00		
	Control (C)	90.33				
First cutting (kg plot^{-1})	S_1 (45 DAS)	0.687	0.790	0.807	0.761	S: 0.015 D: 0.015 S × D: 0.026 S × D × C : 0.074
	S_2 (60 DAS)	0.680	0.700	0.730	0.703	
	S_3 (75 DAS)	0.663	0.683	0.710	0.686	
	Mean	0.677	0.724	0.749		
	Control (C)	0.51				
Leaf yield (kg plot^{-1})	S_1 (45 DAS)	1.50	1.57	1.71	1.60	S: 0.04 D: 0.04 S × D: 0.07 S × D × C : 0.21
	S_2 (60 DAS)	1.47	1.54	1.67	1.56	
	S_3 (75 DAS)	1.37	1.40	1.53	1.43	
	Mean	1.44	1.50	1.64		
	Control (C)	1.26				
Leaf yield (q ha^{-1})	S_1 (45 DAS)	74.07	77.53	84.44	79.01	S: 0.95 D: 0.95 S × D: 1.65 S × D × C : 4.70
	S_2 (60 DAS)	72.59	76.04	82.46	77.03	
	S_3 (75 DAS)	67.65	69.13	75.55	70.61	
	Mean	71.11	74.07	80.98		
	Control (C)	61.72				
Branches plant^{-1}	S_1 (45 DAS)	6.00	6.58	7.13	6.57	S: 0.05 D: 0.05 S × D: 0.08 S × D × C : 0.23
	S_2 (60 DAS)	5.77	6.48	6.80	6.35	
	S_3 (75 DAS)	5.50	6.37	6.68	6.19	
	Mean	5.76	6.48	6.87		
	Control (C)	5.31				
Days to 50 % flowering	S_1 (45 DAS)	108.33	107.67	105.67	107.22	S: 0.61 D: 0.61 S × D: 1.05 S × D × C : 2.99
	S_2 (60 DAS)	108.67	108.33	106.33	107.78	
	S_3 (75 DAS)	109.00	108.67	107.33	108.00	
	Mean	108.67	108.22	106.11		
	Control (C)	111.33				
Pods plant^{-1}	S_1 (45 DAS)	21.43	22.17	24.04	22.55	S: 0.01 D: 0.01 S × D: 0.02 S × D × C : 0.07
	S_2 (60 DAS)	21.55	22.50	23.29	22.44	
	S_3 (75 DAS)	21.68	22.49	22.95	22.37	
	Mean	21.55	22.39	23.43		
	Control (C)	20.76				

The number of branches per plant was significantly influenced by the stage of foliar application, kinetin (6-BA) dosage, and their interaction. Application at 45 DAS (S1) resulted in the highest number of branches (6.57), while the lowest (6.19) was observed with application at 75 DAS (S3). Among the doses, 75 ppm kinetin (D3) significantly increased branching (6.87), compared to the minimum value of 5.76 recorded with 25 ppm (D1). The interaction D3S1 (75 ppm at 45 DAS) produced the greatest number of branches (7.13), whereas D1S3 (25 ppm at 75 DAS) gave the lowest (5.50). Except for D1S3, all treatment combinations significantly outperformed the control (5.31). Exogenous application of cytokinins, particularly benzyl adenine, is known to enhance plant biomass by promoting lateral bud development, which subsequently leads to increased side shoot formation. The observed increase in branches can be credited to cytokinin's ability to disrupt apical dominance and promote the outgrowth of lateral buds (Al-Isaw and Al-Janabi 2021). Higher concentrations of benzyl adenine resulted in more side shoots, consistent with the findings of Khalil *et al.* (2006) in lentil and Menaka *et al.* (2018) in chickpea.

