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REVIEW ARTICLE

Modulating physiological constraints, abiotic stress and yield of sesame: Nutrients and plant growth regulators effects

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Abstract

Sesame (*Sesamum indicum* L.) is a crucial oilseed crop, yet it currently achieves only about 25% of its genetic yield potential. To harness the full potential of sesame, it is essential to develop well-defined phenotypes and crop architectures that exhibit a more effective source-sink relationship tailored to the specific cropping environment. Numerous physiological constraints hinder yield optimization, including indeterminate growth, poor source-sink relationships, flower drop, low seed retention and capsule and seed shattering. Notably, these constraints are interactions between nutrient and plant growth regulators, both significantly influence the growth and overall productivity of sesame. Sesame cultivation is currently limited by low yields due to a lack of production strategies. This study suggested improving sesame productivity through the application of nutrients and plant growth regulators. Future research programs need to develop the best research strategies for economic and sustainable development.

Keywords

nutrients; physiological constraints; plant growth regulators; sesame; yield

Introduction

Sesame (*Sesamum indicum* L.) is an inevitable oilseed crop belonging to the family Pedaliaceae. It is also known as the "queen of oilseeds" that contains high levels of antioxidants *viz.* sesamol, sesamin and sesamolin and high content of unsaturated fatty acids which prevent rancidity. It is referred to as the "poor man's ghee" and was the first edible oil consumed by humankind (1). Globally, sesame covers an area of 6.57 million hectares with an annual production of approximately 2.94 million tons with a productivity of 479 kg ha^{-1}. Global sesame production in the aspects of area, production and productivity are provided in Table 1.

In India, Uttar Pradesh, Maharashtra, Madhya Pradesh, Rajasthan and Gujarat share the top rank followed by Tamil Nadu during 2021-2022 with the production of 79 lakh metric tons from 156 lakh hectares and the productivity of 502 kg ha^{-1} (2). Rajasthan has the largest sesame area (0.59 million hectares) and West Bengal has the highest production (0.19 million tons). In Tamil Nadu, Villupuram, Thanjavur and Erode share the top 3 rank followed by Karur with a total production of 2.79 lakh metric tons from 4.7 lakh hectares with a productivity of 589 kg ha^{-1} (3).

Sesame is a short-day plant, but many varieties have adapted to various light periods (4). In India, sesame is primarily grown during the Kharif season, accounting for approximately 75% of total production in India (5). It is also grown as a summer and semi-rabi crop because of its to thrive in diverse climatic conditions. However, it is resilient to hot climates with temperatures ranging from 25°C to 30°C for optimal growth, but it does not tolerate frost or prolonged drought (6). Notably, low temperatures during flowering can lead to pollen sterility and premature flower drop. High temperatures above 40°C during flowering can reduce fertilization, resulting in fewer capsules per plant. At 40°C, sesame plants initiated flowering at 50 days after sowing (DAS), whereas under optimal conditions (28°C), flowering commenced around 46 DAS. However, elevated temperatures induced stress in the source-sink relationship, leading to complete floral abortion and ultimately resulting in zero yield. In contrast, under optimal conditions, the yield was approximately 2.07 g/plant (7).

Although, sesame cultivation, especially under rainfed conditions faces physiological constraints that can have a significant impact on yield and quality of crop. One of these challenges is the plant's vulnerability to a variety of abiotic stresses such as waterlogging and drought, resulting in reduced crop productivity (8). Moreover, sesame plants are prone to capsule shattering and low seed retention, which can result in significant seed loss and further reduce yield (9).

Addressing these physiological constraints requires a multifaceted approach, improved agronomic practices and the application of nutrients and plant growth regulators (10). Nipping practices in sesame at 30 and 60 DAS lead to control of indeterminate growth and improve the efficiency of translocating assimilates to the sink organ (11). In addition, foliar spraying of micronutrients (Zn, Cu, Fe, Mn and Mo) significantly improved yield and oil content of sesame (12). The plant growth regulators (PGRs) play a significant role in regulating the various physiological processes in plants. Paclobutrazol (PBZ), a PGR, shows positive effects by improving leaf greenness, leaf area, source-sink relationship, total biomass production and seed yield with reduced seed shattering in sesame (13).

