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REVIEW ARTICLE

Physiological and biochemical adaptations of sesame (*Sesamum indicum* L.) to climate stress: A comprehensive review

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Abstract

Sesame (*Sesamum indicum* L.), often called the queen of oilseeds, plays a crucial role in nutrition, oil production and rural livelihoods. Despite its inherent resilience, sesame remains vulnerable to climate change, especially as it is largely cultivated on rainfed and marginal lands. Rising temperatures, erratic rainfall patterns and extreme weather events significantly affect its productivity. Critical developmental stages such as flowering and seed filling are particularly sensitive, experiencing yield losses up to 40-70 % under combined drought and heat stress. These abiotic stresses also reduce seed size and weight and alter oil quality by disrupting fatty acid composition. However, genotypic variability offers promising drought and heat-tolerant sesame lines with adaptive physiological and biochemical traits. Advances in molecular breeding, omics technologies and genome editing (e.g., CRISPR-Cas9) provide hope for climate-resilient sesame improvement. Agronomic interventions like mulching, biofertilizers and precision irrigation further enhance resilience. This review consolidates recent research on sesame's physiological, biochemical and genetic responses to climate stress and explores integrated strategies for sustainable sesame cultivation under future climate scenarios.

Keywords: abiotic stress; biochemical responses; climate change; climate-resilient agriculture; physiological responses; sesame

Introduction

Sesame (*Sesamum indicum* L.) is an important oilseed crop valued for its high oil content (50–60 %) and stability. It is widely used in food, pharmaceuticals and cosmetics. Rich in antioxidants like lignans and tocopherols, sesame offers health benefits such as anti-inflammatory and cardioprotective effects. Despite its potential, it remains underutilized in modern agriculture and nutrition. Sesame is moderately tolerant to heat and drought, making it suitable for cultivation in marginal and rainfed areas. It adapts to stress through physiological traits like waxy cuticles and deep rooting and biochemical responses such as proline accumulation and antioxidant enzyme activity. However, extreme temperatures and erratic rainfall still limit its productivity. With the availability of genomic tools, sesame breeding has progressed beyond traditional methods. Recent developments include genome sequencing, QTL mapping and gene editing, enabling identification of traits linked to stress tolerance, oil content and maturity. These tools support the development of resilient, high-yielding cultivars. As climate change intensifies, sesame holds promise as a climate-resilient crop. Integrated breeding, improved agronomic practices and expanded research on its stress response mechanisms are essential to unlock its full potential in food security and climate-smart agriculture (1). Due to its high oil (50–60 %) and nutritional content, the crop is important for health and food security (2). It has diverse applications in food, pharmaceuticals and industry, including its use in antiseptics, bactericides and as a potential biofuel (3, 4). Rich in antioxidants, sesame is consumed for its health benefits. Its diverse bioactive components include phytosterols, tocopherols and lignans, giving it anti-cancer, anti-hypertensive and anti-oxidation properties (5). Furthermore, the adoption of new agro-genetic methodologies has the potential to enhance the profitability and productivity of farmers (6). Overall, sesame is still underutilised in food, medicine and cosmetics when considering its unique nutritional profile and health benefits. Above their culinary value worldwide, sesame seeds aid in health prevention activities which are noteworthy. In Tamil Nadu, the sesame snack *ellu urundai* (sesame sweet balls) is healthy, with various other cream-filled sesame snacks strewn about. Their sesame flavour and crunchy texture open doors to many cultures. Sesame (*Sesamum indicum*) has base temperatures of 7.6–12.6 ˚C for germination and cardinal temperatures of 43.9–50.5 ˚C for its ceiling (7). Optimum growth is from 24–30 ˚C and anything above 40 ˚C is harmful.

Sesame exhibits remarkable mechanisms for dealing with drought, like proline and glycine accumulation, cuticular wax formation and vascular sclerenchyma alterations in xylem vessels (8). It has the potential to be tolerant to drought, but with some refinement. Its drought tolerance is associated with functional root traits, potassium in leaves and moisture in leaf tissues (9). Recent studies emphasise the importance of understanding sesame responses to abiotic stressors for cultivar development. Traits of drought-tolerant sesame genotypes include improved root function, moderate accumulation of osmoprotectants and elevated activity of antioxidant enzymes-peroxidases in particular (10). Tolerance to various stresses is improved due to the upregulation of ROS-scavenging enzymes via defense signalling pathways associated with the overexpression of osmotin-like proteins (11). Drought-resistant mutants exhibit adaptive mechanisms such as changes in xylem vessels and proline accumulation (8). Current advances have transformed sesame from an orphan crop to a crop rich in genomic resources (10). Its sequencing has provided insights into the level of genetic diversity it possesses and the pathways involved in the oil biosynthesis (12). Omics technologies and biotechnological advances have transformed sesame research by creating new opportunities for the identification of genes and QTLs associated with significant traits, including yield, stress tolerance and oil content (1). To boost nutritional and oil security, sesame's potential needs to be harnessed through a blend of conventional and molecular breeding plans (2). Combining biotechnological methods such as CRISPR-Cas9 with genomic approaches like GWAS and genomic selection offers promising opportunities to develop sesame cultivars with enhanced resistance to abiotic stress (13). Continued research, together with collaborative efforts, is crucial for overcoming the remaining challenges related to developing climate-resilient varieties of sesame and enhancing crop productivity. Efforts to improve sesame varieties and cultivation techniques are necessary to meet the growing global demand and fully utilise its potential (3). In this context, the present study aims to analyse the physiological and biochemical responses of sesame to major abiotic stresses, particularly heat and drought and identify the most vulnerable growth stages affecting yield and oil quality, to evaluate the genotypic variability and adaptive mechanisms among sesame cultivars, with emphasis on traits contributing to climate resilience through physiological, biochemical and molecular responses and to explore recent advances in breeding technologies and agronomic practices, including omics tools, genome editing and climate-smart strategies, aimed at enhancing sesame productivity under changing climate conditions.

