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REVIEW ARTICLE

# Impact of climate change on oilseed production - A review

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## Abstract

Oilseeds are vital to global agriculture, providing essential edible oils, high-protein livestock feed and raw materials for bio-based industries. Climate change poses a threat to the productivity, quality and sustainability of oilseed crops. This review critically examines the impacts of major climate stressors, including rising temperatures, altered precipitation patterns, elevated atmospheric $CO_2$ levels, increased ozone and the heightened frequency of extreme weather events on the growth, yield and oil quality of key oilseed crops such as soybean, groundnut, rapeseed-mustard, sunflower, safflower and sesame. It explores the physiological and biochemical mechanisms underlying crop responses to climate-induced stress, focusing on reductions in oil content and shifts in fatty acid composition. Climate-related stressors can lead to yield declines ranging from 10 % to 40 %, with heat stress during flowering and seed filling causing up to a 70 % reduction in seed set in sensitive varieties. The review also evaluates adaptive strategies, including the development of climate-resilient cultivars through advanced breeding and biotechnology, the implementation of conservation agriculture and integrated nutrient management and the role of digital tools in monitoring and mitigating stress impacts. Emphasizing the urgent need for integrated research, policy support and sustainable farming practices, this review aims to guide future efforts in enhancing the resilience of oilseed crops.

**Keywords:** abiotic stress; adaptation and mitigation; climate change; crop production; elevated $CO_2$ and ozone; oilseed crops; yield and oil quality

## Introduction

Climate change refers to long-term alterations in the Earth's climate, including shifts in temperature, precipitation and an increase in extreme weather events. These changes result from both natural variability and human activities, particularly the emissions of greenhouse gases from the combustion of fossil fuels, deforestation and industrial processes. This warming trend is linked to changes in precipitation patterns and a heightened frequency of extreme weather events, such as droughts and floods (1). Oilseed crops such as soybean (*Glycine max*), sunflower (*Helianthus annuus*), rapeseed/canola (*Brassica juncea /napus*), groundnut (*Arachis hypogaea*), sesame (*Sesamum indicum*) and safflower (*Carthamus tinctorius*) play a vital role in global agriculture and the economy. They contribute significantly to vegetable oil production and human nutrition by providing essential fatty acids, vitamins and proteins. The oil extraction process also produces protein-rich by-products, mainly used in animal feed, but with rising demand for plant-based proteins, oilseeds are becoming recognized as sustainable protein sources for human consumption (2). Oilseed crops are crucial not only for nutrition but also for industrial uses, including pharmaceuticals, cosmetics and biodiesel. However, the global oilseed industry is facing challenges due to climate variability. Rising temperatures, changing precipitation, increased atmospheric $CO_2$ and extreme weather events are affecting crop health and productivity. Major oilseed-producing regions in North America, South America and Asia are experiencing declines in yields, threatening food security and oil quality. In North America, these shifts lead to reduced crop yields, while in Asia, altered winter patterns negatively impact oilseed growth (3). High temperatures negatively influence traits like biomass accumulation, timing and yield components, compromising oil yield and stability (4). Changes in rainfall and increased droughts affect seed development and alter fatty acid profiles essential for oil quality (5). Elevated atmospheric $CO_2$ can boost photosynthesis and increase biomass and seed yield, but it often reduces seed protein and micronutrient content, lowering nutritional value. Former studies showed that $eCO_2$ can negatively impact seed quality, resulting in lower germination rates and reduced seedling vigor (6). Additionally, tropospheric ozone ($O_3$), a secondary pollutant formed through photochemical reactions, enters plant leaves via stomata, creating reactive oxygen species that harm cells, reduce photosynthetic efficiency and lead to premature senescence. $O_3$ exposure leads to visible foliar injury and significant yield reductions in sensitive oilseed species (7). To combat the impacts of climate change on oilseed production, adopting adaptive agricultural practices is essential. Methods like conservation agriculture, optimized planting schedules and efficient irrigation can improve water-use efficiency, soil health and crop resilience, contributing to the sustainability of oilseed systems (4). A comprehensive strategy that combines advanced plant breeding, climate-smart practices and strong policy support is crucial for protecting oilseed yields in changing climates. Innovations like marker-assisted selection, genomic selection and CRISPR gene editing can help create oilseed varieties more resilient to heat and drought. Supportive policies that fund research and encourage sustainable practices will enhance adaptation to climate challenges.

This review addresses the effects of climate-induced stressors such as drought, heat and changing pest dynamics on key oilseed crops like soybean, mustard, groundnut, sunflower and sesame. It highlights regional vulnerabilities, adaptive traits and yield trends under different climate scenarios, focusing on developing climate-resilient cultivars and integrating precision agriculture technologies.

## Oilseed scenario

### Global oilseed production

Global oilseed production is projected to reach a record high of approximately 692 million tonnes in the 2025/26 marketing year, reflecting a 2.2 % increase of nearly 15 million tonnes compared to the previous year. Increased yields in soybeans, sunflowers, rapeseed, peanuts and palm kernels primarily drive this growth. Soybeans remain the leading oilseed, with an expected production of around 426.8 million tonnes. Rapeseed and sunflower seeds are also expected to recover, reaching approximately 89.6 million tonnes and 56.2 million tonnes, respectively.

The leading oilseed-producing nations include Brazil, the United States, Argentina, China and India. Brazil is at the forefront with a soybean harvest estimated at around 175 million tonnes, which accounts for 59 percent of global exports. The U.S. closely follows with an output of approximately 128 million tonnes of soybeans. Additionally, China, Argentina and India are significant contributors to the production of oilseed crops, as illustrated in Fig. 1, 2 & 3 depicts the current status of oilseed production in India (8).

### Global oilseed trade

The global oilseed trade is expected to grow nearly 3 % and reach around 215 million metric tons by the 2025/26 period, driven by rising exports of soybeans, peanuts and sunflowers. Brazil and the United States are the leading exporters of soybeans, with Brazil accounting for approximately 59 % of the global market, mainly supplying to China.

