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Camelina [*Camelina sativa* (L.) Crantz] in a Changing Climate: A Review of Its Resilience and Physiological Responses to Elevated CO_2 and Temperature

Daniel Manore[1,2]* · **Tewodros Ayalew**[2]

[1]Wachemo University College of Agriculture, Ethiopia, P.O. Box 667, Hossaena, Ethiopia
[2]Hawassa University, College of Agriculture, School of Plant & Horticultural Sciences, P.O. Box 05, Hawassa, Ethiopia

*Corresponding author: daniel.manore@wcu.edu.et

Summary: Climate change, marked by rising atmospheric CO_2 and temperatures, threatens global agriculture and underscores the need for climate-resilient crops like *Camelina sativa*. This review synthesizes camelina's physiological and biochemical responses to elevated CO_2 and temperature. Elevated CO_2 enhances photosynthesis, biomass accumulation, and water-use efficiency, but may alter carbon allocation and downregulate Rubisco activity, with genotype-dependent variation. High temperatures impair photosynthesis, accelerate respiration, and disrupt reproductive processes, reducing yields by up to 84.5% and altering oil composition. While elevated CO_2 can partially mitigate heat stress by expanding the optimal temperature range for photosynthesis, combined stressors often intensify yield losses. Nutrient uptake shifts under these conditions: CO_2 boosts nitrogen assimilation but may reduce phosphorus and micronutrient availability. Adaptation strategies include breeding for stress tolerance, adjusting planting schedules, precision irrigation, and integrated soil and nutrient management. Future research should explore CO_2-temperature interactions under realistic field conditions, identify resilient genotypes through genetic mapping, and apply emerging tools like high-throughput phenotyping and AI. Advancing camelina as a sustainable biofuel and oilseed crop demands coordinated, multidisciplinary approaches to ensure food and energy security under climate change.
Keywords: camelina, climate change, fatty acid composition, stress, phenology, photosynthesis, water use efficiency

Introduction

The impacts of anthropogenic climate change are being experienced globally, with profound consequences across various economic sectors, particularly agriculture (Hussain et al., 2024). Among the most pressing concerns are rising atmospheric CO_2 concentrations and increasing temperatures, which significantly influence crop productivity and food security (Muluneh, 2021). In response, there is growing interest in identifying alternative crops capable of withstanding the stresses associated with climate change. *Camelina Crantz*, a resilient oilseed crop with applications in biofuel production and sustainable agriculture, has emerged as a strategic candidate in this context. To harness camelina's full potential and enhance its resilience under climate stressors, it is essential to understand how elevated CO_2 and temperature levels affect its physiological performance and adaptive capacity (Arshad et al., 2022). Elevated CO_2 can influence plant physiology through the CO_2 fertilization effect, which may lead to both beneficial and adverse outcomes for crop growth and productivity (Ben Mariem et al., 2021). While some species exhibit enhanced photosynthesis, improved water-use efficiency, and increased biomass under elevated CO_2 (Lamichaney et al., 2021), camelina has received comparatively limited research attention in this regard. Accurately predicting camelina's productivity and refining its agronomic management under future CO_2 scenarios, especially those exceeding current atmospheric levels are critical research priorities. In parallel, rising temperatures represent another major dimension of climate change. Elevated temperatures can disrupt plant development, shift phenological stages, and reduce crop yields. Understanding how camelina responds to thermal stress is vital for developing adaptive strategies that ensure its successful cultivation under future climate conditions (Anderson et al., 2023; Smith & Lu, 2024). High temperatures can impair key biological processes such as flowering, pollination, and seed development, ultimately leading to yield reductions and increased crop vulnerability.