Impact of climate change on sesame

Rise in temperature, altered rainfall patterns, increased CO_2 and extreme weather events

The production of sesame is impacted greatly by climate change (Fig. 1). The critical growth period of sesame is impacted by changes in rainfall patterns and the growing season is getting progressively shorter and phenological stages are accelerating due to rising temperatures (14). In Ethiopia, sesame yield has positively responded to higher temperatures, but the rainfall pattern is altering, so the yield is affected. The average rainfall of 36 summers (1983-2023) is around 30 mm, which is optimum for sesame, but the reduction in rainfall, which is below 200 mm per year induces stress and reduces the yield (15).

Climate models predict that sesame cropping regions with increasing temperatures and declining rainfall will, in some cases, result in a yield reduction of 23.31 % (16). These impacts, however, can be mitigated by appropriate adaptation strategies. Previous studies have indicated that, if appropriate planting dates and irrigation methods are applied, an increase in yield of 33.1 % could be achieved (14,16). In addition, cultivation practices as well as the system of water and soil conservation have been effective in reducing climate change risks and securing food supplies at household levels for sesame farmers in Western Ethiopia (17) (Table 1).

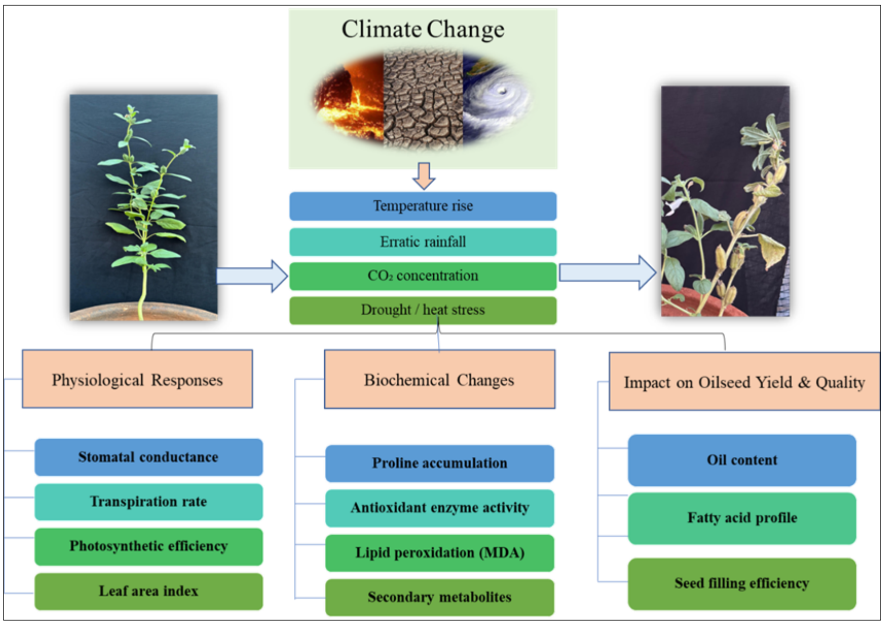

Fig. 1. Impact of climate change on sesame physiological, biochemical responses and oil quality.

Table 1. Impact of rising temperature, altered rainfall patterns, increased CO_2 levels and extreme weather events on sesame

Climate Factor	Growth Stage(s) Affected	Observed Impact
Rising Temperature (15)	Seedling, Vegetative, Flowering, Yield	• Optimal growth occurs at 20–31 °C. • High temperatures (>35 °C) during flowering reduce seed set and oil content. • Long-term warming trends correlate with yield increases in cooler regions but declines in already warm zones.
Altered Rainfall Patterns (15)	Germination, Vegetative, Flowering	• Erratic rainfall disrupts planting schedules. • Excessive rain causes seed rot, poor capsule formation and shattering. • Rainfall variability increases the risk of crop failure in rainfed sesame systems.
Extreme Weather Events (15)	All Stages	• Floods damage young plants and increase disease pressure. • Drought during flowering drastically reduces yield. • Strong winds and late rains cause lodging and seed shattering.
Increased CO_2 Levels (18)	Vegetative, Yield, Seed Quality	• Enhanced CO_2 boosts photosynthesis and biomass accumulation. • May reduce seed protein and mineral content (e.g., Zn, Fe).

