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Innovative approaches for climate-resilient vegetable oilseed farming towards sustainable edible oil production: A systematic review

Manisha Bihani
Department of Pharmacognosy, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, Karnataka, 560035, India https://orcid.org/0000-0002-5718-8177

Pooja Ganeshdas Bhutada
Department of Pharmaceutics, The Oxford College of Pharmacy, Bangalore, 560068, India
https://orcid.org/0009-0000-9184-4345

Rajakumari Rajendran
rajimpharm@gmail.com

Department of Pharmaceutics, The Oxford College of Pharmacy, Bangalore, 560068, India
https://orcid.org/0000-0002-8334-484X

Rania I.M. Almoselhy
raniaalmoselhy@gmail.com

Oils and Fats Research Department, Food Technology Research Institute, Agricultural Research Center, Giza, 12619, Egypt https://orcid.org/0000-0001-6314-6144

Monica Channakeshava
Department of Pharmaceutical Quality Assurance, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, Karnataka, 560035, India https://orcid.org/0009-0008-8996-1794

Krupa B. Manjunath
Department of Pharmacognosy, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, Karnataka, 560035, India https://orcid.org/0009-0002-2503-5392

Navneet Reddy Babu
Department of Pharmacognosy, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, Karnataka, 560035, India https://orcid.org/0009-0006-7529-1385

Sabu Thomas
International and Inter University Centre for Nanoscience and Nanotechnology, School of Energy Materials, and School of Nanoscience and Nanotechnology, School of Chemical Science, Mahatma Gandhi University, Kottayam, Kerala, 686560, India https://orcid.org/0000-0003-4726-5746

Systematic Review

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Abstract

Climate change poses a significant threat to the sustainability of vegetable oilseed production by negatively impacting crop yields, oil quality, and resource efficiency. These disruptions jeopardize global food security and rural livelihoods. To address these challenges, this systematic review examines innovative, system-based strategies—including genomics-assisted breeding, CRISPR gene editing, precision irrigation, and digital monitoring—that enhance climate resilience in oilseed agriculture. These approaches contribute directly to multiple UN Sustainable Development Goals: SDG 2 (Zero Hunger) by promoting resilient and sustainable food systems; SDG 13 (Climate Action) through climate-smart interventions that reduce greenhouse gas emissions and adapt to climate variability; and SDG 15 (Life on Land) by emphasizing soil health, conservation agriculture, and biodiversity. The review underscores the critical importance of integrated resource management, policy incentives, and capacity-building efforts to scale sustainable solutions. Future research should prioritize interdisciplinary collaborations and supportive policies to ensure the development of resilient, resource-efficient, and environmentally sustainable oilseed production systems, thereby advancing global sustainability commitments.

Introduction

Background on vegetable oilseed production and its significance

Vegetable oilseed production plays a vital role in global agriculture, providing essential nutrients and serving as a primary source of edible oils. Key oilseed crops—including African oil palm, maize, olive, peanut, rapeseed, soybean, sesame, and sunflower—are cultivated worldwide for their nutritional benefits. These crops supply a broad spectrum of macro- and micronutrients that support human health and physiological functions (X. Li et al., 2025). Primarily grown for oil extraction, oilseed crops are rich sources of natural nutrients such as fats, proteins, fatty acids, chlorophyll, tocopherols, squalene, and carotenoids. The global consumption of edible oils exceeds 170 million metric tons annually, highlighting their crucial role in meeting worldwide nutritional demands (Raza et al., 2019).

Climate change and Agriculture interconnection

The relationship between agriculture and climate change is inherently intertwined, characterized by mutual dependence. Climate change primarily induces biotic and abiotic stresses, adversely affecting agricultural regions by diminishing food production capacity, reducing productivity, and impairing land resilience (Nandhini et al., 2025; Raza et al., 2019). These impacts threaten the sustainability of crop systems and necessitate adaptive strategies.