Days to 50% flowering were significantly affected by the stage of foliar application, kinetin (6-BA) dose, and their interaction. The earliest flowering (107.22 days) occurred with foliar spray at 45 DAS (S1), while the latest (108.00 days) was with 75 DAS (S3). Among doses, 75 ppm (D3) led to the earliest flowering (106.11

days), whereas 25 ppm (D1) delayed flowering to 108.67 days. The D3S1 combination (75 ppm at 45 DAS) induced the earliest flowering (105.67 days), significantly earlier than the control (111.33 days) and most other treatments. Application of benzyl adenine at 25 ppm delayed flowering, likely due to the extended period required for vegetative growth and secondary branch development before transitioning to the reproductive phase. This delayed the formation of sufficient floral buds. In contrast, higher cytokinin levels accelerated the shift from vegetative to reproductive growth, promoting earlier flowering. These findings align with those of Rai *et al.* (2019) in green gram and Khalil *et al.* (2008) in lentil.

The data in Table 4 clearly shows that plant height at harvest was significantly affected by both the timing of foliar application and the concentration of kinetin (6-BA). The tallest plants (43.31 cm) were recorded when foliar spray was applied at 45 DAS (S1), likely due to better photosynthetic activity and favorable weather conditions during early growth. In contrast, plants sprayed later at 75 DAS (S3) were shorter (40.86 cm), possibly due to colder temperatures that limited vegetative development. Among the kinetin treatments, the highest plant height (45.92 cm) was achieved with 75 ppm (D3), whereas the lowest (38.04 cm) was noted with 25 ppm (D1). These results highlight the importance of both timing and dosage in optimizing plant growth. Plant height at harvest was significantly influenced by both the stage of foliar application and kinetin (6-BA) dose, with the tallest plants observed at 45 DAS and 75 ppm. Late application and lower doses resulted in reduced growth, likely due to suboptimal environmental conditions. Higher doses of kinetin (6-BA) likely promoted plant growth by stimulating greater cell division and enlargement. Similar findings were reported by Upadhyay and Ranjan (2009) in soybean and Ailenokhuria and Orimadegun (2020) in pigeon pea.

Growth Parameters. The analysis revealed significant effects of foliar application timing, kinetin (6-BA) doses, and their interaction on pod number and pod length in fenugreek (Table 4). Application at 45 DAS (S1) recorded the highest pod count (22.55), while 75 DAS (S3) had the lowest (22.37), likely due to suboptimal environmental conditions. Kinetin at 75 ppm (D3) significantly increased pod number (23.43) compared to the lowest at 25 ppm (D1; 21.55), attributed to enhanced photosynthesis and assimilate translocation. The D3S1 combination (75 ppm at 45 DAS) produced the highest pod count (24.04), whereas D1S1 recorded the lowest (21.43).

Control plots, without kinetin, had the minimum pod number (20.76), highlighting the role of growth regulators in yield improvement. Similarly, pod length was significantly influenced by the treatments. Maximum pod length (9.01 cm) was observed at 45 DAS, and the shortest (8.73 cm) at 75 DAS. Kinetin at 75 ppm (D3) resulted in the longest pods (9.62 cm), while 25 ppm (D1) had the shortest (8.11 cm). Interaction effect was highest in D3S1 (10.36 cm) and lowest in D1S1 (7.87 cm). Control treatment produced the shortest pods (7.15 cm), reinforcing the positive effect of kinetin application. The weight of 25 pods was significantly influenced by stages of foliar application, kinetin (6-BA) doses, and their interaction. The highest pod weight (7.01 g) was recorded at 45 DAS (S1), while the lowest (6.78 g) was noted at 75 DAS (S3). Among doses, 75 ppm kinetin (D3) gave maximum weight (7.19 g), with the D3S1 combination yielding the highest (7.35 g). All kinetin treatments outperformed the control (6.12 g), indicating its positive role in pod development. The present findings are supported by earlier studies conducted by Menaka *et al.* (2018) in chickpea, Upadhyay and Ranjan (2009); Passos *et al.* (2011) in soybean. The observed effects may be attributed to the role of benzyl adenine, a cytokinin known to enhance mitotic activity through increased cell division and elongation. Similar results were also reported by Salem (2018) in cowpea, further validating the outcomes of this investigation.