Sesame is a partially drought-tolerant crop which could complete its life cycle with the sacrifice in oil and yield quality. Melatonin is a hormone which is investigated extensively in human physiology and found to be effective in addressing drought-related oxidative damage in plants (14). Application of salicylic acid (SA) may alleviate the ill effects of drought-like lipid peroxidation (4). Besides, SA mitigates the negative effects, though to a lesser extent compared to potassium nitrate (KNO_3). Overall, the foliar application of KNO_3 provided the highest ameliorative potential to reduce the growth-inhibitory effect of waterlogging (15). This study reveals the role of PGRs and nutrients in modulating major constraints, abiotic stress and yield of sesame. The roles of different nutrients and plant hormones in sesame growth along the concentrations are provided in Table 2.

The application of micronutrients and PGRs significantly enhances the growth, yield and oil content of oilseed crops such as sunflower (*Helianthus annuus*), safflower (*Carthamus tinctorius*), groundnut (*Arachis hypogaea*) and mustard (*Brassica juncea*). Micronutrients like zinc (0.5% $ZnSO_4$) improve auxin synthesis and root growth, boron (0.2% Borax) aids in pollen germination and seed set (16), iron (0.5% $FeSO_4$) enhances chlorophyll synthesis, molybdenum (0.05% ammonium molybdate) boosts nitrogen fixation and manganese (0.5% $MnSO_4$) supports enzyme activation and stress resistance. Meanwhile, PGRs such as PBZ (50-100 ppm) regulate vegetative growth, promote flowering and enhance seed filling (17), while chlormequat chloride (500 ppm) improves branching and prevents lodging and mepiquat chloride (250 ppm) enhances reproductive growth (18) and pod formation, particularly in groundnut.

Materials and Methods

Information sources and search strategy

A systematic literature search was performed using Scopus database https://www-scopus-com.elibrarytnau.remotexs.in/ and Google Scholar http://scholar.google.com thereby making a comprehensive overview on available literature. Various combinations of keywords related to physiological disorders in sesame were considered in searching the research papers. A total of 10 keyword combinations as given in Table 3 were used to search in the database.

Inclusion and exclusion criteria

Inclusion and exclusion criteria were used for the initial screening of the articles to select relevant publications from the search results obtained from the Scopus database. Using the automation filters provided by the

Table 1. Global sesame cultivation and production: area, yield and productivity (FAOSTAT, 2023)

Country	Area (Million Ha)	Production (Million Tonnes)	Productivity (t/ha)
Sudan	4.57	1.37	0.30
India	1.52	0.80	0.53
Myanmar	1.50	0.74	0.49
Brazil	0.58	0.58	1.00
Pakistan	0.40	0.40	1.00
Nigeria	0.34	0.42	1.24
China	0.27	0.46	1.70

Table 2. Impact of nutrients on yield of sesame

Nutrient	Concentration	Specific roles	Reference
Boron	30 ppm	Increase oil content	(12)
Zinc	3000 ppm	Increase in seed yield	(12)
Manganese	4.5 kg/ha	Increase in seed protein content	(17)
Iron	3000 ppm	Increase number of capsules/plants	(15)

Table 3. Keywords used as search strings in Scopus database and Google Scholar

S. No.	Search Strings
1.	"Sesame" and "Physiological Constraints" and "Nutrient effects"
2.	"Sesame" and "Physiological Constraints" and "Plant growth regulators (PGRs)"
3.	"Sesame" and "Abiotic stress" and "Nutrient effects"
4.	"Sesame" and "Abiotic stress" and "Plant growth regulators (PGRs)"
5.	"Sesame" and "Drought" and "Stress mitigation strategies"
6.	"Sesame" and "Waterlogging" and "Stress mitigation strategies"
7.	"Sesame" and "Growth enhancement" and "Stress mitigation strategies"
8.	"Sesame" and "Hormonal regulation" and "Capsule shattering"
9.	"Sesame" and "Capsule shattering" and "Seed Physiology"
10.	"Sesame" and "Seed shattering" and "Paclobutrazol"

databases, non-English were deleted from the records. Publications from the specified subject areas such as Agricultural and Biological Sciences, Biochemistry, Genetics and Molecular Biology, Environmental Science, Chemistry and Multidisciplinary, were included using inclusion criteria.

