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Effect of Plant Growth Regulators on Physiological Productivity and Seed Quality of Soybean [*Glycine Max* (L.) Merill]

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The current study was carried out on soybean variety JS 20-98 seeds that were treated to varying concentrations of plant growth regulators (PGRs). These seeds were used in field studies using Randomised Block Design (RBD) with four replications, and the observations were recorded on phenophasic observations, such as days to 50% flowering, days to pod formation, days to seed formation, days to physiological maturity, and days to field maturity.Determination of dry matter production and its partitioning in various plant parts (leaves, branches, main stem, and pod) at 45 DAS, 60 DAS, 75 DAS, and 90 DAS. Physiological obsdervations (Growth analytical parameters),

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Leaf Area Index (LAI), Leaf Area Duration (LAD), Crop Growth Rate (CGR), Relative Growth Rate (RGR), Specific Leaf Area (SLA), Specific Leaf Weight (SLW), Biomass Duration (BMD), Chlorophyll Content Index (CCI), Relative Water Content (RWC). Yield and yield components included viz; plant height (cm), number of branches plant^{-1}, number of pods plant^{-1}, number of seeds pod^{-1}, pod length (mm), pod width (mm), pod girth (mm), seed index (g), seed yield (g plant^{-1}and kg ha^{-1}), biological yield (g plant^{-1} and kg ha^{-1}), harvest index (%). The biochemical estimation includes moisture (%), ash (%), crude fibre (%), total carbohydrate (%), protein (%), and fat (%). However, seed quality traits include germination (%), seedling length (cm), seed vigour index-I, seed vigour index-II, seedling dry weight (g), root length (cm), and shoot length (cm) in soybean. The treatment GA @ 3 ml L-1 (T5) produced the highest seed yield of 2429.93 kg ha-1, biological yield of 6804.47 kg ha-1, and harvest index of 35.71% among the six PGR treatments on soybean. The greatest value for seed quality parameters, especially germination (%), seedling dry weight (g), seedling length (cm), seed vigour index-I, and seed vigour index-II was recorded under the treatment GA @ 3 ml L-1 (T5).

Keywords: Soybean; plant growth regulators; productivity; seed quality; biological yield.

1. INTRODUCTION

Soybean [*Glycine max* (L.) Merrill] is rapidly becoming the most important oilseed crop in India. It is a leguminous plant belonging to the family Fabaceae and sub-family Papilionaceae [1]. Soybean is recognized around the world as the "Golden bean" or "Miracle crop" or "Yellow jewel" as an oilseed crop that provides inexpensive and balanced nutrition. It is the major crop grown during the *Kharif* season (July-October) in the rainfed areas of our country.

The chemical composition of soybean is 35-40% protein, 20% oil, 25-30% carbohydrate,17% dietary fibre, 5% minerals, and several other components including vitamins [1]. Soybean has about 8 % seed coat or hull, 90 % cotyledons, and 2% hypocotyl. It is also a rich source of calcium, iron, zinc, phosphate, magnesium, vitamin B (thiamine, riboflavin, niacin), and folic acid due to its high bioavailability. Fat-free soybean meal is an important and low-cost protein source for animal feeds and many processed foods.

Soybeans fix nitrogen from the atmosphere (45-65 kg ha^{-1}) via root nodules and add 0.5-1.5 tonnes of organic matter per hectare via defoliation [2]. Organic chemicals known as plant regulators alter physiological processes in plants, although they rarely operate alone since a physiological effect often involves the action of two or more of these compounds. When used at the right growth stages and concentrations, plant growth regulators improve yield components of soybean. Gibberellin is a group of plant hormones that occur in seeds, young leaves, and roots. The name is derived from the Ascomycota phylum member *Gibberella fujikuroi*, a hormone-producing fungus that promotes excessive growth and poor yield in rice plants. There are evidence gibberellins, especially when applied to the entire plant, encourage the growth of major stems. Additionally, they have a role in the bolting (elongation) of rosette plants, such as lettuce, in response to environmental factors including prolonged daylight. In comparison to controls, Wilis soybean cultivars grew taller and produced more pods and seeds after receiving exogenous applications of 50 ppm gibberellin at 3 and 6 weeks after planting [3].

Triacontanol (TRIA) is a natural plant growth regulator found in epicuticular waxes. TRIA is used to increase crop yields on millions of hectares, particularly in Asia. By promoting plant growth, yield, photosynthesis, nitrogen fixation, enzyme activity, free amino acid synthesis, reducing sugar synthesis, and soluble protein synthesis, it is used to increase agricultural production. N-Triacontanol was used exogenously to boost plant growth and yield [4]. Saturated primary alcohol triacontanol (TRIA), which naturally occurs in plant epicuticular waxes has been shown to have growth-promoting effects on plants [5]. Many studies demonstrate how the use of TRIA enhances plant growth and yield (Borowski et al. 2000). TRIA demonstrated improved vegetative growth, chlorophyll content, and dry weight of different plants [6]. SLA, leaf weight ratio and leaves were all greatly improved after application of n-triacontanol.

Waxy-saturated fatty acids are combined to form triacontanol 0.05 % EC. It is a plant growth

regulator produced only from organic components. It improves protein synthesis and photosynthesis in plants. Yields increase as plant cells become more biologically efficient. Triacontanol encourages roots and may increase the percentage of seeds that germinate in soybeans, rice, maize, sorghum, and other crops. Before seeding, it should be soaked for 12 to 24 hours, with 0.1 mg/kg of soaking solution considerably enhancing drought resistance. Triacontanol is found in leafy vegetables, grass, sugar cane, tobacco, and nursery stock. It promotes the synthesis of chlorophyll, enhances photosynthesis, strengthens plants, and has the potential to promote growth. Triacontanol can increase mineral absorption, dry matter accumulation, and crop quality. Keeping in view the above studies the present investigations were undertaken with a vision to investigate the effect of PGRs on growth, phenology, photosynthetic efficiency, productivity and to adjudge the effect of different doses of PGRs on seed quality and biochemical constituents in soybeans.