Impact of drought and heat waves during key growth stages

Sesame growth, development and yield are greatly impacted by heat stress and drought, especially during crucial phases like seed filling and flowering. Plant height, biomass and yield components like seed weight and capsule number are all decreased by these stresses (19). Reduced relative water content, changed levels of chlorophyll and variations in mineral content are examples of physiological reactions. The expression of genes involved in protein processing, hormone signalling and metabolism is altered by drought stress at the molecular level. Metabolomics analysis shows that genotypes resistant to drought accumulate ABA, amino acids and organic acids (20). Heat and drought stress together have a particularly detrimental effect on seed yield and quality (21). Understanding the physiological, biochemical and genetic mechanisms governing seed filling under stress is crucial for developing stress-tolerant varieties and improving crop productivity (21,22) (Table 2).

Regional climate models projecting changes in sesame-growing zones

Recent research utilizing climate models and crop simulation tools predicts notable modifications in sesame-growing regions due to climate change (Table 3).

In Ethiopia, the expected climate scenarios suggest normal sowing dates will yield better results compared to early or late sowing (16). China might face new opportunities for expanding multi cropping and an elongated growing period at higher latitudes (25). A fuzzy-mathematics model was used in a previous study to compare two 21-year periods (1978-1998 vs. 1999-2019) across China's main sesame-producing areas (26). They found that:

- Mean growing-season temperatures increased from 24.48 °C to 25.05 °C which is accompanied by a slight increase in cumulative precipitation from 744.4–754.8 mm, yet there was a drop in sunshine hours, from 6.05–5.55 hr.
- High-suitability areas underwent an expansion of 10.54 % ($28.52 \times 10^6 \rightarrow 31.52 \times 10^6$ ha) which predominantly shifted southward within Henan Province and acutely expanded in Northern Anhui.
- Moderate-suitability areas decreased by 15.48 % ($52.41 \times 10^6 \rightarrow 44.31 \times 10^6$ ha) while low suitability areas increased more than five-fold ($11.71 \times 10^6 \rightarrow 79.91 \times 10^6$ ha) especially in Southwestern Hubei.

Table 2. Impact of drought and heat waves on sesame growth stages

Growth Stage	Impact of Drought and Heat Waves	Reference(s)
Germination and Seedling	• Reduced germination percentage and seedling vigor under drought stress. • Severe drought led to germination failure in some genotypes. • Heat stress impairs seedling development.	(8)
Maturity and Harvest	• Drought accelerates maturity, decreasing oil content. • Heatwaves and water stress reduce dry matter accumulation and yield.	(12)
Flowering	• Drought during flowering reduces seed set, yield and quality. • High temperatures reduce pollen viability, affecting fertilisation and seed filling.	(13)
Vegetative Growth	• Drought stress accelerates growth stages, reducing biomass and yield. • Heat stress prolongs the vegetative phase and alters morphology.	(23)
Capsule Development	• Drought reduces capsule number and seed weight. • Water stress during this stage lowers total yield significantly.	(24)

Table 3. Projected changes in sesame-growing zones based on regional climate models

Region	Climate Model(s) Used	Projected Changes in Sesame Suitability	Reference
North Gondar, Ethiopia	ARDL Time Series Model	Positive association between temperature and sesame yield; negative association with rainfall.	(15)
Western Tigray, Ethiopia	Hadley Centre Global Environmental Model version 2 - Earth System, Australian Community Climate and Earth System Simulator version 1.0, Geophysical Fluid Dynamics Laboratory Earth System Model version 2M	Yield reductions of 5.88 % to 23.31 % under late sowing dates by end-century; up to 33.1 % yield increase with normal sowing dates under mid-century.	(16)
Northern Henan & Hubei, China	MaxEnt Model	Decrease in high climatic suitability areas; increase in low climatic suitability zones.	(18)

- A clear increase in high climatic suitability was observed in Northeast Anhui.
- In general suitability, growth was witnessed in Eastern Jiangxi. In contrast, Northern Henan and Hubei experienced declines in their high and moderate suitability areas. These spatial changes are a result of enhanced average temperatures and shifting precipitation concentration, which indicates the need to redesign plant hardiness zone maps to regions with increased suitability (e.g., Southern Henan, Northern Anhui) and adopt appropriate frameworks for regions with declining values. While Ethiopia and China have received significant attention in climate impact modeling for sesame, insights from other major producers such as India, Myanmar and Sudan are essential to strengthen global relevance. In India, where sesame is cultivated across varied agro-climatic zones, rising temperatures above 35 °C and erratic monsoon rainfall have been shown to reduce seed set and oil content, particularly in central and eastern regions. Studies indicate yield reductions of up to 30–40 % in rainfed areas during terminal drought conditions. In Myanmar, high inter-annual rainfall variability affects sowing and harvesting periods, while late-season heatwaves contribute to flower abortion and yield instability. In Sudan, climate-induced desertification and prolonged dry spells affect sesame grown in the semi-arid zones, with increasing reliance on short-duration and drought-tolerant varieties. These observations emphasize the urgent need for region-specific adaptation strategies and climate-resilient cultivar development to sustain sesame productivity globally.
- **Re-optimize planting zones:** Direct expansion toward areas gaining suitability.
- **Develop heat/drought-tolerant cultivars:** breed or deploy genotypes with early maturity and robust antioxidant responses.
- **Adopt adaptive agronomy:** Implement adjusted sowing dates, optimized irrigation scheduling and soil-water conservation techniques.