Relevancy, duplicates and quality assessment

The PRISMA flow diagram was used to depict the number of studies that were finally taken for systematic literature review. Initially, the Scopus database uses the identification phase and provides publications related to physiological constraints in sesame cultivation. Secondly, the screening phase removed the non-relevant contents, duplicates and selected articles based on original studies reporting physiological, biochemical and molecular mechanisms underlying nutrients and hormones physiology along with field management. Full-text articles were further screened based on relevant titles and abstracts involving automated filters. Finally, the eligibility assessment phase was performed to ensure that, it included all original studies aiming to address physiological constraints in sesame through appropriate management strategies.

Results

Publication analysis from search strings

The database search using 10 keyword combination searches resulted in a total of 870 articles. The search strings were designed to encompass different aspects of sesame physiological constraints. Mainly the search string focused on physiological constraints in sesame and it resulted in 88 publications. The similar information for different combinations of keywords such as sesame, physiological constraints, seed shattering, physiology, genetics, gene expression regulation, phytohormones, gibberellin, abscisic acid, crop yield and abiotic stress.

In this literature review an overview was made of currently available literature on management of physiological constraints in sesame. A total of 870 studies were found in Scopus database and Google Scholar (Fig. 1). Then, these studies were screened using inclusion and exclusion criteria. The most frequent reason for the exclusion of a study was the research of subjects other than physiological constraints in sesame, non-English papers, using this criterion 546 articles were removed. The remaining articles underwent further screening based on the title and abstract. After screening, 125 articles were eliminated for non-existence of predefined keywords in the title, abstract or keywords part of the paper and the publications related to physiological constraints in sesame were alone included. Based on the eligibility criteria, publications that focus on physiological constraints in sesame as the main determinant were also included. Finally, 53 research findings were chosen for quantitative analysis, which had relevance and clarity in addressing physiological constraints in sesame. Results revealed that physiological constraints in sesame were a part of very less studies and were not the main criterion in most of the papers. By using inclusion and exclusion criteria, relevant publications were further refined and filtered to meet appropriate literature evaluation.

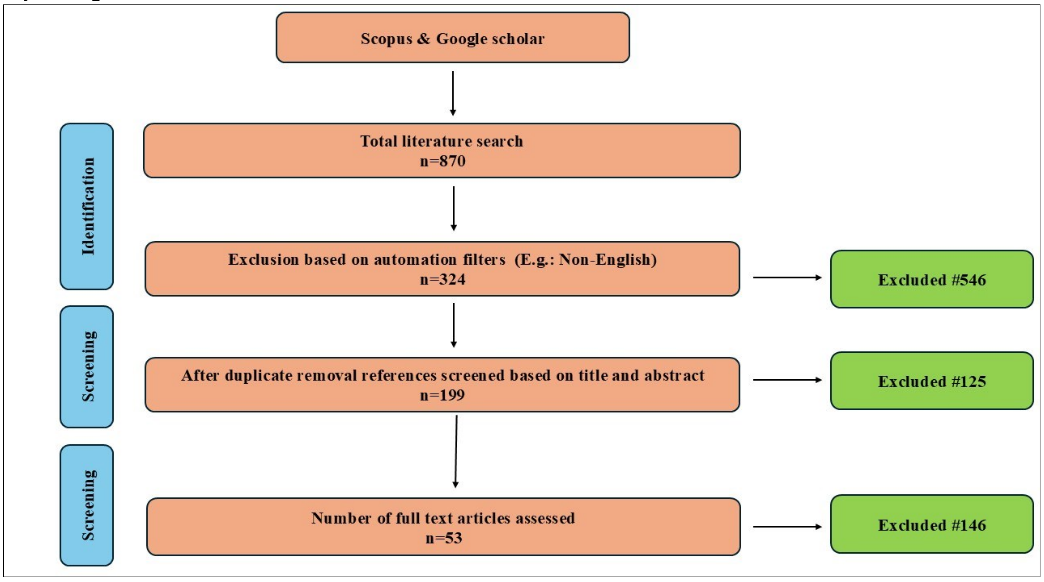

Fig. 1. The PRISMA Flow diagram depicting the number of studies taken for systematic review.