2. MATERIALS AND METHODS

The Present investigation was conducted during the Kharif season 2022 at Experimental Field of Botanical Garden, Department of Plant Physiology, College of Agriculture JNKVV Jabalpur (M.P.). The material and methodologies in the conduct of this investigation are briefly described as follows.

2.1 Experimental Site

A field experiment was conducted at the Experimental Field Botanical Garden, Department of Plant Physiology College of Agriculture Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur.

2.2 Details of the Experiment

The experiment was conducted in the Kharif season of 2022 in a randomized block design with 4 replications and 6 treatments. The details of the treatments used are described in Table 1. The net plot size used was 4.10 m × 3.00 m with distance between rows was kept at 0.45m and the distance between the plots was 0.50m. The total number of plots and number of rows per plot were 24 and 10 respectively. A uniform dose of fertilizer 20 kg N + 60 kg P_2O_5 + 20 kg K_2O ha^{-1} was applied through urea, single super phosphate, and muriate of potash, respectively. A full quantity of nitrogen, phosphorus, and potassium was applied as a basal dose. The seeds of soybean variety JS 20-98 with different concentrations of plant growth regulators (PGRs) were used for field studies.

2.3 Observations Recorded

The observation was subdivided into the following groups and recorded during the crop growth period.

a) **Phenological traits** – Days to 50% flowering, Days to pod formation, Days to seed formation, Days to physiological maturity, Days to field maturity
b) **Physiological traits** - Estimation of leaf area, dry matter production, and partitioning in plant parts (leaves, main stem, branches, pods) at 15-day intervals.
c) **Growth Parameters-**

2.3.1 Leaf area index (LAI)

LAI expresses the ratio of leaf surface (one side only) to the ground area occupied by the plant or a crop stand worked out as per specifications of Gardner et al. [7].

$$LAI = \frac{Total\ leaf\ area}{Land\ area} = LAI = \frac{LA2+LA1}{2/P}$$

Where, LA_1 and LA_2 represent leaf area during two consecutive intervals and 'P' ground area.

2.3.2 Leaf area duration (LAD)

Leaf area duration expresses the magnitude and persistence of leaf area or leafiness during the period of crop growth. It reflects the extent of seasonal integral of light interaction and correlated with yield. LAD was computed as follows: [8].

$$LAD = \frac{LA2 + LA1}{2} \times (t2 - t1)$$

Where, LA_1 and LA_2 represent the leaf area at two successive time intervals (t_1 and t_2).

2.3.3 Crop growth rate (CGR)

The daily increment in plant biomass is termed as the crop growth rate [8] or productivity rate [9], or rate of dry matter production. It was determined as per the following formula suggested by [8].

$$CGR = \frac{W2 - W1}{P(t2 - t1)}$$

Where,

p = ground area (m^2)
W_1 = dry weight per unit area at t_1
W_2 = dry weight per unit area at t_2
t_1 = first sampling and
t_2 = second sampling

2.3.4 Relative growth rate (RGR)

The relative growth rate expresses the dry weight increase in time interval in relation to initial weight. In practical situations, the mean relative growth rate is calculated from measurements at t_1 and t_2. It was calculated as per formula given by [8].

$$RGR = \frac{lnW2 - lnW1}{t2 - t1}$$

W_1& W_2 are dry weight of plants at two successive intervals t_1 and t_2, Ln - Natural log.

2.3.5 Specific leaf area (SLA)

The specific leaf area expresses the ratio between the leaf area (LA) and leaf dry weight (LW) [7].

$$SLA = \frac{\frac{LA2}{LW2} + \frac{LA1}{LW1}}{2}$$

Where LA_1 and LA_2 are the leaf area and LW_1 and LW_2 is the dry weight of leaf.

2.3.6 Specific leaf weight (SLW)

It is the ratio between the leaf dry weight (LW) and the leaf area (LA) it indicates the leaf thickness on the weight basis [7].

$$SLW = \frac{\frac{LW2}{A2} + \frac{LW1}{LA1}}{2}$$

2.3.7 Biomass duration (BMD)

The parameter represents dry weight losses or gains during a unit time period

$$BMD = \frac{W2 - W1}{lnW2 - lnW1} \times t2 - t1$$

2.3.8 Chlorophyll content index (SPAD)

Chlorophyll content which is expressed as grams of chlorophyll per unit ground area [10] and it was determined in at 45, 60 and at 75 DAS stage using a non-destructive method that utilized an optical instrument called “chlorophyll meter” (Model: CCM 200 Made in USA).

2.3.9 Relative water content (RWC) (%)

The plants are sampled and third fully expanded leaves from the top are detached from the shoot at mid-day (between 8:00 and 10:00 AM), quickly peeled in humidified polythene bags then transported to the laboratory and weighted immediately to record their fresh weight. Then the leaves are kept separately in petri dishes filled with distilled water for 4 h. After that the leaves (fully turgid) are weighted again and then kept in oven at 85℃ for 72 h or until a constant dry weight was recorded. These three weights are used to calculate RWC (%) of leaves according to the formula given by Barrs and Weatherly [11].

$$RWC(\%) = \frac{Fresh\ weight - Dry\ weight}{Turgid\ weight - Dry\ weight} \times 100$$

d) **Yield and yield components:** Plant height (cm), Number of branches plant$^{-1,}$ No of pods plant$^{-1,}$ No of seeds pod^{-1}, Pod length (cm), Pod width (cm), Pod girth (cm), 100 seed weight (g), Seed yield (g plant^{-1} and kg ha^{-1}), Biological yield (g plant^{-1} and kg ha^{-1}), Harvest Index (%)

e) **Biochemical parameters:** The soybean seed was analysed for the following biochemical constituents: -

2.3.10 Total ash (%)

The ash content in the seed sample was estimated according to AOAC [12]. The details procedure as described by Banerjee et al. [13].

$$Ash(\%) = \frac{Weight\ of\ ash}{Weight\ of\ sample} \times 100$$

2.3.11 Total crude fibre estimation

The crude fibre estimation was done according to the figure as described by Banerjee et al. [13] by the following formula:-

$$Crude\ fibre\ \% \frac{Loss\ in\ weight\ on\ ignition}{Weight\ of\ sample} \times (w2 - w1) - (w3 - w1) \times 100$$

2.3.12 Estimation of total carbohydrate percentage

Total carbohydrates in the sample were estimated by the hydrolysis method as described in AOAC [12].

