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FULL-LENGTH RESEARCH ARTICLE

The Influence of Plant Growth Modulators on Physiological Yield and Quality Traits of Sesame (*Sesamum indicum*) Cultivars Under Rainfed Conditions

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Abstract Sesame is an important oilseed crop, and the crop yields frequently fluctuate as the crop is largely grown in rainfed and low-fertile lands. Limited water availability negatively affects many physiological processes and the final productivity of sesame. Limited work has been carried out in the past to understand the role of plant growth regulators (PGRs) in modulating sesame growth and development for optimum productivity. A field study was conducted under rainfed conditions to evaluate the response of foliar application of different PGRs such as hormonal-based gibberellic acid (20 ppm); chemical-based thiourea (500 ppm); chemical-constituting structural component-based ortho-silicic acid (380 ppm); and control (water-sprayed) on sesame cultivars: Swetha til, GT-10, TKG-22, and JCSDT-26. The PGRs foliar application was done at the vegetative (25–30 days after sowing), 50% flowering (40–45 days after sowing), and seed development (70–75 days after sowing) stages of the crop. The results revealed that application of different PGRs positively influenced the plant's growth, physiological, yield and quality traits; however, most effective results were obtained with gibberellic acid (20 ppm), followed by ortho-silicic acid (380 ppm), and thiourea (500 ppm) improved the morphological, yield, and yield-attributing traits. The interaction between PGRs and varieties was found significant and among the sesame cultivars, swetha til followed by JCSDT-29 was found most promising. The application of PGRs has significantly improved the plant height, leaf area, number of branches, capsules, seeds/capsules, seed yield oil content, and fatty acid content compared to the control by gibberellic acid, followed by ortho-silicic acid and thiourea. The interaction between PGRs and varieties was found to be significant, and cultivar Swetha til, a white-colored cultivar performed most superiorly among the different tested cultivars in terms of growth, physiology, yield as well and quality traits when treated with GA3 at 20 ppm. The seed yield was enhanced by 25–26%, 11–12%, and 6–7% with the application of gibberellic acid, ortho-silicic acid, and thiourea, respectively, over control. Considering the findings, it can be concluded that the application of PGRs (thiourea, ortho-silicic acid, and gibberellic acid) significantly enhanced the growth, physiology, yield, and quality of sesame under rainfed conditions; however, GA_3 at 20 ppm was found most effective and may not only enhance the optimum productivity but also effective in improving the quality traits of sesame.

Keywords Sesame · Plant growth regulators · Gibberellic acid · Ortho-silicic acid · Thiourea

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Abbreviations

PGRs	Plant growth regulators
GA_3	Gibberellic acid
TU	Thiourea
OSA	Ortho-silicic acid
C	Control
DAS	Days after sowing
DFF	Days to first flower
DOF	Days to 50% flowering
DM	Days to maturity (DM)
PH	Plant height
NBP	Number of branches/plant
LA	Total leaf area
RWC	Relative water content
Pn	Photosynthetic rate
E	Transpiration rate
gs	Stomatal conductance
iWUE	Intrinsic Water Use Efficiency
CT	Canopy temperature
SCMR	SPAD chlorophyll meter readings
NCP	Number of capsules per plant
CL	Capsule length
CW	Capsule dry weight
NSC	Number of seeds/capsule
TW	1000-Seed weight
SYP	Seed yield/plant
HI	Harvest index
OC	Oil content

Introduction

Climate change is a serious threat and a prime concern across the globe for farming due to the higher vulnerabilities of plant systems and the insufficient in-built mechanisms to overcome the detrimental effects of harsh environmental conditions [45]. While rainfall patterns have a significant influence on quantitative and qualitative traits of oilseed crops [23, 50, 51, 61, 62], temperature profiles of the season also have a significant effect on sesame performance [56, 58, 63]. Several chemicals have been reported to enhance plant-in-built mechanisms for sustainable crop yields, either as foliar spray or as soil application [76]. The oldest oilseed crop, sesame (*Sesamum indicum* L.), known for its excellent oil quality, is largely cultivated during the rainy season with poor management and frequently gets exposed to the vagaries of rainfall. The crop is mostly grown for its seeds, which contain the highest amount of oil (nearly 44–55%), protein content (around 25%), and is rich in antioxidants such as sesamin (0.4–1.1%), sesamolin (0.3–0.6%), and are resistant to oxidation, which is due to the presence of its endogenous antioxidant lignans along with tocopherols [11, 68].

Plant growth regulators (PGRs), either chemical-based or hormonal-based, could modulate plant mechanisms to enhance tolerance to abiotic stresses and further stimulate growth and yields [69, 75]. The available kinds of literature highlighted the promotive role of different plant growth-promoting substances in enhancing yield in various oilseed crops, particularly under water-limited conditions [6, 44, 48, 77, 86]. Plant growth regulators are recognized as low-cost and eco- and farmer-friendly technologies for enhancing the production and stress tolerance of standing crops under field conditions. Positive regulatory effects of foliar application of PGRs (thiourea, ortho-silicic acid, and gibberellic acid) on the growth and yield attributes [9, 10, 25, 36, 79, 80] have been reported elsewhere.

The use of hormonal-based PGR, gibberellic acid (GA_3), is becoming popular due to its promising effects on sesame through increasing the number of flowers per plant, number of pods per plant, seeds per pod, and weight of seeds per plant in sesame [9, 25, 36, 79]. Similar responses have also been noticed in soybean [26] and other oilseed crops such as mustard and safflower [39, 70, 72]. Ortho-silicic acid (OSA) is the only available form of silica for plants, and a PGR with a chemical-based and constituting structural component is reported to maintain plant water relations under stress conditions and ensure improved plant tolerance [69]. Few commercially available OSA formulations are widely used to enhance crop yields in wheat [59]; rice [42, 43]; and sorghum [27] under drought conditions. Thiourea (TU), a chemical-based PGR with an amine group, serves as a source of nitrogen (36%) and sulfur (42%), which helps in plant metabolism [54] through the redox-mediated mechanism for growth modulation [83, 84]. Significant improvements in antioxidant defense systems, nitrogen metabolism, plant water relations, and photosynthesis were observed upon foliar application of TU [30, 82]. Further, reports suggest that thiourea improves chlorophyll content, test weight, and stress tolerance [2, 40, 52, 73]. However, the role of TU in modulating the morphological, physiological, and biochemical aspects, particularly in sesame has remained unexplored.

These shreds of evidence indicated that PGRs play a crucial role in plants' morphological, physiological, biochemical, and crop yield traits. Yield limitations due to the vagaries of monsoons continuously threaten sustainable agricultural development, particularly in crops like sesame that are captives in rainfed situations. Lack of information on PGRs on quantity and quality traits, particularly in sesame under rainfed conditions, persists. Therefore, to enhance sesame crop yields under rainfed situations and economic returns, different PGRs were used to study the response of selected sesame cultivars for (i) to estimate the possible role of different PGRs in enhancing the morpho-phenological traits (ii) to understand how PGRs modulate the plant physiological processes in sesame, and (iii) to quantify the effectiveness of PGRs in improving the seed yield and seed qualitative traits.

Materials and Methods

Experimental Site

The experiment was conducted at the ICAR-IIOR Research farm, Narkhoda, Hyderabad during the year 2019 in the *kharif* season. The site is situated at 17°15′16″ N latitude and 78°18′30″ E longitude at an altitude of 542 m above mean sea level. Weather data during the crop growth period were recorded and presented in Fig. 1.

Experimental Material

A total of four sesame (*Sesamum indicum* L.) cultivars, *i.e.*, Swetha til, GT-10, TKG-22, and JCSDT-26, were selected for the experiment (Supplementary Table 1). The foliar application of PGR viz., gibberellic acid at 20 ppm, orthosilicic acid at 380 ppm, and thiourea at 500 ppm along with control (water spray) used as a foliar application at vegetative (25–30 DAS), 50% flowering (40–45 DAS) and seed development (70–75 DAS) stages. The selected varieties were similar in their phenological (40–45 days to 50% flowering) and maturity (90–93 days) behaviors and adapted to semi-arid conditions.

Crop Management and PGR Application

The experiment was designed in a factorial randomized block design (FRBD) with five replications. The soil at the experimental site was sandy loam soil belonging to the chalka soil series of Alfisols order with a poor water holding capacity of 18%. The soil pH was 7.6; EC was 0.36 dSm^{-1}; organic carbon was 0.41%; and clay content was 17.45%, as recorded at the experimental site. The available soil N, P, and K were 235 kg ha^{-1}, 23 kg ha^{-1}, and 401 kg ha^{-1}, respectively, during the experimentation. Each experimental unit was 12 m2 in area, and the seeds were dibbled at a spacing of 45 cm (between rows) × 15 cm (between plants) during the first week of July 2019. The recommended fertilizer dose (40 kg N + 20 kg P_2O_5- + 20 kg K_2O/ha) was applied just before sowing. The PGRs were applied at vegetative (25–30 days after sowing), 50% flowering (40–45 days after sowing), and seed development (65–70 days after sowing) stages. The recommended standard package of practices was followed and prophylactic measures against pests and diseases were followed to raise a healthy crop. The morphological and physiological observations were recorded at full flowering (50–55 days after sowing) and seed development (75–80 days after sowing) stages after 72 h of foliar applications of PGRs, whereas yield measurements were done at physiological maturity, at harvest and after harvest.