Major oilseed species and their economic significance

Globally significant oilseed species—including soybean (*Glycine max*), sunflower (*Helianthus annuus*), rapeseed/canola (*Brassica juncea/napus*), groundnut (*Arachis hypogaea*), sesame (*Sesamum indicum*),

and safflower (*Carthamus tinctorius*)—are critical commodities with substantial economic value. These crops serve as primary sources of edible oil and contribute to human nutrition by providing essential fatty acids, vitamins, and proteins. The by-products of oil extraction, rich in proteins, are traditionally used in livestock feed. With rising demand for plant-based proteins, oilseeds are increasingly recognized as sustainable sources of human dietary protein (Nandhini et al., 2025).

Impact of climate stressors on oilseed crops

This systematic review critically examines the effects of climate-related stressors—including rising temperatures, altered precipitation patterns, elevated atmospheric CO_2 levels, increased ozone concentrations, and the 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 molecular and metabolic pathways involved in plant adaptation, focusing on disruptions in lipid biosynthesis and alterations in fatty acid profiles. Climate-induced stresses can significantly reduce yields—by 10% to 40%—with heat stress during flowering and seed filling causing up to a 70% decline in seed set in thermosensitive cultivars. These stresses impair lipid deposition and modify fatty acid compositions through genetic and physiological mechanisms, compromising crop resilience.

Strategies for enhancing climate resilience

To mitigate these challenges, developing climate-resilient cultivars through genetic improvement, breeding, and molecular biotechnology is imperative. Additionally, adopting conservation agriculture, balanced nutrient management, innovative agronomic practices, and digital tools for monitoring and stress mitigation are essential. An integrated approach involving research, policy frameworks, and sustainable farming practices is crucial for enhancing the resilience of oilseed crops in the face of climate change (Ahmad et al., 2021; Nandhini et al., 2025).

Recent developments in oilseed cultivation in China

In recent years, rising living standards in China have increased demand for vegetable oils. Edible oilseed rape (*Brassica napus* L.), a key crop in China, plays a significant role in ensuring national food and oil security, with a cultivation area of approximately 13.5 million hectares and an annual oil yield of 4.5 to 5 million tons. Changes in temperature, precipitation, and solar radiation have fundamentally altered agricultural climate resources, affecting crop distribution, cropping systems, planting strategies, and overall yield and quality of oilseed crops (Shi et al., 2025).

Processing of oilseeds

Oilseed processing involves multiple steps: cleaning, treatment, drying, dehulling, size reduction, flaking, and oil extraction. Initial cleaning removes foreign materials such as leaves, sticks, stones, metal, dirt, stems, and threads. Prior to further treatments—including washing, cooking, germination, microwaving, or ultrasound—antinutritional compounds must be removed. Moisture content is controlled through drying, and hulls are loosened to facilitate seed processing efficiency (Usman et al., 2023a).

Breeding and biotechnological approaches for heat tolerance

To enhance heat tolerance, traditional methods such as breeding, genetic engineering, marker-assisted selection, and adjusting planting practices—including sowing time and irrigation—are employed. These strategies help crops withstand diverse climatic conditions. Advances in genetic engineering enable targeted modification of genes involved in fatty acid synthesis pathways, increasing the production of desired fatty acids and improving oil quality (Rahman & de Jiménez, 2016).

Scope of the review

This systematic review explores cutting-edge and state-of-the-art (SOTA) approaches in climate-resilient vegetable oilseed cultivation. It evaluates innovative, system-based technologies—including genomics-assisted breeding, gene editing, precision irrigation, and digital monitoring—that aim to mitigate climate change impacts on crop yield and oil quality. Furthermore, it discusses how these strategies align with the UN Sustainable Development Goals and identifies key challenges, policies, and frameworks necessary for their effective implementation. The overarching question addressed is: How can integrated technological, agronomic, and socio-economic interventions foster resilient and sustainable oilseed production systems amid climate change?

