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Research Paper

External application of gibberellic acid to enhance seed yield in rainfed pigeonpea (*Cajanus cajan* (L.) Millisp.)

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ABSTRACT

The present study unveils the pivotal role of GA_3 application challenges associated with pigeonpea such as its concentration and time of application for enhancing yield attributes, rainwater use efficiency, and production economics. The results unveiled that the foliar application of 75 mg/L of GA_3 at flower and pod initiation stages significantly improved pigeonpea yield (2016 kg/ha) and rainwater use efficiency (2.30 kg/ha/mm) as compared to the control (water spray) (1688 kg/ha). Economic analysis revealed that, foliar application of 50 mg/L concentration of GA_3 twice at flower and pod initiation stage at an interval of 15 days recorded the highest benefit-cost ratio (3.63). Thus, study provides valuable insights into optimizing pigeonpea crop production using GA_3 and underscores the importance of effective rainwater utilization in rain fed agricultural systems.

Key words: Dry-matter, Economics, Gibberellic Acid, Pigeonpea

INTRODUCTION

Pigeonpea [*Cajanus cajan* (L.) Millisp], is one of the important food legume crops of the tropics and sub-tropical region of the world. In India, it holds the second position in area and production following chickpeas (Satheesh *et al.* 2021). Pigeonpea is often recognized for its ability to withstand moisture limitations at different crop growth stages owing to its deep root system, however, the stress at the reproduction phase significantly affects the productivity and production (Hingane *et al.* 2015). Further, the wide range of maturity variations allows the crop to adapt to diverse environments and cropping systems (Project Coordinators Report 2023-24). Pigeonpea is largely cultivated by small and marginal farmers in semiarid dry land areas, as it thrives under rain fed conditions and provides protein-rich nutritious food. It plays a vital role in subsistence and rain fed farming systems (Srinivasan *et al.* 2019). In India, pigeonpea is predominantly consumed as a split pulse and serves as a primary and cost-effective source of vegetarian protein (Veeanna *et al.* 2020). Pigeonpea accounts for 16.67% of India's total pulse area and 16.96% of total pulse production (https://desagri.gov.in/statistics-type/advance-estimates/), and a significant proportion of the global production and cultivation area. In India, pigeonpea is mainly cultivated in the Central and Southern states, viz., Maharashtra, Madhya Pradesh, Chhattisgarh, Gujarat, Telangana, Andhra Pradesh, Karnataka, and Tamil Nadu. These regions primarily have medium to deep soils, and pigeonpea is typically grown in a rain-fed environment (Giri *et al.* 2023).

Despite their potential, pigeonpea faces challenges in achieving their maximum yield due to various abiotic and biotic factors. The crop encounters several abiotic stresses throughout its life cycle, with moisture and temperature extremes, photoperiod, and mineral-related stresses being the most significant. Moisture stress is particularly common in pigeonpea due to rain fed cultivation (Choudhary *et al.* 2011). In the semiarid tropics, pigeonpea is frequently grown as an intercrop during the rainy season. Its reproductive growth relies on residual moisture following the harvest of a companion crop. Consequently, crop yields often suffer from terminal drought during the reproductive phase, especially in areas where medium-to-long duration varieties are cultivated (Parthasarathy *et al.* 2013). Moisture stress in low-rainfall, semiarid regions significantly reduces productivity. Nam *et al.* (2001) reported that drought stress at the flowering stage can reduce 40–55% of seed yield. The vegetative growth phase of pigeonpea is longer as compared to the reproductive phase hence, it experiences competition for the assimilation of photosynthate from source to sink. Additionally, there is a notable source limitation i.e., soil moisture, especially during the flowering and pod development stage leads to the dropping of flowers and pre-mature pods.

