Plant Archives Vol. 26, Supplement 2, 2026 pp.2970-2981 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.378

IMPACT OF PACLOBUTRAZOL AND CYCOCEL ON SEED SHATTERING AND PRODUCTIVITY IN SUMMER SESAME (*Sesamum indicum* L.) IN THE LOWER GANGETIC ALLUVIAL ZONE OF EASTERN INDIA

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(Date of Receiving : 26-04-2026; Date of Revision : 28-06-2026; Date of Acceptance :15-07-2026)

ABSTRACT

The yield of summer sesame (*Sesamum indicum* L.) is usually limited by excessive vegetative growth and extreme seed shattering in the lowland Gangetic alluvial zone of eastern India. In West Bengal, sesame is mostly grown in summer season after harvesting of potato. Due to high residual fertility, along with irrigation and sometimes intermittent rainfall, sesame plant generally attains excessive vegetative growth resulting in lower reproductive growth and lower yield. Being an indeterminate crop, sesame exhibits overlapping vegetative and reproductive phases, resulting in competition for photo assimilates. Regulation of vegetative growth using plant growth regulators could improve assimilate partitioning. A field experiment was conducted during 2023–24 and 2024–25 at the Agricultural Experimental Farm, Baruipur, West Bengal, in a randomized block design with three replications. Treatments included control, water spray, cycocel (CCC) at 0.15%, 0.20% and 0.25%, and paclobutrazol at 0.01% and 0.02%, applied at 30 and 60 DAS. Growth regulators significantly reduced plant height, with the highest reduction in CCC 0.25% (20.92%). Yield attributes improved notably, with CCC 0.25% producing higher capsules per plant (71.86) and seeds per capsule (70.16), while paclobutrazol 0.01% recorded higher test weight (2.29 g). Seed shattering was lowest in paclobutrazol 0.02% (8.59%), representing a 54.77% reduction over control. Seed yield was highest with paclobutrazol 0.02% (1151.33 kg ha^{-1}), followed by CCC 0.25% (1136.92 kg ha^{-1}). A higher harvest index (26.65%) indicated improved assimilate partitioning. Economic analysis showed that paclobutrazol @ 0.02% achieved maximum net returns (Rs. 74,481–86,941 ha^{-1}) and benefit–cost ratio (2.08–2.41), indicating superior economic viability. The study demonstrates that application of paclobutrazol or cycocel effectively regulates growth, reduces shattering losses, and enhances productivity of summer sesame under eastern Indian conditions.

Keywords **:** *Sesamum indicum;* Plant Growth Regulators; Paclobutrazol; Cycocel; Seed Shattering; Source–Sink Balance; Yield Optimization; Lower Gangetic Alluvial Zone

Introduction

Sesame is an important edible oilseed crop next to the mustard and groundnut, cultivated widely in West Bengal. It is referred to as a "queen of oilseed crop" and the first oil consumed by a human (Pal et al., 2013). Oilseeds are a vital component of Indian agriculture, accounting for 15.7% of the gross cultivated area and contributing 11% to the total value of agricultural output (Meena *et al*., 2023). In West Bengal, although the demand for oilseeds is substantial, only 43% of the requirement is met through local production, with the remainder being imported from other states or countries (Narayan, 2016). Sesame is a traditional healthy food and the seeds are a good source of fibre which helps in lowering the cholesterol and triglycerides which are the main risk factors of heart disease. Sesame seeds consist of 45 to 50% oil, 20% protein and 14.2% carbohydrates and are used as condiments and ingredients in manufacture of paints, soaps, cosmetics, perfumes and insecticides (Yaseen *et al*., 2021). Sesame has excellent nutritive value with long shelf life. The high level of antioxidants viz. sesamin, sesamolin and sesamol present in sesame inhibit the development of rancidity in the oil (Arab *et al*., 2022). Various Studies claim that sesame seed could assist against the ageing of the human body due to the presence of niacin which, for example, cannot be found in soybeans or rapeseed oil (Namiki, 2007).

In West Bengal, sesame is mostly grown in summer season after harvesting of potato. Due to high residual fertility, along with irrigation and sometimes intermittent rainfall, sesame plant generally attains excessive vegetative growth resulting in lower reproductive growth and lower yield. Managing the crop geometry for manipulating the seed yield in sesame is a challenging task as Sesame (*Sesamum indicum* L.) exhibits an indeterminate growth habit, wherein vegetative and reproductive stages overlap, leading to competition for photo assimilates. The major physiological constraints in sesame production are excessive vegetative growth, lack of photosynthetic activity during the time of seed filling, poor source-sink partitioning and poor seed set (Karnan *et al*., 2023). It is also hypothesized that, for this particular plant, a larger amount of photosynthates goes into the production and support of the vegetative parts rather than translocation to reproductive parts therefore, the plants grow to have taller and more biomass (Lambers *et al*., 2019).

Proper regulation of the growth process and proper assimilation is critical in achieving the reproductive development and seed production in sesame (Haque *et al*., 2025). Growth regulators play a crucial role in regulating the plant architecture as well as directing photo-assimilates into the reproductive parts (Mallick *et al*., 2025). Therefore, any attempts to reduce vegetative growth would be expected to improve the seed yield by diverting the photosynthates to reproductive structures which otherwise goes for vegetative growth.

Seed shattering is another major factor that leads to reduced sesame yield. It refers to the loss of the seeds due to breaking of capsules where seeds develop prematurely either even before or during harvesting, causing valuable seeds to fall to the ground (Ahmed *et al*., 2023). However, this problem can be partly addressed by selecting resistant cultivars or using advanced agronomic techniques such as plant growth regulators (Shah *et al*., 2021). Shattering losses can be caused by internal or external stresses, interactions between plant parts or harvest machinery, and variations in temperature, humidity, and capsule moisture (Saeed *et al*., 2022).