This review synthesizes and critically evaluates current scientific literature on the effects of elevated CO_2 and temperature on camelina's performance. By examining its physiological, biochemical, and growth responses to these environmental variables, the review aims to identify knowledge gaps and research needs essential for climate-resilient camelina cultivation. The insights derived from this review have important implications for stakeholders involved in camelina production, sustainable agriculture, and climate change mitigation. The findings will support researchers, agronomists, and policymakers in formulating targeted strategies to enhance camelina productivity, reduce climate-related risks, and contribute to food and energy security. Moreover, evaluating camelina's oil composition and biofuel potential under changing environmental conditions is crucial for advancing sustainable biodiesel production. Due to its low input requirements and suitability as a rotational crop, camelina offers an environmentally friendly option for climate-smart agriculture. This review also assesses camelina's sustainability under projected climate scenarios by analyzing the effects of elevated CO_2 and temperature on its carbon sequestration capacity, water-use efficiency, and overall environmental footprint. The specific objectives are to document the impacts of these climatic factors on camelina's growth, yield, oil content, and fatty acid composition, thereby providing a comprehensive understanding of its physiological and agronomic responses under climate change. To achieve this, the review draws upon peer-reviewed journal articles, conference proceedings, and government reports. A meta-analytical approach was employed to synthesize findings and ensure robust conclusions. Literature was sourced from major academic databases, including Google Scholar, Scopus, and Web of Science, focusing on publications from 2005 to 2024. Both meta-analysis and meta-regression techniques were applied: the former aggregates effect sizes across studies, while the latter explores how study characteristics influence outcomes. This dual approach enables a nuanced understanding of the variability and consistency in camelina's response to climate change.

Effects of elevated CO_2 on morpho-physiology

Elevated atmospheric CO_2 is a key driver of increased biomass production in crops, primarily through its enhancement of photosynthesis and carbon assimilation (Carmo-Silva & Salvucci, 2012). This stimulation of growth often translates into higher crop yields and improved overall productivity. In camelina, exposure to elevated CO_2 has been shown to promote increased branching and leaf expansion, resulting in a denser canopy structure (Kumar et al., 2012). Such morphological changes can enhance light interception and influence nutrient uptake dynamics, thereby affecting crop performance.

Moreover, elevated CO_2 accelerates several developmental stages in camelina, including flowering, seed germination, and seedling establishment (Hampton et al., 2013), which may alter crop maturity timelines and harvest scheduling. Enhanced CO_2 availability also improves nutrient-use efficiency by enabling more effective nutrient uptake and utilization, although the magnitude of this response is influenced by soil nutrient availability (Wang et al., 2015; Dalal et al., 2015). As a C_3 plant, camelina benefits from increased CO_2 concentrations, which serve as a critical substrate for photosynthesis, leading to greater carbon fixation and biomass accumulation (Wang et al., 2015; Dalal et al., 2015).

Elevated CO_2 also reduces stomatal conductance, thereby decreasing transpiration and enhancing water-use efficiency (Zhang et al., 2012). This physiological adjustment contributes to improved drought tolerance. However, elevated CO_2 may also downregulate the activity of Rubisco the key enzyme responsible for carbon fixation, potentially limiting the photosynthetic gains (Thompson et al., 2017). The extent of Rubisco's response to elevated CO_2 in camelina is influenced by genotype, environmental conditions, and developmental stage (Smith & Lu, 2024). In addition, elevated CO_2 alters carbon partitioning within camelina plants, favoring allocation to above-ground biomass (leaves and stems) over root development (Thompson et al., 2017). This shift can influence plant architecture and resource acquisition strategies. Enhanced CO_2 also promotes water-use efficiency by reducing transpiration through partial stomatal closure, further supporting camelina's adaptation to water-limited environments (Peters et al., 2018; Xu et al., 2016). Furthermore, elevated CO_2 can stimulate the uptake of essential nutrients such as nitrogen and phosphorus by promoting root growth and enhancing nutrient acquisition mechanisms (Dong et al., 2018; Wang et al., 2023). However, it may also alter the carbon-to-nitrogen (C: N) ratio, potentially affecting nutrient distribution and utilization within the plant. Understanding these physiological and biochemical interactions is essential for maintaining nutrient balance and optimizing nutrient-use efficiency in camelina cultivation systems (Doddrell et al., 2023).

Physiological responses to elevated temperature

Elevated temperatures exert both beneficial and detrimental effects on photosynthesis in *Camelina sativa*. Moderate temperature increases can enhance photosynthetic activity by stimulating enzymatic functions and accelerating metabolic reactions (Song et al., 2014) (Figure1), as illustrated in Table 1. However, sustained exposure to high temperatures may denature key enzymes, impairing carbon assimilation and reducing photosynthetic efficiency (Song et al., 2014). Additionally, elevated temperatures intensify transpiration rates due to increased stomatal opening for gas exchange, which leads to greater water loss, physiological stress, and diminished water-use efficiency, ultimately affecting plant growth and productivity (Urban et al., 2017).