Physiological and Quality Traits Estimation

Phenological traits like days to first flower (DFF), days to 50% flowering (DOF), and days to maturity (DM): morpho-physiological traits such as plant height (PH), number of branches/plant (NBP), total leaf area (LA), relative water content (RWC); and photosynthesis-related traits such as photosynthetic rate (Pn), transpiration rate (E), stomatal conductance (gs), intrinsic Water Use Efficiency (iWUE), and canopy temperature (CT) were recorded at flowering (50–55 days after sowing) and seed development (75–80 days after sowing) stages after foliar applications of PGRs in 10 randomly selected plants in each treatment. The SCMR (SPAD chlorophyll meter readings) were also recorded at the above-mentioned intervals using SPAD-502 Plus (Konica Minolta, Inc.) The photosynthesis-related parameters were recorded using an infrared gas analyzer (LICOR 6400) from 10.00 to 13.30 h IST on fully sunny days. The upper 5th leaf from the terminal part of a three plants was selected for photosynthesis-related traits measurements. The relative water content (RWC) was recorded from the upper 3rd leaf from the terminal part of a plant (4–5 leaves and from 2 to 3 plants) taken after PGRs application and calculated using the formula {RWC = [(fresh weight − dry weight)/(turgid weight − dry weight)] × 100}.

The yield and yield-attributing traits like number of capsules per plant (NCP), capsule length (CL), capsule dry weight/plant (CW), number of seeds/capsule (NSC), 1000-seed weight (TW), seed yield/plant (SYP), and harvest index (HI) were recorded in each replication from 10 randomly selected plants after harvest. Biochemical traits such as fatty acid profile and oil content were recorded from the seeds using gas chromatography, an Agilent 7860A, and a nuclear magnetic resonance spectrometer (NMARS), respectively.

Statistical Analysis

The aggregate mean values were subjected to statistical analysis. The essential statistics like variance and coefficient of variation were calculated using the method

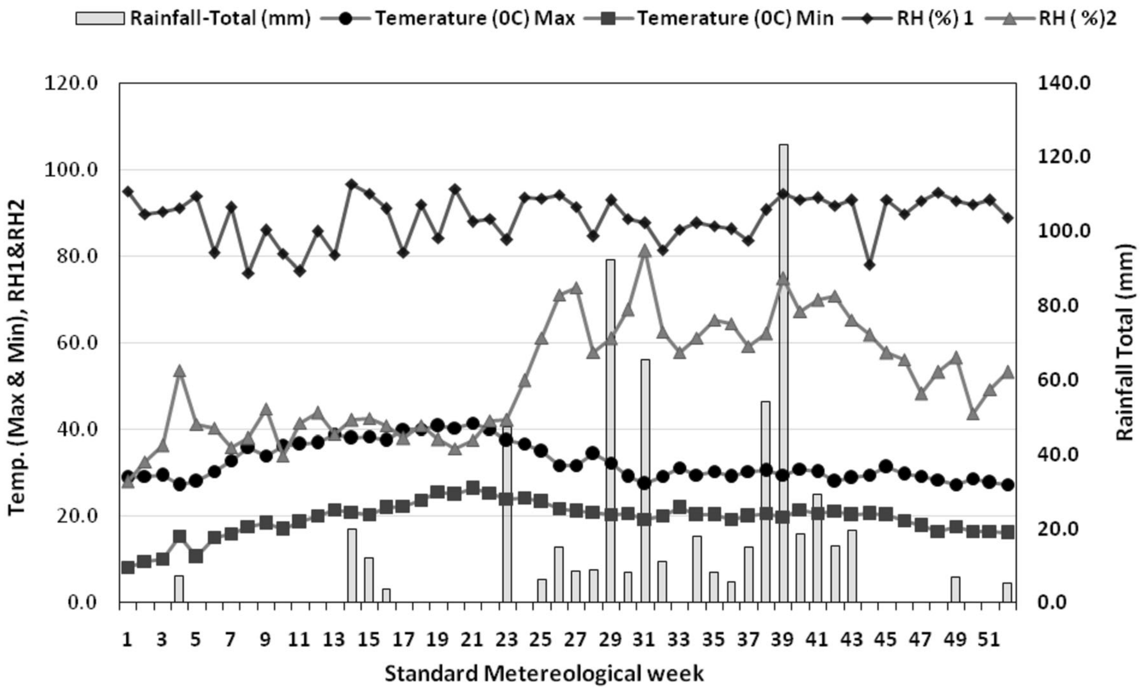

Fig. 1 Weekly meteorological data during crop growth recorded at experimental site (*Kharif* season 2019–2020)

described by Panse and Sukhatme [53]. The analysis of variance was analyzed using two factorial randomized block design to understand the significance of varieties, treatments and their interaction.

Results

Effect of PGRs on Different Morphological and Phenological Traits

The analyses of variance showed that significant differences among treatments (A), accessions (B), and replicates ($p < 0.05$) were observed for various recorded morphological traits. The results revealed that plant height ranged from 53.6 cm (GT-10) to 120.0 cm (swetha til) at the flowering stage. At the seed developmental stage, the range of variation was from 64.6 cm (GT-10) to 121.7 cm (swetha til). The maximum average plant height was recorded with the application of the mean of GA3 in all varieties at both flowering (87.8 cm) and seed developmental stage (112.7 cm); however, among the varieties, swetha til registered the highest plant height with the application of GA3 (20 ppm) at both flowering (120.0 cm) and seed development stage (121.8 cm). In addition, foliar treatment with OSA and TU also improved the plant height among all the sesame cultivars, and the highest plant height was observed in swetha til at both the flowering and seed developmental stages compared to the control (Supplementary Table 2a). The leaf area varied from 482.0 (GT-10) to 1275.1 cm^2 (swetha til) and from 458.5 (TKG-22) to 1142.2 cm^2 (swetha til) at the flowering stage and seed developmental stage, respectively. Similar to PH, among the PGRs, the highest leaf area at both flowering (1147.4 cm^2) and seed developmental stage (965.4 cm^2) was recorded with the application of GA3, whereas among the cultivars, swetha til showed the highest leaf area compared to the rest of the cultivars. The trait total number of branches was recorded and found to vary from 4.80 (TKG-22) to 6.00 (swetha til), and the highest number of branches was noticed when plants treated with GA3 (5.60), followed by OSA (5.30), whereas treatment with TU (5.10) was found at par with the control. Among the cultivars, swetha til followed by JCSDT-29 and GT-10 had the highest number of branches.

The analysis of variance underpinned that there were significant differences among treatments (A), accessions (B), and replicates ($p < 0.05$). The crop phenology traits such as days to first flower varied from 39.0 (GT-10) to 47.3 days (TKG-22); days to 50% flowering from 53.0 (swetha til) to 56.3 days (TKG-22) and days to maturity from 86.3 (TKG-22) to 91.7 days (TKG-22). The mean performance indicated that the application of PGRs caused earliness in the phenology of sesame and a minimum number of days to first flower (39.9 days), 50% flowering (53.4 days), and days to maturity (87.1 days) were observed with the application of GA3 followed by OSA and TU. On the other hand, among the cultivars, swetha til showed the earliest 50% flowering, while TKG-22 matured earliest (Supplementary Table 2b). Among the different PGR (GA, TU, and OSA), the application of GA3 (20 ppm) was found promising and phenological traits such as days to first flower, days to 50% flowering and days to maturity showed earliness by almost 6–7%, 3–4%, and 3–4%, respectively.

Effect of PGRs on Different Physiological Traits

The per se performance revealed that PGRs had a profound effect on SPAD chlorophyll meter readings (SCMR). It was observed that the SPAD values ranged from 37.3 (TKG-22) to 51.5 (swetha til) at flowering and from 41.4 (TKG-22) to 61.7 (swetha til) at the seed development stage. Among the PGRs, the foliar application of TU, followed by GA_3 and OSA at both the flowering and seed development stages, was found to be most promising in improving the SPAD values compared to the control (Supplementary Table 3a and Fig. 2). The cultivar Swetha til recorded the highest SPAD values, followed by JCSDT-29, followed by the rest of the cultivars. The RWC varied from 70.6 (TKG-22) to 83.3% (swetha til) and 74.5 (TKG-22) to 85.9% (GT-10) at the flowering and seed development stages, respectively (Supplementary Table 3a and Fig. 3). The per se performance further showed that the application of TU at both flowering (82.9%) and seed developmental stage (85.5%) was most effective in maintaining a higher RWC, followed by GA_3 and OSA compared to control. On the other hand, among the cultivars, the highest RWC was reported in cultivar swetha til followed by GT-10 at both the flowering and seed development stages.