Table 1. Details of Treatments used in the Experiment

S.No.	Treatment details	Dose (ml L^{-1} water)	Time of Application
1.	T1 (Control)	water	Flower initiation stage (30-35 DAS) and Pod initiation stage (50-55 DAS)
2.	T2 (Gibberellic @ 0.45% SL)	1.5 ml	Flower initiation stage (30-35 DAS) and Pod initiation stage (50-55 DAS)
3.	T3 (Gibberellic acid @0.45% SL)	2.0 ml	Flower initiation stage (30-35 DAS) and Pod initiation stage (50-55 DAS)
4.	T4 (Gibberellic acid @ 0.45% SL)	2.5 ml	Flower initiation stage (30-35 DAS) and Pod initiation stage (50-55 DAS)
5.	T5 (Gibberellic acid @ 0.45% SL)	3.0 ml	Flower initiation stage (30-35 DAS) and Pod initiation stage (50-55 DAS)
6.	T6 (Triacontanol @ 0.05 % EC)	0.5 ml	Flower initiation stage (30-35 DAS) and Pod initiation stage (50-55 DAS)

2.3.13 Estimation of protein % in seeds

The nitrogen content was estimated by the micro-kjeldhal method [12] as under by [14]:

Nitrogen and protein percent were calculated by the following formula:

$$\text{Nitrogen}=\frac{14\times Normality\ of\ H2SO4\times 100}{Weight\ of\ sample\ \times 100}$$

Protein percent in the sample was estimated multiplying nitrogen percent of sample by factor 6.25.
Protein (%) = Nitrogen % x 6.25

2.3.14 Determination of fat percentage

The fat content in the sample was estimated by Pelican Equipment Socs Plus based on the principle of Soxhlet's extraction method as described in AOAC [12]. The extract method used for this purpose is given below:

The percent of fat was calculated by using the following formula:

$$Fat\ (\%) in\ ground\ sample$$

$$= \frac{Wt.of\ flask\ (B) - Wt.of\ flask(A)}{Weight\ of\ sample} \times 100$$

Seed Quality Traits: Germination (%); Seedling length (cm); Seed Vigor Index-I; Seed Vigour Index-II; Seedling dry weight (g); Root length (cm); Shoot length (cm)

3. RESULTS AND DISCUSSION

The present investigationhas revealed various valuable findings in relation to physiological growth determinants, biochemical parameters, and morpho-physiological yield attributing parameters and other physiological traits. The data were statistically analyzed and the experimental results of the present investigation are described as following heads and subheads:

3.1 Phenological Observations

The result in Table 4 revealed that significant differences were observed amongst the treatments for phenophasic development during the entire period of the reproductive phase. The values for days to 50% flowering varied from 33.81 to 38.41 days.Under treatment T1 (38.41 days) required maximum days to attain 50% flowering at par with T2 (36.89 days). However, the minimum time required for 50% flowering was noted in T5 (33.81 days) treatment. Treatment T1 (66.50 days) required a maximum of days for seed formation.An important factor affecting productivity during the reproductive phase is the day to 50% flowering. Early flowering generally promotes a longer duration of the reproductive phase, which has been linked to higher yields in numerous investigations [15]. In the present work, the foliar spray of GA @ 3 ml L^{-1} was found to be superior in terms of days to 50% flowering. The range of days to 50% flowering varied from 33.81 days to 38.41 days. It was found in the present investigation that treatment with GA @ 3 ml L^{-1} (T5) had the shortest time (33.81 days) to reach 50% flowering, which is an important characteristic for increasing the term of the reproductive phase. It has been found that a longer reproductive phase is related to a larger output. T1 (Control) showed the highest time requirements (38.41 days) for 50% flowering.

Similar findings were also noted by Yamaguchi & Kamiya [16] that Gibberellins (GA_3) is essential for the growth of flowers and stem elongation. Ali & Bano [17] observed that plant growth regulators (PGRs), which have a variety of effects on plants, including flowering, growth, ion transport, and fruiting may be useful in maximizing the yield potential of the crops.

The lowest time required for seed formation was observed under T6 (62.08 days) treatment.Similar results also showed agreement with Choudhary et al. [18] who reported that as the leaf became older, the amount of chlorophyll decreased along with grain formation. Treatment T5 (76.08 days) had maximum days to achieve physiological maturityat par with T6 (76.07 days). Treatment T1 (70.45 days) recorded the least period to complete this stage.The timing of crop maturity is largely determined by the plant's capacity to continue the production of fruiting sites [19]. The seed yield of plant^{-1} was significantly and positively correlated with days to maturity in Soybeans.

The treatment T5 (96.85 days) required maximum days to achieve field maturityat par with T4 (95.13 days). Treatment T1 (91.48 days) recorded the lowest period to complete this stage. The results are presented in Table 4.

3.2 Physiological Observations

The result in Fig. 2 revealed that significant differences were observed amongst the treatments with respect to physiological traits throughout the investigation period. The results are presented in Fig. 2.

For several crops, it has been shown that the dry matter partitioning into an organ can be quantitatively described as a function of its potential growth rate relative to that of the other plant organs. The results of the present investigation corroborate the result of Renu [20] who reported that application of GA_3 increased the dry weight of the stem from 0 to 200 ppm. Results of Nabi et al. [21] also support our findings that plant dry weight increased significantly as a result of GA_3, with the highest dry weight observed at 33.3 ppm, which was statistically significant near 50 ppm.