Methodology

This systematic review was conducted using a rigorous, evidence-based methodology to ensure the inclusion of high-quality, relevant publications, in accordance with PRISMA guidelines. The methodology involved the following steps:

2.1. Literature search strategy

A comprehensive literature search was performed using multiple electronic databases and official online search engines, including PubMed, Scopus, Web of Science, and Google Scholar. The search terms employed were “vegetable oils”, “edible oils”, “oilseeds”, “quality and safety”, “climate change”, “climate-resilient crops”, “precision agriculture”, “agricultural economy”, and “oilseed crop adaptation” and related keywords. Boolean operations like AND, OR, and NOT were used to narrow the search results which were limited to English-language articles published in last 20 years, i.e. between 2007–2026.

2.2. Inclusion and exclusion criteria

The inclusion criteria encompassed peer-reviewed research articles and review papers, as well as relevant gray literature such as reports, theses, policy documents, government publications, and conference proceedings that offer unique, unpublished perspectives. These sources were selected based on their presentation of valuable, unbiased information aligned with the review's core themes. Exclusion criteria included articles published in languages other than English with insufficient data, non-peer-reviewed publications, and studies unrelated to the primary topic.

2.3. Selection process

All retrieved records underwent rigorous screening using a reference management system. Additional manual screening was performed to identify and exclude unreferenced or duplicate entries. Two independent reviewers examined the titles and abstracts in detail to determine their eligibility for inclusion in this systematic review.

2.4. Data extraction and synthesis

Data from the selected articles were systematically extracted and qualitatively synthesized. The findings were presented comprehensively, with particular emphasis on the impacts of climate change on oilseed crops. Data presentation included the use of relevant schemes, flow diagrams, figures, and tables to summarize the results in an informative, concise, and visually accessible manner.

Results and Discussion

3.1. Study selection

As shown in Fig. 1, the initial search yielded 18,163 records. After removing duplicates and ineligible records, 1,300 unique records remained for further screening. Of these, 250 reports were selected for retrieval, and ultimately, 102 reports were included in the review.

3.2. Climate change impacts on vegetable oilseed crops production

Climate change is increasingly affecting agricultural systems worldwide. Numerous studies have provided empirical evidence demonstrating the adverse effects of global warming on crop productivity and ecosystem stability across diverse environments. Rapid rises in Earth's surface temperature significantly influence various plant and animal populations, which are beginning to feel the impacts across different agro-ecological zones.

Oilseed crops, alongside food grains, play a vital role in the agricultural economy of the Indian subcontinent. This region is a major contributor to global vegetable oil production, protein meal output, and the cultivation of renewable biofuels. Beyond their traditional use as food sources, crops such as mustard (*B. juncea*, *B. napus*, *B. rapa*), rapeseed (*Brassica species*), and other cruciferous plants are

increasingly recognized as sustainable sources of biodiesel. These crops contribute to energy security and aid in reducing atmospheric CO_2 emissions (Usman et al., 2023b).

However, these crops naturally thrive in mesic (moderately moist) zones that are predicted to be negatively impacted by increasing global temperatures. Rising heat results in drier conditions, making these crops vulnerable to climate stressors such as heatwaves, moisture deficits, and heat stress during critical reproductive stages. Consequently, there is an urgent need to identify and develop alternative oilseed varieties that are better adapted to future climate conditions.

This review aims to highlight how climate change may influence oilseed production. It systematically consolidates existing knowledge regarding the effects of changing climatic conditions on oilseed productivity (Sinha et al., 2025).

Climate warming affects oilseed yields through drought stress, restricted developmental windows, water scarcity, and increased yield variability. Elevated coefficients of variation in yields can lead to crop failures, further threatening production stability. Changes in rainfall patterns and drought conditions impose substantial penalties on yield, impacting the development of fatty acid profiles critical for oil quality. Additionally, elevated tropospheric ozone (eO_3) pose an extra threat, especially to *Brassica juncea* (Indian mustard), where ozone-induced oxidative damage hampers plant health and productivity (Ahmad et al., 2021).