Additionally, trade in oilseed meals and oil is also on the rise, particularly for products derived from sunflower and rapeseed. The increased processing of soybeans is fuelling significant production of meal and oil, which is expected to boost the global vegetable oil trade to about 234.5 million metric tons. Major importers include China, India, the European Union and other densely populated developing countries, highlighting a strong demand across food, feed and industrial markets. The global export and import status of oilseeds is presented in Fig. 4 & 5.

### Impact of climate vulnerability zones on oilseed production

Climate vulnerability zones, areas at risk of issues like drought, heat waves, erratic rainfall, flooding and ozone pollution, are increasingly impacting oilseed production worldwide. Key regions for oilseed farming, such as South Asia, Sub-Saharan Africa, Eastern Europe and parts of Latin America, are recognized as highly susceptible to these climate challenges. For instance, in India and Sub-Saharan Africa, where farmers often cultivate groundnuts and sesame relying on rainwater, frequent droughts and delayed rainy seasons have made it more difficult to maintain productivity and increased the likelihood of crop failures.

In Brazil and Argentina, soybean crops are suffering from heat stress, particularly during critical growth phases, leading to fewer seeds and lower oil content. This issue is especially pronounced in the southern Cerrado and Pampas regions, where heat waves are becoming more frequent. Furthermore, Ukraine and Russia, key players in sunflower production, have experienced significant yield losses due to prolonged dry periods and geopolitical issues that disrupt access to farming essentials like irrigation.