These losses can be reduced by selecting sesame varieties that are less susceptible to shattering and by adopting improved agronomic practices, including the use of plant growth regulators to maintain capsule integrity until harvest (Kuai *et al*., 2017). There are different plant growth regulators, such as paclobutrazol, mepiquat chloride, and chlorocholine chloride (CCC), have been found effective in controlling plant growth and development (Singh, 2017).

Several studies showed that, the plant growth retardants such as paclobutrazol, cycocel(CCC) and ethephon are capable of reducing plant height and thus increased translocation of photo-assimilates to reproductive structures (seed) in sunflower (Spitzer *et al.*, 2011; Polat *et al.*, 2017). However, there is limited research on their use in sesame, particularly under the distinctive agro-climatic conditions of the lower Gangetic alluvial zone of West Bengal. With the above backgrounds in view, a field investigation was carried out to evaluate the effects of cycocel and paclobutrazol on the growth and yield of sesame during the summer season 2022-23 and 2023-24.

Materials and Methods

Field experimentation site

Field investigations were carried out for two consecutive pre-*kharif* seasons (2023–24 and 2024–25) at the Agricultural Experimental Farm, University of Calcutta, Baruipur, South 24-Parganas, West Bengal, India (elevation 9.75 m, latitude 22.22° N, longitude 88.28° E). The soil of the experimental site was silty clay in texture, having 32% sand, 46% silt and 21% clay. Prior to sowing, soil samples from a depth of 0–15 cm were collected and analyzed for physico-chemical properties following standard protocols. The soil was slightly acidic (pH 6.81), with 0.31 dS m^{-1} EC and 0.621% organic carbon. The nutrient profile showed 165.4 kg ha^{-1} available nitrogen, 52.2 kg ha^{-1} available phosphorus and 232.4 kg ha^{-1} available potassium.

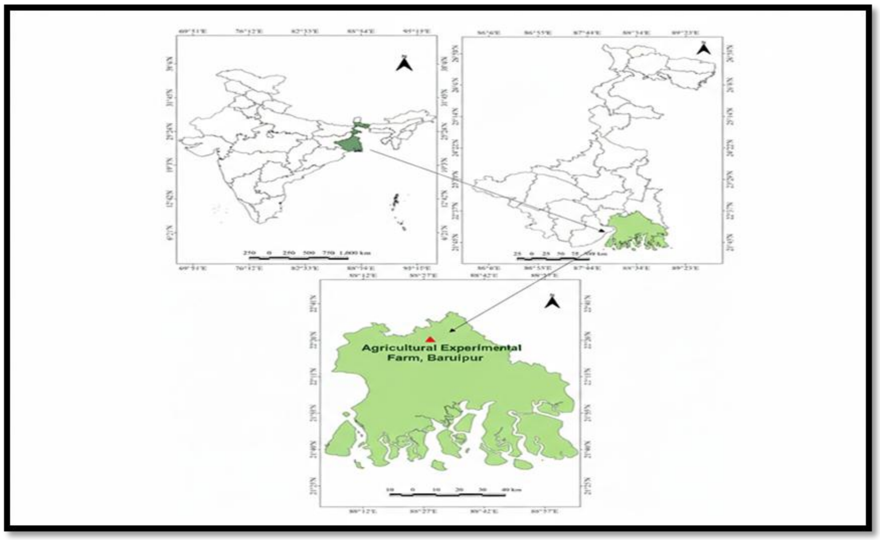

Fig. 1 : Location Map of the experimental area

Experiment design and treatment details

In this experiment, the sesame variety 'Suprava (CUMS-17)' was used. The study aimed to investigate the influence of Cycocel (CCC) and Paclobutrazol on shattering behavior, growth, yield and yield attributes of sesame under the lower Gangetic alluvial zone of West Bengal. A randomized complete block design (RBD) with three replications was adopted, comprising seven treatments: T1 = Control (no spray), T2 = Water spray, T3 = Cycocel @ 0.15%, T4 = Cycocel @ 0.20%, T5 = Cycocel @ 0.25%, T6 = Paclobutrazol @ 0.01% and T7 = Paclobutrazol @ 0.02%. Seeds were sown manually at a spacing of 35 cm × 15 cm using a seed rate of 3 kg ha^{-1}, maintaining a sowing depth of approximately 3–4 cm both the years. Each experimental plot measured 4 m × 2 m and consisted of multiple rows including appropriate spacing for bunds and irrigation channels. Applications of CCC and Paclobutrazol were carried out as foliar sprays at 30 and 60days after sowing.

Agronomic practices and crop data

Land preparation was meticulously carried out and half of the nitrogen was applied as a basal dose at the time of final land preparation. State recommended fertilizer doses(80:40:40 kg ha^{-1}) were applied to sesame. The crop was raised with other recommended package of practices. The sesame seeds were sown on 14^{th} march and were harvested at maturity during 12 June for both the year.

At crop maturity, observations on plant height were taken using a measuring tape, and the number of capsules per plant was recorded from ten randomly selected plants in each plot to determine mean values. To assess seed set, one hundred mature capsules were collected at random from each plot. These capsules were manually threshed, and seeds were counted with the help of a seed counter to compute the average number of seeds per capsule.

For yield estimation, plants from the central $5m^2$ of each plot were manually harvested and kept upright in the field for sun-drying. After sufficient drying, the total above-ground biomass of each harvested bundle was weighed and later expressed as kg ha^{-1}. Clean seed yield was obtained by threshing the dried bundles and removing plant residues. Seed weight was measured using an electronic balance, and seed yield was converted to kg ha^{-1}.