3.3. Challenges faced by traditional cultivation practices

Temperature is a critical environmental factor, with projections indicating an increase of approximately 1.5°C over the next two decades due to climate change. This expected rise poses significant threats to various agronomic traits, including biomass production, phenology, physiology, and yield in oilseed crops. Widely cultivated oilseed crops such as soybean, sunflower, canola, peanut, cottonseed, coconut, palm oil, sesame, safflower, and olive are particularly vulnerable. Of particular concern is the impact of rising temperatures on oil synthesis in these crops, which threatens both the quality and quantity of yields (X. Li et al., 2025; Quinlan & Goslee, 2025).

The innate defence mechanisms of these crops are insufficient to withstand the damaging effects of heat stress, leading to substantial losses in seed and oil production. Consequently, understanding the fundamental mechanisms of genotype-environment interactions—especially those affecting oil synthesis pathways—is essential for developing resilient cultivars (Usman et al., 2023b). Heat tolerance is a complex quantitative trait controlled by numerous genes, presenting significant challenges for molecular characterization and genetic dissection (Ahmad et al., 2021).

Many economically important Brassicaceae crops—including oilseed rape, various vegetables, condiments, and fodder Brassica species—are highly susceptible to white leaf spot disease, which has re-emerged as a significant threat. Under unfavourable weather conditions, the pathogen *Neopseudocercosporella capsellae* causes foliar, stem, and pod lesions. During infection, *N. capsellae* secretes cercosporin—a light-activated, non-host-specific toxin—into host tissues. However, limited

knowledge about pathogen virulence variation and resistance gene sources within brassicas hampers the development of effective control measures (Gunasinghe et al., 2020).

Global food and nutritional security, sustainable development, and efforts to combat deficiencies in proteins, vitamins, iron, zinc, and other micronutrients are increasingly threatened by climate change (Yang, 2024). The production of oilseed crops worldwide faces escalating risks from environmental stresses, including extreme temperatures, flooding, drought, and UV radiation; biological threats such as bacterial, viral, insect, and fungal attacks; soil-related issues like salinity, nutrient deficiencies, microbiome imbalance, and pH variations; and anthropogenic factors including heavy metal contamination, organic pollutants, microplastics, elevated CO_2 levels, and herbicides. These combined stresses significantly impact crop growth, productivity, and harvest quality, thereby threatening the global food system (Nandhini et al., 2025; Sinha et al., 2025).

The increasing prevalence of multiple stressors adversely affects both crop and livestock production systems. When several factors act simultaneously, they can cause severe yield losses and threaten sustainable food production. Modern agriculture faces two major challenges: reducing greenhouse gas emissions to mitigate climate change and developing adaptive strategies to maintain productivity amid increasing extreme weather events such as droughts, floods, and heatwaves. These events not only diminish yields but also compromise the nutritional quality of harvested produce, exacerbating micronutrient deficiencies and malnutrition among vulnerable populations (Eckardt et al., 2023; Usman et al., 2023c).

Soil health is a cornerstone of ecosystem functionality; healthy soils are fundamental to ensuring food and nutritional security, water purification, climate resilience, and human health. The relationship between agricultural productivity and soil biology is primarily based on the premise that improved soil health can mitigate the impacts of climate change by enhancing nutrient and water availability, increasing disease resistance, and ultimately leading to higher yields. Agro-ecological farming systems, which emphasize diversification, adopt ecologically oriented practices such as using locally adapted seeds, incorporating green manure, crop rotation, intercropping, and biological pest management. These methods focus on promoting plant health and efficient water management, thereby contributing to better nutrition and overall sustainability (Gamage et al., 2023).