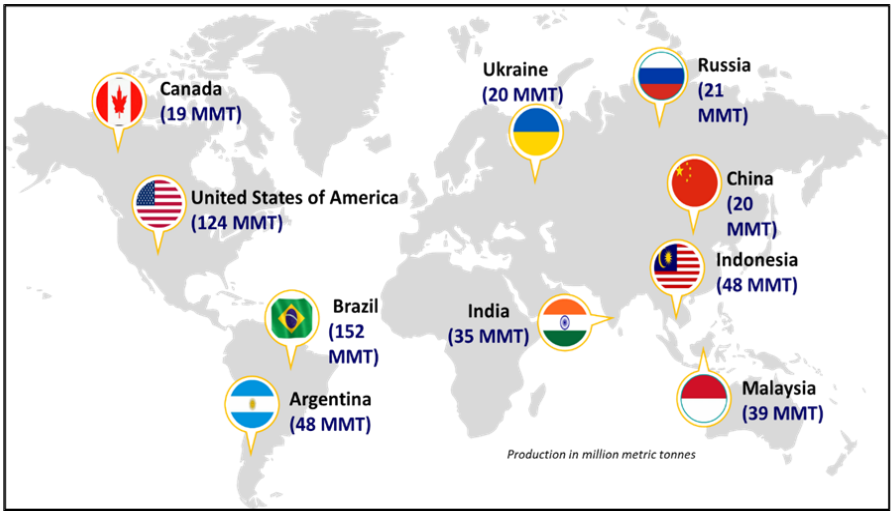


**Fig. 1.** Top leading Countries in oilseed production (Million metric tonnes) (9).

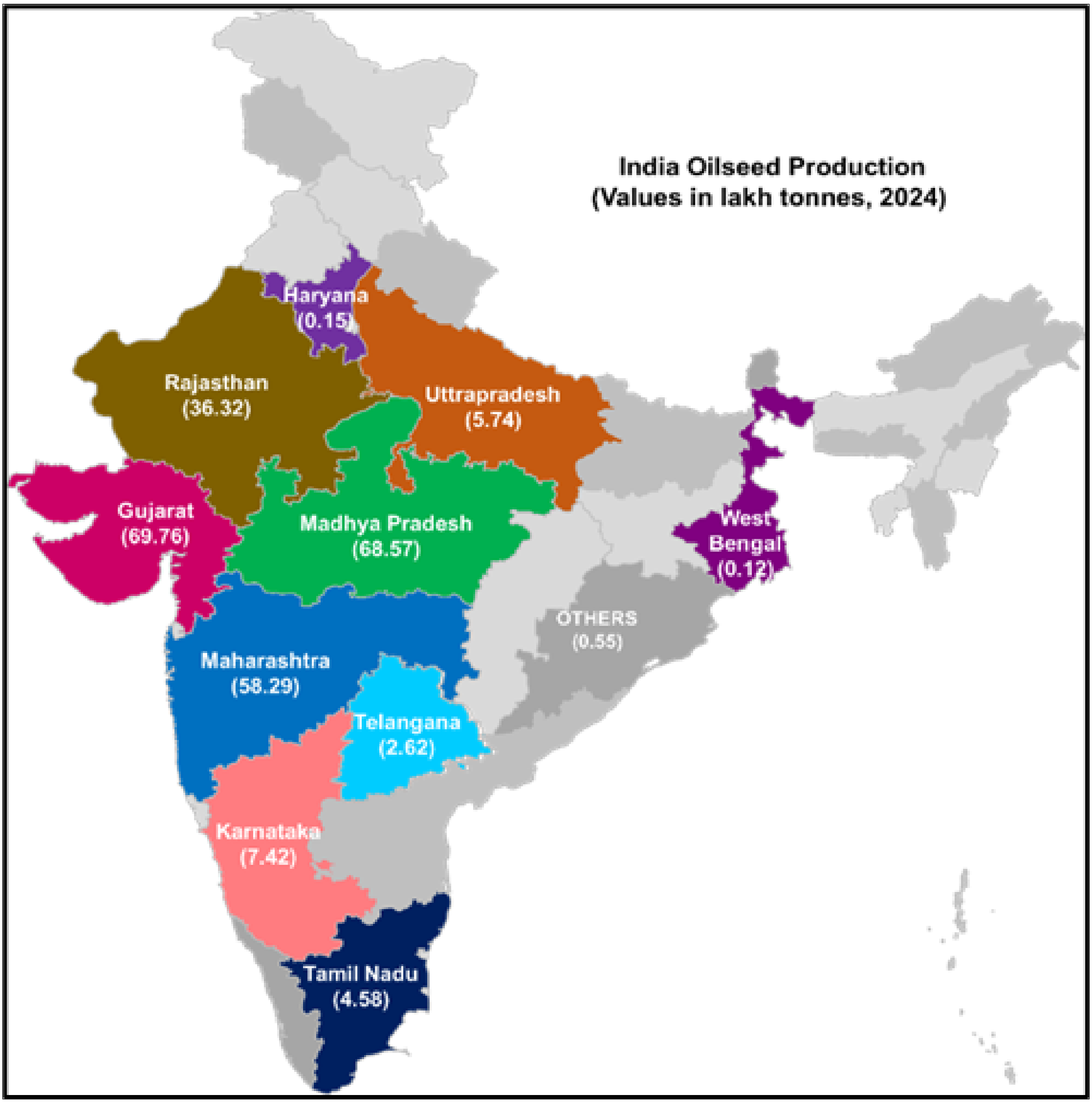


**Fig. 2.** Top leading states in oilseed production (Lakh Tonnes) (9).

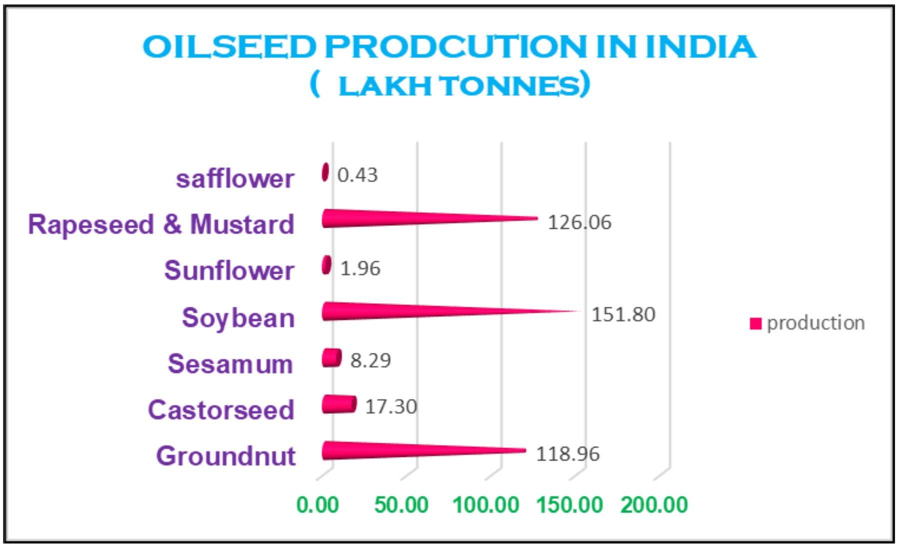


**Fig. 3.** Oilseed production in India (9).

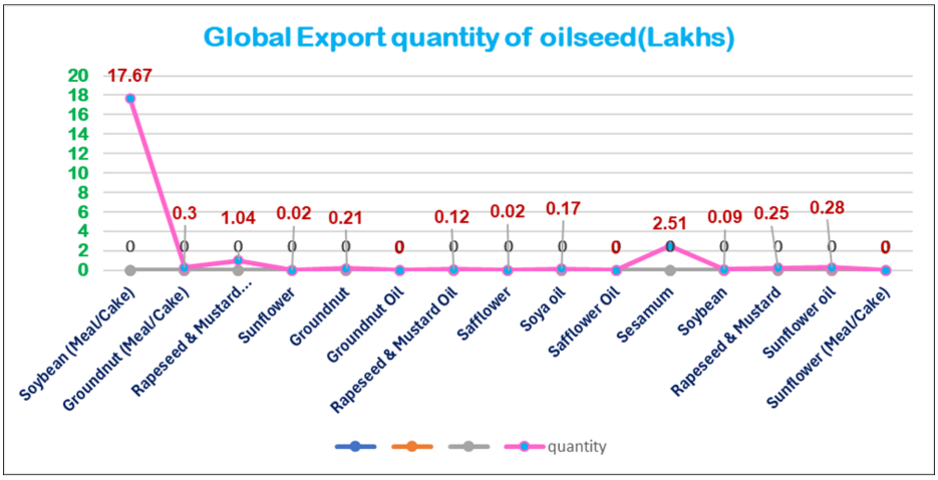


**Fig. 4.** Global Export quantity of oilseeds (Lakhs) (10).

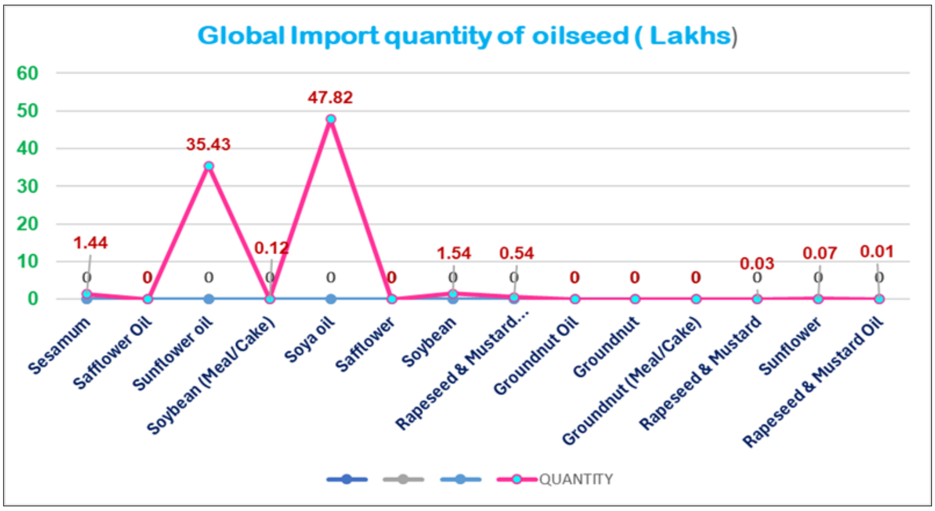


**Fig. 5.** Import quantity of oilseed (Lakhs) (10).

Additionally, in polluted areas, particularly in industrial regions of China and northern India, rising ozone levels and increased carbon dioxide can stress crops such as rapeseed and soybean, hinder photosynthesis and ultimately lowering yields. Looking ahead to 2050, climate models indicate that 10-30 % of the land currently suitable for oilseeds may become unviable due to elevated climate risks. Many vulnerable areas, especially in Africa and South Asia, may lack the necessary resources to adapt to these changes. This situation underscores the urgent need for developing climate-resilient seed varieties, investing in systems that can provide early warnings and implementing comprehensive strategies to adapt and sustain oilseed production in these high-risk regions (11, 12). The climate requirements for oilseed crops are provided in detail in Table 1.