Seed Yield Parameters. The number of nodules per plant after pod harvest was significantly affected by the stage of foliar application, kinetin (6-BA) dose, and their interaction (Table 4). The highest nodule count (4.56) was observed at 45 DAS (S1), and among doses, 75 ppm (D3) recorded the maximum (4.84). The combination D3S1 (75 ppm at 45 DAS) produced the highest number of nodules (4.92), while D1S3 (25 ppm at 75 DAS) had the lowest (3.96). All kinetin treatments outperformed the control (3.78), highlighting its role in enhancing root nodulation. Dry matter accumulation per plant was significantly influenced by the stage of foliar application. The highest accumulation (14.75 g) occurred at 45 DAS (S1), while the lowest (14.50 g) was observed at 75 DAS (S3). Early application likely benefited from favorable conditions, enhancing plant growth and carbohydrate accumulation. Kinetin helps in acquiring more vegetative growth, more photosynthates and ultimately capacity of plants to manufacture more nodules in roots. These results are in line with the findings of Fatima *et al.* (2008) in chickpea

Foliar application stages and kinetin (6-BA) doses significantly influenced seed yield and seeds per pod. The highest seed yield (0.24 kg plot^{-1} and 11.85 q ha^{-1}) and number of seeds per pod (13.06) were recorded with 75 ppm kinetin applied at 45 DAS (D3S1). Minimum values were observed with 25 ppm at 75 DAS (D1S3). Early foliar application (45 DAS) enhanced photosynthate accumulation, improving yield traits. All kinetin treatments outperformed the control, which recorded the lowest seed yield (0.14 kg plot^{-1} and 6.91 q ha^{-1}) and seeds per pod (9.72). On the other hand test weight of fenugreek seeds was significantly influenced by stages of foliar application, kinetin (6-BA) doses, and their interaction. The highest test weight (11.31 g) was recorded with 75 ppm kinetin applied at 45 DAS (D3S1), while the lowest (10.34 g) was seen with 25 ppm at 75 DAS (D1S3). Control plots without growth regulator recorded the minimum test weight (9.80 g) (Table 4). The enhanced seed yield observed may be attributed to the stimulatory effect of kinetin on pod setting and efficient mobilization of assimilates toward reproductive sinks, promoting seed formation and development. Higher kinetin levels likely induced more reproductive sinks, which enhanced photosynthetic activity and translocation of metabolites, resulting in an increased number of seeds per pod. This trend is supported by findings in various legumes, including chickpea, lentil, green gram, pigeon pea, cowpea, and soybean. Furthermore, the increase in seed test weight with higher kinetin doses may be due to improved carbohydrate translocation to developing seeds. These outcomes align with the observations of Fatima *et al.* (2008); Khalil *et al.* (2006); Ananthi and Gomathy (2010); Ailenokhuria and Orimadegun (2020); Salem (2018); Upadhyay and Ranjan (2009).

Table 4: Impact of Kinetin foliar application on growth and seed yield parameters.