To address these challenges, the application of plant growth regulators, both natural and synthetic, has been proven effective in enhancing growth against certain abiotic stresses (Ramesh *et al.* 2019). For instance, in the absence of gibberellic acid (GA_3), drought stress significantly inhibits hypocotyl length and fresh weight in rice. In such cases, the application of GA_3 partially improves the water status of the seedlings and supports protein synthesis (Taiz and Zeiger 2006). Moreover, the external application of GA_3 has been observed to have positive effects on different plant species under stress conditions. In cotton, it led to an increase in the net photosynthetic rate, stomatal conductance, and transpiration rate (Kumar *et al.* 2001). Similarly, Sitka spruce (*Picea sitchensis*) stimulated pollen and seed cone production, even when the plant was subjected to drought stress (Philipson 2003).

Plant hormones play a crucial role in regulating various developmental stages of plants by enhancing physiological efficiency, particularly in terms of the plant's photosynthetic ability, which ultimately contributes to achieving higher productivity. Among these regulators, gibberellins stand out as diterpene plant hormones derived from geranylgeranyl diphosphate, a diterpenoid precursor. They exert control over multiple aspects of growth, including seed germination, stem elongation, flowering, fruit development grain development, and the transition from meristem to shoot (MacMillian 2002). Additionally, gibberellins interact with environmental factors like light, temperature, and water (Gupta and Chakrabarty 2013). The primary objective of this study is to examine how varying concentrations of gibberellic acid and the timing of foliar application impact the growth, yield parameters, rainwater use efficiency, and production economics of pigeonpea.

MATERIALS AND METHODS

Experimental Location

The present study conducted a field experiment during the rainy seasons over three years (2018-2020) at the Pulses Research Unit, Dr. Panjabrao Deshmukh KrishiVidyapeeth, Krishi Nagar, Akola Campus, Maharashtra, India. The latitude and longitude coordinates of the location are 20.42^0N and 72.0^0E, respectively, with an altitude of 307 M above the mean sea level.

The experimental plot's soil consisted of 34.6% sand, 25.1% silt, and 48.7% clay. The pH of the soil was 8.2 (using a 1:2.5 soil-to-water ratio), and it had a field capacity of 34.1% and a permanent wilting point of 14.5%. The bulk density of the soil was determined to be 1.48 Mgm^3. additionally, the soil contained 0.43% organic C, with 193 kg/ha of available nitrogen, 23 kg/ha of 0.5 M NaHCO3 extractable available phosphorus, and 451 kg/ha of NH_4OAc extractable available potassium.

Akola receives the rainfall from the South-West Monsoon, typically commencing in mid-June and lasting until September last week. The monsoon season's mean precipitation was approximately 770 mm, spread over 40 to 45 rainy days. Specifically, during the rainy seasons of 2018, 2019, and 2020, the pigeonpea crops at the research site received the rainfall of 895 mm, 929 mm, and 771 mm, respectively (Fig. 1 (a)).

Layout and experimental details

The experiment was laid out in a randomized complete block design with three replications and two factors. There were four concentrations of gibberellic acid (C_1: 0 mg/L, C_2: 25 mg/L, C_3: 50 mg/L, and C_4: 75 mg/L) and three timings of foliar application (T_1: at flower initiation, T_2: at pod initiation, and T_3: at flower and pod initiation) across three seasons (2018, 2019, and 2020).

Each experimental plot measured to 7.5m × 7.2 m (L × W) with eight rows, spaced 90 cm apart. The selected pigeonpea variety for the experiment was 'PKV-Tara', which was planted on the 23rd of June 2018, 27th of June 2019, and 1st of July 2020. The excess plants were subsequently thinned to maintain a distance of 30 cm between the plants.

Crop management

To ensure optimal crop growth, the following crop management practices were employed. First, the seed of 'PKV-Tara' pigeonpea variety was treated with a fungicide mixture comprising carboxin 37.5% + thiram 37.5% at a rate of 3g/kg of seed. Following this, the seeds were inoculated with *Rhizobium* bacteria inoculum at a rate of 25g/kg of seed before planting.

For the rain fed pigeonpea crop, the

recommended fertilizer dosage was administered at the time of planting. This involved the application of 25 kg of nitrogen, 50 kg of phosphorus, and 30 kg of potassium through urea, single super phosphate, and muriate of potash as a basal application ha^{-1}.