## Crop-specific response to climate change

Climate change affects the yield and hinders efforts to boost yields, where rising temperatures may exacerbate drought stress and accelerate crop development, while also raising crop yield variability and the likelihood of yield failures. The effects of climate change on crop growth are illustrated in Fig. 6.

### Mustard (*Brassica sp.*)

Mustard species, such as *Brassica juncea* and *Brassica napus*, are highly sensitive to climatic stressors, particularly during germination, seed development and flowering. Climate change imposes thermal, hydric and atmospheric stresses that substantially affect productivity, oil quality and plant health. High temperatures during flowering reduce pollen viability and fertilization rates, leading to a yield decline of 20 % to 30 % in *Brassica juncea* (14). Elevated temperatures also disrupt seed oil accumulation and enzymatic activity, causing oxidative stress and poor seed quality (15).

Drought stress further exacerbates yield losses, ranging from 17 % to 94 %, depending on timing and severity (16). It also alters the fatty acid profile of the oil, decreasing nutritional quality (17). Increased levels of ozone ($eO_3$) have a detrimental impact on photosynthesis in Indian mustard, leading to a significant reduction in chlorophyll levels and decreased stomatal conductance, which ultimately results in lower yields. In response to this oxidative stress, plants activate key antioxidant enzymes such as superoxide dismutase (SOD),

**Table 1.** Climate requirements of the oilseed crop (13)

| Oilseed Crop | Optimal Temperature (°C) | Rainfall (mm) | Soil Type | Growing Season |
|---|---|---|---|---|
| Sesame | 25- 35 | 500 - 650 | Well-drained sandy Loam | Warm Season |
| Sunflower | 20 - 25 | 500 - 750 | Loam<br>Sandy loam | Spring-summer |
| Groundnut | 25 - 30 | 500 - 1000 | Light sandy loam, well-drained | Warm Season |
| Mustard | 18 - 25 | 400 - 600 | Sandy loam | Cool Season |
| Soyabean | 20 - 30 | 600 - 1200 | Well-drained loam to clay loam | Summer |
| Castor | 20 - 30 | 600 - 1000 | Well-drained Loamy soil | Warm Season, Drought-tolerant |

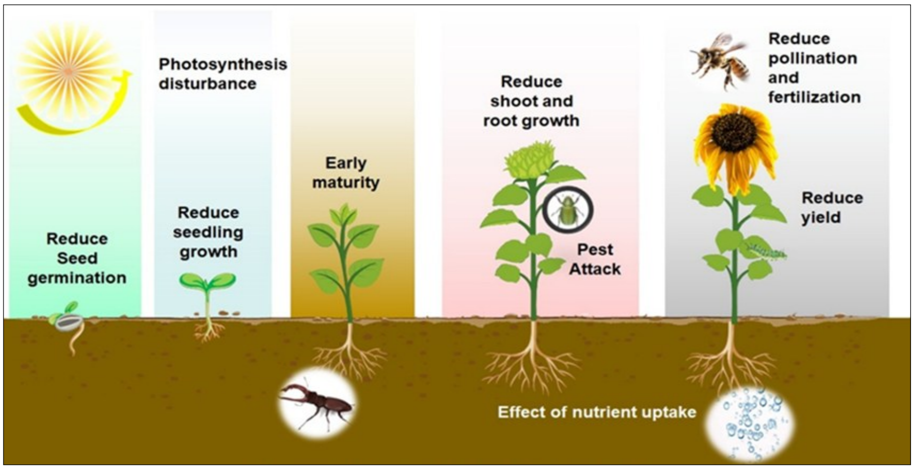


**Fig. 6.** Climate change impact on crop growth.

catalase (CAT), peroxidase (POX) and ascorbate peroxidase (APX) to combat the effects. Elevated carbon dioxide ($eCO_2$) directly promotes robust plant growth by enhancing photosynthesis and boosting chlorophyll content, which increases the leaf area index and improves water use efficiency. Furthermore, higher $CO_2$ levels effectively reduce ozone absorption by promoting stomatal closure. $eCO_2$ unequivocally mitigates some of the harmful effects of $eO_3$ (18). Additionally, exposure to ozone ($O_3$) can increase oxidative stress in plants, which may reduce their ability to defend themselves. This makes them more susceptible to diseases, such as wilt and leaf spots. Elevated $CO_2$ enhances the photosynthetic rate, resulting in increased biomass accumulation in mustard crops (19). The progression of powdery mildew in *Brassica juncea*, concluding that the ideal conditions for outbreaks occur at temperatures between 25 °C and 30 °C, with nighttime lows above 10 °C and relative humidity below 50 %. For instance, Alternaria blight alone can cause a yield loss of 10-80 % under conducive climatic conditions (20).

**Groundnut *(Arachis hypogaea)***

Groundnut, or peanut, is an important oilseed crop grown in tropical and subtropical regions. Its productivity and oil quality are affected by climatic factors such as temperature, water availability, pollutants and biotic stresses, which are worsening due to climate change. High temperatures during flowering can lead to issues like flower abortion and reduced seed set, with studies showing that maximum temperatures of 30.1 °C and 31.2 °C can decrease seed set by 7 % and 14 %, respectively. When subjected to heat stress, there is generally an increase in saturated fatty acids, such as palmitic and stearic acids, while the levels of unsaturated fatty acids, including oleic and linoleic acids, tend to decrease. This alteration negatively impacts the quality of the oil and diminishes its nutritional value (21). Higher levels of $CO_2$ (550 and 700 ppm) led to a decrease in kernel yield per plant by 32.28 % and 28.40 %, respectively, although pod yield remained stable (22, 23).