Regulation of indeterminate growth by PBZ

The habitus of sesame exhibits indeterminate growth that leads to reduced source to sink ratio and excessive vegetative growth, which in turn interrupts synchronization of maturity and the mechanical harvest of crops (19). The crop growth is regulated by level of endogenous hormones like gibberellic acid (GA) and abscisic acid (ABA) and the inhibition of gibberellins controls both indeterminate growth and excess transpiration through higher harvest index can be achieved (20). A plethora of reports confirmed that indeterminate crop growth is controlled by the application of chemicals such as PBZ, mepiquat chloride (MC) and chlormequat chloride (CCC) (18). PBZ a triazole group PGR usually suppress the shoot growth and increases the thickness of young stems by depositing high photoassimilates (19). PBZ inhibits the GA biosynthesis and results in controlled vegetative growth, transpiration, increased harvest index (HI) and water use efficiency (WUE) at the concentration of 400 mg L^{-1} (20). Besides, it also increases the production and stabilization of ABA, which in turn reduces the transpiration rate, leading to partial stomatal closure (21).

Applying 300 mg L^{-1} concentration of PBZ improves the seed yield and decreases the seed shattering by 30% (13). MC also have significant impact on morpho-physiological traits of sesame crops. Notably, MC application reduced plant height by inhibiting the internode elongation and increasing seed set percentage (18). Similarly, increase in 1000 seed weight was recorded in the foliar application of 500 ppm chlormequat chloride (22). Also, application of 200 mg L^{-1} of MC and 400 mg L^{-1} PBZ improves oil quality and seed yield of sesame (13).

Mechanism of PBZ

PBZ inhibits GA biosynthesis by inactivating cytochrome-dependent P450 oxygenase enzymes like KO, KAO and ABA8'OH. This redirects accumulated GGDP towards ABA production, increasing ABA levels while preventing its degradation. As a result, ABA stabilization reduces stomatal aperture slightly, minimizing transpiration and controlling indeterminate growth (Fig. 2).

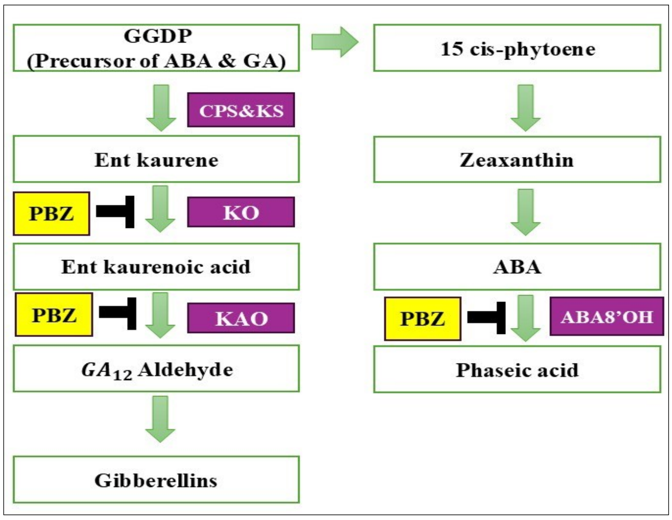

Fig. 2. Role of PBZ in regulating terpenoid pathway. GGDP Geranyl geranyl diphosphate**,** PBZ- Paclobutrazol, CPS - ent-Copalyl-diphosphate Synthase, KO - ent-Kaurene Oxidase, KAO - ent-Kaurenoic Acid Oxidase, KS - ent-Kaurene Synthase, PSY - Phytoene Synthase. ABA'8OH – ABA'8 hydroxylase.

Source-sink relationship

Source-sink relationship refers to the translocation of photosynthates from the area of photosynthesis to the area of utilization, in terms of sesame it is from the leaves (source) to capsules (sink) (23). The indeterminate nature of sesame performs simultaneous growth of both vegetative and reproductive phases which results in competition for assimilates. The broad lower leaf and the canopy structure hinder the lower branches from sunlight interception causing lesser capsule and seed production in lower branches (24).

Nipping, the removal of the apical portion, significantly influences plant growth by reducing auxin production and inhibiting apical dominance, leading to improved carbohydrate and sugar translocation to lateral branches (25). It enhances stem diameter and capsule weight and reduces plant height, thereby optimizing yield in sesame. Additionally, salicylic acid (SA) increases leaf area duration further CO_2 assimilation and accelerates the benefits of nipping except for apical dominance inhibition (26). Studies indicate that SA application (100 ppm) along with nipping at 30 DAS enhances sesame productivity (11) (Table 4), while other findings suggest both processes function independently (25).