3.4. Conventional strategies for oilseed crop adaptation

Oilseed crops include several edible oilseeds such as groundnut (*Arachis hypogaea*), rapeseed-mustard (*Brassica spp.*), sunflower (*Helianthus annuus*), soybean (*Glycine max*), sesame (*Sesamum indicum*), safflower (*Carthamus tinctorius*), and Niger (*Guizotia abyssinica*). Additionally, two edible but non-edible species—castor (*Ricinus communis*) and linseed (*Linum usitatissimum*)—are also significant. In fact, oilseeds are the second-largest agricultural commodity after cereals. To optimize agronomic practices amid climate change and evolving environmental stresses, it is essential to incorporate adaptive strategies that maintain productivity and quality. Conventional breeding and agronomic approaches remain fundamental tools for enhancing the resilience of oilseed crops (Raza et al., 2025).

3.4.1. Conventional breeding strategies

The primary goal of traditional breeding is to develop high-yielding cultivars suited to favorable environmental conditions. Consequently, breeders worldwide focus on producing high-yield varieties to improve overall agricultural productivity. Both conventional breeding and transgenic approaches have advanced our understanding of the polygenic nature of heat stress tolerance. Multiple genes control various traits critical for heat tolerance at different tissues and growth stages of the plant (Driedonks et al., 2016; Gamage et al., 2023).

Enhancing the heat stress resilience of oilseed crops through conventional breeding techniques—including hybridization, artificial selection, and induced mutagenesis—is ongoing. However, these methods are complex due to the polyploid nature of many oilseed crops and require significant time and labor investments.

The increasing demand for oilseeds over the coming decade can be addressed through advanced molecular breeding techniques, such as complementary breeding tools, which accelerate crop improvement programs to develop climate-resilient varieties (Majeed et al., 2021). Transgenic technology has already been successfully applied in oilseed crops to enhance a broad range of traits. While conventional breeding has been extensively used to improve heat stress tolerance in various crops—including oilseeds—these methods are inherently time-consuming and labor-intensive.

As an alternative, precise and effective genome editing technologies—such as CRISPR/Cas (Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR-associated protein)—have emerged as promising tools for targeted genetic modifications in plants. Although the application and development of CRISPR/Cas-based technologies in oilseed crops are still in the early stages, it is evident that these high-precision molecular tools have the potential to significantly enhance productivity, improve climate resilience, and reduce the environmental footprint—thus contributing to sustainable production and the global demand for oilseed products (Driedonks et al., 2016).

3.5. Soil and water management practices

Soil nutrients are vital for plant growth, reproductive success, fruit quality, and overall development. These nutrients can be classified into macronutrients and micronutrients, both of which play crucial roles in metabolic and physiological processes. During physiological and biochemical activities, these elements contribute to the harmonious development of fruits.

Macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S) are required in large quantities to support energy metabolism, enzymatic functions, and structural components. In contrast, micronutrients—including iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), molybdenum (Mo), boron (B), nickel (Ni), cobalt (Co), silicon (Si), sodium (Na), and chlorine (Cl)—are needed in smaller amounts (Bacelar et al., 2024).

Oilseed crops tend to exhibit slow growth during the initial stages, making them particularly vulnerable to weed competition. Therefore, effective weed control during this critical period is essential. However, weed management options for most oilseed crops are limited. Consequently, adopting integrated weed management strategies that incorporate preventive, cultural, mechanical, chemical, and biotechnological approaches—such as the use of 'little hammers'—is important (Choudhary et al., 2022).

Nutrients are fundamental resources necessary for the complete development of crops. Excessive weed growth competes with crops for these nutrients, especially nitrogen (N) and potassium (K). This competition leads to significant depletion of soil nutrients, adversely affecting soil fertility, fertilizer efficiency, and crop yields. Weeds tend to absorb more nutrients from the soil profile and, as a result, often contain higher nutrient levels than the crop plants themselves (Choudhary & Meena, 2022).