In groundnut crops, rising temperatures and drier conditions have led to an increase in fungal diseases. Notably, dry root rot caused by *Macrophomina phaseolina* thrives in temperatures between 25 and 35 °C, particularly during periods of low moisture, while stem rot from *Sclerotium rolfsii* can result in yield losses as high as 80 % (24). Additionally, groundnut is affected by foliar pathogens like early and late leaf spots, rust, web blotch and *Aspergillus flavus*, which also prosper in extreme heat and moisture levels (25). Elevated $CO_2$ concentrations can boost net photosynthesis by up to 56 %, while photorespiration may decrease by approximately 36 % (26)

**Soybean (*Glycine max*)**

Rising temperatures can reduce pollen viability and shorten reproductive periods, potentially leading to a decrease in yields of up to 19 % in anticipated climate conditions (27). Irregular rainfall and drought pose significant risks to yields during key growth phases like flowering and pod formation. Additionally, climate-related stresses can lower seed nitrogen content by 20 % and affect oil quality by altering fatty acid profiles (28). Furthermore, increased $CO_2$ and temperatures may boost the competitiveness of $C_4$ weeds over soybeans, which are $C_3$ plants, resulting in possible yield declines of 30-45 % if not managed properly, highlighting the necessity for integrated weed management strategies (29). Changes in temperature and precipitation can cause water stress, negatively affecting soybean growth and their ability to absorb nutrients (30). A reduction of 20 % in rainfall can also harm soybean development, leading to water stress and reduced leaf area (31). Elevated $CO_2$ levels can influence flower structure and pollen production, resulting in smaller flowers and lower pollen viability (32). On a positive note, higher $CO_2$ levels may enhance leaf $CO_2$ uptake by 39% and canopy photosynthesis by 59 %, potentially boosting seed yield by 15 % (33). However, increased ozone levels can adversely affect flower structure, resulting in smaller blooms and diminished pollen viability, which hinders fertilization and fruit development (28). Soybean rust *(Phakopsora pachyrhizi)* outbreaks are also more frequent in humid-warm settings, with potential yield reduction ranging from 10% to 80% (34). Soybean plants exhibit enhanced vegetative growth and improved leaf characteristics under elevated $CO_2$ conditions, indicating a potential increase in yield (35).

**Sesame**

Sesame is known for its drought tolerance, allowing it to grow well in dry areas. However, it still faces problems from unpredictable rainfall, rising temperatures, pests and poor soil (36). Sesame (*Sesamum indicum*) is negatively affected by ozone ($O_3$) as it enters through the plant's stomata. This exposure leads to the formation of reactive oxygen species (ROS), which can harm the structure of chloroplasts. As a result, photosynthesis is hindered, leading to issues like leaf yellowing, tissue damage and early aging of the leaves. These problems ultimately contribute to a decline in the plant's overall growth, reproduction, quality and yield (37). Furthermore, ozone disrupts the plant's natural antioxidant defences by affecting both its enzymatic (like SOD, CAT and POD) and non-enzymatic systems. This disruption leads to increased levels of hydrogen peroxide, higher lipid peroxidation and more ion leakage (38).

#### Sunflower

High temperatures during the reproductive phase can lead to reduced seed development and increased production of empty seeds, negatively impacting overall productivity. High temperatures during the reproductive phase can lead to reduced seed development and increased production of empty seeds, negatively impacting overall productivity (39). Increased temperatures and high irradiation significantly impair photosynthetic efficiency, with reductions in key performance indices observed in sunflower hybrids (40). Elevated $CO_2$ levels can enhance photosynthesis and water use efficiency, but this does not necessarily translate to improved reproductive outcomes (39). Increased temperatures can lead to a reduction in sunflower yield, with projections suggesting a potential decrease of up to 25 % by 2050 due to climate change. Climate change is expected to alter water availability, impacting water use efficiency (WUE) in sunflowers. Enhanced WUE is anticipated under elevated $CO_2$, but this is contingent on maintaining optimal soil moisture levels (41). High ozone levels led to early leaf senescence and leaf drop, reducing the photosynthetic area and negatively impacting biomass accumulation and yields (38). Drought conditions during flowering were known to lower seed oil content, with severe droughts causing oil content to drop below 40-43 %, along with reductions in seed and oil yields (42). Elevated $CO_2$ levels, when coupled with higher temperatures, sped up the development of sunflowers but may have also reduced the grain-filling period, leading to smaller seeds (43). Furthermore, altered root exudates due to elevated $CO_2$ influenced soil microbial communities, affecting nutrient availability and overall plant health (44).

#### Safflower

Safflower's growth is influenced by temperature and moisture levels, with optimal conditions enhancing photosynthetic efficiency and biomass accumulation. Furthermore, highlighted that aphids, a major pest affecting safflower, tend to thrive in warmer conditions, leading to increased and more severe infestations (45). Prolonged drought and higher temperatures impair the plant's natural defences, making safflower more susceptible to fungal pathogens such as *Alternaria carthami* and *Fusarium spp*. (43). Inconsistent rainfall patterns intensify infestations by sucking insects like whiteflies and jassids, which prefer humid environments. Pests such as the safflower fly (*Acanthiophilus helianthi*) and pathogens like rust caused by (*Puccinia carthami*) are projected to extend their reach into previously uninfected areas (46). The physiological and biochemical responses of major oilseed crops to climate stress are summarized in Table 2. The effects of climatic stress on oil quality are presented in Table 3. Furthermore, the direct and indirect benefits of oilseed crops in the context of climate change are illustrated in Fig. 7, while yield losses associated with climate change are detailed in Table 4.

## Adaptation strategies

The increasing threats posed by climate change, rising temperatures, erratic precipitation, soil degradation and intensifying biotic stresses necessitate comprehensive adaptation strategies to sustain oilseed production. Effective adaptation helps crops survive under stress and ensures yield stability, oil quality and economic viability. These strategies integrate agronomic practices, genetic improvement, soil management and ecological approaches, forming a multidimensional defence against climatic adversities. Strategies for adapting to climate change are illustrated in Fig. 8.