Reducing capsule shattering

Capsule shattering in sesame refers to the loss of seeds from capsules that break open prematurely either before or during harvesting. It is due to internal or external stresses like harvest maturity, temperature fluctuation and capsule moisture that significantly reduce sesame production by up to 50% (12, 13). Genes are the master regulator for capsule shattering, but the mechanism is completely dependent on hormonal regulation which is manipulated by external application of PGRs (27). Varieties with high funiculus diameter recorded high seed retention and less seed shattering (28).

Ethylene and abscisic acid are the major hormones involved in capsule shattering by the formation of dehiscence zone (DZ) in the dorsal and ventral suture, which is regulated by β-glucase, cellulase, polygalacturonase and other cell wall degrading enzymes (29). Sudden spiking of ethylene concentration in the capsule results in rapid activation of β-glucase, pectinase which degrades cellulose, pectins and cell wall in funiculus which causes seed shattering (28).

Also, the increase in ABA concentration stimulates ethylene production, which causes capsule shattering as a cascade effect of increasing ethylene within the capsule to activate all the cell wall degrading enzymes (Fig. 3). To

Table 4. Nipping and foliar application of salicylic acid (SA) on yield traits

Treatments	Capsules/ plant	Seeds/ capsule	1000 seed weight (g)
Control (A)	83.1	44.5	2.9
Nipping at 30 DAS + SA 100 ppm spray at 30 DAS (B)	109.5	79	3.2
Nipping at 30 DAS + SA 100 ppm spray at 45 DAS (C)	98.3	73.5	3.1
Nipping at 45 DAS + SA 100 ppm spray at 30 DAS (D)	97.3	66.1	3.1

*DAS - Days after sowing, **SA - Salicylic acid

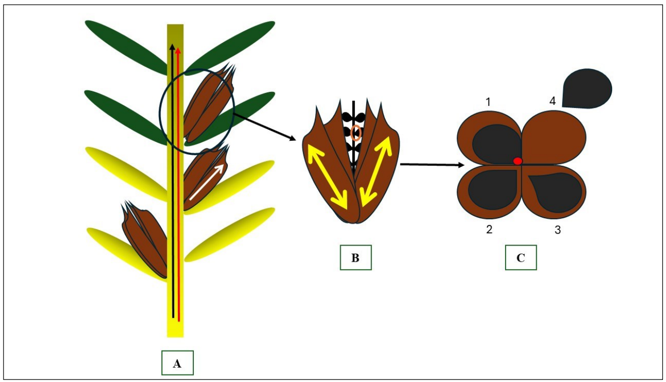

Fig. 3. Hormonal crosstalk in Capsule and seed shattering **A.** The red and black arrows on the plant indicate the upregulation of abscisic acid (ABA) and ethylene, respectively. In the capsule, the white arrow indicates the upregulation of ethylene within the capsule. **B.** The double-sided yellow arrow represents the upregulation of cell wall-degrading enzymes, such as cellulase and polygalacturonase. **C.** The red dot in the first compartment marks the formation of the dehiscence zone. The second compartment illustrates the detachment of the seed from the funicle. The third compartment represents the complete detachment of the seed, making it ready for dispersal, while the fourth compartment depicts the final stage of seed shattering.

reduce capsule shattering it is necessary to inhibit the biosynthesis of ethylene, thereby application of exogenous ethylene inhibitors like aminoethoxy vinyl glycine (AVG), $CoCl_2$ (Cobalt chloride), SA (30). A study found that PBZ treatment at the rate of 450 mg L^{-1} improved the plant biomass, capsule count and seed yield, whereas 600 mg L^{-1} lowered the shattering of capsules (13). PGRs and genetic strategies offer complementary ways to tackle capsule shattering in sesame. Genetic approaches, like marker-assisted selection, can breed sesame varieties with inherently stronger capsules that are less prone to shattering (31). These genes include transcription factors, such as SiKAN1, which regulate the expression of other genes involved in capsule development, as well as genes encoding cell wall changing enzymes like polygalacturonases and xyloglucan endotransglucosylases/ hydrolases (XTHs), which influence capsule wall strength and integrity (32). However, environmental conditions can still cause some shattering. Specifically, PGRs can modulate factors like cell wall structure and abscission, thereby contributing to improved shatter resistance. Studies have shown that PBZ helps to form thicker capsule walls and potentially alter the structure of the abscission layer, the zone where the capsule eventually splits open (28). By strengthening the capsule and potentially delaying or changing the abscission process, PBZ can help reduce shattering, especially under environmental conditions that might otherwise promote it. Therefore, integrating genetically improved varieties, focusing on genes like SiKAN1 and those encoding cell wall-changing enzymes, with applications of PBZ could provide an effective approach to minimizing seed losses in sesame production.