Higher temperatures also accelerate respiration, diverting energy away from biomass accumulation and yield formation, thereby potentially reducing overall productivity (Sharma et al., 2022). To counteract heat stress, camelina synthesizes protective molecules such as heat shock proteins and osmolytes like proline and soluble sugars, which stabilize cellular structures and help maintain turgor pressure (Mehta & Vyas, 2023). Heat stress during reproductive stages poses significant risks to camelina's yield potential. It can disrupt pollination processes, reduce pollen viability, and impair seed set, resulting in lower seed yield and oil content (Nadakuduti et al., 2023).

Warmer conditions may also accelerate developmental phases including vegetative growth, flowering, and seed maturation leading to earlier crop maturity (Hatfield & Prueger, 2015; Xiao et al., 2021). Although elevated temperatures often trigger earlier flowering, they may also shorten the flowering period, thereby limiting opportunities for successful pollination and fertilization (Geissler et al., 2023). Excessive heat further compromises pollen viability and germination capacity, reducing fertilization success and overall productivity (Rizzitello, 2016), as shown in Table 1.

Table 1. Morphological and physiological responses of camelina to increased CO_2 and temperature

Response Type	Morpho-Physiological Parameter	Impact of Elevated CO_2	Impact of Elevated Temperature	Sources
Growth	Plant height, biomass, growth rate	Enhanced biomass and growth due to increased photosynthesis	Reduced growth and biomass under extreme heat; moderate warming may promote growth	Smith & Lu (2024)
Leaf morphology	Leaf area, thickness, stomatal density	Increased leaf area and thickness; reduced stomatal density	Decreased leaf area; increased stomatal density under cooler conditions	Carmo-Silva & Salvucci (2013)
Photosynthesis	Photosynthetic rate, Rubisco activity	Elevated photosynthetic rate and Rubisco activity	Reduced efficiency due to enzyme denaturation at high temperatures	Dalal et al. (2015)
Water use efficiency	Transpiration rate, stomatal conductance	Improved efficiency via reduced stomatal conductance	Increased transpiration and water stress due to heat-induced stomatal opening	Ahmed et al. (2020)
Stomatal conductance	Gas exchange regulation via stomatal aperture and density	Decreased conductance (gs) due to partial stomatal closure, enhancing water-use efficiency	Increased gs due to higher vapor pressure deficit (VPD), leading to heat stress	Hofmann et al. (2025)
Yield	Seed yield, oil content, seed quality	Increased seed yield and oil content under elevated CO_2	Reduced seed yield and altered oil composition under heat stress	Yohannes et al. (2025)
Phenology	Flowering time, maturity duration	Accelerated flowering and earlier maturity	Shortened flowering duration and earlier maturity, limiting pollination and seed development	Weiss et al. (2024)
Stress responses	Antioxidant activity, membrane stability	Enhanced antioxidant defense and membrane integrity	Increased oxidative stress and compromised membrane stability under high temperatures	Ahmad et al. (2020)
Nutrient uptake	Uptake of nitrogen (N), phosphorus (P), potassium (K)	Improved uptake due to stimulated root growth and nutrient acquisition	Reduced nutrient uptake efficiency due to impaired root function under heat stress	Gregg et al. (2024)

Effect of elevated CO_2 on camelina yield and biomass

Elevated atmospheric CO_2 concentrations exert both beneficial and adverse effects on Camelina sativa (Carmo-Silva & Salvucci, 2012). One of the primary advantages is the stimulation of crop yield, as increased CO_2 enhances photosynthetic activity and carbon assimilation, resulting in greater biomass accumulation. This physiological boost contributes to higher seed and oil yields, which are economically valuable for camelina cultivation (Figure1). Empirical studies have demonstrated that elevated CO_2 promotes increased biomass production, reflected in expanded leaf area and overall plant size, thereby enhancing crop productivity (Dalal et al., 2015; Zhang et al., 2012).

However, elevated CO_2 also alters carbon partitioning, often favoring allocation to above-ground biomass (leaves and stems) at the expense of root development. This shift can influence yield stability, resource acquisition, and stress resilience (Karlsson Potter et al., 2023). While elevated CO_2 generally enhances yield, it may also modify oil quality. Changes in the fatty acid composition under high CO_2 conditions can affect the nutritional value and functional properties of camelina oil, with implications for both biofuel applications and human consumption (Arshad et al., 2022). In parallel, rising temperatures associated with climate change present additional challenges to camelina's growth, development, and productivity. Heat stress can impair physiological processes, shorten developmental phases, and reduce yield potential (Angelini et al., 2020; Anderson et al., 2023).