3.6. Pest and disease control under changing climates

Climatic changes significantly affect pest dynamics in oilseed crop production and influence overall yields. Managing major insect pests of oilseed crops involves the use of integrated pest management (IPM) strategies, including resistant varieties, potential biocontrol agents, and innovative approaches aimed at improving both the quality and quantity of oilseed yields. Effective IPM practices encompass the deployment of pest-resistant cultivars, biological control agents such as parasitoids, predators, and entomopathogens (e.g., Bacillus thuringiensis, Beauveria bassiana, and Trichoderma species), cultural practices like crop rotation, intercropping, and trap cropping, mechanical control methods, and the judicious use of selective insecticides when necessary (Abrol & Shankar, 2016).

Over the past three to four decades, climatic changes have markedly influenced pest populations and their behaviors. Research has demonstrated that factors such as elevated temperatures, increased CO_2 levels, ozone, ultraviolet-B radiation, and shifts in water availability or humidity can affect the incidence and severity of pest infestations. These impacts have been observed across tropical, plantation, and forest ecosystems.

To ensure sustainable production in the face of climate change, adaptive IPM strategies are essential. Such strategies should incorporate climate-resilient crop varieties, enhance biological control methods, utilize precision pest monitoring technologies, and implement region-specific management practices. Most studies suggest that the risk of pest outbreaks will generally increase within agricultural ecosystems under projected climate change scenarios, underscoring the need for proactive and integrated management approaches to maintain productivity and sustainability.

3.7. Limitations of traditional approaches

Traditional breeding and agronomic methods have limited effectiveness in addressing modern agricultural challenges for oilseed crops. Introducing wild relatives through introgression is also highly challenging and time-consuming using conventional breeding techniques. Furthermore, agronomic limitations exacerbate breeding problems by contributing to environmental degradation. Conventional oilseed production heavily relies on synthetic inputs and irrigation water, leading to issues such as soil

acidification, groundwater depletion, and fertilizer runoff, which cause eutrophication of water bodies. Additionally, crops often lack the adaptive capacity to withstand new stress combinations, such as simultaneous heat and drought conditions under elevated CO_2 levels.

Local farming systems require complete transformation, as geographic shifts in suitable cultivation areas are occurring faster than the cycles for variety replacement. To sustainably increase oilseed productivity, new strategies are essential. These include expanding irrigation facilities, employing moisture conservation techniques such as mulching, timely weed management, careful seed selection with optimal seed rates, appropriate sowing time and methods, varietal selection, crop rotation, cultivating heat- and drought-resistant varieties, implementing integrated nutrient management with micronutrients, seed inoculation with Rhizobium cultures, and adopting integrated pest management and intercropping practices (Gupta & Gupta, 2016; H. Wang et al., 2024).

3.8. Innovative approaches for climate-resilient oilseed farming

Climate change has become a significant obstacle to agricultural production, especially for vegetable oilseed crops such as soybean, groundnut, rapeseed, mustard, sunflower, sesame, and castor. Changes in temperature patterns, irregular rainfall, severe weather events, and the use of pesticides have compromised yield stability and adversely affected oil quality. Addressing these challenges requires climate-smart interventions that integrate genetic improvement, improved crop management, digital tools, and supportive policies (M. Li et al., 2020; Sahoo et al., 2025b).

Climate change poses a substantial challenge to global agriculture, necessitating innovative strategies to ensure sustainable livelihoods and food security. In response to these concerns, climate-smart agriculture has emerged as a strategic approach aimed at mitigating climate-related impacts, boosting agricultural productivity, and enhancing resilience (Bhatnagar et al., 2024b).

3.8.1. Genetic and breeding technologies

3.8.1.1. Marker-assisted breeding and genomic selection

The integration of stress-tolerant traits into oilseed crops is being revolutionized by advanced breeding techniques such as Genomic Selection (GS) and Marker-Assisted Selection (MAS). MAS relies on genetic markers—specific DNA fragments linked to desirable traits—to efficiently identify plants possessing characteristics like drought, heat, or disease resistance, thereby eliminating the need for time-consuming field trials (Varshney et al., 2020).