Seed yield

The role of different macro and micronutrients has been well-established in plant metabolism. Foliar application of liquid fertilizers and granules is the main effective approaches which rapidly and directly supply the missing nutrients required in flower branches, leaves and seeds in oil seed crops (33). The main obstacle lies in the physiological problems associated with macro and micronutrient deficiencies, such as hormonal imbalances that lead to reduced sesame yields (34).

The micronutrients (Fe, Zn, Mn) in foliar spray on sesame improved their physiology, growth and yield (35). The utilization of either zinc or iron alone, or in combination with organic fertilizers, has resulted in improved growth, development and yield of sesame (36). Iron fertilizer had a significant effect on sesame seed yield (35). Foliar application of boron (B) solutions improved cell wall formation, pollen germination and pollen tube growth, thereby enhancing plant growth and yield (17). Furthermore, the steady supply of macronutrients and Zn was found to increase stem height and nodes for capsule development in sesame. Major macronutrients like nitrogen, phosphorus and potassium along with micronutrients such as zinc and manganese are influencing the growth and yield of sesame (37).

Seed oil content

Sulphur (S) plays a significant role in determining seed yield and quality of sesame. S is an important part of various plant proteins and plays a critical role in root growth and seed production. Sulfur binds with metal cofactor iron (Fe) for rapid electron transport in mitochondria and chloroplast (38). It also increases the availability of other nutrients such as phosphorus, potassium and zinc suppresses the uptake of sodium and chlorine which are toxic to plant growth and development (39). Furthermore, its application improves the fatty acid quality in seeds while its deficiency reduces the oil content and quality of oilseeds (18). Sesame requires more sulfur for its growth compared with cereals, as S promotes pod formation, whereas its deficiency can abort the pods (40). Therefore, sulphur application may increase the seed yields and oil yield and improve the oil quality by decreasing the concentrations of saturated fatty acids (palmitic and stearic acid).

Drought

Yield loss and disruption in biochemical homeostasis caused by the unavailability of water in a plant's life cycle is called drought (41). Drought has the potential to affect the length of critical growth stages like flowering, pod and seed filling and physiological maturity (42). It has a significant impact on shoot traits, which also reflects cellular processes like photosynthesis in sesame (43). Drought plants suffer from the accumulation of reactive oxygen species (ROS), content, ethylene and ABA production with the continuous effect of stomatal closure and diminishing photosynthetic enzyme activity (4). Resistance to drought stress is induced by the application of PGRs (30) and nutrients (44).

Nutrients act as osmoprotectants, signaling molecules and enzyme regulators in plants during drought (45). Enzymes which are involved in carbon and nitrogen metabolism are mostly potassium (K^+) dependent. Application of K^+ provides osmoprotection, chlorophyll retention and reduced rate of chlorosis by improved sugar translocation and accumulation (46). Increased antioxidant enzymes and proline accumulation were observed in zinc (Zn) application. Capsule parameters like weight, length, numbers and seed yield were found to be