Additionally, a pre-emergence herbicide, specifically Pendimethalin 30 EC, was promptly applied right after planting to control weed growth effectively. As the crop grew, mechanical weed control measures were implemented whenever deemed necessary to maintain crop health and productivity.

Utilization of gibberellic acid

The analytical grade gibberellic acid (GA_3) ($C_{19}H_{22}O_6$) with ≥95% active ingredient (e.i.) based on High-performance liquid chromatography manufactured by Sigma-Aldrich (SML1959, GA_3-AM) was used for the preparation of different concentrated spray solution. To initiate the procedure, a stock solution of 1000 mg/L was prepared by accurately weighing 1.11g of gibberellic acid (90% a.i.) on the electric weighing balance (Mettler Toledo, Balance XPR2U) and transferring it into a two-liter capacity beaker. Distilled water was added to the beaker, and the mixture was stirred for two minutes using a glass rod. The volume was ultimately adjusted to 1.0 liter by transferring the solution into a 1.0 liter capacity volumetric flask, which was further supplemented with distilled water. From this stock solution, various concentrations were derived, specifically 25 mg/L, 50 mg/L, and 75 mg/L.

Sampling

Ten representative plants were selected randomly from the middle of the net plot area and tagged for recording observations on different yield attributes. The final harvesting dates were determined by conducting successive destructive sampling, with a focus on identifying the conversion of the maximum percentage of healthy mature pods, indicated by their brown coloration. The area used for final yield determination during specific dates (1st January 2019, 21st January 2020, and 26th December 2020) was 37.26 m^2.

To obtain the seeds, manual threshing of the pigeonpea pods was performed, and the weight of the final clean seeds was recorded. The estimation of dry matter was carried out 150 days after planting. This involved cutting the plants at ground level and then separating them into leaves stems (including branches), and reproductive parts (buds, flowers, and pods). Subsequently, these separated plant parts were dried in an oven set at 65ºC for 72 hours. The dry weights of the leaves, stems, and reproductive parts were recorded individually.

Rainwater use efficiency (RUE)

Rainwater use efficiency (RUE) refers to the measure of how effectively rainwater was utilized to achieve seed yield in agricultural practices. It is calculated by dividing the seed yield (kg/ha) by the cumulative rainfall (mm) received from planting to harvest. The formula for Rainwater Use Efficiency (RUE) is given as.

$$RUE = \frac{Yield\ (kg/ha)}{Cumulative\ rainfall\ (mm)}$$

In India, pigeonpea is cultivated entirely under rain fed conditions without any irrigation, the RUE value also serves as an indicator of water productivity or water use efficiency for rain fed treatment (Sharma *et al.* 2013). This metrics helps in assessing the crop's ability to convert rainfall into productive output, emphasizing the significance of efficient rainwater utilization in rain fed agricultural systems.

Economic evaluation of pigeonpea cultivation

An economic study was conducted to assess the profitability of pigeonpea cultivation across various treatments. The evaluation focused on production cost, gross and net returns, and the benefit-cost ratio. The detailed methodology is presented below:

Production cost

To determine the production cost of pigeonpea, all expenses associated with the cultivation process were considered. This included preparatory tillage, seed purchase, fertilizers, bio fertilizers, insecticides, fungicides, weedicides, gibberellic acid, labor costs for inter-cultivation and spraying of insecticides, fungicides, and gibberellic acid, as well as expenses incurred for harvesting threshing and cleaning of the pigeonpea crop seed.

Gross returns

For calculating the gross returns from pigeonpea cultivation, the minimum support price (MSP) for the crop declared by the Department of Agriculture and Cooperation, Government of India during the crop year 2020-21 seasons was considered. The MSP was set at Rs. 60/kg. Gross returns were derived by multiplying the pigeonpea seed yield (kg/ha) with the MSP.

Gross returns (Rs/ha) = Pigeonpea seed yield (kg/ha) × MSP (Rs./ha)

Net returns

The net returns from pigeonpea cultivation were calculated by deducting the production cost from the gross returns. This provided a clear measure of the profitability of each treatment.