Physiological responses of sesame to climate stress

Effects of high temperature on germination, photosynthesis and transpiration

High temperature stress, especially the photosynthetic activities of a plant, can be deleterious. It impairs Rubisco activity, decreases chlorophyll content and modifies the structure of the chloroplast; Photosystem II (PSII) is preferentially more damaged than Photosystem I (PSI) under heat stress due to the higher thermal sensitivity of the D1 protein and the oxygen-evolving complex in PSII, which are prone to denaturation and photoinhibition under elevated temperatures (27). The production of reactive oxygen species and damage to membranes both increase as a result of heat stress (22). Photosynthesis in sesame leaves suffers as PSII efficiency and chlorophyll content decline sharply above 38 °C, rubisco activity drops and stomatal closure further limits CO_2 uptake - together causing up to a 50 % reduction in net photosynthetic rate under prolonged high-temperature regimes (28). High temperatures (>35 °C) can impair enzyme activity and cell division required for seed germination. Heat stress disrupts water uptake by seeds and damages plasma membranes, reducing seed viability.

Heat stress (e.g., exposure to 40 °C for 24–48 hr) can reduce radicle elongation by 35–67 % during germination without necessarily lowering the total germination rate. This stress is associated with increased Reactive Oxygen Species (ROS) production, malondialdehyde (MDA) accumulation, hormonal shifts (↑ABA, ↓IAA) with oxidative abscisic acid signalling, as well as the upregulation of antioxidant enzymes (SOD, CAT, POD) in the roots of both heat tolerant and sensitive sesame varieties (29). Transpiration first increases due to the rise in vapour-pressure deficit. As stomata close to save water, leaf cooling becomes less effective and Water Use Efficiency (WUE) decreases. Heat-tolerant genotypes retain higher stomatal conductance and WUE than sensitive ones under the same heat treatment (30).

WUE under drought and heat conditions

Concerning various physiological processes, a combination of drought and heat stress affects crop growth and yield significantly (31,32). Complex relationships exist between WUE and yield potential, as well as drought resistance, though WUE remains crucial for plant functioning in water-limited environments (33). Changes in root growth, transpiration, photosynthesis and the buildup of osmolytes like proline are just a few of the morphological, physiological and biochemical adaptations that plants make in response to these stresses (31,32). Drought stress in sesame increases proline content and stomatal resistance while decreasing chlorophyll content, seed yield and relative water content (8). Crop establishment methods, foliar growth regulator application and soil management techniques are management strategies to reduce the effects of stress (32). Developing drought-tolerant cultivars through selection and mutation breeding offers promising prospects for improving crop resilience in arid and semi-arid regions. Breeding programs led by institutions such as ICRISAT and Ethiopian research centers have made progress in identifying and promoting drought-resilient sesame varieties like Humera-1 and Setit-1, which are widely cultivated in parts of East Africa for their tolerance and stable yields under stress (8). Drought stress has a significant impact on proline concentration, antioxidant enzyme activity, relative water content, net photosynthesis and even stomatal conductance, all of which contribute to WUE modulation in sesame genotypes (9). Meanwhile, the impact of heat stress is particularly pronounced when the temperature exceeds 40 °C: increasing vapour pressure deficit causes proportional elevation in transpiration. In a bid to minimise water loss, sesame plants need to close their stomata (Fig. 2). However, this turns out to block CO_2 diffusion and suppress photosynthesis, thus affecting WUE. Not all sesame genotypes respond the same way to drought and heat. Stress-tolerant varieties like 'Taka-2' demonstrated significantly higher WUE compared to susceptible varieties such as 'Shandaweel-3', owing to better stomatal regulation and deeper root systems (34) (Table 4).

Flowering and seed setting delays or failure due to stress

Environmentally induced stresses during sesame flowering directly impair crop yields (36). A previous study has reported that high pollen temperature (>40 °C) during the flowering and seed development phases negatively affects pollen viability, stigma receptivity and seed formation resulting in partial or complete failure of fertilisation (Fig. 3). These factors exacerbate the problem because climate change also affects sesame production and oil yield (24). The most stress-sensitive phase of crop development is the reproductive stage, which further exacerbates the issues of