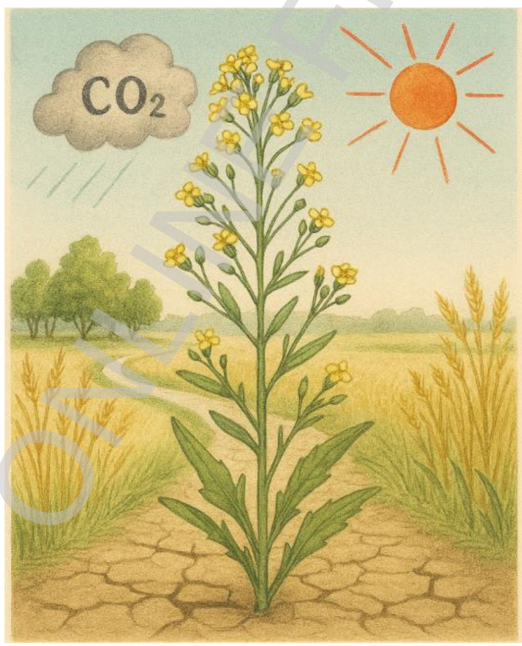

Figure 1. Environmental drivers of photosynthesis and camelina crop performance

Seed yield and oil composition

High temperatures alter the synthesis and accumulation of fatty acids in camelina seeds, affecting the oil's fatty acid composition. Elevated temperatures can change the levels of saturated, monounsaturated, and polyunsaturated fatty acids, impacting the oil's nutritional quality and stability (Smith & Lu, 2024), as shown in Table 2. Heat stress accelerates lipid oxidation, leading to the formation of free radicals and the degradation of fatty acids (Zhuang et al., 2022). This reduces the oil's stability, shelf life, nutritional value, and health benefits. Although heat stress triggers the production of antioxidant enzymes and phytochemicals to scavenge reactive oxygen species (ROS), prolonged exposure can overwhelm these defenses, causing oxidative stress and cellular damage (Fortunato et al., 2023).

Table 2. Effect of elevated temperature on camelina

Impact	Description	Sources
Reduced seed yield	Heat stress can reduce seed yield by up to 84.5%	(Nadakuduti et al. 2023)
Impaired oil accumulation	Elevated temperatures decreased oil content by 54.1%.	(Nadakuduti et al. 2023)
Altered fatty acid composition	Temperature fluctuations affect oil composition and nutritional quality	(Brock et al., 2020)
Increased transpiration rates	Higher temperatures increase water loss, reducing water-use efficiency	(George et al. 2018)

Interactive effects of increased CO_2 and temperature

The interactive effects of increased CO_2 and temperature on camelina crops have garnered significant scientific interest due to anticipated climate changes (Carmo-Silva & Salvucci, 2012). Both elevated CO_2 levels and rising temperatures are key components of climate change, and understanding their combined effects on crop growth and development is crucial for predicting future agricultural productivity (Kope, 2024). The interaction between elevated CO_2 and temperature on photosynthetic responses is complex and depends on factors such as plant species, growth conditions, and the magnitude of CO_2 and temperature changes (Jeong et al., 2018). Generally, increased CO_2 concentrations mitigate the negative effects of high temperatures on photosynthesis by expanding the temperature range for optimal photosynthetic activity (Keenan et al., 2023). This occurs because higher CO_2 levels improve water-use efficiency and reduce stomatal conductance, minimizing water loss and lowering the risk of heat-induced damage.

Plants can acclimate to changing environmental conditions, including elevated CO_2 and temperature, over time (Yamori & Ghannoum, 2022). They can modify their photosynthetic machinery by increasing the abundance of enzymes involved in carbon fixation, thus optimizing photosynthetic performance under these conditions (Cheng et al., 2016). However, the benefits of elevated CO_2 are not unlimited. Factors such as nutrient availability, light intensity, and environmental stresses such as drought or extreme temperatures can restrict photosynthetic responses. In addition, some plant species may reach a saturation point where further increases in CO_2 do not proportionally enhance growth (Zanetti et al., 2021).