Net returns (Rs./ha) = Gross returns (Rs./ha) – Production cost (Rs./ha)

Benefit-Cost Ratio (B: C Ratio)

The benefit-cost ratio (B: C ratio) is a crucial indicator of the economic feasibility of pigeonpea cultivation. It was computed by dividing the gross returns by the production cost.

$$\text{B: C Ratio} = \frac{\text{Gross Returns (Rs./ha)}}{\text{Production Cost (Rs./ha)}}$$

Statistical analysis

Employing a randomized complete block design for this experiment, we conducted the statistical analysis using OPSTAT (Sheoran *et al.* 1998).

RESULTS AND DISCUSSION

Impact of seasonal rainfall on pigeonpea growth, yield attributes and final seed yield

Pigeonpea crop experienced varying rainfall during the 2018, 2019, and 2020 cropping seasons, the total precipitation received was 895 mm, 929 mm, and 771 mm, respectively (Fig. 1a). Uniform rainfall distribution was during 2018 and 2019 providing sufficient water during the reproductive phase. However, a rainfall deficit was faced during flower initiation and pod formation in the year 2020 (Fig. 1b).

In 2019, the pigeonpea plants showed significant improvements in plant height, the number of branches/plant, number of pods/ plant and seed yield/plant (Table 1). The number of branches played a crucial role in determining productivity in 2019 as compared to the 2018 and 2020 cropping seasons. The manifestation of a higher number of branches and yield level in 2019 was realized due to the favorable rainfall distribution during the grand vegetative growth and reproductive stages, as a result, the yield levels in 2019 surpassed the crop year of 2018 and 2020 (Table 2). The yield in 2019 was 36% higher than in 2018 and a remarkable 89% higher than in 2020. The availability of adequate rainfall during the crucial reproductive phases significantly contributed to enhancing both the growth and yield parameters of pigeonpea in 2019.

Effect of gibberellic acid (GA_3) concentration on yield attributing parameters and RUE in pigeonpea

In the present investigation, the impact of gibberellic acid concentrations on both the plant height and number of primary branches of pigeonpea plants was found to be non-significant, as indicated in Table 1. The results suggest that varying the concentration of gibberellic acid did not lead to any significant changes in pigeonpea plant height or the number of branches. The study also unveiled the impact of gibberellic acid application during the later stages of crop growth did not significantly alter either plant height or the number of branches/ plant. However, the effectiveness of gibberellic acid appeared to be dependent on the growth stage, highlighting the importance of applying it at the right time for optimal results. Similar findings were reported by Dawar *et al.* (2020) in their study on blackgram (*Vigna mungo* L.).

Application of GA_3 at 50 mg/L resulted in a significant increase in the total number of pods plant^{-1} (229) compared to the control (193), however, among the different concentrations (25, 50 and 75 mg/L) there was no significant difference. A similar trend was also recorded for the seed yield (kg/ha). It was significantly higher (2016 kg/ha) with 75 mg/L compared to the control (1688 kg/ ha), but among the different concentrations, there were no significant differences (Table 2). The seed index was significantly higher with 75 mg/L GA_3 concentration as compared to control and 25 mg/L GA_3 concentrations. This implies an optimal concentration of GA_3 elicits a biological response in pigeonpea and helps in the manifestation of yield and its attributing traits (Dhakne *et al.* 2015, Upadhyay and Rajeev 2015). Furthermore, the 75 mg/L concentration of GA_3 led to 19.4%, 3.3%, and 0.3% more yield than the control, 25, and 50 mg/L concentration, respectively, likely attributed to improved photosynthesis, nutrient uptake, and positive effects on seed development. This application may also promote cell division and enlargement in developing seeds, leading to larger seeds (Wang *et al.* 2017, Kumar and Sharma 2021).