Maintaining a lower canopy temperature by plants is an adaptive mechanism under rainfed conditions. A lower canopy temperature (CT) favors optimum metabolic activities and plants achieve such conditions by increasing the water absorption and transpiring more water. The per se performance showed that rainfed conditions increase the plants' canopy temperature; however, application of PGRs significantly lowers the canopy temperature. The CT was varied from 29.3 (swetha til) to 31.3 °C (GT-10 and TKG-22) at the flowering stage, whereas from 29.0 (swetha til) to 30.7 °C (TKG-22) at the seed development stage. The minimum canopy temperature among the cultivars was recorded in swetha til followed by JCSDT-29. The lowest canopy temperature when treated with GA_3 at both flowering (30.1 °C) and seed development stage (29.4 °C), indicating that growth regulators have a direct role in maintaining favorable tissue water content and lowering the leaf temperatures (Supplementary Table 2b and Fig. 3). The application of OSA and TU also lowers the canopy temperature at both the flowering and seed development stages compared to the control.

The results showed that the photosynthetic rate ranged from 9.8 (GT-10) to 18.9 μ mol CO_2 m^{-2} s^{-1} (swetha til) and from 11.9 (GT-10) to 21.2 μ mol CO_2 m^{-2} s^{-1} (swetha til) during flowering and seed development stage, respectively (Supplementary Table 3b). Likewise, transpiration rates showed a range of variation from 0.70 (GT-10) to 2.48 m mol H_2O m^{-2} s^{-1} (TKG-22) at the flowering stage, whereas 1.28 (JCSDT-29) to 2.25 m mol H_2O m^{-2} s^{-1} (TKG-22) at seed developmental stage. Data about stomatal conductance (gs) revealed a range of 0.66 (TKG-22) to 1.31 m mol H_2O m^{-2} s^{-1} (swetha til) and from 0.79 (GT-10 and TKG-22) to 1.36 m mol H_2O m^{-2} s^{-1} (GT-10) at the seed developmental stage (Supplementary Table 3c and Fig. 3). Substantial improvement was recorded concerning intrinsic water use efficiency (iWUE) under the influence of plant growth regulators (Supplementary Table 4a, Fig. 3). It was significantly varied at both flowering (9.1–19.2 μ mol mol^{-1}) and seed development stage (10.3–24.8 μ mol mol^{-1}). The mean data indicated that physiological traits such as photosynthetic rate, stomatal conductance, and intrinsic water use efficiency were found most promising with the application of GA_3 followed by OSA and TU, whereas treatment with TU and OSA was found most effective in lowering the transpiration rate among sesame cultivars. Among the cultivars, cultivar Swetha til followed by JCSDT-29 maintains a high photosynthetic rate, stomatal conductance, and intrinsic water use efficiency; however, the lowest transpiration rate was observed in TKG-22 followed by GT-10.

Effect of PGRs on Various Yield Contributing and Yield Traits

The various yield traits showed significant ($p < 0.05$) differences among the cultivars due to the application of different PGRs. The results showed that the yield-attributing traits such as capsule length {1.85 (GT-10) to 2.17 cm (swetha til)} capsule dry weight {4.5 (TKG-22) to 11.9 g (swetha til)}, number of capsule plant-1 {59.9 (TKG-22) to 108.8 (JCSDT-29)}, number of capsule plant-1 {58.0 (TKG-22) to 83.3 (swetha til)}, and test weight {2.30 (TKG-22) to 3.64 g (swetha til)} varied significantly (Table 1, Supplementary Table 4b, and Fig. 4). Among the different tested PGRs, the foliar application of GA3 (20 ppm) followed by OSA (380 ppm) was found to be most effective in improving the yield-contributing traits of sesame cultivars compared to the control. Similarly, among the cultivars, swetha til, followed by JCSDT-10, was found to be superior compared to the rest of the cultivars. Furthermore, data pertaining to seed weight per plant {11.47 (TKG-22) to 16.23 g (swetha til)} and harvest index {13.1

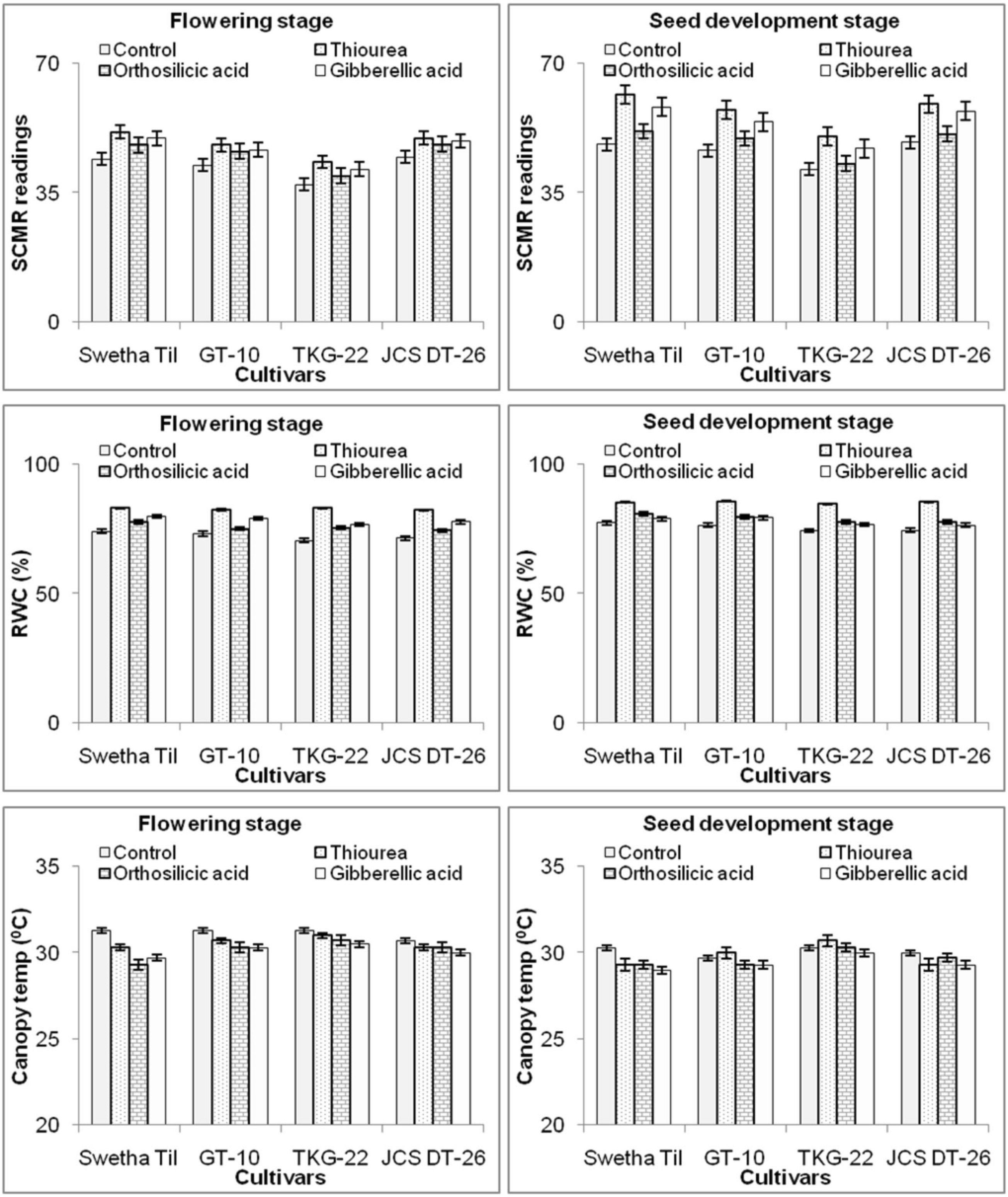

Fig. 2 Effect of different PGRs on physiological traits (SCMR: SPAD chlorophyll meter readings, reading, RWC: relative water content and canopy temperature) at flowering and seed development stage among sesame cultivars. Data are the means of five replicated plants for each cultivar ($p < 0.05$)