Water relations

Under drought conditions, water availability becomes limited, posing challenges to water uptake regardless of CO_2 and temperature levels (Wahab et al., 2022). Elevated CO_2 can improve camelina drought tolerance by enhancing water-use efficiency, enabling more effective water uptake under water-limited conditions (Bukhari et al., 2022). However, the effects of increased CO_2 and temperature on water uptake vary according to camelina genotype and environmental conditions. Different cultivars may exhibit distinct physiological and morphological traits that influence their water uptake strategies. Factors such as soil moisture, nutrient availability, and irrigation practices also play a role (Ahmad et al., 2020).

The interactive effects of CO_2 and temperature also influence the development and structure of camelina root systems, which is critical for water uptake. Elevated CO_2 levels can stimulate root growth, increasing root length, density, and branching. A well-developed root system enhances water uptake efficiency, allowing camelina to access water from deeper soil layers, particularly under drought-prone conditions (Pan et al., 2011). These adaptations can enhance biomass production and oil yield by promoting increased carbon assimilation (Rangaswamy et al., 2021). However, these benefits may be influenced by additional factors such as nutrient availability, pest and disease pressures, and the duration and severity of high-temperature events.

Nutrient uptake

Elevated atmospheric CO_2 concentrations can stimulate photosynthetic activity in *Camelina sativa*, potentially enhancing nitrogen (N) uptake due to increased biomass accumulation and heightened metabolic demand. This may contribute to elevated seed protein content, offering agronomic and nutritional benefits (Gao et al., 2018). However, the effects of elevated CO_2 on phosphorus (P) uptake remain inconclusive. Some studies report improved root growth and enhanced P acquisition, while others suggest reduced P uptake, possibly due to dilution effects or shifts in rhizosphere microbial dynamics (Mndela et al., 2022). Moreover, elevated CO_2 can influence micronutrient availability; for example, it may reduce iron (Fe) solubility in calcareous soils, thereby increasing the risk of Fe deficiency in plants.

Rising temperatures generally accelerate microbial activity and organic matter decomposition, promoting N mineralization and increasing its availability to crops (Hui et al., 2024). However, excessively high temperatures can lead to significant N losses through volatilization, leaching, and denitrification, ultimately reducing N availability for camelina. Elevated temperatures may also enhance chemical weathering and the breakdown of organic matter, potentially increasing P release from soil minerals and organic sources (Silveira & O'Connor, 2013). Nonetheless, extreme heat can suppress microbial-mediated P mineralization, potentially offsetting these benefits.

Mechanisms underlying the response to elevated CO_2 and temperature

Camelina exhibits various physiological and biochemical responses to elevated CO_2 and temperature (Carmo-Silva & Salvucci, 2012). These responses enable plants to adapt to changing environmental conditions. Under increased CO_2, camelina reduces stomatal conductance, decreases transpiration, and improves water-use efficiency. However, higher temperatures can increase stomatal conductance, leading to higher transpiration rates and potential water loss, negatively impacting the plant's water status and productivity (Xu et al., 2016); see Table 3. Elevated CO_2 levels enhance camelina's photosynthesis by increasing CO_2 availability and improving the efficiency of the enzyme RuBisCO, resulting in better carbon assimilation and increased biomass production. Similarly, higher temperatures can boost photosynthetic rates through increased enzymatic activity, enhancing carbon assimilation (Weber & Bar-Even, 2019). Both elevated CO_2 and temperature can induce oxidative stress in camelina by promoting reactive oxygen species (ROS) production. To counteract this, camelina activates antioxidant defense mechanisms, including enzymes like superoxide dismutase, catalase, and peroxidase. Plant hormones such as abscisic acid and jasmonic acid also regulate camelina's responses to elevated CO_2 and temperature through signaling pathways (Wang et al., 2020).

Table 3. Interactive effects of CO_2 and temperature on camelina

Study Focus	Experimental conditions	Key findings	Sources
Growth and yield responses	Elevated CO_2 (700 ppm) + increased temp. (+5°C)	Increased CO_2 enhanced biomass/seed yield, but higher temperatures reduced benefits	Streck (2005)
Photosynthetic efficiency	Elevated CO_2 (800 ppm) + moderate temp. increase (+4°C)	Elevated CO_2 improved photosynthetic rates, but higher temperatures reduced chlorophyll content	(Ahmad et al., 2023)
Oil content and composition	Elevated CO_2 (600 ppm) + temp. stress (30°C day/25°C night)	Increased CO_2 boosted oil content; higher temperatures altered fatty acid composition	Ahsan et al. (2024)
Water use efficiency	Elevated CO_2 (750 ppm) + increased temp. (+6°C)	Elevated CO_2 improved water-use efficiency, but higher temperatures increased water demand	Zhang et al. (2022)
Nutrient uptake and partitioning	Elevated CO_2 (650 ppm) + temp. stress (35°C day/28°C night)	Elevated CO_2 enhanced N uptake; high temperatures reduced nutrient partitioning to seeds	Zhang et al. (2022)
Interactive stress response	Elevated CO_2 (700 ppm) + heat stress (40°C for 5 days)	Combined stress reduced seed yield more than individual stresses	Zhang et al. (2022)