To determine thousand-seed weight, a representative bulk sample from each plot was used. From this sample, four sets of one thousand seeds were counted with a seed counter, individually weighed, and their mean weight was calculated. Seed losses due to shattering were also assessed by collecting shed seeds from a known ground area (m^2) in each plot. The recovered seed amount was weighed using an electronic balance and converted into kg ha^{-1} to quantify shattering.

At physiological maturity, the pods from these plants were carefully removed and allowed to dry under sunlight for ten days. After drying, the pods were examined to record the number that had opened and released seeds as well as those that remained intact. The average count per plant was then determined for each plot. The extent of seed shattering was expressed as a percentage, calculated using the following formula:

$$\text{Seed shattering (\%)} = \left(\frac{\text{Shattered pods}}{\text{Shattered pods} + \text{Non-shattered pods}}\right) \times 100$$

Statistical analysis

The statistical analysis was conducted using an analysis of variance (ANOVA) for a randomized complete block design (RCBD) and Collected data from two years were subjected to average analysis as per the procedures outlined by Gomez and Gomez (1984). The F-values were compared, and the critical difference (CD) was computed at the 5% level of significance. All statistical analyses and graphical representations were performed using MS Excel and OriginPro version 9.8.0.200.

Pearson correlation coefficients were calculated using Microsoft Excel, and significance levels were interpreted based on standard correlation thresholds.

Result and Discussion

Effect on plant growth

Plant Height (cm)*:* Plant height was significantly influenced by the application of plant growth regulators, with the extent of response depending on both concentration and stage of crop growth.

At 45 DAS, plant height varied between 68.67 and 77.03 cm. The tallest plants were recorded under water spray (T2: 77.03 cm), which was statistically comparable with the untreated control (T1:76.04 cm). All treatments reduced plant height relative to the control, with the greatest reduction at this stage was observed with paclobutrazol at 0.02% (T7: 9.69%), followed by CCC at 0.25% (T5: 7.11%). However, these differences were not statistically significant, indicating that the suppressive effect of growth retardants was not clearly expressed during the early growth phase.

At 60 DAS, treatment effects became more distinct and statistically significant. The control recorded the maximum height (T1: 92.51 cm), while all growth regulator treatments reduced plant height to varying degrees. CCC at 0.25% proved most effective, resulting in a 13.74% reduction, followed by CCC at 0.20% (10.44%) and paclobutrazol at 0.02% (9.43%). The progressive decline in plant height with increasing concentrations reflects a clear dose-dependent response.

At harvest, the differences among treatments were more pronounced. Plants treated with water spray reached the greatest height (T2:129.15 cm), slightly exceeding the control (125.37 cm), indicating no inhibitory effect. In contrast, all growth regulator treatments significantly suppressed plant height. The highest reduction was recorded with CCC at 0.25% (20.92%), followed by CCC at 0.20% (13.26%) and paclobutrazol at 0.02% (12.20%). Paclobutrazol consistently reduced plant height across all stages, although its effect was less pronounced than that of CCC.

Overall, CCC was more effective than paclobutrazol in reducing plant height, particularly at higher concentrations. The magnitude of inhibition increased from 45 DAS to harvest, suggesting a cumulative effect of growth retardants over time.

The remarkable inhibition of plant height because of growth retardant application appears to be due to its effect in slowing down of cell division and reducing cell expansion (Magnitskiy *et al.*, 2006). It has been also suggested that cycocel have anti-gibberellins dwarfing agents, which led to the deficiency of gibberellins and finally blocking the conversion of geranyl pyrophosphate to capably I- pyrophosphate which is the first step in gibberellins synthesis (Soliman *et al.*, 2022). Accordingly, the reduction in plant height might be due to the retardation of transverse cell division, particularly in stellar cambium which is the zone of the meristematic activity at the base of the internodes (Desta & Amare, 2021; Karunananda & Peiris., 2010).

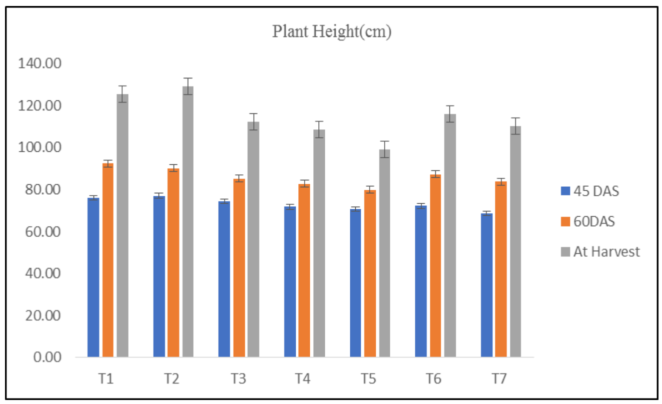

Fig. 2 : Plant height of sesame influenced by treatments at various growth stage

Effect on Yield attributing characters

Capsules plant^{-1}: The number of capsules plant^{-1} varied significantly among treatments, with the highest value recorded under Cycocel (CCC) at 0.25% (71.86 capsules plant^{-1}). This treatment was markedly superior to all others and resulted in a 35.84% increase over the control.

Among paclobutrazol treatments, PBZ @ 0.02% (T7) recorded 63.98 capsules plant^{-1}, which was statistically at par with T4 but inferior to T5. The control (T1) recorded the lowest number of capsules (52.90 plant^{-1}), whereas water spray (T2) showed only a marginal improvement (54.67 plant^{-1}).

The observed increase in capsule number with CCC application can be explained by its ability to suppress gibberellin synthesis, which limits excessive vegetative growth and favours the allocation of assimilates toward reproductive structures.