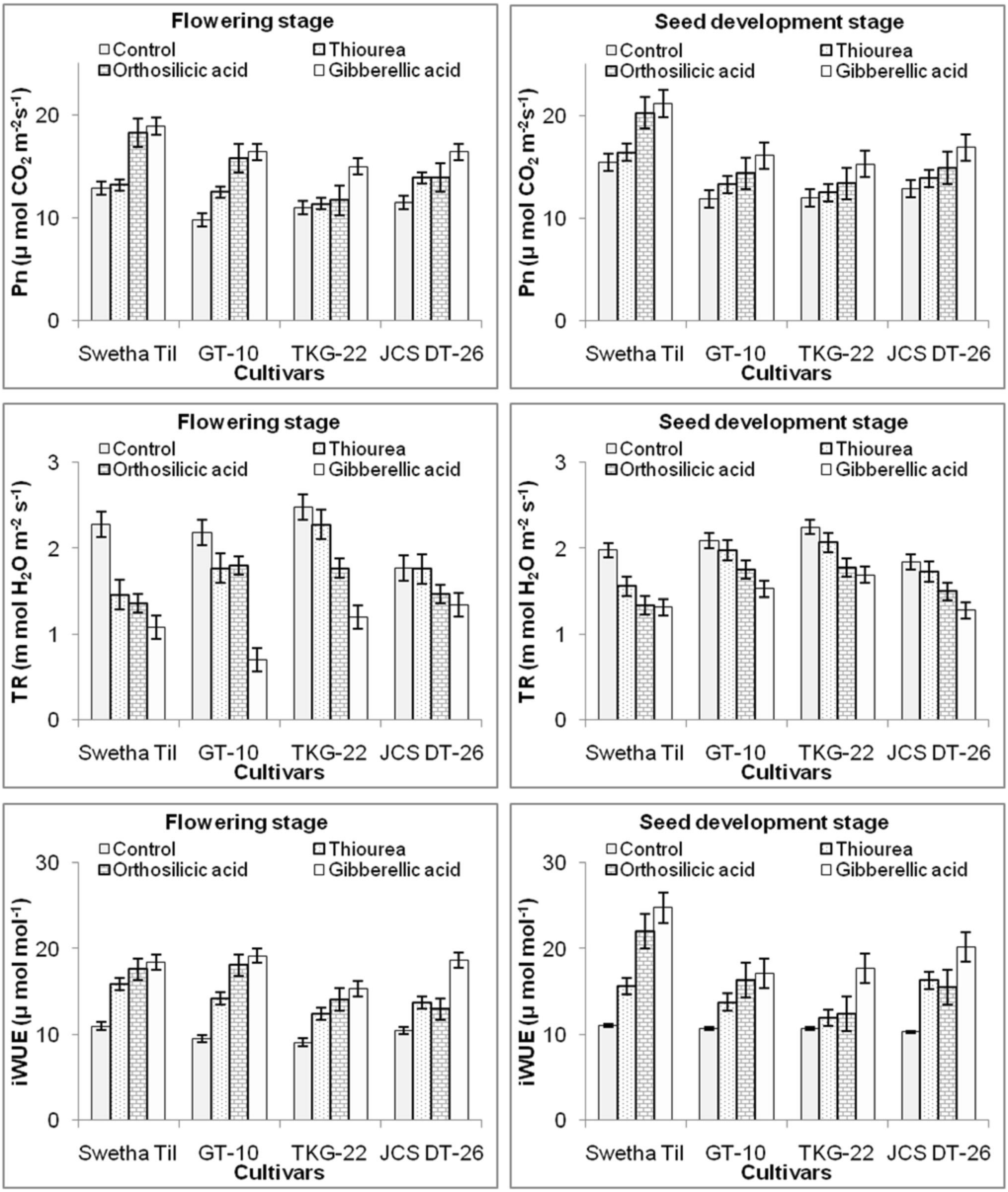

Fig. 3 Effect of different PGRs on physiological traits (Pn: photosynthetic rate, TR: transpiration rate and iWUE: intrinsic water use efficiency) at flowering and seed development stage among sesame cultivars. Data are the means of five replicated plants for each cultivar ($p < 0.05$)

(TKG-22) to 23.0% (swetha til)} showed significant differences (Fig. 4). The percent increase calculations indicated that the application of all three PGRs, viz., GA3 (25–26%), OSA (10–11%), and TU (6–7%), significantly enhanced the seed yield in sesame and among the cultivars.

Table 1 Influence of plant growth regulators (TU: 500 ppm; OSA: 380 ppm; GA_3: 20 ppm and C: water sprayed) on seed yield/plant, harvest index and oil content traits of sesame (varieties-V1: Swetha Til; V2: GT-10; V3: TKG-22 and V4: JCSDT-29) at flowering stage and seed development stage

Treatments	Seed yield/plant (SYP)					Harvest index (HI)					Oil content (OC)				
	V1	V2	V3	V4	M	V1	V2	V3	V4	M	V1	V2	V3	V4	M
Control	12.57	11.73	11.47	12.00	11.9	19.5	16.5	13.1	17.4	16.7	42.2	41.6	43.3	45.9	43.3
GA_3	16.23	14.27	14.23	15.03	14.9	23.0	20.3	19.5	22.0	21.2	49.8	48.6	48.5	49.5	49.1
OSA	14.47	12.80	12.83	13.10	13.3	21.4	19.0	17.8	20.3	19.6	49.2	49.0	48.1	49.2	48.9
TU	13.57	12.13	12.53	12.70	12.7	20.2	17.7	16.1	18.3	18.1	49.3	49.2	48.0	49.0	48.9

	SYP S. Em ±	SYP CD (5%)	HI S. Em ±	HI CD (5%)	OC S. Em ±	OC CD (5%)
Varieties	0.06	0.17	0.08	0.22	0.42	0.82
PGRs	0.06	0.17	0.08	0.22	0.42	0.82
Interaction	0.11	0.33	0.15	NS	0.84	1.64

Trt treatment, *M* mean, significance level: 5% level

Among the cultivars, the highest seed yield was observed in cv. swetha til followed by JCSDT-29 (Fig. 5).

Effect of PGRs on Biochemical Traits

Sesame oil is legendary for its stability as a result of its oxidation resistance; it is also a rich source of saturated and unsaturated fatty acids. The oil content among sesame cultivars ranged from 41.6 (GT-10) to 49.8% (swetha til). With respect to oil content, it was reported that the foliar application of GA_3 was most promising in improving the oil content, followed by TU and OSA. The GA_3 increased the oil content by almost 13.4%, whereas both OSA and TU enhanced the oil content by almost 12.9% among sesame cultivars. The highest oil content was recorded in cv. JCSDT-29, followed by swetha til, which had the maximum oil content of GA_3 (Supplementary Table 5 and Fig. 4). Results showed that both saturated (palmitic acid) and unsaturated (oleic and linoleic acid) fatty acids were improved upon the application of PGRs. The palmitic acid varied from 8.2 to 11.6%, the oleic acid from 42.4 to 49.8%, and the linoleic acid from 33.7 to 42.8%. It was reported that application of GA3 followed by OSA was most effective in improving the both saturated and unsaturated fatty acids in sesame, whereas among the cultivars, swetha til was performed superiorly compared to the rest of the cultivars and control.

Discussion

The sesame cultivation is mostly restricted to the arid/semi-arid regions. Maintaining the yield potential of sesame genotypes through the application of different PGRs is an important avenue of research to enhance productivity under rainfed conditions. The improvement in plant's resistance to the different stresses, together with drought stress results in accelerated growth and development processes [7]. In the present study, an apparent relationship between PGRs and growth parameters has been established in sesame. It was observed that the application of PGRs not only improved plant growth by regulating the plant's physiological processes but also significantly contributed to enhanced seed yield (almost 25–26%) in sesame under rainfed conditions. The recent findings suggested that crop growth and physiological parameters can be used for the estimation of plants' ability to withstand adverse climatic conditions [2–4, 51, 62, 74]. A remarkable increase in total leaf area (72–74%), plant height (30–50%), and the number of branches (9–10%) was observed due to the application of GA_3 followed by TU and OSA as compared to control. The application of GA_3 might have aided in cell elongation and turn stem elongation, by increasing the wall plasticity and consequently [16] improving the growth traits [37, 79]. In addition, increased leaf area due to application of GA3 captured more light which ultimately results in enhanced plant's dry weight [34].

The application of PGRs enhanced the trait expression under rainfed conditions among cultivars tested. Earlier reports suggested that the limited water availability during crop growth drastically reduced the physiological trait expression in sesame [4, 51, 67, 75]. Results indicated that the SPAD values an index of the pigment chlorophyll are essential to harvest photons [13]. Our results showed that the SPAD values in tested varieties were increased by 14–15% at flowering and 23–24% at the seed development stages upon application of TU under rainfed conditions. The enhancing effect of TU on SPAD values was due to the