Phenological changes

The synchronization of camelina phenological changes is critical and can be significantly affected by the interactive effects of increased CO_2 and temperature (Weiss et al., 2024). These factors can interact with other environmental variables, leading to unpredictable outcomes. On the one hand, elevated CO_2 and temperature can accelerate phenological stages, resulting in earlier flowering, shorter growth cycles, and faster maturation (Jagadish et al., 2016). Although this may enhance agricultural productivity, it can also disrupt the natural synchronization of ecological processes. For example, earlier flowering may not align with pollinator activity, potentially reducing pollination success and seed set (Miller-Rushing & Inouye, 2009). This highlights the importance of understanding the interactive effects of environmental factors on phenological changes to ensure sustainable agricultural practices.

Strategies to adapt camelina to climate change

Adapting *Camelina sativa* to climate change requires a multifaceted approach, beginning with selective breeding for traits such as heat tolerance, drought resilience, and resistance to pests and diseases (Zanetti et al., 2021). Breeding programs aim to develop cultivars capable of maintaining high productivity under elevated CO_2 concentrations and rising temperatures. Another key strategy involves optimizing planting time and crop management practices based on projected changes in temperature and precipitation. Adjusting planting schedules ensures that camelina encounters favorable environmental conditions during critical growth stages, thereby enhancing yield stability (Sajid & Hu, 2022; see Table 4). Efficient water management is also essential. Techniques such as precision irrigation, deficit irrigation, drip systems, and mulching, combined with soil moisture monitoring and irrigation scheduling tools, can significantly improve water-use efficiency and mitigate the effects of water scarcity (Peters, 2023).

Maintaining soil health is fundamental to climate adaptation. Practices such as crop rotation, cover cropping, and the incorporation of organic matter improve soil structure, enhance nutrient availability, and increase water-holding capacity (Manore et al., 2025). Regular soil testing and balanced fertilization further support optimal nutrient management (Angon et al., 2023). Integrated pest and disease management (IPDM) strategies, including crop rotation, biological control agents, and the use of resistant cultivars, are critical for minimizing yield losses under shifting climatic conditions. Finally, farmer education and capacity-building programs play a pivotal role in promoting climate-smart agriculture. Training initiatives focused on climate change impacts, adaptive strategies, and best management practices empower farmers to implement effective, locally tailored solutions (Sinore & Wang, 2024; see Table 4).

Table 4. Molecular mechanisms of camelina responses to climate change

Study Focus	Molecular Mechanisms	Key Findings	Approach	Reference
Drought stress response	Gene expression (DREB, LEA, P5CS)	Upregulation of stress-responsive genes; osmoprotectant accumulation	RNA-seq, qPCR	(Ghorbani et al., 2022)
Heat stress adaptation	Omics analysis (transcriptomics, metabolomics)	Identification of HSPs and metabolic pathways for thermotolerance	Transcriptomics, metabolomics	(Heidari et al., 2024)
Salinity tolerance	Genetic engineering (SOS1, NHX genes)	Enhanced ion homeostasis; improved growth under salinity	CRISPR/Cas9 transgenic approaches	Wani et al. (2020)
Cold stress resilience	Gene expression profiling (CBF, COR)	Activation of cold acclimation pathways; cryoprotective compounds	Microarray, qPCR	(Fang et al., 2023)
Heavy metal stress	Omics studies (transporters, detox genes)	Genes involved in metal uptake/transport/detoxification identified	Transcriptomics, proteomics	Singh et al. (2016)
Enhanced productivity	Genetic engineering of lipid biosynthesis	Increased seed oil content; improved fatty acid composition	CRISPR/Cas9, RNAi	Subedi et al. (2020)
Multi-stress resilience	Integrated omics analysis	Multi-stress-responsive genes/pathways identified	Multi-omics integration	Raza et al. (2023)
Recent advances in resilience	GWAS and gene editing for stress tolerance	Discovery of novel stress-responsive loci; resilient varieties	GWAS, CRISPR/Cas9	(Jayakody et al., 2024)

Future research directions

Knowledge gaps and research needs

Current research on *Camelina sativa*'s response to climate change has largely focused on the effects of elevated CO_2 or increased temperature in isolation. However, understanding the interactive effects of these factors is essential for accurate prediction and effective crop adaptation. Elevated CO_2 may partially offset the negative impacts of high temperatures by enhancing photosynthetic efficiency, improving water-use efficiency, and increasing tolerance to heat stress.