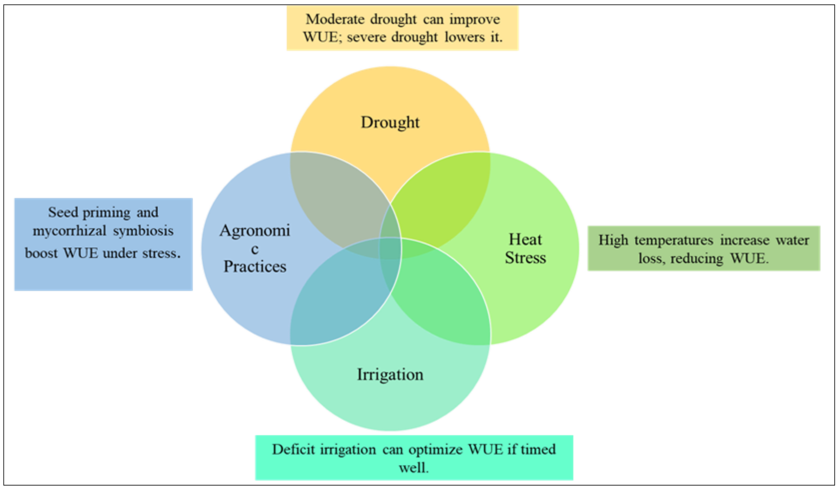

Fig. 2. Impact of climate change on water use efficiency on sesame.

Table 4. Impact of drought and heat stress on WUE in sesame

Stress Condition	Observed Effect on WUE	Study Details	Reference
Drought Stress	Drought significantly reduced WUE in sesame.	Field and physiological studies showed decreased photosynthetic efficiency and transpiration regulation under water deficit.	(10)
Heat Stress	Increased temperatures reduced WUE by increasing transpiration losses.	Sesame plants exposed to higher temperatures experienced accelerated transpiration, lowering the net water-use efficiency.	(35)
Combined Drought + Heat Stress	Dual stress had a compounded negative effect on WUE.	Combined drought and heat led to stronger reductions in biomass, photosynthesis and WUE than single stress alone.	(35)

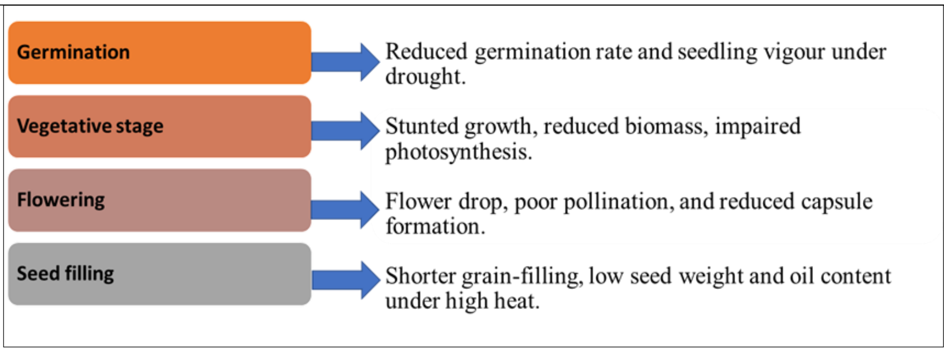

Fig. 3. Impact of heat stress on different stages of sesame.

crop productivity (37). The objectives of the investigation entail developing stress resilient sesame phenotypes, assessing desirable traits and hybridising with the cultivated sesame's wild relatives (24). It is imperative to understand the unique characteristics of the stress reproductive stage phenomena to enhance crop yield under harsh conditions, as well as the crop's physiological and molecular stress responses to adverse conditions (37). The knowledge helps refine advanced breeding strategies and technologies aimed at developing climate-resilient cultivars through sophisticated breeding approaches. Considerable focus on reproductive stage sensitivity should be given to develop resilient sesame cultivars (Table 5).

Heat stress impact on flowering sterility

Temperature above 32 ˚C can disturb anther dehiscence, leading to the destruction of either partial or total fertilisation owing to the disruption of pollen viability. In sesame and other crops, exposure to ≥ 35 °C during flowering can cause pollen sterility, dysfunction of the stigma and lower the chances of seeds set (35) (Fig. 4).

Drought-induced flower abortion

Abortion of capsules caused due to water-stricken flowers leads to a reduced number of young flowers, while this is increased with capsule ramps. Post-flowering drought results in withholding soil moisture for 14 days after flowering can lead to a yield reduction of up to 37 % in sesame, primarily due to a decrease in the number of seeds per capsule rather than seed size (38).

Combined effects of heat and drought stress

The impact of drought and heat stress together at the time of flowering tends to work additively. Drought-heat episodes enhance oxidative tissue damage caused to the reproductive system and lead to flower senescence. There is a lack of direct studies on sesame, but studies done on other plants confirm that harsher stress tends to augment flower loss and severely impact the chances of seed set (35).

Table 5. Impact of stress conditions on sesame flowering

Stress Condition	Effect on Flowering	Mechanism	Reference
Drought Stress	Significantly reduced flowering intensity and seed yield.	Impairs physiological processes, leading to decreased flower production.	(10)
Combined Drought + Heat Stress	Severe reduction in flowering and seed yield.	Synergistic effects impair reproductive processes more than individual stresses.	(10)
Heat Stress	Accelerated flowering and reduced seed yield.	Alters reproductive development, leading to early flowering and reduced seed set.	(35)

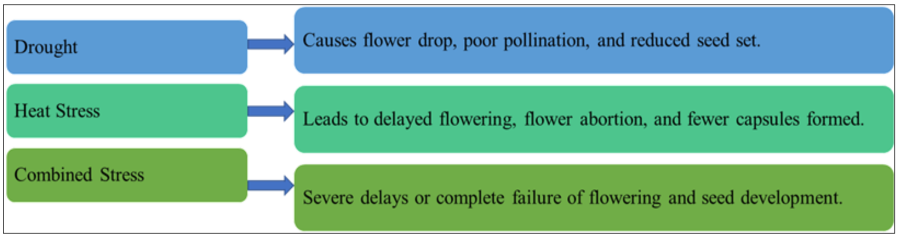

Fig. 4. Impact of climate change on sesame flowering.