Rather than waiting for observable phenotypes, this method enables selection at the molecular level, significantly accelerating the breeding process. Building upon MAS, Genomic Selection employs markers distributed across the entire genome to estimate breeding values for complex, polygenic traits that are challenging to measure directly—such as yield under environmental stress. These genomic techniques

greatly enhance the accuracy and efficiency of crop improvement programs while reducing reliance on traditional, long-term approaches for adapting crops to climate variability (Crossa et al., 2017).

Beyond MAS and GS, genomics-assisted breeding now integrates high-throughput phenotyping, bioinformatics, and environmental modelling to improve selection precision and predict plant performance across diverse climates. In oilseed crops, breeders can identify genotypes with desirable traits such as deep rooting, water-use efficiency, or altered metabolism, which confer stress resistance, and incorporate these into elite lines. Advances in next-generation sequencing and big-data analytics enable the exploration of broader genetic diversity, including for quantitative traits. As a result, genomics-based breeding has become the cornerstone for developing climate-resilient cultivars capable of maintaining yield and oil quality amid unpredictable weather conditions (Tester & Langridge, 2010; Varshney et al., 2021).

3.8.1.2. CRISPR/Cas9 gene editing for stress tolerance

Modern genome-editing platforms, such as CRISPR/Cas9 (Fig. 2), have revolutionized plant improvement by enabling precise modifications to genetic material. This technology enhances stress tolerance without the need to introduce foreign genes. CRISPR functions as a programmable molecular scissors, allowing targeted deletion, alteration, or regulation of genes involved in stress response pathways. As a result, it produces plants that are more resilient to drought, oxidative damage, salinity, heat, and other stresses (Zhang et al., 2020).

For example, editing transcription factor genes such as DREB and NAC, which regulate stress-response signaling pathways, has demonstrated significant improvements in abiotic stress tolerance across various crops. By modifying regulatory DNA sequences, CRISPR enables precise control of gene expression, ensuring that defense mechanisms are activated only when necessary. This approach conserves resources during normal growth (Chen et al., 2019).

In oilseed crop improvement, CRISPR accelerates the development of climate-ready cultivars by facilitating targeted trait enhancement that traditionally requires multiple breeding cycles. Its multiplexing capability—allowing the simultaneous editing of multiple genes—makes it possible to develop crops with combined tolerance to heat and drought (C. Wang et al., 2020).

Furthermore, CRISPR-edited plants that contain no foreign DNA (SDN-1 type edits) are often regulated separately from genetically modified organisms (GMOs) under various regulatory frameworks, which promotes faster acceptance. Due to its precision and regulatory flexibility, CRISPR/Cas9 is considered one of the most powerful technologies supporting climate-resilient agriculture (Crossa et al., 2017b; R.K., R.M., & S.M.E. Varshney, 2020).

3.8.1.3. Development of resilient cultivars

The primary objective of genomic and gene-editing initiatives is to develop oilseed cultivars that maintain both high yield and quality under environmental stress. Breeders focus on traits such as early

maturity—to avoid terminal drought or heat—vigorous root systems for improved water uptake, and enhanced photosynthetic efficiency in warmer climates. By integrating measurable trait loci (QTLs) associated with resilience and productivity, along with adaptability factors, these improved cultivars help reduce yield fluctuations and stabilize farmers' incomes under both rainfed and irrigated systems. Advanced breeding programs now employ integrated predictive models to assess cultivar performance across various climate scenarios, ensuring consistent productivity in future conditions (Pixley et al., 2023; Soltani et al., 2020).

These enhanced cultivars contribute to increased food and oil security by withstanding harsh environments and minimizing the risk of crop failure. For example, to address unpredictable monsoon patterns, region-specific mustard and groundnut cultivars with improved resistance to heat and drought have been introduced in several parts of Asia. These resilient cultivars offer both economic and nutritional benefits by combining high oil yields with temperature tolerance. To meet upcoming climatic challenges, further advancements in trait discovery and breeding innovation are essential (Reynolds et al., 2015).