The enhancement in capsule number with CCC application may be attributed to its role as a gibberellin biosynthesis inhibitor, which restricts excessive vegetative growth and promotes a more favourable distribution of assimilates toward reproductive organs. This shift enhances flowering, minimizes flower drop, and ultimately improves capsule formation (Balouchi *et al*., 2023)

Paclobutrazol also contributed to an increase in capsule number, especially at higher concentrations (0.02%), which can be linked to its growth-retarding effects and its influence on assimilate partitioning (Barman *et al*., 2018). As a triazole compound, paclobutrazol interferes with gibberellin synthesis, thereby modifying plant growth and improving yield attributes under certain conditions (*Desta & Amare, 2021*).

Comparable trends have been reported in several crops, where the application of CCC and paclobutrazol improved yield-related traits like capsules per plant (Raj *et al.,* 2019; Lubis *et al.*, 2013).

Seeds capsule^{-1}: Cycocel (CCC) application had a marked effect on the number of seeds per capsule. The highest value was observed with CCC at 0.25% (T5:70.16 seeds capsule^{-1}), which was statistically comparable with the 0.20% treatment (T4:69.53 seeds capsule^{-1}), but remained significantly higher than the other treatments. These two treatments resulted in increases of 29.18% and 28.02%, respectively, over the control.

Among the paclobutrazol treatments, PBZ @ 0.02% (T7) recorded 65.58 seeds capsule^{-1}, which was significantly higher than PBZ @ 0.01% (T6) (59.72 seeds capsule^{-1}) but inferior to higher levels of CCC. The control (T1) recorded the lowest value (54.31 seeds capsule^{-1}).

The increase in seed production with the use of plant growth inhibitors like CCC and PBZ is consistent with previous research findings reported by Hanchinamath (2005), which revealed that these compounds enhance the allocation of assimilates toward reproductive structures stimulate increased seed development. Cycocel and paclobutrazol function by limiting vegetative growth and optimizing reproduction by manipulating hormonal balance, specifically by inhibiting the production of gibberellin (Abdel-Gawad *et al*., 2025).

Test weight(g): The effect of plant growth regulators on 1000-seed weight is presented in Table 5. Although some variation was observed among treatments, the differences were not statistically significant (CD at P = 0.05: NS) during both years.

Among the treatments, paclobutrazol at 0.01% recorded the highest 1000-seed weight (T6: 2.29 g), followed by paclobutrazol at 0.02% (T7: 2.25 g) and CCC at 0.25% (T5: 2.23 g). The lowest value was noted in the control (T1:1.93 g). The increase in seed weight under these treatments may be associated with a reduction in seed number, which could have decreased competition for assimilates during seed development (Ahmed *et al*., 2023). Similar trends have also been reported in canola, where reduced seed number contributed to improved seed weight (Kuai *et al*., 2015).

The relatively higher seed weight observed with paclobutrazol treatments may be attributed to its role in restricting vegetative growth and promoting a more efficient partitioning of assimilates towards developing seeds, thereby improving grain filling (Kamran *et al*., 2018). Growth retardants such as paclobutrazol and CCC are known to influence source–sink relationships by enhancing the allocation of photosynthates to reproductive organs, which can contribute to improved seed development (Secondo & Reddy, 2018).

These findings are in line with earlier studies, for instance, Gerdakaneh *et al*. (2018) reported that the application of paclobutrazol increased thousand-seed weight in pumpkin (*Cucurbita pepo* L.).

Effect on Yield:

The analysis of results revealed that the yield parameters were significantly affected by the application of growth regulators during both years.

Seed yield and biological yield (kg ha^{-1}): Among the treatments, paclobutrazol @ 0.02% (T7) recorded the highest seed yield with an average mean of 1151.33 kg ha^{-1}, which was closely followed by Cycocel (CCC) @ 0.25% (T5) (1136.92 kg ha^{-1}) and paclobutrazol @ 0.01% (T6) (1092.33 kg ha^{-1}). The increase in seed yield under these treatments was 35.64%, 33.94% and 28.69% over control, respectively.

Lower values were recorded under control (848.83 kg ha^{-1}) and water spray (869.40 kg ha^{-1}). This increased seed yield could be due to better yield contributing factors like capsule number per plant and seeds per capsule, along with efficient allocation of photosynthates towards reproductive parts. This observation is consistent with previous studies that showed that growth retardants improve crop yield by modifying source–sink relationships and reducing excessive vegetative growth (Behera *et al*., 2017; Qureshi *et al*., 2024; Kamran *et al*., 2018; Yadav *et al*., 2022).

Biological yield exhibited a trend similar to other yield parameters. The highest biological yield was recorded with paclobutrazol at 0.01% (T6:4517.37 kg ha^{-1}), followed by CCC at 0.25% (T5: 4425.78 kg ha^{-1}) and paclobutrazol at 0.02% (T7: 4409.75 kg ha^{-1}). The increase over the control ranged from 1.11% to 7.94%, with the maximum improvement observed under the lower concentration of paclobutrazol.

Harvest index (%)

There was a significant influence of treatments on the harvest index, suggesting better partitioning of assimilates to economic yield. Treatment T7 (paclobutrazol @ 0.02%) had the maximum harvest index value (26.65%), followed by treatment T5 (CCC @ 0.25%) and T6 (PBZ @ 0.01%) had values of 25.70% and 24.18%, respectively.

The increment in harvest index due to these treatments suggests better utilization of the total plant biomass towards economically desirable yield components. The distribution of biomass between vegetative and reproductive organs, however, was influenced by the application of growth retardants such as paclobutrazol and cycocel. These regulators tend to suppress excessive vegetative growth while promoting reproductive development and root expansion (Berry & Spink, 2012, (Ghosh *et al*., 2010). In addition, variations in the concentration of these substances can improve the efficiency of nutrient uptake and utilization in plants, further contributing to enhanced productivity (Espindula *et al*., 2009).