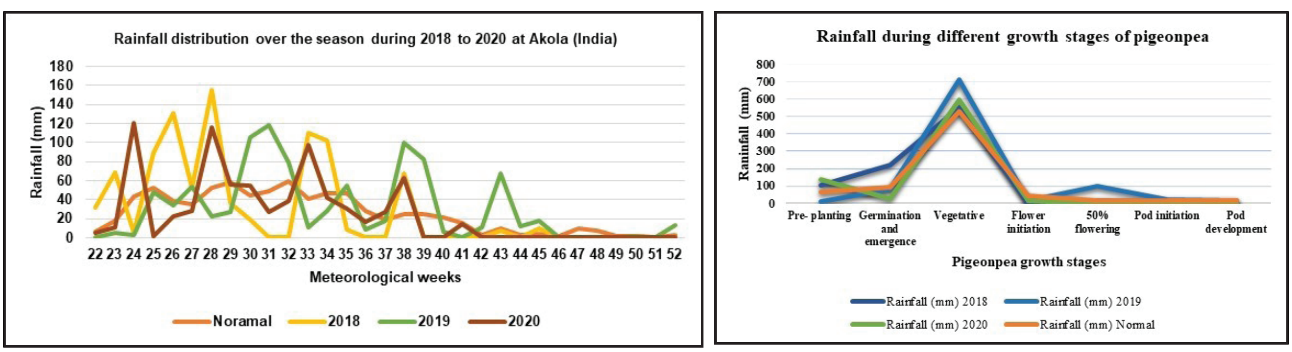
Similarly, the 75 mg/L concentration of GA_3 significantly improved rainwater use efficiency (RUE) compared to the control treatment. However, there was no significant difference between different concentrations. As GA_3 is a growth hormone, it might have a positive effect on root growth and water uptake, resulting in improved water accessibility and utilization by the plants (Giri *et al.* 2018). Different concentrations of GA_3 enhanced the harvest index as compared to the control treatment, indicating a higher allocation of photosynthates to harvested parts. This phenomenon could lead to improved seed yields and productivity in pigeonpea (Range and Giri 2020).

Effect of concentration of GA_3 on pigeonpea dry-matter accumulation and its partitioning at 150 days after planting

At 150 days after planting, the effect of different concentrations of GA_3 on dry matter accumulation in various parts of pigeonpea plants was examined. While pigeonpea stems showed no significant response to the different concentrations of GA_3, However, the leaves (24%), reproductive parts (21%), and total dry matter accumulation (13%) exhibited a significant increase with 75 mg/L GA_3 treatment as compared to the control **(**Fig. 2a**).**Whereas, there were no statistically significant differences among different concentrations.GA_3 played a greater role in dry matter accumulation in leaves and reproductive parts, suggesting its role in promoting leaf growth, photosynthesis, and flowering or fruit development (Charles and Dawson 2023).

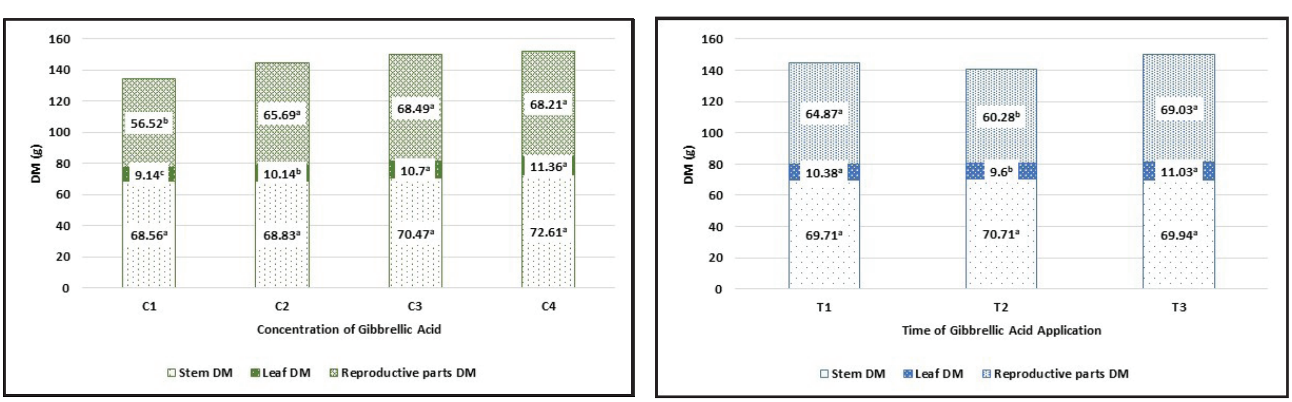
Effect of GA_3 foliar application time on yield attributing parameters and RUE in pigeonpea