Similar results were also noted by Vagner et al. [22] that the application of GA_3 produced more leaves at the latter stage of growth. LAD expresses the magnitude and persistence of leaf area or leafiness or photosynthetic longevity during crop growth, which is a major factor in contributing to photo-assimilate production. According to Chauhan et al. [23], there was a positive and substantial correlation between the amount of dry matter accumulated at 50 % flowering and the LAD assessed 30-45 days after sowing (DAS) in soybean. GA effectively increased CGR from 30 to 45 to 45 to 60 DAS and improved the factors that contributed to yield in soybean crops. This finding also supports the present study. In comparison to the control, soybean plants treated with GA significantly increased CGR, RGR, and NAR at 60 DAS. The findings of Sarkar et al. [24] also corroborate the findings of this investigation. The data on RGR showed that it decreased as growth advanced and maximum RGR was noticed at 45-60 DAS. A significant difference was observed for RGR. Maximum RGR was noted by treatment with GA @ 3 ml L^{-1} (0.0857). Foliar spray of GA @ 3 ml L^{-1} exhibited an increment of 13.20% in relative growth rate over control in soybean. Days of maturity and seed yield plant^{-1} were shown to be strongly and positively correlated. Applying GA_3 (50-200 ppm) to seeds or leaves improved TDM, LAI, RGR, and NAR. The present results also supported the findings of Kumar et al. [25] and Rahman et al. [26]. Significant differences were observed at all stages. In this research, foliar applications of GA @ 2.5 ml L^{-1} (T4) were found to be superior in terms of increasing the specific leaf area at 75-90 DAS. GA @ 2.5 ml L^{-1} (T4) exhibited an enhancement of 72.93% in specific leaf areas over control in soybean. The present study highlighted that SLW in T5 (GA @ 3 ml L^{-1}) was found to be enhanced from the early growth span reaching the peak at 60-75 DAS followed by a decline in remaining later growth phases. Foliar spray of GA @ 3 ml L^{-1} exhibited enhancement of 25.63% in specific leaf weight over control. The decline in later growth phases was attributed to the per unit decrease in the assimilatory power of the assimilatory apparatus during this period. The above finding has proximity to the results of Niung et al. [27]. The results about biomass duration indicated significant differences among the treatment at all the stages. The biomass duration increased from 45 DAS to maturity. Treatment with GA @ 3 ml L^{-1} had significant maximum BMD at 45-60 DAS, 60-75 DAS, and 75-90 DAS. Foliar spray of GA @ 3 ml L^{-1} exhibited an enhancement of 46.98 % in biomass duration over control. The present finding is also similar to the findings of Rahman et al. [28]. The investigations revealed that treatment with GA @ 3 ml L^{-1} had significantly

highest CCI which is a desirable character correlated with photosynthetic efficiency. Foliar spray of GA @ 3 ml L^{-1} exhibited an increment of 11.15% in chlorophyll content index over control in soybean. Taiz and Zeiger [29] noted that the increasing levels of photosynthetic pigments (chlorophylls and carotenoids) brought on by GA_3 are what cause chloroplast size and number to increase, as well as the activity of plastids, Rubisco, and the rate at which photosynthetic CO_2 is assimilated. Our findings corroborate with the results of El Karamany et al. [30] and Shao *et al*. 2014 %. In this study, it was confirmed that treatment with GA @ 2 ml L^{-1} observed higher relative water content (RWC) and it was significantly superior to other treatments. Foliar spray of GA @ 2 ml L^{-1} exhibited an enhancement of 13.20% in relative water content over control. The RWC may indicate the balance between water supply to leaf tissue and transpiration rate through its relationship to cell volume.

3.3 Various Structural Yield Attributes and Yields of Soybean in Various Treatments

The range of plant height was found to be 41.85 cm to 55.13 cm. Treatment T3 (GA @ 2 ml L^{-1}) recorded significantly the highest (55.13 cm) plant height, whereas, the minimum was recorded in control (41.85 cm). The plant height increased slowly during the early stage of crop growth (up to 30 DAS) and thereafter, increased severely up to 45 DAS stage, again growth increased at 75 to 90 DAS. At harvest, plant height declined. Foliar spray of GA @ 2 ml L^{-1} exhibited an increment of 31.73 % in plant height over control in the present studies. The results of the present investigation showed that in all of the growth periods, the number of branches per plant in various treatments of varied concentrations of GA @ 3 ml L^{-1} was shown to be significant. In this research, foliar applications of GA @ 3 ml L^{-1} (T5) were found to be superior in terms of increasing the number of branches per plant. Foliar spray of GA @ 3 ml L^{-1} exhibited an enhancement of 72.93% in several branches of $plant^{-1}$ over control. The findings of the present investigations corroborate the findings of Sarkar *et al*. [24]. The range of number of pods $plant^{-1}$ was found to be 40.60 to 62.74. Foliar applications of GA @ 3 ml L^{-1} (T5) were found to be superior in terms of increasing the number of pods $plant^{-1}$. Foliar spray of GA @ 3 ml L^{-1} exhibited an enhancement of 54.53% in the number of pods $plant^{-1}$ over control. The range of number of seeds pod^{-1} was found to be 1.76 to 2.49. The foliar spray of Triacontanol @ 0.5 ml L^{-1} (T6) was found to be superior over untreated control. The highest value for a number of seeds pod^{-1} was noted under the T6 treatment. Foliar spray of Triacontanol @ 0.5 ml L^{-1} (T6) exhibited an enhancement of 41.48% in a number of seeds $plant^{-1}$over control. Kumar et al. [31] studied that the number of pods per plant and the number of seeds per pod were positively connected with pod length. Singh *et al*. (2015) reported that the application of GA_3 in peas increased the pod's length. Similar results were supported by our investigation. The range of pod width was found to be 5.20 mm to 7.26 mm. The foliar spray of GA @ 3 ml L^{-1} was found to be superior to the rest of the others. The highest pod width was recorded under the T5 treatment and the minimum value was found under the T1 treatment. Foliar spray of GA @ 3 ml L^{-1} exhibited an increment of 39.61% in pod width $plant^{-1}$ over control in soybean. the pod girth in various treatments at varied GA concentrations was determined to be significant. The foliar spray of GA @ 3 ml was found to be superior for pod girth. The range of pod girth was found to be 5.10 mm to 8.11 mm. The foliar spray of GA @ 3 ml L^{-1} was found to be superior to the rest of the others. The highest pod girth was recorded under T5 and the minimum value was found under control. Foliar spray of GA @ 3 ml L^{-1} exhibited an increment of 59.01% in pod girth $plant^{-1}$ over control. The various observations related to growth parameters as an effect to various treatments are picturized in Fig. 2.