#### Agronomic adjustments: Sowing dates and varietal choice

Adjusting sowing dates to match the shifting climatic windows is one of the simplest yet highly effective strategies. Crops sown earlier or later can avoid critical stress periods, particularly heat waves during the flowering or seed filling stages. For instance, in semi-arid regions, advancing sowing by 10-15 days has been shown to reduce yield losses in groundnut and soybean during intense heat periods (61). Perennial grain and oilseed plants present a sustainable approach for adapting to climate change by enhancing resilience against unpredictable weather and changing species distributions. These agricultural systems can boost environmental advantages and aid in climate change adaptation by promoting better soil health and minimizing erosion (62).

#### Soil health management: Biochar, organic amendments and conservation

Maintaining soil health is central to improving the resilience of oilseed systems. Biochar, a carbon-rich material produced from biomass pyrolysis, has been shown to enhance soil physical properties, such as porosity and water retention capacity. In drought-prone areas, biochar applications have improved plant -available water, directly benefiting crops like safflower and sesame during dry spells (63, 64). When biochar is combined

**Table 2.** Physiological and biochemical responses of major oilseed crops under climate stress

| Crop | Stress | Physiological change | Biochemical change | References |
|---|---|---|---|---|
| **Mustard** | $CO_2$ and Ozone | $eCO_2$ enhances photosynthesis, chlorophyll production, leaf area index (LAI) and water use efficiency (WUE) by improving carbon absorption, whereas $eO_3$ diminishes these factors due to oxidative stress and restricted $CO_2$ uptake. | Increased levels of $O_3$ lead to the breakdown of chlorophyll and boost the activity of antioxidant enzymes (SOD, CAT, POX and APX) as a result of oxidative stress. Conversely, heightened $CO_2$ levels improve chlorophyll content and regulate antioxidant enzyme activity. | (18) |
| **Sunflower** | Drought Stress | Photosynthesis is hindered<br>There is a decrease in leaf area and biomass growth | Increased levels of reactive oxygen species (ROS). Upregulated antioxidant enzymes (SOD, CAT). Accumulation of proline. | (4, 47) |
| **Groundnut** | Drought Stress | Decrease in leaf water potential<br>Decreased stomatal conductance and growth | Higher levels of proline and soluble sugars increased catalase and peroxidase activity. | (48) |
| **Soybean** | Heat Stress | Decreased pollen viability<br>Lower levels of chlorophyll and reduced photosynthetic efficiency | Heat shock proteins (HSPs) are triggered; Elevated levels of proline, glycine betaine and activity of antioxidant enzymes | (49) |
| **Sesame** | Drought Stress | Plant height and leaf area have decreased, resulting in reduced water use efficiency and lower rates of photosynthesis. | Induced heat shock proteins (HSPs)<br>Higher concentrations of proline, glycine betaine and activity of antioxidant enzymes. | (50) |

**Table 3.** Effect of climatic stresses on oil quality

| Crop | Stress type | Fatty acid alterations | References |
|---|---|---|---|
| **Soybean** | Drought | ↑ Oleic acid, ↓ Linoleic and Linolenic acids | (51) |
| **Sunflower** | Heat Stress | ↑ Oleic acid; ↓ Linoleic acid | (52) |
| **Rapeseed (Canola)** | Elevated Temperature | ↓ Oleic acid, ↑ Erucic and Linolenic acids | (53) |
| **Groundnut** | Drought | ↑ Saturated FA (palmitic, stearic); ↓ Unsaturated FA (oleic, linoleic) | (54) |
| **Sesame** | High Temperature | ↑ Palmitic and stearic acids; ↓ Oleic acid | (55) |
| **Safflower** | Drought + Heat | ↑ Saturated FAs: ↓ Linoleic acid | (56) |
| **Mustard** | Ozone | ↓ Erucic acid | (18) |

**Table 4.** Yield loss due to climate change

| Oilseed crop | Yield loss | Impact of climate change | Reference |
|---|---|---|---|
| **Rapeseed** | 10-25% | Heat stress, Drought stress, Premature pod and shattering | (57) |
| **Indian Mustard** | 20-25% | Increased $O_3$ levels, declines relative growth rate, crop growth rate and yield parameters | (18) |
| **Soyabean** | 11-25% | High $CO_2$ level, Heat stress | (58) |
| **Sesame** | 10-35% | Drought, High temperature, Erratic rainfall | (59) |
| **Groundnut** | 10-40% | Drought stress, High Temperature | (60) |