The time of GA_3 application on pigeonpea was non-significant on plant height and the number of branches/plant across different concentrations (Table 1). However, for seed yield



(a) (b)

Fig. 1. (a) Rainfall pattern over the crop season at Akola in 2018, 2019, and 2020 and its comparison with the normal rainfall. (b) Comparison of the rainfall distribution during the different growth stages of the pigeonpea crop at Akola in 2018, 2019, and 2020 with the normal rainfall.



(a) (b)

Fig. 2. (a) Effect of gibberellic acid concentration on pigeonpea dry-matter accumulation in the stem, leaf, reproductive parts, and total dry-matter. (b) Effect of gibberellic acid application time on pigeonpea dry-matter accumulation in the stem, leaf, reproductive parts, and total dry-matter.

per plant the application of GA3 twice, at flower and pod initiation stages, resulted in higher pod production (231 pods/plant) and seed yield (61g/ plant) compared to single applications at either stage: flower initiation (218 pods/plant, 57g seed yield/plant) or pod initiation (204 pods/plant, 55g seed yield/plant). Similarly, for seed yield, GA_3 application at both flower and pod initiation stages recorded high seed yield (2031 kg/ha) and stalk yield (4166 kg/ha) compared to single applications at either flower initiation (1911 kg/ha seed yield, 3893 kg/ha stalk yield) or pod initiation stage (1806

Table 1. Effect of GA_3 concentration and time of application on pigeonpea yield attributes

Treatment	Plant height (cm)	Branches/ plant	Pods/ plant	Seed index (g)	Seed yield/ plant (g)
Year					
2018	182^{b}	16^{c}	217^{b}	9.33^{c}	53^{b}
2019	194^{a}	20^{a}	269^{a}	9.41^{b}	82^{a}
2020	183^{b}	18^{b}	167^{c}	9.52^{a}	38^{c}
SEm±	1.96	0.27	2.64	0.01	0.92
LSD (P=0.05)	5.54	0.77	7.46	0.02	2.60
GA_3 concentration					
Control (water spray)	183^{a}	18^{a}	193^{b}	9.35^{c}	51^{b}
25 mg/L	186^{a}	18^{a}	222^{a}	9.42^{b}	59^{a}
50 mg/L	187^{a}	18^{a}	229^{a}	9.45^{a}	60^{a}
75 mg/L	189^{a}	18^{a}	226^{a}	9.47^{a}	61^{a}
SEm±	2.27	0.31	3.05	0.01	1.06
LSD (P=0.05)	NS	NS	8.62	0.03	3.01
Time of GA_3 application					
Flower initiation (FI)	186^{a}	18^{a}	218^{b}	9.39^{b}	57^{b}
Pod initiation (PI)	184^{a}	18^{a}	204^{c}	9.41^{b}	55^{b}
Flower & pod initiation (FI& PI)	188^{a}	18^{a}	231^{a}	9.46^{a}	61^{a}
SEm±	1.96^{a}	0.27	2.64	0.01	0.92
LSD (P=0.05)	NS	NS	7.46	0.02	2.60

Means followed by the same letter do not differ significantly at the 0.05 probability level.

Table 2. Effect of GA_3 concentration and time of application on pigeonpea Yield, Harvest Index (HI), and Rainwater Use Efficiency (RUE)