Kumar et al. [25] revealed that pod length was found to have a substantial and favourable correlation with seed yield per plant. The use of GA_3 had a considerable impact on pod length. Treatment with GA @ 3 ml L^{-1} results exhibited a significantly higher seed index. The present research showed that the significant maximum harvest index was recorded in T5 (10.03 g). Foliar spray of GA @ 3 ml L^{-1} exhibited enhancement of 16.76% in seed index over control. Our findings also support the findings of Abdul Karim and Haque Sarkar (2002). The range of seed yield g $plant^{-1}$ was found to be 4.62 g to 9.43 g. A foliar spray of GA @ 3 ml L^{-1} (T5) was found to be superior over control. The range of seed yield kg ha $^{-1}$ was found to be 1861.42 g to 2429.93 g. A foliar spray of GA @ 3 ml L^{-1} was found to be superior to the control. GA @ 3 ml L^{-1} exhibited an increment of 59.01% in seed yield over control. The present study indicated that the seed yield in various

treatments of different concentrations of GA @ 3 ml L^{-1} was found to be significant. The foliar spray of GA @ 3 ml L^{-1} was found to be superior in terms of enhancement of seed yield. GA @ 3 ml L^{-1} exhibited an enhancement of 30.54% in seed yield over control in soybean.

3.4 Biochemical Parameters

Foliar spray of GA @ 2 ml L^{-1} (T3) exhibited an increment of 11.36% in moisture percent over control in soybean. Foliar application of GA @ 2.5 ml L^{-1} exhibited an increment of 87.79% in ash percent over control. (%). The fibre content in any crop improves laxative characteristics in the crop. The present experiment showed that the treatment T4 (9.38%) had the maximum crude fibre contents. The treatment T1 (6.35%) exhibited the minimum value. Foliar spray of GA @ 2.5 ml L^{-1} exhibited an increment of 47.71% in crude fibre over control. These results are in agreement with those of Hussain *et al.* (1993). A foliar spray of Triacontanol @ 0.5 ml L^{-1} exhibited an enhancement of 35.15% in total carbohydrate (%) over control. The higher carbohydrate content in seeds was attributed to the higher photosynthetic rate and subsequent mobilization of assimilates in economic parts. Accumulation of organic solutes, like carbohydrates, is a common response of plants exposed to stress conditions as a defence mechanism. The seed legumes, which contain about 20-40% protein on a dry weight basis, are a great source of protein. The protein content, however, varied greatly not just between species but also between cultivars; for example, the protein content of chickpeas ranges from 12.4% to 20.8% [32].

The range of the soybean protein content was between 38.38% to 43.38%. The investigations indicated that T4 (GA @ 2.5 ml L^{-1}) possessed the highest (43.38%) protein content. Foliar spray of GA @ 2.5 ml L^{-1} exhibited an enhancement of 43.38% in protein (%) over control. The range of the soybean fat content was found to be 17.38% to 20.43 %. Treatment with GA @ 1.5 ml L^{-1} results exhibited significantly higher fat %. The present research showed that a significant maximum fat (%) was recorded in T2 (20.43). A foliar spray of GA @ 1.5 ml L^{-1} exhibited an enhancement of 6.21% in fat (%) over control in soybean. The results are described in Table 2.

3.5 Seed Quality Traits

Foliar spray of GA @ 3 ml L^{-1} exhibited an enhancement of 15.30% in germination (%) over control. The present investigations are also by Haba et al. [33] and Wu et al. [34]. Hyun et al. [35] found that GA_3 directly controls the synthesis of protein and RNA (ribonucleic acid), promoting photosynthesis, seed germination, flowering, stem elongation, leaf growth, and cell division in plant shoots. The range of seedling length was found to be 19.22 cm to 24.19 cm. In this study, it was confirmed that treatment with GA @ 3 ml L^{-1} (T5) observed higher seedling length and it was significantly superior to other treatments. Sowing good quality seeds leads to lower seed rate, better emergence, less replanting, more uniformity, and vigorous early growth which helps to increase resistance to insects and disease and economic preposition also. The estimations of seed quality traits are presented in Table 3 [36,37].

Foliar application of GA @ 3 ml L^{-1} (T5) is superior in terms of seed vigour index-I over the rest of the treatments. The present research showed that the significant maximum vigour index-I was recorded under treatment T5 (2142.51). GA @ 3 ml L^{-1} exhibited an enhancement of 45.18% in seed vigour index-I over control. Seed vigour index-II is the best way of measuring the vigour of the seed as it measures the dry matter accumulation rate of the normal seedlings. GA @ 3 ml L^{-1} (T5) is superior in terms of seed vigour index-II. The present research revealed that the maximum vigour index -II was noted under T5 (67.14). Foliar application of GA @ 3 ml L^{-1} exhibited an enhancement of 42.79% in seed vigour index-II over control in soybean. Foliar application of GA @ 3 ml L^{-1} is superior in terms of seedling dry weight over the rest of the treatments. The range of seedling dry weight varied from 0.5001 g to 0.7593 g. The present research showed that a significant maximum value for seedling dry weight was recorded under treatment T5 (0.7593 g). Foliar spray of GA @ 3 ml L^{-1} exhibited enhancement of 51.83 % in seedling dry weight over control in soybean. The growth and metabolism of the plant root system is supported by the process of photosynthesis occurring in the leaves. Photosynthate from the leaves is transported via the phloem to the root system.