Future studies should prioritize investigating the combined effects of elevated CO_2 and temperature under realistic climate scenarios, ideally through controlled growth chamber experiments (Chang et al., 2023).

Although some studies have examined genetic variation within camelina populations, further research is needed to identify genotypes with superior tolerance to both elevated CO_2 and temperature. Expanding germplasm evaluation and conducting advanced genetic analyses—such as population genetics and quantitative trait loci (QTL) mapping—can help uncover key genes and molecular markers associated with climate resilience. This genetic insight is critical for guiding breeding programs aimed at developing climate-resilient camelina cultivars (Chaudhary et al., 2020). Beyond physiological and agronomic traits, it is equally important to assess the economic viability and sociocultural implications of cultivating camelina under changing climatic conditions. Understanding farmer preferences, market dynamics, and regional adoption potential will ensure that camelina contributes meaningfully to sustainable agriculture and climate adaptation strategies.

Emerging technologies and approaches

Emerging technologies are increasingly being employed to investigate the effects of elevated CO_2 and temperature on *Camelina sativa*. Controlled environment chambers allow researchers to simulate future climate scenarios with precision, facilitating detailed studies of camelina's physiological and developmental responses under stress conditions (Angon et al., 2023). High-throughput phenotyping platforms, equipped with advanced imaging systems, enable real-time monitoring of key traits such as growth rate, leaf morphology, and stress tolerance. In parallel, genomic selection and marker-assisted breeding techniques are being used to identify and develop genotypes with enhanced resilience to climate stressors (Chawade et al., 2019; see Table 5).

Table 5. Integration of emerging technologies for climate-resilient camelina management

Technology	Application in Camelina	Benefits	Challenges	Sources
Precision Agriculture	GPS-guided machinery for planting/fertilization	Optimizes resource use; reduces waste; improves yield	High initial costs; technical expertise	Júnior et al. (2024)
Remote Sensing	Satellite/drone imaging for crop monitoring	Real-time stress detection (drought, disease, etc.)	Limited resolution; weather dependency	(Ennouri et al., 2025)
IoT Sensors	Soil/climate sensors for data collection	Continuous data for decision-making	Requires connectivity; maintenance	Kumar et al. (2024)
AI and Machine Learning	Predictive modeling for yield forecasting	Accurate prediction under changing climates	Data-intensive; high computational power	Usigbe et al. (2024)
GIS	Spatial mapping for optimal cultivation sites	Identifies suitable regions under future climate	Needs integration with other data sources	Escandón-Panchana et al. (2024)
Automated Irrigation Systems	Smart irrigation using real-time data	Reduces water waste; efficient use in drought areas	High installation costs; energy dependency	Ahmed et al. (2023)

Stress-resistant and inherent adaptations

Camelina exhibits notable thermal adaptability, with seeds capable of germinating at temperatures as low as 2–3 °C, and winter biotypes tolerating freezing conditions down to –14 °C. This resilience makes the crop well-suited for both early spring and late autumn sowing (Ahmad et al., 2023). In North Italy, winter cultivars yielded about 2 t/ha, significantly more than spring types (Ghidoli et al., 2023). Additionally, camelina's low nutrient demands requiring minimal fertilization reduce costs and environmental impact (Zanetti et al., 2021). Its natural resistance to pests and diseases minimizes pesticide use, crucial for organic farming (Neupane et al., 2022). Genomic tools further enhance camelina's resilience. CRISPR-Cas9 techniques have modified traits for improved oil profiles and reduced antinutritional factors, ensuring their potential in sustainable agricultural systems (Kagale et al., 2016; Ghidoli et al., 2023) Table 6.