Treatment	Seed yield (kg/ha)	Stalk yield (kg/ha)	HI (%)	RUE (kg/ha mm)
Year				
2018	1869^{b}	3788^{b}	33.02^{b}	2.09^{b}
2019	2538^{a}	4327^{a}	36.92^{a}	2.73^{a}
2020	1341^{c}	3786^{b}	26.16^{c}	1.74^{c}
SEm±	32	69	0.17	0.03
LSD (P=0.05)	90	195	0.49	0.09
GA_3 concentration				
Control (water spray)	1688^{b}	3710^{b}	30.90^{b}	1.93^{b}
25 mg/L	1952^{a}	3939^{a}	32.53^{a}	2.22^{a}
50 mg/L	2009^{a}	4057^{a}	32.54^{a}	2.29^{a}
75 mg/L	2016^{a}	4163^{a}	32.17^{a}	2.30^{a}
SEm±	37	80	0.20	0.04
LSD (P=0.05)	104	225	0.57	0.11
Time of GA_3 application				
Flower initiation (FI)	1911^{b}	3893^{b}	32.31^{a}	2.17^{b}
Pod initiation (PI)	1806^{c}	3842^{b}	31.56^{b}	2.06^{c}
Flower & pod initiation (FI & PI)	2031^{a}	4166^{a}	32.24^{a}	2.31^{a}
SEm±	32	69	0.17	0.03
LSD (P=0.05)	90	195	0.49	0.09

Means followed by the same letter do not differ significantly at the 0.05 probability level.

kg/ha seed yield, 3842 kg/ha stalk yield). Dual foliar applications resulted in 6% and 12% higher yield advantages over single applications at flower initiation and pod initiation, respectively (Table 2). Rainwater use efficiency also improved significantly with dual applications (2.31 kg/ha/mm) compared to single applications at flower initiation (2.17 kg/ha/mm) and pod initiation (2.06 kg/ha/mm), with rainwater utilization increasing by 6% and 13%, respectively.

The foliar application of GA_3 at flower and pod initiation stages has synchronized the plant's growth and reproductive processes, increasing the potential for pod production by reducing flower drop during flowering time application. As a result, more flowers are likely to develop into pods, increasing overall pod production (Khatun *et al.* 2016). Moreover, the dual application of gibberellic acid at flower and pod initiation stages leads to more extensive and heavier seeds. This is due to the prolonged exposure of the plant to the growth-promoting hormone, which helps maintain a balanced hormonal environment and fosters seed development (Kumar and Sharma 2021).

Additionally, using gibberellic acid at critical stages like flower and pod initiation can improve rainwater use efficiency, contributing to better overall growth and yield (Dawar *et al.* 2020). It is worth noting that the effects of GA_3 on pigeonpea can vary for different plant parts. While it promotes leaf and reproductive part growth, it does not significantly affect stem growth or overall dry matter accumulation. Economically, the dual foliar application of gibberellic acid at flower and pod initiation stages has been found to have a higher benefit-to-cost (B: C) ratio, making pigeonpea cultivation using gibberellic acid more economically viable (Kumar and Sharma 2021).

Effect of time of foliar GA_3 application on pigeonpea dry-matter accumulation and its partitioning at 150 days after planting

The foliar gibberellic acid application significantly increased pigeonpea leaf and reproductive parts' dry matter. Two foliar applications led to higher dry matter than single applications at flower initiation or pod initiation stages. However, the time of foliar application did not significantly affect total pigeonpea dry matter at 150 days after planting (Fig. 2b).

Economic studies on the effect of gibberellic acid concentrations and time of application on pigeonpea profitability

Table 3 summarizes the influence of various gibberellic acid treatments on pigeonpea production

Table 3. Effect of GA_3 concentration and time of application on pigeonpea economics

Treatment	Production cost (INR ha)	Gross returns (INR ha)	Net returns (INR ha)	Benefit: Cost ratio
Year				
2018	32000^b	112142^b	80142^b	3.50^b
2019	33990^a	152275^a	118285^a	4.46^a
2020	30421^c	80471^c	50050^c	2.64^c
SEm±	98	1934	1837	-
LSD (P=0.05)	286	5672	5389	-
GA_3 concentration				
C_1: Control (water spray)	30369^d	101261^b	70892^b	3.31^b
C_2: 25 mg/L	31980^c	117101^a	85121^a	3.61^a
C_3: 50 mg/L	32778^b	120556^a	87778^a	3.63^a
C_4: 75 mg/L	33422^a	120933^a	87511^a	3.58^a
SEm±	109	2160	2051	-
LSD (P=0.05)	321	6336	6016	-
Time of GA_3 application				
T_1: Flower initiation (FI)	32123^b	114648^b	82526^b	3.52^b
T_2: Pod initiation (PI)	31757^c	108359^c	76602^c	3.38^c
T_3: Flower & pod initiation FI & PI)	32532^a	121882^a	89350^a	3.70^a
SEm±	95	1871	1776	-
LSD (P=0.05)	278	5487	5210	-