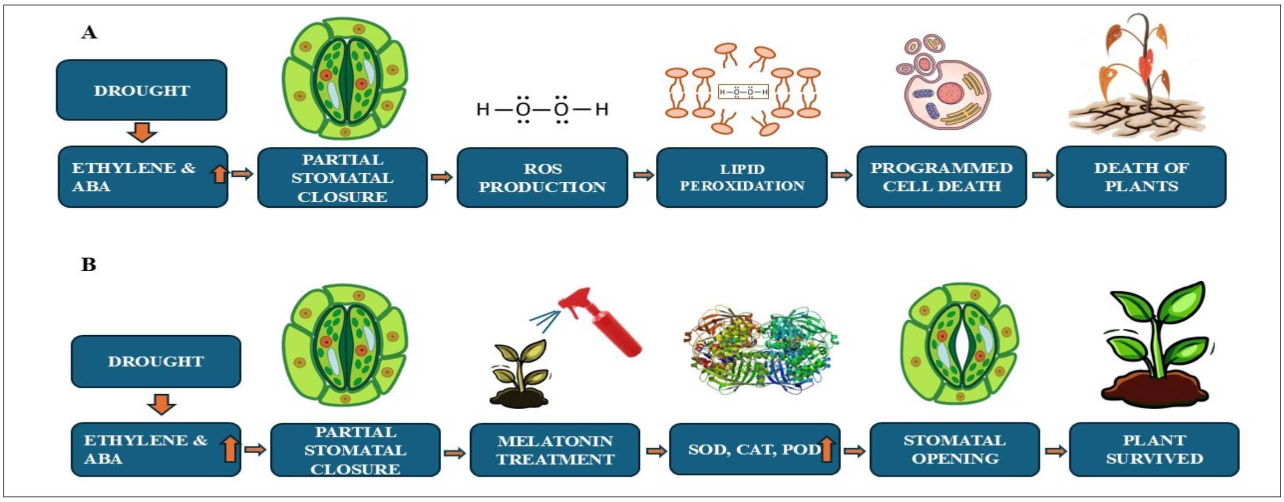

Fig. 4. Significant differences between without melatonin (A) and with melatonin applied (B) plants in drought.

highest under the application of Zn at 3000 ppm (16). Selenium application of 5 ppm at the vegetative stage resulted in increased leaf area duration, prevention of chlorophyll degradation and high seed weight (47).

Drought affects the endoplasmic reticulum (ER) the most among intercellular components which cause protein misfolding and leads to programmed cell death (48). Melatonin is a low molecular weight phytohormone that responds to stress environments through hormonal interaction. Exogenous application of melatonin improves gas exchange parameters like intercellular CO_2, stomatal conductance and transpiration rate (41). Considering root growth, melatonin improves lateral root length of sesame by endogenous SA production (30). Application of 100 µM melatonin during drought helps plants to produce enzymatic and non-enzymatic antioxidants by protein stabilization and counteract ROS and lipid peroxidation (49).

The exogenous application of melatonin induces endogenous production of phyto melatonin. After stomatal closure, the rise in ROS stimulates the melatonin to enhance the production of antioxidant enzymes (27) (Fig. 4), which in turn supports osmoprotectants to open and close the stomata, thus helping the plant survive.

Waterlogging

Sesame is highly susceptible to waterlogging, a major threat to sesame production. Even short periods of waterlogging reduce sesame growth and development, leaf area index, chlorophyll content, plant dry matter accumulation, capsule number and increase the number of aborted seeds, thus decreasing the yield (10). The critical stage of sesame to water logging is seedling establishment stage (20 DAS), which is the most susceptible to waterlogging conditions and leads to reduced yield by up to 35% (15). Waterlogging in sesame recorded the highest reactive oxygen species (ROS) and malondialdehyde (MDA) production due to higher lipid peroxidation. It inhibits ROS-scavenging enzymes like catalase and peroxidase. This cascade of negative effects results in diminished nitrate reductase activity, reduced nutrient uptake, increased oxidative stress and a cumulatively decrease in photosynthetic rate (8).

The increase in ethylene and ABA lead to the production of hydrogen peroxide (H_2O_2), which is the major ROS produced during waterlogging conditions which induces the closing of stomata by inhibiting influx of K^+ion channels (Fig. 5) (50). Under waterlogged conditions, sesame becomes vulnerable to various stresses due to the absence of osmoprotectant. External application of