Table 6. Trait improvements in oilseed crops via advanced breeding techniques

Breeding approach	Key traits modified	Outcome	Sustainability impact	Sources
CRISPR-Cas9	Fatty acid elongase (FAE1)	High oleic acid (>70%)	Stable frying oils, reduced hydrogenation	Ozseyhan (2018)
RNAi suppression	Glucosinolate transporters (GTR)	60–80% GSL reduction in meal	Safe animal feed (40% inclusion)	Ghidoli et al. (2023); Sharma et al. (2024)
Synthetic hybrids	Growth habit x oil composition	Winter-hardy + high-omega-3 lines	Extended geographic adaptation	Ortiz et al. (2020)
Mutagenesis	Plant architecture gibberellins signaling)	Semi-dwarf varieties	Wind resilience, mechanical harvesting	Dharshini et al. (2025)

Conclusions

Based on this comprehensive review, *Camelina sativa* demonstrates significant potential as a resilient crop in a changing climate. Elevated CO_2 generally enhances photosynthesis, biomass, and seed yield (up to 30%) by improving water-use efficiency and carbon assimilation. However, rising temperatures pose a severe threat, potentially reducing seed yield by up to 84.5% and oil content by 54.1% through impaired pollination and altered fatty acid composition. Critically, the interaction of these factors reveals that the benefits of elevated CO_2 can partially mitigate heat stress, but combined challenges still significantly impact productivity. To harness camelina's potential, adopting targeted adaptation strategies—such as breeding climate-resilient varieties using advanced genomics, optimizing planting schedules, and implementing precision water management—is essential. Its inherent low-input requirements and stress tolerance solidify camelina's role in future sustainable and climate-smart agricultural systems.

Author contributions: Both authors jointly contributed to the conception and design of the study. We collaboratively collected and synthesized the literature review, performed the data analysis, and interpreted the findings. The manuscript was co-written, with each author actively engaged in drafting, revising, and refining the text. Both authors approved the final version of the article and agree to be accountable for all aspects of the work, ensuring accuracy and integrity throughout the research and publication process.

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Ethical issues statement: This study did not involve human participants, animal experiments, or the use of sensitive personal data. Therefore, ethical approval and informed consent were not required. The authors affirm that the research was conducted in accordance with accepted academic and scientific standards, and no ethical issues are associated with this work.

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Lanik [*Camelina sativa* (L.) Crantz] i klimatske promene: pregled otpornosti i fizioloških odgovora na povišeni nivo CO_2 i temperaturu

Daniel Manore · Tewodros Ayalew

Sažetak: Klimatske promene, obeležene porastom atmosferskog CO_2 i temperatura, ugrožavaju globalnu poljoprivredu i naglašavaju potrebu za usevima otpornim na klimu poput lanika (*Camelina sativa*). Ovaj pregled uključuje fiziološke i biohemijske odgovore lanika na povišen nivo CO_2 i temperaturu. Povišen nivo CO_2 poboljšava fotosintezu, akumulaciju biomase i efikasnost korišćenja vode, ali može promeniti raspodelu ugljenika i smanjiti aktivnost Rubisco-a, sa varijacijama zavisnim od genotipa. Visoke temperature narušavaju fotosintezu, ubrzavaju disanje i remete reproduktivne procese, smanjujući prinose do 84,5% i menjajući sastav ulja. Iako povišeni CO_2 može delimično ublažiti toplotni stres proširivanjem optimalnog temperaturnog opsega za fotosintezu, kombinovani izazivači stresa često intenziviraju gubitke prinosa. Unos hranljivih materija se menja pod ovim uslovima: CO_2 povećava asimilaciju azota, ali može smanjiti dostupnost fosfora i mikronutrijenata. Strategije adaptacije uključuju oplemenjivanje za toleranciju na stres, prilagođavanje rasporeda sadnje, precizno navodnjavanje i integrisano upravljanje zemljištem i hranljivim materijama. Buduća istraživanja trebalo bi da istraže interakcije CO_2-temperature u realnim uslovima na polju, identifikuju otporne genotipove putem genetskog mapiranja i primene nove alate poput visokoproduktivnog fenotipizovanja i veštačke inteligencije. Budućnost lanika kao usev za proizvodnju održivih biogoriva i uljarica zahteva koordinisane, multidisciplinarne pristupe kako bi se osigurala bezbednost hrane i energije u uslovima klimatskih promena.

Ključne reči: efikasnost korišćenja vode, fenologija, fotosinteza, klimatske promene, lanik, sastav masnih kiselina, stres