Foliar application of Triacontanol @ 0.5 ml L^{-1} is superior in terms of seedling root length over the rest of the treatments. The present research showed that a significant maximum value for seedling root length was recorded under treatment T6 (9.83). A foliar spray of Triacontanol @ 0.5 ml L^{-1} exhibited an enhancement of

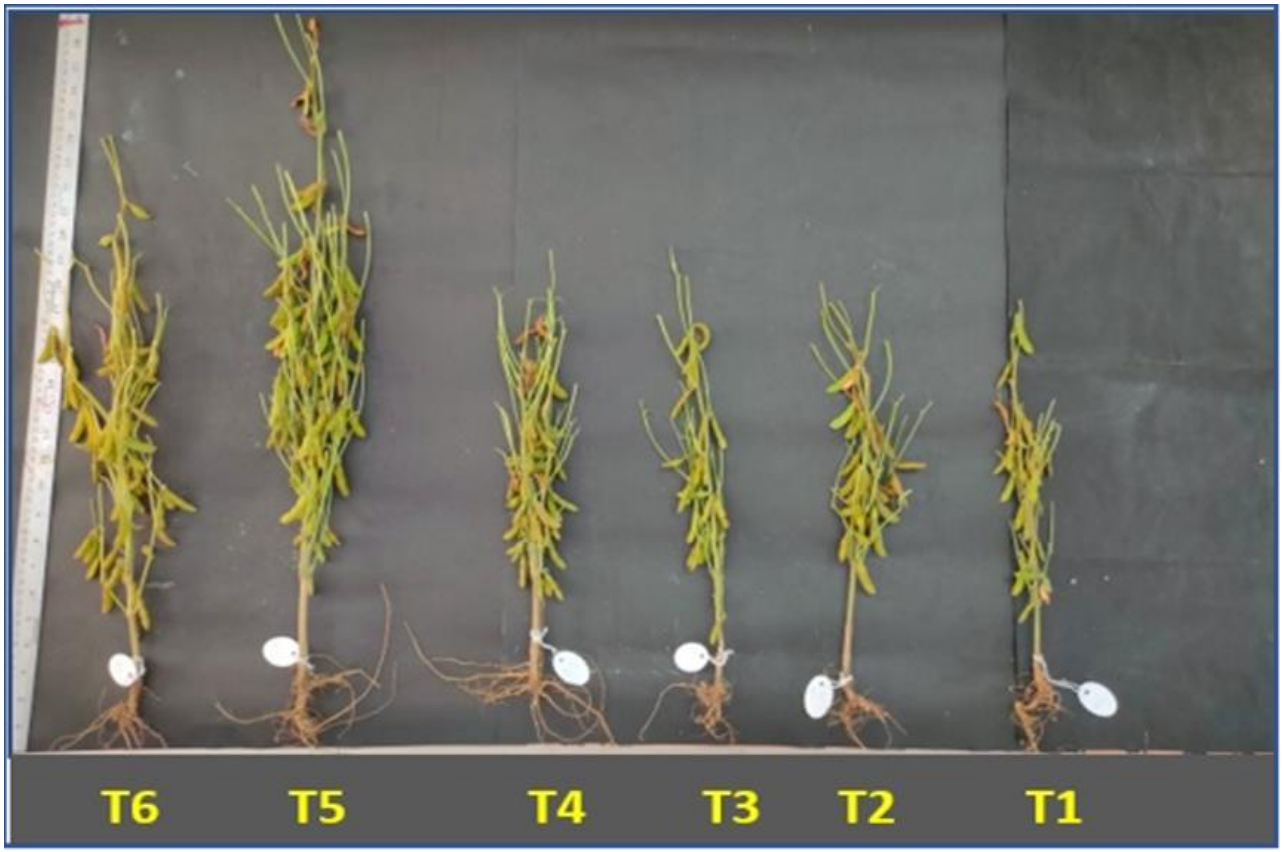
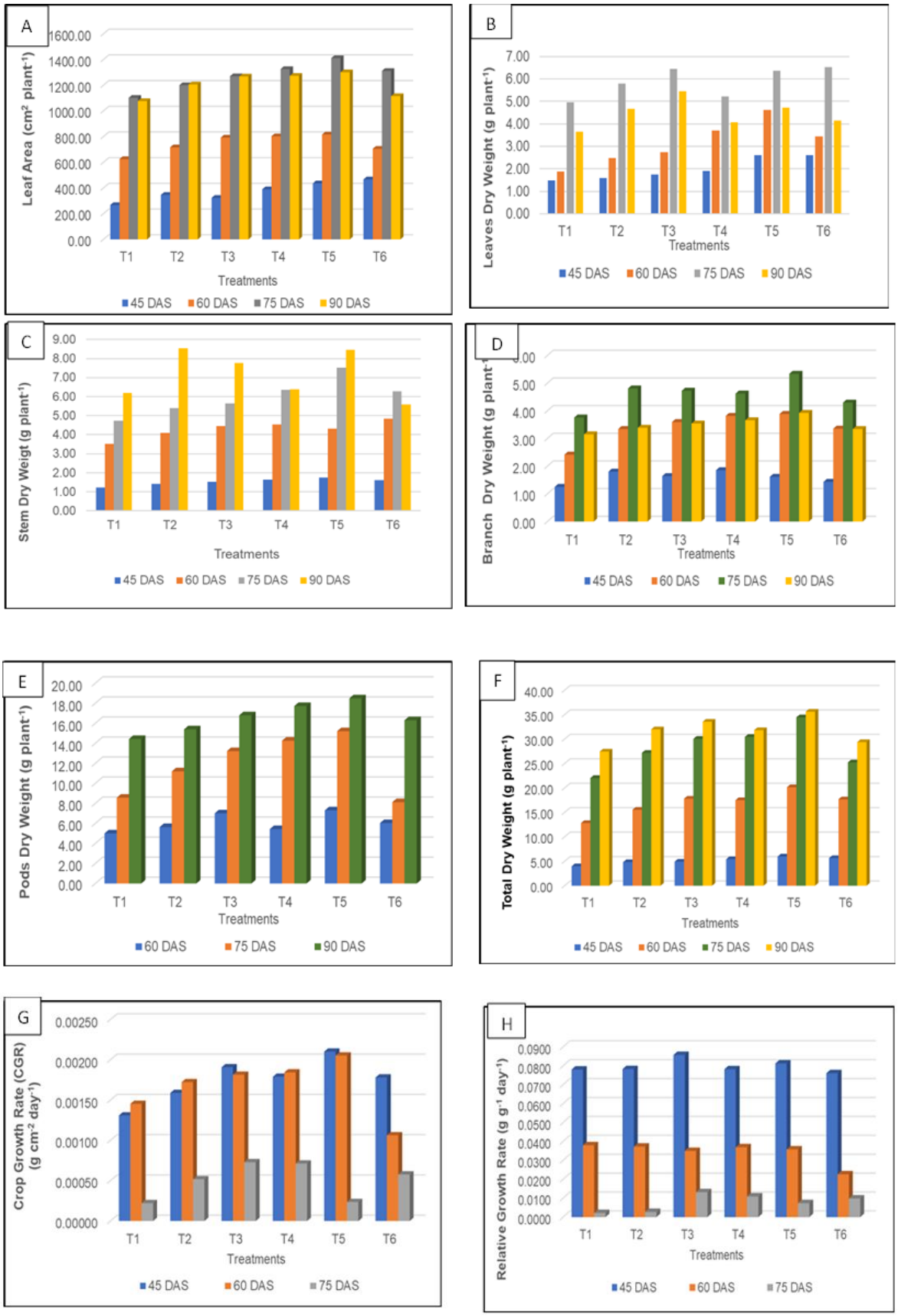