Shattering %:

Shattering is one of the most significant problems in sesame, which limits high productivity. Therefore, reducing losses would be helpful for improving productivity economically (Ahmed *et al*., 2023). The maximum amount of shattering was found in the control (T1), with an average value of 18.99%, suggesting that the loss of production was severe in terms of capsule shattering. Paclobutrazol @ 0.02% (T7) showed the minimum level of shattering (8.59%), followed by paclobutrazol @ 0.01% (T6) (10.00%) and CCC @ 0.25% (T5) (11.36%).

The improved resistance to capsule shattering may have been due to the role of paclobutrazol on capsule formation, including its effects on maturity (Gan *et al*. 2008), the thickening of the capsule wall structure (Child *et al*. 2003) and changes in dry matter production and moisture content (Kuai *et al*. 2015).

Table 2: Effect of Different Growth Regulator Treatments on the Shattering Percentage of Sesame

Treatments	Shattering %			
	2024	2025	Average	% decreased over control
T1 : Control	19.20	18.78	18.99	_
T2 : Water Spray	18.38	17.93	18.16	4.37%
T3 : Cycocel (CCC) @ 0.15 %	14.80	14.22	14.51	23.60%
T4 : Cycocel (CCC) @ 0.20 %	13.15	12.73	12.94	31.86%
T5 : Cycocel (CCC) @ 0.25 %	11.47	11.25	11.36	40.18%
T6 : Paclobtrazol @ 0.01 %	10.13	9.87	10.00	47.34%
T7 : Paclobtrazol @ 0.02 %	8.77	8.42	8.59	54.77%
SEm(±)	0.03	0.15	0.07	–
CD (P=0.05)	0.09	0.47	0.22	–

The reduction in shattering with increasing concentration of growth regulators suggests a dose-dependent mechanism, where paclobutrazol was found to have a superior effect compared to CCC. Nevertheless, the mechanisms behind the transformation of capsule structure and shatter resistance by paclobutrazol still require further investigation (Kuai *et al*., 2015).

Shattering may depend on genetic and environmental factors and high levels of shattering may decrease economic yield. The obtained results agree with previous findings showing that paclobutrazol decreases capsule shattering (Mehmood *et al*., 2021).

Correlation and regression analysis

Correlation and regression were analysed for understanding the interrelationships among growth parameters, yield attributes, and seed yield, and to identify the key determinants of productivity.

The results from correlation analysis indicated that seed yield had a positive correlation with harvest index (r = 0.98). This finding indicated the efficiency of assimilates partitioning toward economic yield as an important contributor to seed productivity. Seed yield and biological yield also had a positive correlation (r = 0.80), suggesting that increased biological yield leads to higher productivity if assimilates are properly distributed.

Among the yield components, test weight and number of capsules per plant had a positive correlation with seed yield (r = 0.78; r = 0.67, respectively). These results pointed out that the two factors played an important role in determining the sinks and hence seed production. Seeds per capsule also had a positive but relatively weak correlation with seed yield (r = 0.49).

The relationship between seed yield and shattering percentage was negative but very highly significant (r = -0.95). It clearly indicated that less seed loss is important to increase production levels. Likewise, plant height had a negative relationship with seed yield (r = -0.80). Vegetative parts should be restricted as much as possible for effective reproduction.

Interrelationships among traits revealed that harvest index had a negative relationship with shattering percentage (r = -0.93). Harvest index indicated assimilation of assimilates, which in turn, resulted in a reduction in seed shattering. Capsules per plant had a very highly significant positive relationship with seeds per capsule (r = 0.91).

The correlation analysis was further supported by regression analysis. A strong and positive linear relationship between seed yield and harvest index (R^2 = 0.97) was found, confirming yield enhancement depends upon effective partitioning of assimilated assimilates within the plant. Seed yield had a strong and negative relationship with shattering percentage (R^2 = 0.94).

The presence of a moderately positive correlation between seed yield and the number of capsules per plant (R^2 = 0.60) suggested that seed yield is also affected by reproductive parameters.

In summary, the results of both correlation and regression analyses confirm that seed yield is mainly controlled by harvest index, biological yield, and test weight, while high losses due to shattering and vegetative vigour are major limiting factors. These findings highlight the importance of improving assimilate partitioning and reducing yield losses for enhancing crop productivity.

Traits	PH	CP	SC	TW	BY	HI	SH	SY
PH	1	-0.95**	-0.89**	-0.36	-0.45	-0.81**	0.64*	-0.80**
CP		1	0.91**	0.2	0.23	0.72**	-0.46	0.67*
SC			1	-0.06	0.02	0.57*	-0.32	0.49
TW				1	0.95**	0.66*	-0.76**	0.78**
BY					1	0.66*	-0.80**	0.80**
HI						1	-0.93**	0.98**
SH							1	-0.95**
SY								1