Biochemical changes under climate stress

Accumulation of proline, soluble sugars and antioxidant enzymes

Drought stress causes a variety of biochemical changes in sesame plants. They synthesise osmoprotectants, like glutathione, soluble sugars and proline, which help maintain cellular homeostasis and protect against oxidative stress (10,26). In sesame plants undergoing abiotic stress, ROS act as dual functional agents: a signalling entity and a harmful one (39,40). If ROS levels are within set limits, some defence mechanisms will get triggered, however, an excessive amount of ROS will lead to the damaging of cellular components due to oxidation, also known as oxidative damage (41). To maintain an equilibrial state of ROS, sesame plants have antioxidant mechanisms, both enzymatic and non-enzymatic.

At the molecular level, the generation of ROS such as superoxide anions (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (•OH) occurs predominantly in chloroplasts, mitochondria and peroxisomes under abiotic stress. These ROS act as both signalling molecules and damaging agents, triggering MAPK (Mitogen-Activated Protein Kinase) cascades and transcription factors like WRKY, DREB and NAC, which regulate stress-responsive genes. Antioxidant enzymes such as superoxide dismutase (SOD) catalyse the dismutation of superoxide radicals into H_2O_2, which is subsequently detoxified by catalase (CAT) and ascorbate peroxidase (APX) through the ascorbate-glutathione (AsA-GSH) cycle. This cycle is vital for maintaining cellular redox homeostasis and protecting macromolecules from oxidative damage.

In parallel, plant hormone signalling pathways exhibit intricate crosstalk to coordinate responses to ROS-induced stress. For example, elevated abscisic acid (ABA) levels during drought activate SnRK2 kinases, which phosphorylate ABF/AREB transcription factors, modulating genes involved in stomatal closure and osmoprotectant biosynthesis. Additionally, interactions between ABA and ethylene signalling pathways can modulate antioxidant responses, while jasmonic acid (JA) and salicylic acid (SA) pathways fine-tune Systemic Acquired Resistance (SAR) and oxidative balance. The convergence of ROS and hormonal signals at the transcriptional level fine-tunes the expression of stress-responsive genes, creating a robust defence network in sesame under climate stress.

Enzymatic antioxidants include SOD, CAT, APX and glutathione reductase (GR); whereas non-enzymatic antioxidants include ascorbic acid, glutathione and tocopherols (41,42). All these systems work synergistically together to neutralise ROS and protect the plant from oxidative stress (39,41). Adding active oxygen species and boosting the antioxidant mechanism aids plant tolerance to different forms of abiotic stresses(39,42) (Table 6).

Antioxidant enzymes like SOD, CAT and peroxidase, which lessen the effects of ROS, are more active in drought-tolerant sesame genotypes (18). According to transcriptomic analyses, genes related to hormone signalling pathways, stress response and amino acid metabolism, specifically ethylene and ABA, are upregulated (10,20). Drought-tolerant genotypes accumulate more ABA, amino acids and organic acids (20). These adaptive responses help sesame plants maintain root integrity, photosynthetic activity and overall drought tolerance (46).

Hormonal responses under abiotic stress

Through intricate signalling networks and crosstalk mechanisms, plant hormones are essential for controlling abiotic stress responses (47,48). While other hormones like SA, JA and ethylene are involved in different stress signalling pathways, ABA plays a key role in mediating drought and osmotic stress responses (49,50). Sesame plant responses to various stresses can be fine-tuned by hormonal interactions, which can be antagonistic or synergistic. For example, ethylene may lessen resistance to chewing herbivores during flooding, while ABA and JA may work in concert to increase insect resistance under drought stress (49). The intricate crosstalk between stress-responsive and growth-promoting hormones, such as gibberellins, auxins and cytokinin, allows sesame to balance stress adaptation and development (50). Understanding these hormonal networks is crucial for developing stress-tolerant crops(47,48).

Impact on oil yield and quality in sesame under climate stress

Abiotic stresses such as heat and drought not only reduce seed yield in sesame but also significantly affect oil content and quality. Under moderate to severe drought stress, oil yield reductions of

Table 6. Impact of stress conditions on proline accumulation in sesame

Stress Condition	Effect on Proline Accumulation	Mechanism	Reference
Drought Stress	Significant increase in proline content in sesame leaves under drought conditions.	Drought induces osmotic stress, leading to enhanced proline biosynthesis as an osmoprotectant.	(10)
Combined Drought + Heat Stress	Marked increase in proline content due to synergistic effects of combined stresses.	Combined stresses exacerbate osmotic and oxidative stress, leading to a significant rise in proline accumulation.	(10)
Heat Stress	Elevated proline levels observed in sesame plants subjected to high-temperature stress.	Heat stress triggers oxidative stress, prompting proline accumulation to mitigate cellular damage.	(43)
Salt Stress	Proline accumulation observed in sesame under saline conditions.	Salt stress induces osmotic imbalance, enhancing proline synthesis to stabilize cellular structures.	(44)
Foliar Application of Proline	Increased proline content in sesame plants treated with foliar proline application.	Exogenous proline application boosts internal proline levels, enhancing stress tolerance mechanisms.	(45)

20–40 % have been reported, primarily due to impaired seed development and reduced photosynthate partitioning to seeds. Combined heat and drought stress can lead to even greater declines, with up to 50–70 % reduction in total oil yield in susceptible genotypes.