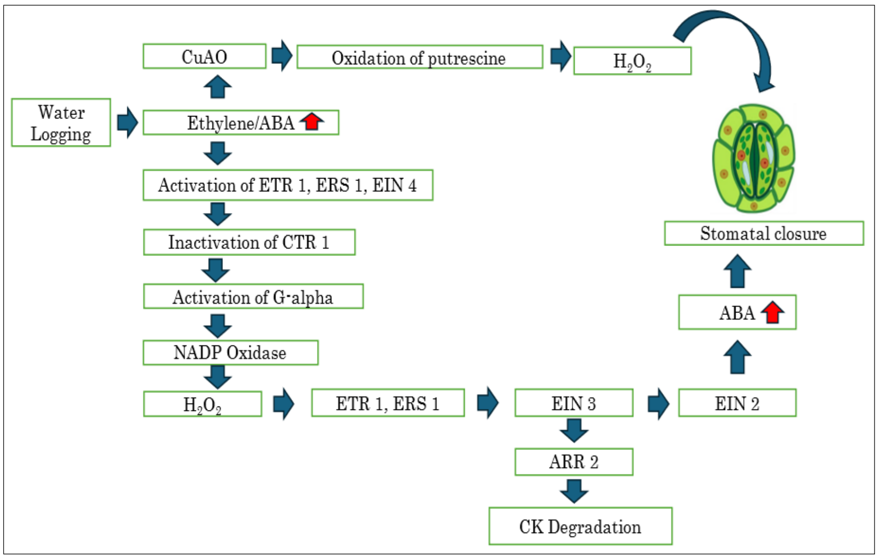

Fig. 5. Elucidation on two-way production of H_2O_2 on stomatal closure. H_2O_2 is responsible for closing of stomata or indirectly increasing Ca^{2+} in the guard cell for stomatal closure by reducing the volume of the guard cell. H_2O_2- Hydrogen peroxide, CuAO - Copper amine oxidase, EIN2 - Ethylene insensitive 2, EIN3 - Ethylene insensitive 3, EIN4 - Ethylene insensitive 4, ERS1 - Ethylene response sensor 1, ETR1 - Ethylene receptor 1, CTR1- Constitutive triple response 1, NADP- Nicotinamide adenine dinucleotide phosphate, ARR 2 - Arabidopsis response regulator 2, CK – Cytokinin, ABA-Abscisic acid.

glutathione acts as the osmoprotectant and enhances the activity of antioxidant enzymes like catalase (CAT), ascorbate peroxidase (APX), peroxidase (POD), glutathione peroxidase (GPX) and glutathione S-transferase (GST) (51).

The appropriate usage of micronutrients and PGRs can retrieve sesame plants from waterlogging stress delving further by the application of potassium nitrate(KNO_3 at 5 g L^{-1}), SA at 100 ppm results in increased survival percentage, plant height, seed yield and reduced activity of ROS and MDA. Furthermore, the application of calcium silicate increases the cell wall integrity and decreases the ROS by enhancing antioxidant enzymes, along with improved lipid biosynthesis and micronutrient absorption in sesame (52). Therefore, studies are needed to optimize the concentration of PGRs for increased sesame seed production under water stress. The specific effect of ameliorants along with the concentration is provided in Table 5.

Conclusion

For the growing oilseed demand, it is necessary to review the appropriate utilization of nutrients and plant growth regulators to address the inborn physiological constraints like indeterminate growth, poor source-sink relationship, capsule shattering and abiotic stress like drought and waterlogging. The combination of agronomic practices like nipping and hormones provides more promising results in improving yield and quality parameters. Developing sesame varieties with indehiscent capsules (non-shattering type), waterlogging tolerance and high water-use efficiency will benefit sesame production. Our review further calls for the standardization of appropriate dosages of growth retardants in rainfed conditions and nutrients on waterlogged stress.

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Authors' contributions

All authors contributed to the study's conception and design. Study of the work, material preparation, literature collection and manuscript preparation were performed by MNK. VR, AS, SA and RR contributed to the review and technical guidance of the work. MNK, VR, LA and RS were associated with the study and manuscript preparation. VR, SA and AS did the reviewing and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: All authors do not have any conflict of interests to declare.

Ethical issues: None

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Table 5. Summary table explains the role of different nutrients and plant growth regulator in addressing drought and waterlogging

	Drought		
Nutrients	**Concentrations**	**Ameliorative effects**	**References**
Selenium	5 ppm	Improved proline accumulation	(47)
Potassium	1.5 g/pot	Improved sucrose accumulation	(44)
Zinc ($ZnSO_4$)	3000 ppm	Higher capsule/plant	(16)
Boron (H_3BO_3)	2000 ppm	Higher test weight	(16)
	PGRs		
Salicylic acid	83 ppm	Increased root growth	(30)
Cytokinin	25 ppm	Higher number of leaves/ plants	(52)
	Waterlogging		
Nitrogen (Urea)	1500 ppm	Improved nitrate reductase activity	
Potassium (KNO_3)	5000 ppm	Reduced MDA content	
Calcium ($Ca (NO_3)_2$)	4100 ppm	Increase in chlorophyll content	
	PGRs		
Auxin (NAA)	25 ppm	Reduced transpiration rate	
Salicylic acid	100 ppm	Improves number of roots/plants	(15,53)
Tricyclazole	50 ppm	Improved survival percentage under waterlogging	

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