Fig. 3 : Correlation heatmap of various traits of sesame

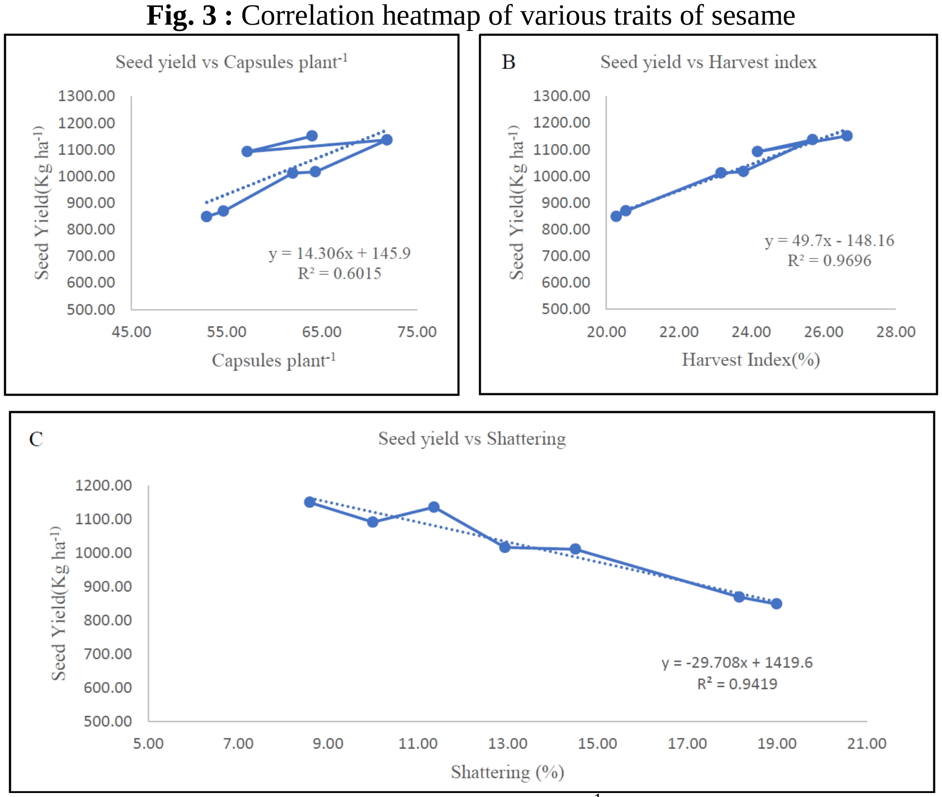

Fig. 4: Regression analysis of seed yield with (A)Capsules plant^{-1}, (B)harvest index (%), (C) shattering (%)

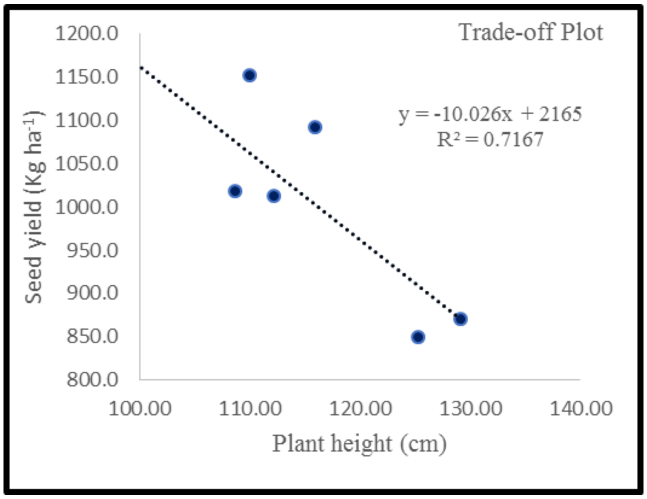

Fig. 4: Relationship between plant height and seed yield

Trade-off Between Plant Height and Seed Yield in Sesame

An important inverse relationship was seen between plant height and seed production (Fig. X), which could be demonstrated from the linear regression analysis ($y = -10.026x + 2165$; $R^2 = 0.7167$). Since the slope was negative, it showed that increased height decreased seed production, hence demonstrating a trade-off between vegetative growth and reproductive output. Approximately 71.67% of the variation in seed yield could be attributed to plant height, suggesting the importance of canopy structure to productivity.

The observed trade-off suggests that plant height was critical in maximizing yield potential and too much vegetative growth would result in wastage of photosynthates. Thus, the use of plant growth retardants appears to optimize plant architecture for improved productivity and reduced seed shattering.

Dose–response of seed yield to cycocel and paclobutrazol application

Seed yield increased with increasing concentrations of both cycocel (CCC) and paclobutrazol (PBZ) (Fig. X). A strong linear relationship was observed for CCC ($y = 1063.6x + 844.19$; $R^2 = 0.9431$), indicating a consistent improvement in yield with increasing concentration.

Paclobutrazol also showed a positive response ($y = 15125x + 879.58$; $R^2 = 0.8897$), although the rate of increase tended to decline at higher concentrations, suggesting a possible optimum level.

Seed yield was increased by increasing concentrations of CCC and paclobutrazol (PBZ) (Figure X). A significant linear regression was recorded for CCC ($y = 1063.6x + 844.19$, $R^2 = 0.9431$) due to constant improvement in yield.

PBZ showed a similar trend ($y = 15125x + 879.58$; $R^2 = 0.8897$), although the rate of increase tended to decline at higher concentrations, suggesting a possible optimum level.

The more stable response in CCC and the slight plateau in PBZ indicate that excessive doses may not proportionally increase yield. As shown from the results, excessive amounts of PBZ and CCC would not enhance seed production as much as the current amounts used.