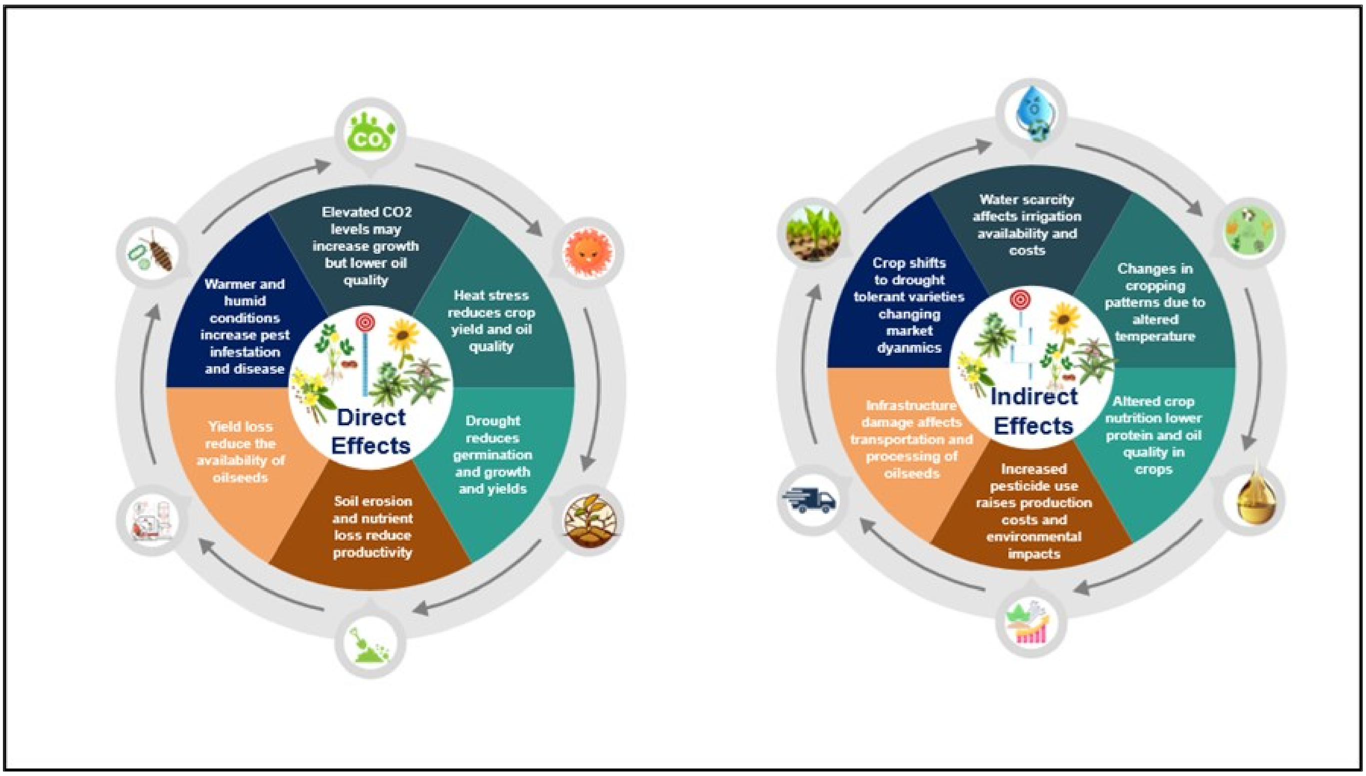


**Fig. 7.** Direct and indirect Benefits of the oilseed crop due to climate change.

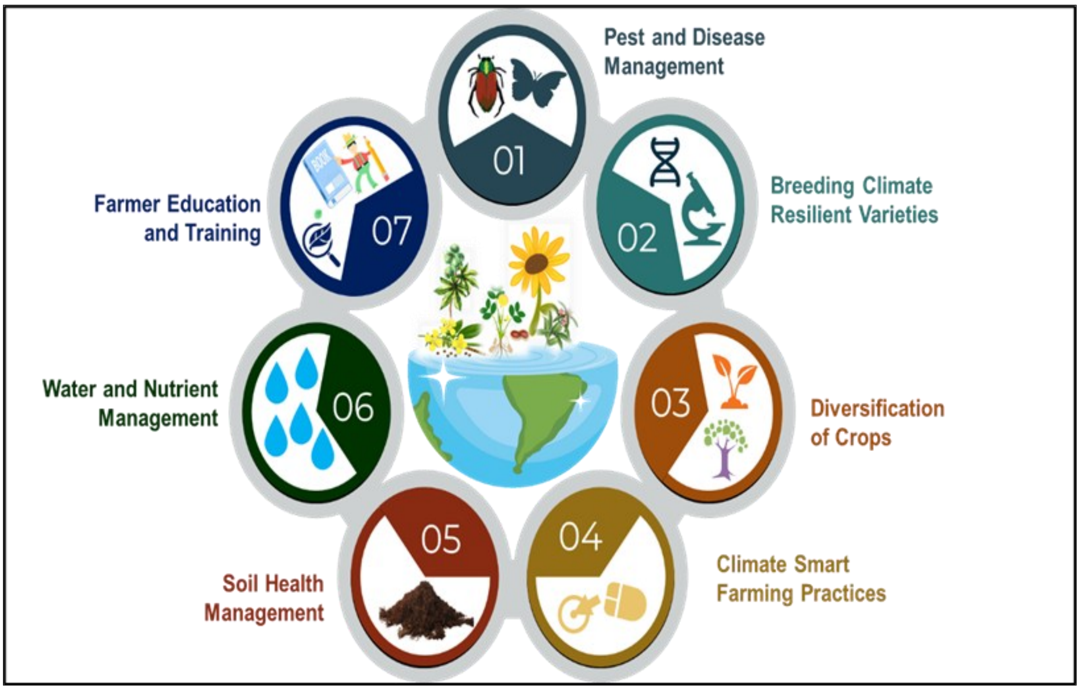


**Fig. 8.** Strategies for adapting to climate change.

with organic amendments, including compost, farmyard manure and green manures, the synergistic effects enhance soil microbial activity, nutrient cycling and carbon sequestration. This not only improves soil fertility but also mitigates greenhouse gas emissions from agriculture (65). Cover crops, particularly leguminous species like sun hemp, enrich the soil with biologically fixed nitrogen and improve soil aggregation, reducing the need for synthetic fertilizers (66).

Both organic and synthetic mulches play an important role in keeping soil moisture consistent and regulating temperature. They also help to control weed growth and promote healthy soil organisms. A recent study highlighted some findings that straw mulch can cool down the soil and slow down the flowering process, while using plastic film mulch helps retain moisture and boosts plant growth (67).

**Water and nutrient management**

INM combines different nutrient sources, such as farmyard manure (FYM), vermicompost and chemical fertilizers, to maximize nutrient availability and improve soil fertility. Research indicates that INM can result in considerable increases in crop yields, with enhancements ranging from 1.3 % to 66.5 % over traditional methods (68). Integrated Nutrient Management (INM) practices also play a role in boosting nutrient use efficiency and resilience to climate variability, which is essential for oilseed crops dealing with fluctuating weather conditions.

Enhancing the efficiency of water and nitrogen usage is an essential strategy for adaptation. A framework that combines optimization and simulation can improve agricultural management by considering climate variability and soil characteristics, resulting in considerable reductions in the use of irrigation water and nitrogen fertilizer (69). Switching to drip irrigation can help minimize the amount of moisture on leaves, which in turn lowers the chances of fungal diseases and boosts the overall health of the plants (70).