Fig. 1. Differences in yield characters due to variable treatment doses


A
Leaf Area (cm² plant⁻¹)
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS 90 DAS
B
Leaves Dry Weight (g plant⁻¹)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS 90 DAS
C
Stem Dry Weigt (g plant⁻¹)
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS 90 DAS
D
Branch Dry Weight (g plant⁻¹)
5.00
4.00
3.00
2.00
1.00
0.00
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS 90 DAS
E
Pods Dry Weight (g plant⁻¹)
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
T1 T2 T3 T4 T5 T6
Treatments
60 DAS 75 DAS 90 DAS
F
Total Dry Weight (g plant⁻¹)
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS 90 DAS
G
Crop Growth Rate (CGR) (g cm⁻² day⁻¹)
0.00250
0.00200
0.00150
0.00100
0.00050
0.00000
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS
H
Relative Growth Rate (g g⁻¹ day⁻¹)
0.0900
0.0800
0.0700
0.0600
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000
T1 T2 T3 T4 T5 T6
Treatments
45 DAS 60 DAS 75 DAS

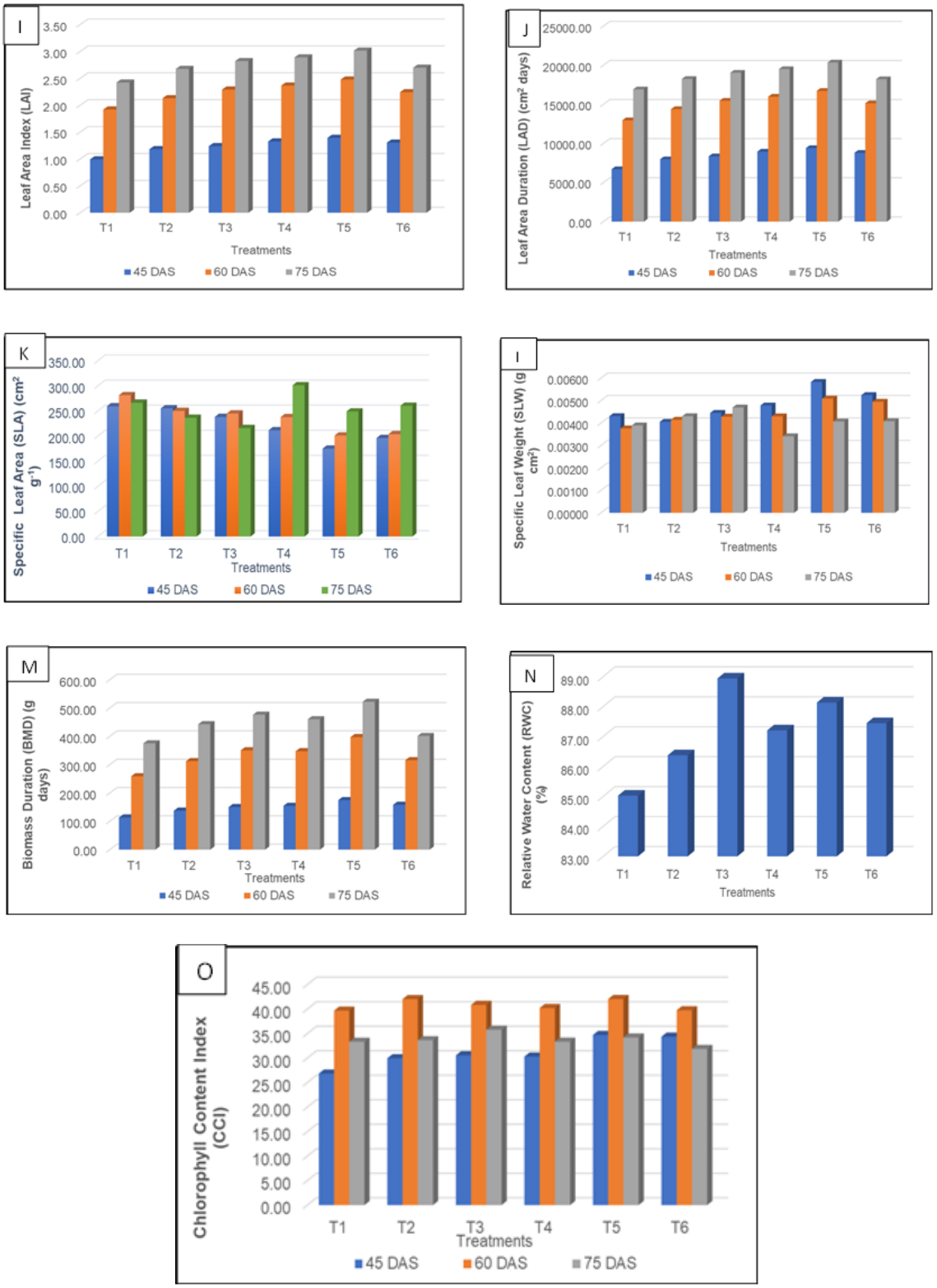


Fig. 2. Differences amongst the treatments for physiological observations viz. A) Leaf Area; B) Leaves dry weight; C) Stem dry weight; D) Branch dry weight; E) Pods dry weight; F) Total dry weight; G) Crop Growth Rate; H) Relative growth rate; I) Leaf Area Index; J) Leaf Area Duration; K) Specific Leaf Area; L) Specific Leaf Weight M) Biomass Duration; N) Relative water content O) Chlorophyll content

Table 2. Results recorded for Biochemical parameters

Treatments	Protein (%)	Fat (%)	Crude fibre (%)	Ash (%)	Moisture (%)	Total carbohydrate (%)
T1 (Control)	38.38	17.38	6.35	3.36	9.73	17.27
T2 (GA @1.5 ml L^{-1})	40.38	20.43	7.74	6.19	9.74	18.31
T3 (GA @ 2.0 ml L^{-1})	42.61	18.35	7.82	5.34	11.86	18.80
T4 (GA @ 2.5 ml L^{-1})	43.38	19.19	9.38	6.31	10.44	16.53
T5 (GA @ 3.0 ml L^{-1})	41.32	16.38	9.10	6.30	10.65	20.51
T6 (Triacontanol @ 0.5 ml L^{-1})	39.44	18.46	8.41	5.56	11.28	23.34
Mean	40.92	18.36	8.13	5.51	10.61	19.13
SEm±	0.2004	0.1069	0.1834	0.1398	0.1020	0.1171
CD at 5%	0.6040	0.3223	0.5527	0.4215	0.3074	0.353

Table 3. Results recorded for Seed quality traits

Treatments	Germination (%)	Seedling length(cm)	Seed Vigour Index-I	Seed Vigour Index-II	Root length (cm)	Shoot length (cm)	Seedling dry weight (g)
T1 (Control)	76.79	19.22	1475.69	38.41	4.67	12.09	0.5001
T2 (GA @1.5 ml L^{-1})	83.94	22.53	1890.58	59.16	6.35	13.95	0.7048
T3 (GA @ 2.0 ml L^{-1})	87.32	22.85	1994.99	64.16	6.65	13.4	0.7352
T4 (GA @ 2.5 ml L^{-1})	80.04	23.51	1882.15	58.39	7.11	13.45	0.7294