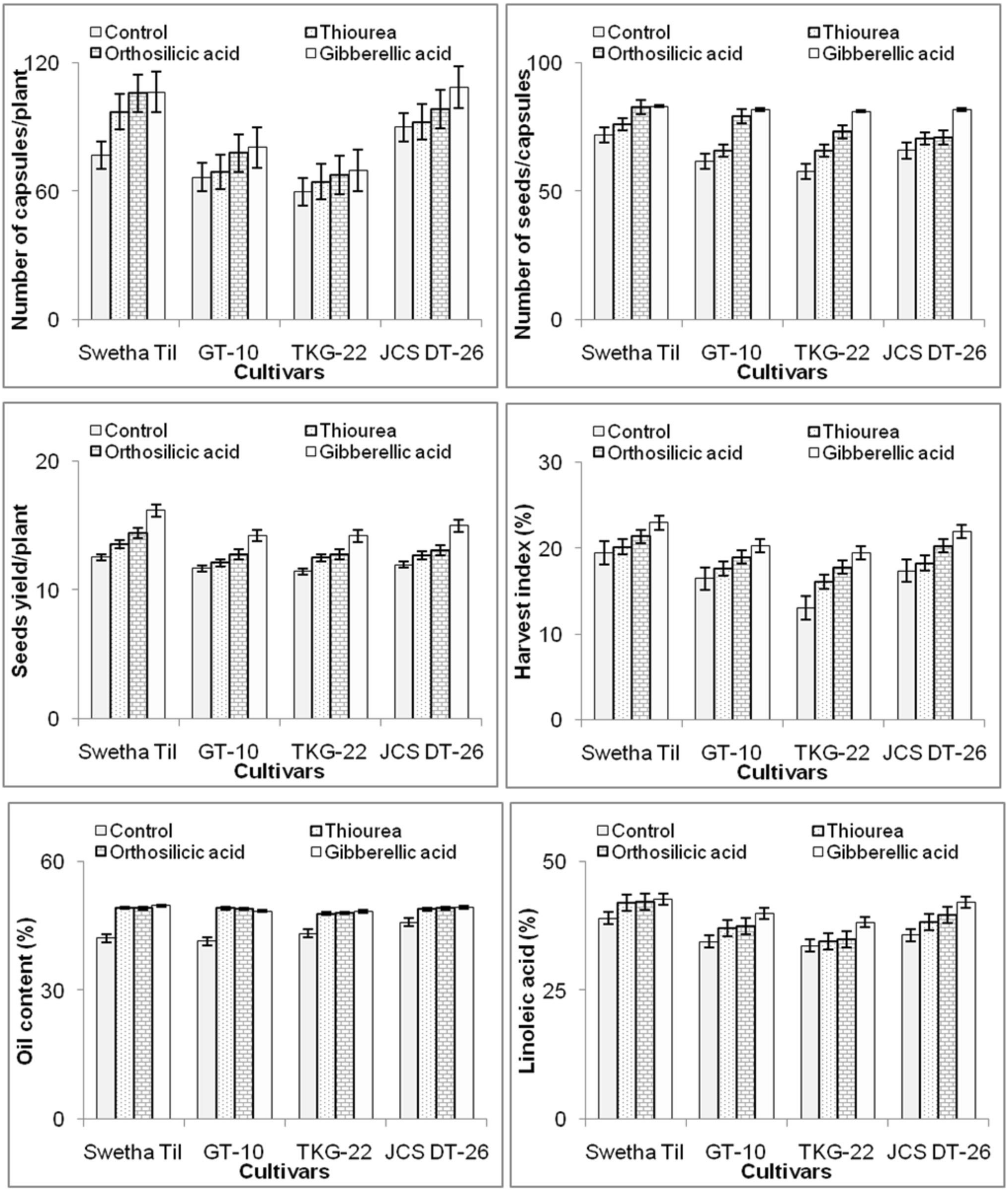

Fig. 4 Effect of different PGRs on yield contributing, yield and biochemical traits (number of capsules/plant, number of seeds/capsule, oil content and linolenic acid) among sesame cultivars. Data are the means of five replicated plants for each cultivar ($p < 0.05$)

presence of 'amine' and 'thiol' group that probably act as a ROS (reactive oxygen species) scavenger or maybe supplier of nutrients under water-limited conditions [52, 54, 60, 76]. Moreover, the application of TU improves the photosynthesis efficiency, which is strongly linked with the up-regulation of genes related to large subunits of

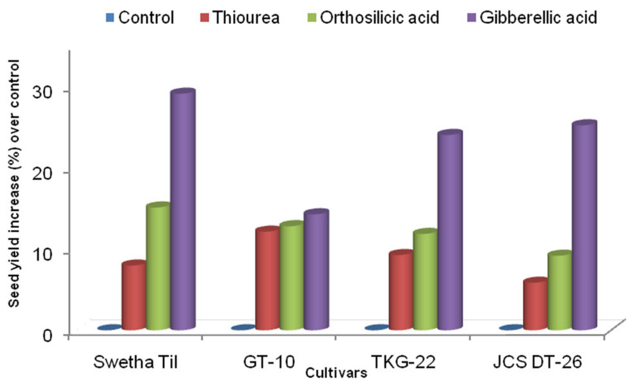

Fig. 5 Percent increase in seed yield due to application of different PGRs among the sesame cultivars. Data are the means of five replicated plants for each cultivar ($p < 0.05$)

Rubisco that protect the photosynthetic assembly under water-limited conditions. This corroborates the views of Vineeth et al. [81].

Another important trait under water-limited conditions is leaf tissue relative water content, an indirect measure of tissue water status since even mild water stress has been reported to affect the RWC [4, 20, 50, 51]. Our results indicated that the application of different PGRs, particularly TU significantly improves the RWC (13–15%) in sesame cultivars under rainfed conditions. These results are in good agreement with the findings of Akladious et al. [1] in sunflower. During the early plant growth and developmental stages, limited water availability impairs the biosynthesis of chlorophyll, ceases the rate of photosynthesis and relative water content, and ultimately results in lower seed yields [14]. Thiourea plays an essential role in plant growth, development, and yield formation [47, 89]. The application of TU under water-limited environments brings down the water consumption by plants [83] and enhances the water use efficiency [21].

Previous studies revealed that moisture stress negatively affects the photosynthetic rate and other related parameters in sesame [22, 23, 66, 75, 85]. Similar to this, water-limited conditions restrict all photosynthesis-related parameters of sesame in the present study. However, results indicated that the application of GA_3 followed by OSA and TU significantly improved the photosynthetic rate and other related traits as compared to the control. These results are found in well accordance with the findings of Behera et al. [10] in sesame. Yuan et al. [87] suggested that foliar application of GA_3 promotes the development of chloroplasts by promoting the levels of protochlorophyllide oxidoreductase (POR) [69], prolonged chlorophyll synthesis, stimulates the Rubisco activity [46], and subsequently, photosynthetic efficiency which contributes to improved physiological activity. Khan et al. [32, 35] reported that the application of GA_3 significantly increased the photosynthetic rate in mustard which is due to enhanced activity of the carbonic anhydrase enzyme. The enzyme carbonic anhydrous helps maintain a constant supply of CO_2 to Rubisco and also plays a crucial role in photosynthetic CO_2 fixation in the stroma [78]. On the other hand, the role of TU in improving photosynthetic efficiency and maintaining redox homeostasis through its broad range of ROS scavenging activity has been already established [31, 81]. Application of silicon particularly at higher concentrations enhanced water uptake, transpiration rate and stomatal conductance in plants [15]. Silicon helps in maintaining an optimum CO_2 levels for photosynthesis and prevents photo-inhibition under water deficit conditions. Zhang et al. [90] revealed that silicon promotes the transcription of some photosynthesis-associated genes, improves the photochemical process, and consequently enhances the process of photosynthesis.

Apart from the soil moisture, the atmospheric temperature is the other climatic variable that has a great influence on germination, growth, capsule formation [38] and yield of sesame [57]. No doubt, cultivars with lower canopy temperatures secured higher yields as reported in other studies [10, 41, 51]. Due to the importance of evaporative cooling as a major component of the leaf energy balance, leaves temperature can be used as an indicator for rates of water loss or stomatal opening. Our results showed that the application of PGRs significantly lowered the CT and increased the stomatal conductance. The cv. Swetha til had minimum canopy temperature and higher stomatal conductance when treated with GA_3, followed by OSA, and TU. Application of GA_3 increased the number of stomata, dimension of stomata, and stomata pore size [28]. Water uptake is crucial for seed yield in any crop [41, 64, 65]. Under water stress conditions, a plant's ability to control the size of the stomatal opening is an important mechanism to control water loss. Alongside, Goring [24] stated that the increased stomatal conductance due to the application of GA_3 has been related to the higher accumulation of carbohydrates and potassium in guard cells of treated plants that may influence the speed and degree of stomata opening. Hence, by maintaining a favorable water uptake and controlling the stomata size, opening and closing of stomata and stomatal conductance plants tend to regulate leaf temperatures. In addition, the role of OSA in maintaining leaf water status by closing stomata, increasing relative water content and cell turgor pressure under water deficit conditions was also established in previous studies such as Ratnakumar et al. [59] and Wakchaure et al. [83, 84]. Therefore, it can be concluded that these surrogate traits such as SCMR, RWC, and CT greatly contributed to the enhancement of final seed yield with the application of PGRs.

In sesame, seed yield is a complex trait that depends upon several yield-contributing traits. The results suggested that yield-contributing traits such as NCP, CWP, NSC, TW, TDM, and SWP were improved due to the application of PGRs. Among the different PGRs tested, GA_3 followed by OSA was found most superior and improved all the yield-contributing traits including seed yield compared to the control and rest of the PGRs. The per se performance revealed that NCP by almost 24–25%, NSC by 27–28%, seed yield by 33–34%, and harvest index by 26–27% increased with the application of GA_3 and these results are in corroboration with the reports of Khan et al. [33, 34] in mustard; whereas Vekaria et al. [22], Hadif [24], and Thuc et al. [79] in sesame. Application of GA_3 improves the plant's fruit-set ability, increases the number of fruits [55], reduces fruit shattering and enhances translocation of photo assimilates to seeds [33] in mustard. In addition, foliar application with GA_3 probably contributed to seed formation, and their optimum nourishment, and reduced the number of aborted seeds [12]. During the grain-filling stage, GA_3 has a positive role in promoting the development of embryos that subsequently results in grain-filling process, and an increase in mean grain weight [87]. GA_3 improves the weight of seeds compared to control but the observed difference was not significant, indicating GA_3 is not very effective in improving seed mass. On the other hand, Silicon was also proven to enhance economic yields in crop plants by modifying the mobilization of photo assimilates source-sink relationships, increasing photosynthesis, conductance of mesophyll cells, nutrient use efficiency from vegetative tissues to reproductive organs [18, 19].