The fatty acid composition of sesame oil also shifts under stress. Under drought conditions, the oleic acid content (normally ranging from 35–45 %) may decline by 5–12 %, while linoleic acid (typically 35–50 %) can increase by a similar margin. For example, in certain genotypes, drought stress reduced oleic acid from 41.2–29.6 %, while linoleic acid increased from 37.8–48.9 %, altering the unsaturated fatty acid balance and nutritional profile of the oil.

Heat stress also impacts lipid biosynthesis enzymes, particularly Fatty Acid Desaturases (FADs), disrupting the conversion of saturated to unsaturated fatty acids. This results in a decline in polyunsaturated fatty acids and a relative increase in saturated ones such as palmitic and stearic acids. Heat exposure (>38 °C during seed filling) has been shown to reduce total unsaturated fatty acids by 8–15 %, compromising oil fluidity and shelf-life. Additionally, abiotic stress can alter the biosynthesis of lignans, key antioxidants in sesame oil. Drought and heat stress have been observed to reduce sesamin and sesamolin concentrations by 15–30 %, while increasing their glycoside forms, affecting oil stability and nutraceutical value. These quantitative changes underscore the importance of selecting and breeding sesame genotypes with stable oil content and composition under stress conditions and adopting agronomic practices that mitigate the impact of climatic extremes.

Changes in oil content under temperature and water stress

Factors such as temperature and lack of water are especially critical when it comes to the oil content or composition of oilseed crops like sesame. Changes in the environment can alter oil accumulation and fatty acid profiles by changing the expression or activity of lipid biosynthetic enzymes (50). Varieties of sesame with high oil content have been shown to greatly express genes related to lipid biosynthesis during the later stages of seed development (51). High sesame oil yield appears to be dependent on the rate of active oil biosynthesis, which must continue for an extended period during the later stages of seed development (52). While a lack of water can hinder plant growth and seed production, its impact on oil yield varies. While severe water stress can reduce oil yield, moderate stress may not have a significant effect. Oleic and linoleic acid contents show cultivar-specific responses to drought stress, which also affects the composition of fatty acids (53). Developing resilient, high-yielding oilseed crops in a variety of environmental conditions requires an understanding of these stress responses.

Oil content may not be impacted by water deficit, but seed yield is decreased (53). While linoleic acid content rises during drought stress, oleic acid levels fall (54). Applying nitrogen, however, can reverse this effect; higher nitrogen dosages cause oleic acid to rise while linoleic acid falls (54). FADs susceptibility to environmental influences is the cause of these alterations (50). Furthermore, drought stress changes the antioxidative lignan content, increasing lignan glycosides and decreasing sesamin and sesamolin (40). Abiotic stresses effects on oil composition emphasise the necessity of methods to reduce environmental impacts on storage lipid production to produce reliable, superior oil crops (Table 7).

Seed size, weight and maturity duration shifts

Climate change and water deficits have a significant impact on sesame, particularly on seed size, weight and time to maturity. During the flowering and pod filling periods, high temperatures and water scarcity decrease cell division, nutrient translocation and seed size, weight and oil content (55). Drought stress during flowering in crops such as sesame and groundnut, particularly at various developmental stages, leads to an exacerbated reduction in yield in comparison to other stages. Strikingly, these crops undergo changes in the length of time it takes to reach maturity, resulting in either an acceleration or delay of a stage termed as physiological maturity, which is critical for harvest aid planning (24). In efforts to combat these concerns, researchers are focused on developing drought-resistant cultivars while trying to identify features associated with terminal drought tolerance, such as low canopy temperature and high relative water content (56).

Genotypic variability and climate resilience in sesame

Climate-resilient sesame varieties and their stress tolerance mechanisms

Distinct genotypic variations in sesame are observable with drought stress and tolerant varieties show better physiological and biochemical adaptations. Drought-tolerant genotypes under stress maintain high levels of osmoprotectant retention, antioxidant enzyme activity and root architecture (10). As per transcriptomic and metabolomic studies, drought-tolerant sesame genotypes activate the genes responsible for scavenging ROS, amino acids and stress response more efficiently than their susceptible counterparts (20). At the molecular level, drought-tolerant sesame genotypes exhibit enhanced expression of stress-responsive genes, including SiDREB2A, which is involved in

Table 7. Abiotic stress impacts on sesame yield, oil quality and biochemical traits