Minimum support price of pigeonpea seeds= Rs. 60/kg
Means followed by the same letter do not differ significantly at the 0.05 probability level.

costs. The application of 75 mg/L gibberellic acid resulted in the highest production cost at Rs. 33,422/ha, while the control treatment had the lowest cost at Rs. 30,369/ha. Gross returns were calculated based on the minimum support price declared by the Government of India (Rs. 60/kg). The 75 mg/L concentration treatment yielded the highest gross returns of Rs. 1,20,933/ha, outperforming the control treatment's returns of Rs. 1,01,261/ha. The 25 and 50 mg/L concentration showed gross returns at par with the 75 mg/L treatment. Regarding net returns, the 50 mg/L concentration treatment yielded the highest net returns at Rs. 87,778/ha, surpassing the control treatment's net returns of Rs. 70,832/ha. The 25 and 75 mg/L concentration resulted in net returns at par with the 50 mg/L treatment. The B: C ratio was significantly influenced by these treatments. Specifically, the 50 mg/L concentration treatment demonstrated a significantly higher B: C ratio of 3.63 compared to the control treatment's ratio of 3.31. The 25 and 75 mg/L concentration resulted in B: C ratios at par with the 50 mg/L treatment.

The cost of production varied depending on the application time. The highest cost, Rs. 32,532/ha, occurred with two applications (flower and pod initiation stages), while the lowest cost, Rs. 31,757/ha, was observed with one application (pod initiation stage). Gross returns were highest at Rs. 1,21,882/ha when gibberellic acid was applied twice, followed by Rs. 1,14,648/ha and Rs. 1,08,359/ha for two separate applications at flower initiation and pod initiation stages, respectively. Net returns hectare^{-1} was significantly influenced by the foliar application timing. Two applications at both stages resulted in the highest net returns, Rs. 89,350/ha, whereas separate applications at flower initiation and pod initiation stages yielded lower net returns of Rs. 82,526/ha and Rs. 76,602/ha, respectively. The benefit-cost (B: C) ratio was also affected by the timing of foliar gibberellic acid application. Two applications at both stages resulted in the highest B: C ratio of 3.69, while separate applications at flower initiation and pod initiation stages led to B: C ratios of 3.52 and 3.38, respectively. The increased production cost of gibberellic acid application may be a concern, it could be justified by higher gross and net returns, as well as a more favorable benefit-to-cost (B: C) ratio, indicating that the benefits of increased crop yield outweighed the higher production costs (Kumar and Sharma 2021).

CONCLUSION

The findings from the present study showed that the concentration and time of application of GA_3 have a significant impact on pigeonpea seed yield and its attributing parameters and RUE. Specifically, the application of GA_3 at a concentration of 75 mg/L led to higher seed yield, stalk yield, seed index, and RUE compared to the control. This con centration resulted in the most substantial positive effect on the leaf, reproductive parts, and total dry matter accumulation in pigeonpea plant. When GA_3 was applied twice, at both the flower and pod initiation stages at an interval of 15 days, it resulted in higher pod conversion and seed yield as compared to single applications at either stage. Economic studies revealed that the application of GA_3 at a concentration of 50 mg/L twice at both flower and pod initiation stages resulted in higher net returns and benefit-cost ratio compared to other treatments. Further, the use of GA_3 will also improve the rainwater use efficiency under rain fed condition this could be the major leads for further research to understand the underlying molecular mechanisms behind the positive results to help the millions of dry land farmers across the countries.

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AUTHOR CONTRIBUTION

Conceptualization: MDG, SN, IPS, Field sampling: MDG, NKP, YVI, PVS. Statistical analysis: MDG, NKP. SN, Writing-original draft: MDG. Writing-review and editing: MDG, SN, IPS, AB, all authors have read and agreed to the published version of the manuscript.

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