Sesame is known for its superior oil quality and the results of the current study suggested that GA_3 (20 ppm) application is highly promising in improving the oil content and quality traits (saturated and unsaturated fatty acid) of seeds. Foliar application of GA_3 improved the oil content by almost 13–14% in sesame and these results are found in agreement with the reports of Aytac and Kinaci [5] and Nizamani et al. [49] in Brassica. The fatty acid profiling showed that the application of GA_3 significantly influenced both saturated (palmitic acid) and unsaturated (oleic and linoleic acid). Treatment with GA_3 at 20 ppm increased the palmitic acid by almost 23–24%, oleic acid by around 12–13%, and linoleic acid by nearly 13–14% in sesame cultivars. However, the variation among the cultivars for both oil content and fatty acid contents was not much higher. These findings are in agreement with the reports of Ijaz et al. [29] on canola, and Hamza [26] on safflower. The foliar application of GA_3 can be attributed to the enhanced synthesis of enzymes that are directly associated with the synthesis of and metabolisms of fatty acid [16, 17].

Conclusions

The exogenous foliar application of PGRs has significantly improved the morphological, physiological, total seed yield, and quality traits such as oil and fatty acid content in the sesame cultivars tested. Most of the traits responded better with the application of gibberellic acid (20 ppm), followed by ortho-silicic acid (380 ppm) and thiourea (500 ppm). Swetha til, a white-colored cultivar followed by JCSDT-29 were registered superior morpho and yield attributes for most of the traits studied; whereas thiourea was found highly effective in improving the physiological traits. The enhanced seed yield was 25–26%, 10–11%, and 6–7% recorded with the application of gibberellic acid, ortho-silicic acid, and thiourea over control. Based on various trait responses, it can be concluded that the foliar application of gibberellic acid at 20 ppm is recommended for optimum productivity under rainfed conditions for the sesame variety swetha til.

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Data availability Access to cultivar resequencing data can be obtained by contacting the corresponding author. All other datasets generated and analyzed for this study are included in the article/Supplementary Material**.**

Declarations

Conflict of interest The authors do not have any conflicting interests.

References

1. Akladious SA (2013) Influence of thiourea application on some physiological and molecular criteria of sunflower (*Helianthus annuus* L.) plants under conditions of heat stress. Protoplasma 251:625–638. https://doi.org/10.1007/s00709-013-0563-2
2. Amin AA, Abd El-Kader AA, Shalaby MAF, Gharib FAE, Rashad EM, Teixeira da Silva JA (2013) Physiological effects of salicylic acid and thiourea on growth and productivity of maize plants in sandy soil. Commun Soil Sci Plant Anal 44:1144–1155. https://doi.org/10.1080/00103624.2012.756006

3. Anjum F, Wahid A, Farooq M, Javed F (2011) Potential of foliar applied thiourea in improving salt and high temperature tolerance of bread wheat (*Triticum aestivum*). Int J Agric Biol 13:251–256
4. Anusha PL, Pasala R, Kulasekaran R, Pandey BB, Virupaksham U, Perika S (2023) Analysing the SPAD dynamics of water-stressed vs. well-watered sesame (Sesamum indicum L.) accessions and establishing their relationship with seed yield. Peer J 11:e14711. https://doi.org/10.7717/peerj.14711
5. Aytac Z, Kinaci G (2009) Genetic variability and association studies of some quantitative characters in winter rapeseed (B*rassica napus* L.). Afr J Biotech 8:3547–3554
6. Banoo M, Sinha BK, Chand G, Sinha R, Gupta M, Sharma M, Dogra S, Kouser F, Kour M, Sharma D (2022) Response of growth retardants paclobutrazol and cycocel on morphological characteristics in indian mustard (brassica juncea L.) genotypes under rainfed condition. J Pharm Innov 11(12):715–719
7. Bartlett MK, Detto M, Pacala SW (2019) Predicting shifts in the functional composition of tropical forests under increased drought and CO_2 from trade-offs among plant hydraulic traits. Ecol Lett 22:67–77. https://doi.org/10.1111/ele.13168
8. Beebe SE, Rao IM, Blair MW, Acosta-Gallegos JA (2013) Phenotyping common beans for adaptation to drought. Front Physiol 4(35):1. https://doi.org/10.3389/fphys.2013.00035
9. Behera S, Padhiary AK, Rout S, Nayak A, Behera D, Nanda PK (2017) Effect of plant growth regulators on morpho-physiological and yield parameters of some sesame (Sesamum indicum L.) cultivars. Int J Curr Microbiol App Sci 6(11):1784–1809. https://doi.org/10.20546/ijcmas.2017.611.215
10. Behera S, Padhiyari AK, Jena M (2018) Effect of plant growth regulators on morphophysiological and yield parameters of some sesame (Sesamum indicum L) cultivars. 6th Global Summit on Plant Science, Valencia, Spain. J Plant Biochem Physiol. https://doi.org/10.4172/2329-9029-C1-003
11. Borchani C, Besbes S, Blecker CH, Attia H (2010) Chemical characteristics and oxidative stability of sesame seed, sesame paste, and olive oils. J Agric Sci Technol 12:585–596
12. Boultior C, Morgan DG (1992) Development of oilseed rape buds, flowers and pods invitro. J Expt Bot 43(253):1089–1096
13. Caffarri S, Tibiletti T, Jennings RC, Santabarbara S (2014) Comparison between plant photosystem I and photosystem II architecture and functioning. Curr Protein Pept Sci 15(4):296–331. https://doi.org/10.2174/1389203715666140327102218
14. Chattha MB, Khan I, Mahmood A, Chattha MU, Anjum SA, Ashraf U, Zain M, Bilal U (2017) Seed priming with thiourea improves the performance of late sown wheat. J Agric Res 55:29–39
15. Chen D, Wang S, Yin L, Deng X (2018) How does silicon mediate plant water uptake and loss under water deficiency? Front Plant Sci 9:281. https://doi.org/10.3389/fpls.2018.00281
16. Colebrook EH, Thomas SG, Phillips AL, Hedden P (2014) The role of gibberellin signalling in plant responses to abiotic stress. J Exp Biol 217:67–75. https://doi.org/10.1242/jeb.089938
17. Dar TA, Uddin M, Khan MMA, Ali A, Hashmi N, Idrees M (2015) Cumulative effect ofgibberellic acid and phosphorus on crop productivity, biochemical activities and trigonelline production in Trigonella foenumgraecum L. Cogent food Agric 1:1–14. https://doi.org/10.1080/23311932.2014.995950
18. Detmann K, Araújo W, Martins S, Fernie AR, Da Matta F (2013) Metabolic alterations triggered by silicon nutrition: is there a signalling role for silicon? Plant Signal Behav 8:e22523. https://doi.org/10.4161/psb.22523
19. Detmann KC, Araújo WL, Martins SC, Sanglard LM, Reis JV, Detmann E, Rodrigues FA, Nunes-Nesi A, Fernie AR, DaMatta FM (2012) Silicon nutrition increases grain yield, which, in turn, exerts a feed-forward stimulation of photosynthetic rates via enhanced mesophyll conductance and alters primary metabolism in rice. New Phytol 196:752–762. https://doi.org/10.1111/j.14698137.2012.04299.x
20. Dias MC, Correia S, Serôdio J, Silva AMS, Freitas H, Santos C (2018) Chlorophyll fluorescence and oxidative stress endpoints to discriminate olive cultivars tolerance to drought and heat episodes. Sci Hortic 231:31–35. https://doi.org/10.1016/j.scienta.2017.12.007
21. Garg BK, Burman U, Kathju S (2006) Influence of thiourea on photosynthesis, nitrogen metabolism and yield ofcluster bean (Cyamopsis tetragonoloba L. Taub.) under rainfed conditions of Indian arid zone. Plant Growth Regul 48:237–245. https://doi.org/10.1007/s10725-006-0002-x
22. Gopika K, Ratnakumar P, Guhey A, Manikanta ChLN, Pandey BB, Ramya KT, Rathnakumar AL (2022) Physiological traits and indices to identify tolerant genotypes in sesame (*Sesamum indicum* L.) under deficit soil moisture condition. Plant Physiol Rep 27:744–754. https://doi.org/10.1007/s40502-022-00701-9
23. Gopika K, Ratnakumar P, Pandey BB, Manikanta ChLN, Ramya KT, Rathnakumar AL, Guhey A (2023) Source and sink traits and their relationship under deficit soil moisture stress conditions in an indeterminate crop: sesame (Sesamum indicum L.). Plant Prod Sci 26(2):153–163. https://doi.org/10.1080/1343943X.2023.2203404
24. Goring H, Koshuchuwa S, Deckert C (1990) Influence of gibberellic acid on stomatal movement. J plant physiol 186:367–374. https://doi.org/10.1016/S0015-3796(11)80235-0
25. Hadif WM (2019) Interaction effects of drought episode after temporary wilting point and gibberellic acid (GA3) on the growth and yield of sesame (Sesamum indicum L.). Plant Arch 19(2):4307–4315
26. Hamza M (2015) improving petal, seed and oil yields of safflower using melagrow, gibberellic acid and cytokinin. J Plant Prod Mansoura Univ 6(6):809–820. https://doi.org/10.21608/JPP.2015.49823
27. Hattori T, Inanagaa S, Arakib H (2005) Application of silicon enhanced drought tolerance in sorghum bicolor. Physiol Plant 123:459–466. https://doi.org/10.1111/j.1399-3054.2005.00481.x
28. Ibrahim ES, Mahmoud SA, Abdelmageed AM, Bayoumi TY (2017) Influence of gibberellic acid on beta vulgaris L. plants under drought conditions. Egypt J Agron 39(1):99–116. https://doi.org/10.21608/agro.2017.634.1057
29. Ijaz M, Sher A, Sattar A, Shahid M, Nawaz A, Ul-Allah S, Tahir M, Ahmad S, Saqib M (2019) Response of canola (Brassica napus L.) to exogenous application of nitrogen, salicylic acid and gibberellic acid under an arid climate. Soil Environ 38(1):90–96. https://doi.org/10.25252/SE/19/71619
30. Kaya C, Sarioğlu A, Akram NA, Ashraf M (2019) Thiourea-mediated nitric oxide production enhances tolerance to boron toxicity by reducing oxidative stress in bread wheat (Triticum aestivum L.) and durum wheat (Triticum durum Desf.) plants. J Plant Growth Regul. https://doi.org/10.1007/s00344-019-09916-x
31. Kelner MJ, Bagnell R, Welch KJ (1990) Thiourea react with superoxide radicals to yield a sulfhydryl compound. Explanation protective effect against paraquat. J Biol Chem 265:1306–1311
32. Khan NA (1996) Effect of gibberellic acid on carbonic anhydrase, photosynthesis, growth and yield of mustard. Biol Plant 38:145–147. https://doi.org/10.1007/BF02879650
33. Khan NA, Ansari HR (1997) Effect of gibberellic acid spray and basal nitrogen and phosphorus on productivity and fatty acid composition of rapeseed-mustard. J Agron Crop Sci 179(1):29–33. https://doi.org/10.1111/j.1439-037X.1997.tb01144.x
34. Khan NA, Ansari HR (1998) Effect of gibberellic acid spray during ontogeny of mustard on growth, nutrientuptake and yield