Parameters	Stages of application (S)	Kinetin Doses (D)			Mean	$CD_{0.05}$
		D_1 (25 ppm)	D_2 (50 ppm)	D_3 (75 ppm)		
Pod length (cm)	**S_1 (45 DAS)**	7.87	8.81	10.36	9.01	**S: 0.05**
	S_2 (60 DAS)	8.08	8.97	9.48	8.84	**D: 0.05**
	S_3 (75 DAS)	8.39	8.77	9.03	8.73	**S × D: 0.09**
	Mean	8.11	8.85	9.62		**S × D × C : 0.26**
	Control (C)	7.15				
weight of 25 pods (g)	**S_1 (45 DAS)**	6.65	7.03	7.35	7.01	**S: 0.03**
	S_2 (60 DAS)	6.50	6.93	7.16	6.86	**D: 0.03**
	S_3 (75 DAS)	6.41	6.87	7.07	6.78	**S × D: 0.05**
	Mean	6.52	6.94	7.19		**S × D × C : 0.15**
	Control (C)	6.12				
Nodules plant^{-1}	**S_1 (45 DAS)**	4.16	4.60	4.92	4.56	**S: 0.03**
	S_2 (60 DAS)	4.07	4.56	4.82	4.49	**D: 0.03**
	S_3 (75 DAS)	3.96	4.43	4.78	4.39	**S × D: 0.04**
	Mean	4.07	4.53	4.84		**S × D × C : 0.13**
	Control (C)	3.78				
Dry matter accumulation plant^{-1} (g)	**S_1 (45 DAS)**	14.35	14.80	15.11	14.75	**S: 0.02**
	S_2 (60 DAS)	14.18	14.65	14.98	14.61	**D: 0.02**
	S_3 (75 DAS)	14.07	14.55	14.89	14.50	**S × D: 0.04**
	Mean	14.20	14.67	14.99		**S × D × C : 0.12**
	Control (C)	13.89				
Seed yield plot^{-1} (kg)	**S_1 (45 DAS)**	0.20	0.21	0.24	0.22	**S: 0.01**
	S_2 (60 DAS)	0.19	0.20	0.21	0.20	**D: 0.01**
	S_3 (75 DAS)	0.16	0.17	0.18	0.17	**S × D: 0.01**
	Mean	0.18	0.19	0.21		**S × D × C : 0.03**
	Control (C)	0.14				
Seed yield hectare^{-1}	**S_1 (45 DAS)**	9.87	10.37	11.85	10.70	**S: 0.26**
	S_2 (60 DAS)	9.38	9.87	10.37	9.87	**D: 0.26**
	S_3 (75 DAS)	7.90	8.39	8.88	8.39	**S × D: 0.45**
	Mean	9.05	9.54	10.37		**S × D × C : 1.29**
	Control (C)	6.91				
Number of seeds pod^{-1}	**S_1 (45 DAS)**	10.64	12.09	13.06	11.93	**S: 0.03**
	S_2 (60 DAS)	10.50	11.82	12.88	11.73	**D: 0.03**
	S_3 (75 DAS)	10.31	11.50	12.72	11.51	**S × D: 0.05**
	Mean	10.48	11.80	12.89		**S × D × C : 0.14**
	Control (C)	9.72				
Test weight (g)	**S_1 (45 DAS)**	10.41	10.84	11.31	10.85	**S: 0.04**
	S_2 (60 DAS)	10.37	10.75	11.08	10.73	**D: 0.04**
	S_3 (75 DAS)	10.34	10.66	10.95	10.65	**S × D: 0.07**
	Mean	10.37	10.75	11.11		**S × D × C : 0.20**
	Control (C)	9.80				
Harvest index (%)	**S_1 (45 DAS)**	25.47	25.95	29.05	26.82	**S: 0.76**
	S_2 (60 DAS)	24.60	25.13	25.77	25.09	**D: 0.76**
	S_3 (75 DAS)	20.79	21.32	22.23	21.45	**S × D: 1.32**
	Mean	23.62	24.06	25.68		**S × D × C : 3.76**
	Control (C)	18.45				
Biological yield (q ha^{-1})	**S_1 (45 DAS)**	38.74	39.96	40.78	39.83	**S: 0.04**
	S_2 (60 DAS)	38.37	39.63	40.24	39.41	**D: 0.04**
	S_3 (75 DAS)	37.99	39.34	39.93	39.09	**S × D: 0.07**
	Mean	38.37	39.64	40.32		**S × D × C : 0.21**
	Control (C)	18.45				

Table 5: Impact of Kinetin foliar application on seed quality parameters of fenugreek seeds.