Stress Type	Yield Impact	Oil Quality Impact	Biochemical and Antioxidant Changes	Suggested Adaptation	Reference(s)
Drought Stress	40-60 % reduction due to limited water availability	Decrease in oil content, decrease in oleic acid, increase in linoleic acid	Increase in proline, decrease in antioxidant enzymes like SOD and CAT, increased ROS	Use of drought-tolerant genotypes, improve soil moisture retention	(10,35,53)
Heat Stress	Reduced seed set and flower abortion	Decline in oil quality, increase in saturated fatty acids, reduction in sesamin and sesamolin	Increase in proline, lipid peroxidation, reduction in enzymatic antioxidant activity	Use of heat-resilient varieties, mulching, shading techniques	(35,50,54)
Combined Drought and Heat	Up to 70 % yield loss	Significant decline in oil quality, altered fatty acid ratios and lignan content	Severe oxidative stress, depletion of antioxidant defenses, increased MDA	Breeding for combined stress tolerance, multi-stress screening	(10,21,35)
Salinity (if relevant)	Yield reduction due to osmotic and ionic imbalance	Altered fatty acid composition (limited data in sesame)	Increased proline accumulation, enhanced osmoprotectant levels	Use of salinity-tolerant genotypes, soil amendments	(44,45)

dehydration tolerance and QTLs such as qDTY-1.3, associated with drought tolerance and yield stability under water-limited conditions (13). These advancements provide valuable strategies for improving sesame's resilience against abiotic stresses in light of changing climate conditions.

Breeding strategies for improved drought and heat tolerance

Breeding strategies aimed at improving tolerance to drought and heat involve selecting traits such as early flowering, high harvest index and more efficient water usage. Transfer of genes for stress-tolerance through molecular approaches is regarded as a modern method, while the traditional method involves crossing plants having certain features (57). Breeding programs have incorporated yield-based selection and combined it with physiological screening under stress (58). High-throughput phenotyping, genomic selection and gene editing are examples of advanced techniques that present new opportunities to speed up the development of climate-resilient crops (59). As evidenced by the breeding of temperate maize for the US corn belt, long-term improvement strategies necessitate the integration of trait information across scales and transdisciplinary teams in order to take advantage of new opportunities.

The use of biotechnology and genomics enabled breeders to enhance climate resilient sesame crops considerably and drought and salinity tolerance-related genes have been discovered through genome-wide association studies and QTL mapping (13). Key sesame traits and stress-responsive networks are highlighted through sesame transcriptomics, proteomics, metabolomics and genomics. By utilising transcriptomic and metabolomic profiling, important drought-responsive genes and metabolites have been identified; drought-tolerant genotypes have been documented to have heightened stress response pathway activation and protective metabolite accumulation, like amino acids and ABA (21). Genomic resources have transformed sesame from an 'orphan crop' to a 'genomic resource-rich crop', pioneering diverse breeding strategies (10). Although ethical and regulatory concerns are valid, CRISPR-Cas9 genome editing holds great potential for modifying genes with harsh abiotic stress tolerances (13).

Research gaps and future directions

Research gaps

- Limited multi-environmental validation of climate-resilient sesame genotypes, particularly under combined drought and heat stress.
- Insufficient molecular-level insights into gene regulatory networks controlling oil biosynthesis and stress tolerance.
- Lack of region-specific agronomic models and forecasts tailored to sesame under varying climate scenarios, especially in South Asia and Africa.
- Inadequate integration of omics approaches (transcriptomics, proteomics, metabolomics) in breeding programs for sesame improvement.
- Sparse long-term studies on the cumulative effects of climate stress on sesame's nutritional profile and seed longevity.

Future directions

- Develop stress-resilient sesame cultivars through CRISPR-Cas9, genomic selection and QTL mapping for traits like yield stability, oil quality and antioxidant capacity.
- Establish high-throughput phenotyping platforms to rapidly screen for abiotic stress tolerance traits under field and controlled conditions.
- Expand simulation modelling and remote sensing tools to predict sesame productivity under future climate scenarios.
- Promote interdisciplinary collaborations to integrate breeding, physiology, climate science and agronomy for climate-smart sesame cultivation.
- Explore biochemical and hormonal pathways in more depth to identify novel targets for genetic engineering and precision breeding.

Conclusion

Sesame, despite its natural tolerance to heat and drought, remains vulnerable to the accelerating impacts of climate change-particularly during sensitive stages like flowering and seed filling. Abiotic stresses significantly reduce yield and oil quality by disrupting physiological, biochemical and molecular processes. While genotypic variability and stress-adaptive traits offer opportunities for resilience, effective climate-smart solutions require an integrated approach. Advancements in genomics, molecular breeding and agronomic practices, along with region-specific forecasting and participatory breeding, are crucial for developing climate-resilient sesame cultivars. Strengthening interdisciplinary research and investment will be key to securing sesame's role in sustainable agriculture and nutrition under future climate scenarios.

Authors' contributions

VSS conceptualized and wrote the manuscript**,** GV supervised the work and revised the manuscript. DG, SA, KR, TK, KB and KS contributed through critical review and suggestions. All authors read and approved the final manuscript.

Compliance with ethical standards

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