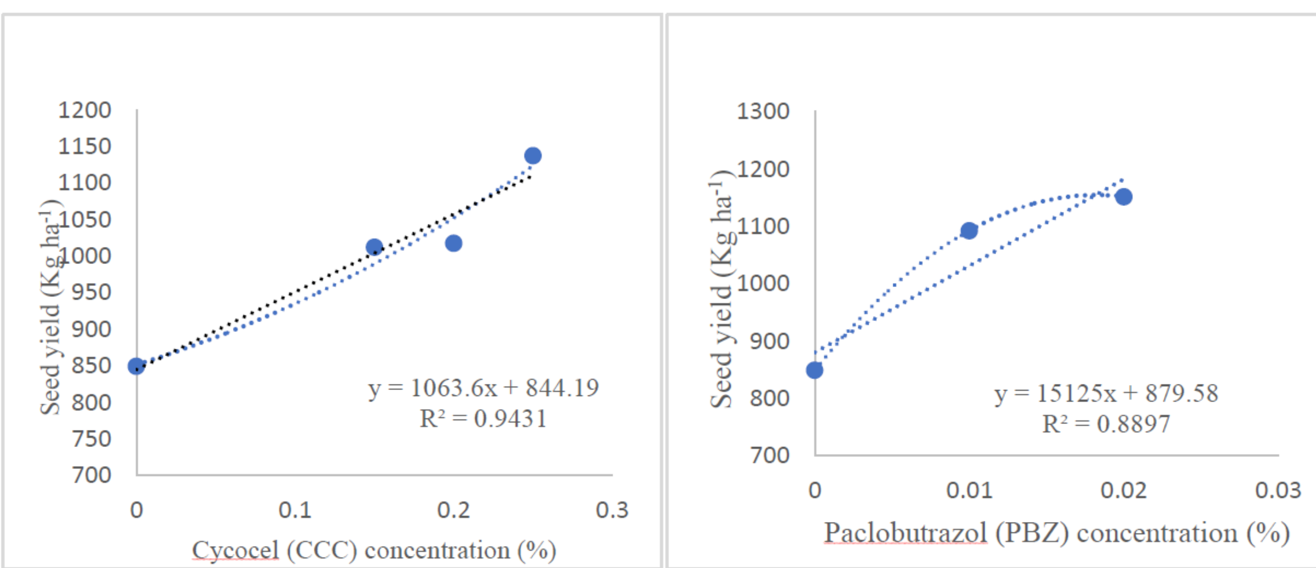

Fig. 3: Relationship between cycocel (CCC) and paclobutrazol (PBZ) concentrations and seed yield of sesame

Principal component analysis (PCA) for growth, yield attributing and yield parameters of sesame

The PCA biplot explains a large proportion of the total variation, first principal component (PC1) accounts for 81.11%, and the second (PC2) accounts for 14.60%, explaining an overall variance of 95.71%. This indicates that the two-dimensional plot adequately represents the relationship of variability in the variables and treatment effects.

PC1 distinctly shows differences between treatments, with variables such as biological yield, harvest index, seeds per capsule, and test weight showing strong positive loadings along this axis. This indicating that these traits are positively associated and collectively contribute to the major proportion of variability. In contrast, plant height and shattering percentage were positioned in the opposite direction along PC1, indicating their negative association with yield and related traits.

Moreover, PC2 allows to discriminate between the different types of treatments further, especially between those affected by biological yield variability and those connected with seeds capsule^{-1} and test weight, which contribute negatively to the current principal component. The lengths of the arrows are proportional to the degree of contribution made by the respective variables in explaining the variance.

Overall, the PCA revealed a clear separation between yield-enhancing factors and yield-limiting factors, highlighting the importance of assimilate partitioning and reduced shattering in improving sesame productivity

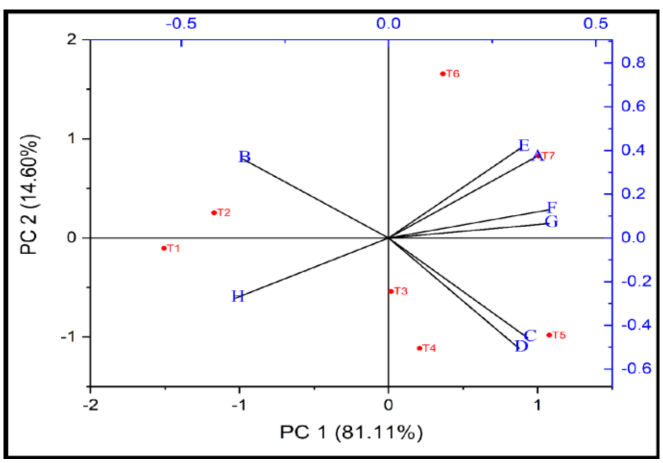

Fig. 6: Principal component analysis (PCA) biplot showing association among traits and treatments

Production Economics

The economic analysis indicated that variation in profitability among the treatments was mainly due to their returns rather than cost of production since it was almost the same for all treatments. Control (T1) and water spray (T2) were the least economically efficient, having the lowest returns and B:C ratios.

Among the growth regulator treatments, the best response of Cycocel treatment was seen with increased doses, where the return and B:C ratio of CCC @ 0.25% (T5) was improved. However, paclobutrazol had better results compared to other growth regulators. The highest economic returns were obtained with paclobutrazol @ 0.02%, having the maximum net returns and B:C ratios in both the years.

The benefit–cost (B:C) ratio clearly indicated differences in economic viability among the treatments. Among all treatments, T7 (paclobutrazol @ 0.02%) recorded the highest B:C ratio of 2.08 and 2.41 during 2024 and 2025, respectively, this means for every rupee invested resulted in a return of Rs. 2.08-2.41, hence the most efficient and profitable treatment.

Table 3: Economic Analysis of Sesame as Influenced by Different Growth Regulator Treatments

Treat-ments	Total cost (Rs/ha)		Gross return (Rs/ha)		Net Return (Rs/ha)		B:C	
	2024	2025	2024	2025	2024	2025	2024	2025
T1	33200	33575	81603	94205	48403	60630	1.46	1.81
T2	35100	35475	83423	96428	48323	60953	1.38	1.72
T3	36150	36525	94023	113195	57873	76670	1.6	2.1
T4	36500	36875	100979	106459	64479	69584	1.77	1.89
T5	36850	37225	108398	122260	71548	85035	1.94	2.28
T6	35418	35793	107356	115162	71938	79369	2.03	2.22
T7	35736	36111	110217	123052	74481	86941	2.08	2.41

(The cost of cultivation was estimated using prevailing market prices of inputs. A uniform base cost of cultivation of Rs. 33,200 ha^{-1} in 2024 and Rs. 33,575 ha^{-1} in 2025 was considered for all treatments. The cost of growth regulators was calculated based on market rates, with Cycocel (CCC) priced at Rs. 700 per 500 ml and paclobutrazol at Rs. 318 per 50 ml. The cost of spraying, including water and labour charges, was taken as Rs. 500 ha^{-1}.