Parameters	Stages of application (S)	Kinetin Doses (D)			Mean	$CD_{0.05}$
		D_1 (25 ppm)	D_2 (50 ppm)	D_3 (75 ppm)		
Germination percentage	S_1 (45 DAS)	90.15	92.52	94.18	92.29	S: 0.02 D: 0.02 S × D: 0.03 S × D × C : 3.42
	S_2 (60 DAS)	89.87	92.29	93.72	91.96	
	S_3 (75 DAS)	89.11	91.44	92.92	91.16	
	Mean	89.71	92.08	93.61		
	Control (C)	88.48				
Seedling length (cm)	S_1 (45 DAS)	19.15	21.35	23.37	21.29	S: 0.03 D: 0.03 S × D: 0.05 S × D × C : 0.15
	S_2 (60 DAS)	18.74	21.04	22.46	20.75	
	S_3 (75 DAS)	18.40	20.75	22.13	20.43	
	Mean	18.77	21.05	22.65		
	Control (C)	18.07				
Seedling dry weight (g)	S_1 (45 DAS)	41.41	42.83	43.63	42.62	S: 0.18 D: 0.18 S × D: 0.31 S × D × C : 0.90
	S_2 (60 DAS)	40.73	41.67	41.77	41.39	
	S_3 (75 DAS)	40.38	40.70	40.90	40.66	
	Mean	40.84	41.74	42.10		
	Control (C)	38.84				
Seed vigour index-I	S_1 (45 DAS)	1726.37	1975.68	2200.75	1967.60	S: 7.89 D: 7.89 S × D: 13.67 S × D × C : 38.90
	S_2 (60 DAS)	1684.40	1941.40	2105.26	1910.36	
	S_3 (75 DAS)	1669.92	1897.08	2056.39	1864.46	
	Mean	1683.56	1938.05	2120.80		
	Control (C)	1664.50				
Seed vigour index -II	S_1 (45 DAS)	3733.11	3962.77	4108.91	3934.93	S: 42.30 D: 42.30 S × D:73.27 S × D × C : 208.52
	S_2 (60 DAS)	3660.57	3845.89	3915.00	3807.15	
	S_3 (75 DAS)	3598.26	3721.91	3800.25	3706.81	
	Mean	3663.98	3843.53	3941.39		
	Control (C)	3422.60				
Electrical Conductiviy ($dS\ m^{-1}$)	S_1 (45 DAS)	0.091	0.087	0.086	0.088	S: 0.01 D: 0.01 S × D: 0.01 S × D × C : 0.05
	S_2 (60 DAS)	0.093	0.090	0.088	0.090	
	S_3 (75 DAS)	0.093	0.092	0.089	0.091	
	Mean	0.092	0.090	0.087		
	Control (C)	0.095				

Foliar application stages, kinetin (6-BA) doses, and their interaction significantly influenced harvest index and biological yield in fenugreek. The highest harvest index (29.05%) and biological yield (40.78 q ha^{-1}) were recorded with 75 ppm kinetin at 45 DAS (D3S1). The lowest values were observed with 25 ppm at 75 DAS (D1S3). All kinetin treatments performed significantly better than the untreated control (Table 4). These findings are consistent with those reported by Upadhyay and Ranjan (2009) in soybean.