T5 (GA @ 3.0 ml L^{-1})	88.54	24.19	2142.51	67.14	8.68	13.83	0.7593
T6 (Triacontanol @ 0.5 ml L^{-1})	81.32	22.05	1793.5	55.31	9.83	11.35	0.6803
Mean	82.99	22.39	1863.24	57.09	**7.21**	**13.01**	**0.6848**
SEm±	1.3716	0.3632	43.5473	1.5076	**0.4962**	**0.4106**	**0.0161**
CD at 5%	4.1344	1.0948	131.2657	4.5444	**1.4956**	**1.2378**	**0.0485**

Table 4. Results recorded for Phenological Traits

Treatments	Days to 50% flowering	Days to Pod formation	Days to Seed formation	Days to Physiological maturity	Days to Field maturity
T1 (Control)	38.41	55	66.5	70.45	91.48
T2 (GA @1.5 ml L^{-1})	36.89	52.89	64.75	72.48	93.48
T3 (GA @ 2.0 ml L^{-1})	35.7	52.47	64.17	74.19	94.29
T4 (GA @ 2.5 ml L^{-1})	35.08	51.89	63.05	75.2	95.13
T5 (GA @ 3.0 ml L^{-1})	33.81	50.38	61.32	76.08	96.85
T6 (Triacontanol @ 0.5 ml L^{-1})	35.89	52.09	62.08	76.07	94.77
Mean	35.96	52.45	63.64	74.08	94.33
SEm±	0.2391	0.3595	0.2612	0.3834	0.3585
CD at 5%	0.7206	1.0835	0.7875	1.1557	1.0808

110.49% in seedling dry weight over control. A significant difference was observed for seedling shoot length. The foliar spray of GA @ 1.5 ml L^{-1} was found to be superior to the untreated control. The range of seedling shoot length varied from 11.35 cm to 13.95 cm. Treatment T2 (13.95 cm) possessed maximum seedling shoot length. Foliar spray of GA @ 1.5 ml L^{-1} exhibited enhancement of 15.38% in seedling dry weight over control.

4. CONCLUSION

Gibberellic acid and Triacontanol being a cofactor for a large number of enzymes involved in hormone synthesis and plant metabolism, it was hypothesized that GA @ 3 ml L^{-1} will stabilize yield and enhance the seed quality of soybean. The present study justifies our hypothesis through the improvement of growth analytical attributes, yield, and yield attributes physiological efficiency by the seed treatment with GA @ 3 ml L^{-1}. Out of six treatments of PGRs on soybean the highest seed yield of 2429.93 kg ha^{-1} and biological yield of 6804.47 kg ha^{-1} and harvest index of 35.71 % was recorded under the treatment GA @ 3 ml L^{-1} (T5). The highest value for seed quality attributes particularly germination (%), seedling dry weight (g), seedling length(cm), seed vigour index-I, and seed vigour index-II was recorded under the treatment GA @ 3 ml L^{-1} (T5). Hence the foliar spray with GA @ 3 ml L^{-1} is recommended to farmers for maximum productivity, physiological efficiency, and seed quality.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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