characteristics. J Agron Crop Sci 181(1):61–63. https://doi.org/10.1111/j.1439037X.1998.tb00399.x
35. Khan NA, Ansari HR, Mobin M (1996) Effect of gibberellic acid and nitrogen on carbonic anhydrase activity and mustard biomass. Biol Plant 38:601–603. https://doi.org/10.1007/BF02890614
36. Kumar A, Singh SN, Khan MA (2018) To know the effect of foliar application of thiourea and potassium nitrate on physiological growth at different stages of sesame (Sesame indicum L.). J Pharmacogn Phyto chem 7(2):2156–2158
37. Kumar RN, Singh R, Khan W (2021) Effect of spacing and plant growth regulators on growth and yield of zaid sesame (Sesamum indicum L.). Int J Curr Microbiol App Sci 10(3):205–210. https://doi.org/10.20546/ijcmas.2021.1003.028
38. Langham DR (2007) Phenology of sesame. In: Janick J, Whipkey A (eds) Issues in new crops and new uses. ASHS Press, Alexandria, pp 144–182
39. Lone NA, Mir MR, Khan NA (2005) Effect of gibberellic acid on physiological attributes and yield of mustard(B*rassica juncea* L.). Appl Biol Res 7:24–26
40. Mani F, Bettaieb T, Zheni K, Doudech N, Hannachi C (2012) Effect of hydrogen peroxide and thiourea on fluorescence and tuberization of potato (Solanum tuberosum L.). J Stress Physiol Biochem 8:61–71
41. Manikanta C, Pasala R, Kaliamoorthy S, Basavaraj PS, Pandey BB, Vadlamudi DR, Nidamarty M, Guhey A, Kadirvel P (2023) Safflower (Carthamus tinctorius L.) crop adaptation to residual moisture stress: conserved water use and canopy temperature modulation are better adaptive mechanisms. Peer J 11:e15928. https://doi.org/10.7717/peerj.15928
42. Mauad M, Crusciol CAC, Nascente AS, Filho HG, Lima GPP (2016) Effects of silicon and drought stress on biochemical characteristics of leaves of upland rice cultivars. Rev Cienc Agron 47(3):532–539. https://doi.org/10.5935/1806-6690.20160064
43. Mbaraka SR, Abayisenga JC, Nkurunziza C, Rucamumihigo FX, Habimana S, Nguyen LV, Gasangwa I, Neeru J, Mutamuliza E, Rwalinda FM, Rushemuka P (2021) Effect of combined application of foliar sprays of orthosilicic acid (OSA) with basal NPK fertilizer on growth and yield of rice (Oryza sativa L.). SILICON 14(10):5207–5212. https://doi.org/10.21203/rs.3.rs-457545/v1
44. Mehmood MZ, Qadir G, Afzal O, Din AMU, Raza MA, Khan I, Hassan MJ, Awan SA, Ahmad S, Ansar M, Aslam MA (2021) Paclobutrazol improves sesame yield by increasing dry matter accumulation and reducing seed shattering under rainfed conditions. Int j plant prod 15(3):337–349. https://doi.org/10.1007/s42106-021-00132-w
45. Minhas PS, Rane J, Ratnakumar P (2017) Abiotic stress management for resilience agriculture. Springer, Berlin, pp 01–517
46. Nath N, Mishra SD (1990) Changes in RuBPcase activity of developing and senescing barley leaves and its alteration by plant growth regulators. Indian J Exp Biol 28(7):665–670
47. Naz S, Perveen S (2021) Response of wheat (Triticum aestivum L. var. Galaxy-2013) to pre sowing seed treatment with thiourea under water stress. Pak J Bot 53(4):1209–1217. https://doi.org/10.30848/PJB2021-4(20)
48. Nehal N, Khan A, Sharma N, Tripathi SK, Singh M (2018) Role of GA3, SA and ABA on growth and yield of Indian mustard [Brassica juncea (L.) Czern. & Coss.] under rainfed condition. J Pharmacogn Phyto chem 7(2S):199–203
49. Nizamani MR, Ansari MA, Siddiqui MA, Nizamani GS, Nizamani F, Naz M, Mastoi AH (2018) Effect of gibberellic acid on yield and yield attributes of canola (Brassica napus L.) varieties. Indian J Sci Res 6(8):863–880
50. Pandey BB, Ratnakumar P, Ramesh K, Qureshi MAA, Sowjanya LG, Guhey A (2021) Leaf potassium status for drought tolerance: the hunt for promising sesame. J Plant Nutr 45(18):2774–2786. https://doi.org/10.1080/01904167.2022.2043374
51. Pandey BB, Ratnakumar P, Usha KB, Dudhe MY, Lakshmi GS, Ramesh K, Guhey A (2021) Identifying traits associated with terminal drought tolerance in sesame (Sesamum indicum L.) genotypes. Front Plant Sci 12:739896. https://doi.org/10.3389/fpls.2021.739896
52. Pandey M, Srivastava AK, D'Souza SF, Penna S (2013) Thiourea, a ROS scavenger, regulates source-to sink relationship to enhance crop yield and oil content in Brassica juncea (L.). PLoS ONE 8:e73921. https://doi.org/10.1371/journal.pone.0073921
53. Panse VG, Sukhatme PV (1964) Statistical methods for agricultural workers, 2nd edn. ICAR, New Delhi
54. Perveen A, Wahid A, Mahmood S, Hussain I, Rasheed R (2015) Possible mechanism of medium supplemented thiourea in improving growth, gas exchange, and photosynthetic pigments in cadmium-stressed maize (Zea mays). Brazilian J Bot 38:71–79. https://doi.org/10.1007/s40415-014-0124-8
55. Pramanik K, Mohapatra PP (2017) Role of auxin and gibberellins growth, yield and quality of tomato – a review. Int J Curr Microbiol App Sci 6:1624–1636. https://doi.org/10.20546/ijcmas.2017.611.195
56. Ramesh K, Mahapatra A, Dhir BC, Vishnuvadhan Reddy A (2020) Low temperature stress dictates the successof rice fallow sesame in Odisha - An analysis. J Oilseeds Res 37:110
57. Ramesh K, Dhir BC, Harisudan C, Ramanamurthy KV, Aziz qureshi A, Praduman Yadav (2022) Evidence of atmospheric temperature stress on the prospects of rice fallow sesame in Odisha. In: Paper presented at the National Conference on Managing Weather and Climate Risks in Agriculture, SKUAT, pp 24–26
58. Ramesh K, RatnaKumar P, Harisudan C, Bhaskar S, Vishnuvardhan Reddy A (2019) Sesame (*Sesamum indicum*) in the rice fallow environment -a critical appraisal. J Oilseeds Res 36(4):1–9
59. Ratnakumar P, Deokate PP, Rane J, Jain N, Kumar V, Berghe DV, Minhas PS (2016) Effect of ortho-silicic acid exogenous application on wheat (Triticum aestivum L.) under drought. J Funct Environ Bot 6(1):34–42. https://doi.org/10.5958/2231-1750.2016.00006.8
60. Ratnakumar P, Khan MIR, Minhas PS, Sultana R, Per TS, Deokate PP, Nafees A, Khan Y, Singh RJ (2016) Can plant bioregulators minimize the crop productivity losses caused by drought, heat stress and salinity?An integrated review. J Appl Bot Food Qual 89:113–125. https://doi.org/10.5073/JABFQ.2016.089.014
61. Ratnakumar P, Manikanta CHLN, Pandey BB, Gopika K, Kusumakumari P, Ramesh K, Ramya KT, Rathnakumar AL (2021) Adaptations and mitigation strategies for oilseed crops under abiotic stress: step towards climate resilience. In: Prakash M, Gomathi R, Basu PS, Vanaja M, Kalarani MK (eds) Physiological interventions for developing climate resilient pulses & oil seed crops. International Books & Periodical Supply Service, New Delhi, pp 69–91
62. Ratnakumar P, Pandey BB, Lakshmi GS, Ramesh K, Guhey A, Reddy AV (2021) An insight into the mechanisms of intermittent drought adaptation in sesame (Sesamum indicum L.): linking transpiration efficiency and root architecture to seed yield. Acta Physiol Plant 43(11):148. https://doi.org/10.1007/s11738-021-03324-z
63. Ratnakumar P, Ramesh K (2019) Influence of sowing environments on yield of sesame genotypes under shiftingweather conditions of Deccan Plateau (Telangana). J Oilseeds Res 36(4):54–56
64. Ratnakumar P, Vadez V (2011) Tolerant groundnut (*A. hypogaea* L.) genotypes to intermittent drought maintains high harvest