Seed Quality parameters. Foliar application stages, kinetin (6-BA) doses, and their interactions significantly affected seed quality parameters in fenugreek. The best results for germination (94.18%), seedling length (23.37 cm), dry weight (43.63 g), and seed vigour indices I and II (2200.75 and 4108.91) were achieved with 75 ppm kinetin at 45 DAS (D3S1). The lowest values were consistently seen in D1S3 (25 ppm at 75 DAS). Early application at 45 DAS improved seed physiological quality due to favorable environmental conditions. Higher kinetin dose (75 ppm) produced bold, vigorous seeds with better germination, seedling traits, and seed vigour. Electrical conductivity, an inverse measure of seed vigour, was lowest (0.086 dS m^{-1}) in D3S1 and highest (0.093 dS m^{-1}) in D1S3 (Table 4). All kinetin treatments significantly outperformed the control. These results confirm that 45 DAS foliar spray with 75 ppm kinetin optimizes seed quality traits in fenugreek. The application of treatment D3 (6-BA @ 75 ppm) resulted in the production of physiologically superior, bold seeds with higher dry matter content, leading to improved and uniform germination. Germination serves as an indicator of seed lot quality and its potential to establish a healthy crop stand under varying field conditions. The enhanced seed quality may be attributed to foliar application at 45 DAS, which supported the development of well-filled seeds rich in food reserves. These, in turn, gave rise to robust seedlings with higher dry weight. In contrast, applications at later stages (60 and 75 DAS) were less effective, possibly due to a sudden temperature drop.

Economics of leaf and seed production. Economic analysis of fenugreek treatments showed that foliar application of 75 ppm kinetin (6-BA) at 45 DAS (Trt3) yielded the highest returns for both leaf and seed production. For leaf production, Trt3 recorded the maximum gross return (Rs. 337760), net return (Rs. 266511), and B:C ratio (3.74:1). For seed production, Trt3 also showed the highest gross return (Rs. 142200), net return (Rs. 60451), and B:C ratio (0.74:1). The control treatment (T10) was least profitable for both leaf and seed production. T10 recorded the lowest gross returns, net returns, and B:C ratios in both production systems (Table 6 and 7).

Table 6: Economics of leaf production in fenugreek.

Treatments	Gross return (Rs. ha^{-1})	Cost of cultivation (Rs. ha^{-1})	Net return (Rs. ha^{-1})	B: C ratio
Trt_1	296280	65509	230771	3.52:1
Trt_2	310120	68378	241742	3.54:1
Trt_3	337760	71249	266511	3.74:1
Trt_4	290360	65509	224851	3.43:1
Trt_5	304160	68378	235782	3.45:1
Trt_6	329840	71249	258591	3.63:1
Trt_7	270600	65509	205091	3.13:1
Trt_8	276520	68378	208142	3.04:1
Trt_9	302200	71249	230951	3.24:1
Trt_{10}	247000	62640	184360	2.94:1

Table 7: Economics of seed production in fenugreek.

Treatments	Gross return (Rs. ha^{-1})	Cost of cultivation (Rs. ha^{-1})	Net return (Rs. ha^{-1})	B:C Ratio
Trt_1	118440	76009	42431	0.56:1
Trt_2	124440	78878	45562	0.58:1
Trt_3	142200	81749	60451	0.74:1
Trt_4	112560	76009	36551	0.48:1
Trt_5	118440	78878	39562	0.50:1
Trt_6	124440	81749	42691	0.52:1
Trt_7	94800	76009	18791	0.25:1
Trt_8	100680	78878	21802	0.28:1
Trt_9	106560	81749	24811	0.30:1
Trt_{10}	82920	73140	9780	0.13:1

CONCLUSIONS

The study concluded that the treatment D3S1 (6-BA @ 75 ppm at 45 DAS) was the most effective among all treatments and control. It gave the highest leaf and seed yields along with superior yield-attributing traits like pod length, pods per plant, and seeds per pod. Seed quality parameters such as test weight, germination, seedling vigor, and lowest electrical conductivity were also best in this treatment. It recorded the highest B:C ratio of 3.74:1 for leaf and 0.74:1 for seed production. Hence, this treatment is recommended for fenugreek cultivation in mid-hill regions of Himachal Pradesh after multi-location testing.

FUTURE SCOPE

The findings need validation across diverse agro-climatic regions to confirm their wider applicability. Future research should explore the long-term effects of kinetin on soil health, seed storability and plant metabolism. Investigating the combined use of kinetin with other biostimulants and integrating it into precision farming practices could further enhance crop productivity. Additionally, expanding studies to other fenugreek varieties and legume crops will help develop crop-specific application strategies.

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