Economic returns were computed using the Minimum Support Price (MSP) of Rs. 9,267 per quintal for 2024–25 and Rs. 9,846 per quintal for 2025–26. The stover value was uniformly considered at Rs. 2 per kg for both years.)

Conclusion and Recommendation

The study showed that the use of plant growth retardant like cycocel and paclobutrazol effectively reduced excessive vegetative growth and improved yield in summer sesame. Both cycocel and paclobutrazol enhanced yield attributes and productivity by improving assimilate partitioning and reducing seed shattering. Among the treatments, paclobutrazol @ 0.02% performed best, recording higher seed yield, better harvest index, and minimum shattering loss, along with superior economic returns. Cycocel @ 0.25% also improved yield components but was slightly less effective overall.

Therefore, foliar application of paclobutrazol @ 0.02% at 30 and 60 DAS is recommended for maximizing sesame productivity under the lower Gangetic alluvial conditions. In situations where paclobutrazol is not available, cycocel @ 0.25% may be used as a suitable alternative

Table 4: Effect of Different Growth Regulator Treatments on Plant Height (cm) of Sesame at Various Growth Stages

Treatments	Plant height(cm)											
	45DAS				60DAS				At Harvest			
	2024	2025	Average	% decreased over control	2024	2025	Average	% decreased over control	2024	2025	Average	% decreased over control
T1	74.53	77.56	76.04	_	90.32	91.66	92.51	_-	123.68	127.05	125.37	-_
T2	75.33	78.72	77.03	-1.30%	88.66	94.69	90.16	2.54%	127.30	131.00	129.15	-3.02%
T3	71.89	76.82	74.35	2.22%	82.21	88.13	85.17	7.93%	110.37	114.07	112.22	10.49%
T4	69.97	73.55	71.76	5.63%	80.51	85.19	82.85	10.44%	105.63	111.84	108.74	13.26%
T5	68.54	72.72	70.63	7.11%	76.04	83.56	79.80	13.74%	96.44	101.85	99.14	20.92%
T6	69.90	74.59	72.24	5.00%	85.64	88.82	87.23	5.71%	112.77	119.18	115.98	7.49%
T7	69.03	68.32	68.67	9.69%	82.08	85.49	83.79	9.43%	106.87	113.28	110.08	12.20%
SEm(±)	2.08	2.46	1.27	–	2.30	1.80	1.45	–	1.23	1.60	1.30	–
CD (P=0.05)	NS	NS	3.91	–	7.10	5.56	4.48	–	3.80	4.93	4.00	–

Table 5: Effect of Different Growth Regulator Treatments on Yield Attributes of Sesame

Treatments	No of Capsules plant-1				No of seeds capsule-1				1000 seeds wt (g)			
	2024	2025	Average	% increased over control	2024	2025	Average	% increased over control	2024	2025	Average	% increased over control
T1	53.07	52.74	52.90	_	50.83	57.78	54.31	_	1.95	1.92	1.93	_
T2	55.2	54.14	54.67	3.35%	54.70	61.73	58.21	7.18%	2.09	2.04	2.07	7.25%
T3	61.9	61.98	61.94	17.09%	64.53	69.14	66.84	23.07%	2.17	2.18	2.17	12.44%
T4	65.93	62.73	64.33	21.61%	70.10	68.97	69.53	28.02%	2.15	1.93	2.04	5.70%
T5	74.73	68.99	71.86	35.84%	69.03	71.28	70.16	29.18%	2.22	2.24	2.23	15.54%
T6	57.53	56.82	57.18	8.09%	59.00	60.45	59.72	9.96%	2.25	2.33	2.29	18.65%
T7	64.13	63.83	63.98	20.95%	63.70	67.47	65.58	20.75%	2.29	2.21	2.25	16.58%
SEm(±)	2.06	1.43	1.17	–	1.97	1.24	1.11	–	0.01	0.10	0.05	–
CD (P=0.05)	6.35	4.41	3.62	–	6.07	3.81	3.43	–	NS	NS	NS	–

Table 6: Effect of Different Growth Regulator Treatments on Yield of Sesame

Treatments	Seed yield (kg ha^{-1})				Biological yield (kg ha^{-1})				Harvest index (%)			
	2024	2025	Average	% increased over control	2024	2025	Average	% increased over control	2024	2025	Average	% increased over control
T1	810.00	887.67	848.83	_	4080.00	4290.50	4185.25	_	19.85	20.69	20.27	_
T2	829.00	909.80	869.40	2.42%	4129.00	4334.20	4231.60	1.11%	20.08	20.99	20.54	1.11%
T3	945.00	1079.00	1012.00	19.22%	4170.00	4557.25	4363.63	4.26%	22.66	23.68	23.17	4.26%
T4	1021.00	1013.33	1017.17	19.83%	4202.67	4356.23	4279.45	2.25%	24.29	23.28	23.79	2.25%
T5	1101.67	1172.17	1136.92	33.94%	4255.00	4596.57	4425.78	5.75%	25.89	25.50	25.70	5.75%
T6	1085.33	1099.33	1092.33	28.69%	4474.33	4560.40	4517.37	7.94%	24.26	24.10	24.18	7.94%
T7	1120.00	1182.67	1151.33	35.64%	4333.33	4486.17	4409.75	5.36%	26.95	26.36	26.65	5.36%
SEm(±)	13.80	16.84	11.25	–	17.65	38.95	23.16	–	0.08	0.32	0.16	–
CD (P=0.05)	42.54	51.90	34.65	–	54.40	120.03	71.37	–	0.24	0.99	0.48	–

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