index and has small leaf canopy under stress. Funct Plant Biol 38:1016–1023. https://doi.org/10.1071/FP11145
65. Ratnakumar P, Vadez V, Nigam SN, Krishnamurthy L (2009) Assessment of transpiration efficiency in peanut (*A. hypogaea* L.) under drought by lysimetric system. Plant Biol 11:124–130. https://doi.org/10.1111/j.1438-8677.2009.00260.x
66. Ravitej KN, Ratna Kumar P, Narender Reddy S, Yadav P, Gourishankar V, Srikanth B, Padmaja D (2020) Physiological and biochemical traits of sesame (*Sesamum indicum* L.) cultivar under rainfed conditions. Int J Chem Stud 8:2277–2281
67. Ravitej KN, Ratnakumar P, Pandey BB, Reddy SN, Shnaker G, Padmaja D (2019) Morpho physiological and yield traits of sesame varieties under rainfed conditions. J Oilseeds Res 36:16–21
68. Reshma MV, Balachandran C, Arumughan C, Sunderasan A, Sukumaran D, Thomas S, Saritha SS (2010) Extraction, separation and characterisation of sesame oil lignan for nutraceutical applications. Food Chem 120:1041–1046. https://doi.org/10.1016/j.foodchem.2009.11.047
69. Richter R, Behringer C, Müller IK, Schwechheimer C (2010) The GATA-type transcription factors GNC and GNL/CGA1 repress gibberellin signaling downstream from DELLA proteins and PHYTOCHROME INTERACTING FACTORS. Genes Develop 24(18):2093–2104. https://doi.org/10.1101/gad.594910
70. Saini PK, Yadav RK, Pratap M (2017) Effect of foliar application of GA3, on yield and quality of indian mustard [Brassica Juncea (L.) Czern. & Coss.] under sodic soil. Int J Curr Microbiol App Sci 6(12):4156–4159. https://doi.org/10.20546/ijcmas.2017.612.477
71. Sarkar PK, Haque MS, Karim MA (2002) Effects of GA_3 and IAA and their frequency of application on morphology, yield contributing characters and yield of soybean. J Agron 1:119–122
72. Sher A, Usman Ali M, Ijaz M, Sattar A, Ul-Allah S, Qayyum A, Khan MB (2017) Foliar application of thioureaimproves the safflower yield and quality. J Med Spice Plants 22(2):78–83
73. Singh A, Bali A, Kumar A, Yadav RK, Minhas PS (2022) Foliar spraying of potassium nitrate, salicylic acid, and thiourea effects on growth, physiological processes, and yield of sodicity stressed paddy (Oryza sativa L.) with alkali water irrigation. J Plant Growth Reg 41(5):1989–1998. https://doi.org/10.1007/s00344-022-10575-8
74. Singh RP, Singh D (2017) Response of lentil to thiourea application under rainfed conditions of Central India. Int J Curr Microbiol App Sci 6:2556–2560. https://doi.org/10.20546/ijcmas.2017.603.289
75. Sravanthi AL, Ratnakumar P, Reddy SN, Eswari KB, Pandey BB, Manikanta ChLN, Ramya KT, Sonia E, Mohapatra S, Gopika K, Anusha PL, Yadav P (2021) Morpho-physiological, quality traits and their association with seed yield in sesame (Sesamum indicum L.) indigenous collection under deficit moisture stress. Plant Physiol Rep 27(1):132–142. https://doi.org/10.1007/s40502-021-00621-0
76. Srivastava AK, Ratnakumar P, Minhas PS, Suprasanna P (2016) Plant bio-regulators for sustainable agriculture; integrating redox signaling as a possible unifying mechanism. Adv Agron 137:237–278. https://doi.org/10.1016/bs.agron.2015.12.002
77. Sujata G, Baliyan V, Avtar R, Mehrotra S (2023) Alleviating drought stress in Brassica juncea (L.) Czern & Coss. by foliar application of biostimulants—orthosilicic acid and seaweed extract. Appl Biochem Biotechnol 195(1):693–721. https://doi.org/10.1007/s12010-022-04085-2
78. Sultemeyer D, Schmidt C, Fcck HP (1993) Carbonic anhydrases in higher plants and aquatic microorganisms. Physiol Plant 88:179–190. https://doi.org/10.1134/S0006297915060048
79. Thuc LV, Sakagami J, Khuong NQ, Orgill S, Huu T, Lang NTT, Nhan PP (2021) Effects of spraying gibberellic acid doses on growth, yield and oil content in black sesame (*Sesamum indicum* L.). Asian J Crop Sci 13:1–8. https://doi.org/10.3923/ajcs.2021.1.8
80. Vekaria GB, Rakholiya KD, Vora VD, Patel JT, Sutaria GS, Vekaria PD (2017) Response of sesame (Sesamum indicum L.) to growth regulator under dry farming condition. Int J Curr Microbiol App Sci 6(3):1113–1120. https://doi.org/10.20546/ijcmas.2017.603.129
81. Vineeth TV, Kumar P, Krishna GK (2016) Bioregulators protected photosynthetic machinery by inducing expression of photo-respiratory genes under water stress in chickpea. Photosynthetica 54:234–242. https://doi.org/10.1007/s11099-016-0073-5
82. Wakchaure GC, Minhas PS, Meena KK, Singh NP, Hegade PM, Sorty AM (2018) Growth, bulb yield, water productivity and quality of onion (Allium cepa L.) as affected by deficitirrigation regimes and exogenous application of plant bio–regulators. Agric Water Manag 199:1–10. https://doi.org/10.1016/j.agwat.2017.11.026
83. Wakchaure GC, Minhas PS, Ratnakumar P, Choudhary RL (2016) Effect of plant bio-regulators on growth, yield and water production functions of sorghum [*Sorghum bicolor* (L.) Moench]. Agric Water Manag 177:138–145. https://doi.org/10.1016/j.agwat.2016.07.020
84. Wakchaure GC, Minhas PS, Ratnakumar P, Choudhary RL (2016) Optimising supplemental irrigation for wheat (*Triticum aestivum* L.) and the impact of plant bio regulators in a semi-arid region of Deccan Plateau in India. Agric Water Manag 172:9–17. https://doi.org/10.1016/j.agwat.2016.04.004
85. Wang X, Wang M, Yan G, Yang H, Wei G, Shen T, Wan Z, Zheng W, Fang S, Wu Z (2023) Comparative analysis of drought stress-induced physiological and transcriptional changes of two black sesame cultivars during anthesis. Front Plant Sci 14:1117507. https://doi.org/10.3389/fpls.2023.1117507
86. Yagum T, Tongpang Longkumer L, Kikon N, Amlari I, Tzudir L (2023) Effect of PGRs on yield, quality parameters and economics of linseed (Linum usitatissimum L.) cultivation under rainfed conditions of Nagaland. Biol Forum 15(7):38–44
87. Yang JC, Zhang JJ, Wang ZQ, Zhu QS, Wang W (2001) Hormonal changes in the grains of rice subjected to water stress during grain filling. Plant Physiol 127:315–323. https://doi.org/10.1104/pp.127.1.315
88. Yuan L, Xu DQ (2001) Stimulation effect of gibberellic acid short-term treatment on leafphotosynthesis related to the increase in Rubisco content in broad bean and soybean. Photosynth Res 68(7):39–47. https://doi.org/10.1023/A:1011894912421
89. Zain M, Khan I, Chattha MU, Qadri RWK, Anjum SA, Hassan MU, Mahmood A, Ilyas M (2017) Foliar applied thiourea at different growth stages modulated late sown wheat. Pakistan J Sci 69(1):39. https://doi.org/10.13140/RG.2.2.19363.96801
90. Zhang Y, Yu SHI, Gong HJ, Zhao HL, Li HL, Hu YH, Wang YC (2018) Beneficial effects of silicon on photosynthesis of tomato seedlings under water stress. J Integr Agric 17(10):2151–2159. https://doi.org/10.1016/S2095-3119(18)62038-6