**Pest and disease management**

Current management strategies are focusing on climate-smart integrated pest management (IPM). This approach integrates methods like predictive monitoring, using resistant crop varieties, practicing crop rotation, implementing cover crops (including mixtures of biofumigant Brassicaceae) and employing biological control agents. The goal is to lessen the reliance on chemical solutions while promoting environmentally friendly pest control practices (71). Recent studies have shown that selecting for beneficial microbiome traits in oilseed rape (canola) improves resistance to both soil-borne pathogens and insect pests, while also contributing to drought tolerance (72). Rotating oilseed crops with non-host plants, such as cereals or legumes, is an effective way to break the cycles of pests and diseases. Studies have shown that mixing up these crop rotations can greatly lessen the severity of diseases and reduce weed growth compared to growing the same crop continuously (73). Incorporating tools such as traps, row covers and smart traps connected to the Internet of Things (IoT) provides effective and environmentally friendly ways to manage early pest problems (74). Combining natural fungicides and plant-based solutions like neem extracts can boost the effectiveness of chemical treatments while also lowering the risks to the environment and our health (75).

**Genetic improvement and biotechnological innovations**

Cutting-edge biotechnological techniques, including high-throughput phenotyping and genome-wide association studies, have the potential to speed up the development of resilient oilseed varieties. Genetic advancements offer long-term, sustainable solutions to climate stress. The deployment of marker-assisted selection (MAS) and genomic selection allows breeders to identify and incorporate stress-tolerant genes rapidly. In crops like rapeseed-mustard and sunflower, significant progress has been made in identifying quantitative trait loci (QTLs) linked to drought and heat tolerance. Modern tools such as CRISPR-Cas9 enable precise gene editing, targeting genes involved in stress signalling pathways, photosynthesis efficiency and root architecture. Editing genes associated with abscisic acid (ABA) regulation has improved drought tolerance by enhancing stomatal control in several oilseed crops (4). Additionally, transgenic approaches have been explored for introducing foreign genes that confer resistance to abiotic and biotic stresses. However, regulatory and socio-economic factors influence the adoption of such technologies. Modern techniques like high-throughput phenotyping, genomic selection, QTL mapping and marker-assisted selection are essential for discovering and combining resistance genes. The idea of "Breeding 4.0" brings together machine learning, big data analysis and genomic databases, enabling scientists to forecast which combinations of genes will thrive under various stressors like pest infestations, drought and extreme heat (76, 77).

**Future prospects: integration of technology and policy**

Successful adaptation strategies depend on policy support and technology. Investing in education and digital tools can enhance climate-resilient agriculture and improve farming practices. Pennycress (*Thlaspi arvense L.*) is gaining attention as a winter annual oilseed crop suitable for biofuel production.

## Conclusion

Climate change is posing a serious and escalating threat to oilseed production worldwide. It disrupts key physiological processes in crops, reduces their yield potential and alters the relationships between crops and pests or pathogens. This is happening due to higher temperatures, fluctuating rainfall, increased levels of $CO_2$ and ozone in the atmosphere and more frequent extreme weather events. Oilseed crops such as soybeans, groundnuts, sunflowers, sesame and mustard respond differently to these climatic challenges, influenced by their genetic makeup, growth stage and the specific conditions of the region where they are grown. To cope with these issues, various adaptation strategies have been developed. These include breeding climate-resilient crop varieties, changing planting schedules, practicing conservation agriculture and employing integrated nutrient and pest management techniques, as well as precision irrigation. Such strategies can significantly improve crops' resilience, enhance the efficiency of resources and stabilize yields, even in stressful conditions.

However, many smallholder farmers struggle to adopt these methods due to economic challenges, limited knowledge, variations in how effective these strategies are in different regions and restricted access to new technologies. Moreover, breeding crops that can withstand multiple stresses is complex due to the nature of polygenic traits and interactions between genotypes and their environments, alongside the scarcity of climate-resilient seeds.

To effectively tackle these climate-related challenges, a comprehensive approach is necessary. This should combine advancements in genomics, climate-smart farming practices, decision-support tools and innovations that prioritize farmers' needs. Strengthening research and extension services, promoting successful practices through supportive policies and encouraging international cooperation will be vital in this process.

In summary, while climate change poses significant hurdles for the sustainability of oilseed production, it also presents an important chance to rethink and enhance oilseed agriculture. By embracing scientific advancements and inclusive strategies, we can ensure productivity, resilience and food security even in uncertain climate conditions.

## Future prospects

The future of oilseed production in the face of climate change relies on new genetic technology, digital farming methods and sustainable practices. Advances in genetic engineering, particularly tools like CRISPR-Cas9 and genomic selection, are crucial for developing oilseed varieties that can withstand stresses such as heat, drought and saline soils, while also being more resistant to pests.

Digital tools, including remote sensing and climate modelling, help farmers monitor environmental changes and make better decisions about planting and managing resources. Each type of oilseed crop has its specific challenges to overcome. Sesame is drought-tolerant but heat-sensitive; canola suffers yield losses from high temperatures; sunflower has moderate drought tolerance but is vulnerable to extreme weather, while groundnut is highly susceptible to heat and moisture stress. Research into crop-specific genetic traits for stress tolerance is vital. Elevated $CO_2$ may enhance photosynthesis but can be limited by heat stress and nutrient dilution.

To combat climate-induced risks, strategies like disaster preparedness, sustainable practices and efficient water management (e.g., drip irrigation) should be implemented. Integrating oilseed cultivation into climate-smart agriculture frameworks will help reduce greenhouse gas emissions. Collaborative research across genomics, agronomy and climate science, along with supportive policies, is essential for ensuring sustainable oilseed production to meet global demands in a changing climate.

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## Authors' contributions

NV done literature collection, conceptualization and writing original draft. BK carried out supervision, visualization and critical revision. DP carried out supervision. BRPV carried out supervision and reviewing. KRK carried out supervision, visualization. KG carried out editing and critical reviewing. GC carried out editing and critical reviewing. GJ carried out critical revision. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors declare that they have no known competing interests.

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