3.8.2. Agronomic and cultural practices

3.8.2.1. Conservation agriculture and minimal tillage

Conservation agriculture is based on three core principles: minimizing soil disturbance, maintaining continuous soil cover, and diversifying crops. These practices collectively foster a balanced agroecosystem that enhances soil structure, increases water retention, and supports biological diversity (Giménez et al., 2021; Marais et al., 2022). Reduced tillage practices effectively decrease soil erosion, improve water infiltration, and bolster the resilience of fields against drought and extreme rainfall, particularly in oilseed-based agricultural systems. Crop residues left on the soil surface act as natural mulch, regulating soil temperature, conserving moisture, and promoting beneficial soil microorganisms. Together, these actions improve resource efficiency and contribute to the long-term sustainability of agricultural production. Additionally, minimizing tillage reduces fuel consumption and greenhouse gas emissions associated with traditional plowing (Couto et al., 2021; Kassam et al., 2009).

Conservation agriculture also enhances the soil's resilience to climate variability by increasing soil organic carbon and improving aggregate stability. It encourages deeper root growth, efficient nutrient cycling, and stable crop yields under stress conditions. For smallholder farmers, adopting minimum tillage offers a cost-effective strategy that promotes consistent productivity. When combined with cover crops and crop residue retention, conservation agriculture creates a microclimate within the soil that shields crops from heat and moisture stress. This approach supports sustainable development by improving the structural, chemical, and biological properties of the soil (Daryanto et al., 2017; Pittelkow et al., 2015).

3.8.2.2. Crop rotation involves sequential cultivation

In oilseed-based farming systems, crop rotation is a time-honoured practice that involves the systematic cultivation of different crops on the same land over successive seasons. This approach enhances soil fertility, reduces pests and diseases, and maximizes resource utilization. The effectiveness and adaptability of crop rotation are demonstrated through various cycle lengths, such as three-year and four-year rotations, incorporating crops like legumes, cereals, and cover crops.

Intercropping, on the other hand, involves growing two or more crops simultaneously within the same field. This method exploits complementary interactions among crops to improve productivity, resource efficiency, and system resilience. By systematically alternating crops and integrating diverse species within a single agricultural system, farmers can mitigate pest and disease pressures, enhance soil health, optimize resource use, and promote ecological diversity.

Intercropping is considered an ancient agricultural technique that involves planting diversified crops with low input requirements, thereby improving the quality of the agroecosystem. Compared to monocultures, intercropping tends to increase yield stability and reduce the need for chemical inputs, especially when leguminous plants are involved. This practice contributes to environmental benefits by decreasing water and soil pollution as well as greenhouse gas emissions (Fig. 3).

Therefore, integrated crop rotation and intercropping practices serve as a biological insurance framework, helping to mitigate the impacts of climate variability and sustain productivity in oilseed farming (Moreira et al., 2024).

3.8.2.3. Use of biofertilizers and organic amendments

Bio-fertilizers are natural mixtures that contain beneficial microorganisms such as mycorrhizal fungi, phosphorus-solubilizing bacteria, and nitrogen-fixing bacteria. They play an essential role in improving various physical properties of the soil. By forming symbiotic relationships with plant roots, mycorrhizal fungi enhance soil structure, increase water infiltration, reduce erosion, and improve aeration (Fig. 4). Additionally, these fungi boost the soil’s water retention capacity, thereby increasing drought resistance. Biofertilizers also help reduce soil compaction—an effect partly attributed to earthworms facilitated by the decomposition of organic matter—which in turn promotes better root penetration and nutrient uptake (Ghimirey et al., 2024).

Soil amendments such as compost, biosolids, green and animal manure, biochar, hydrochar, bagasse, humic substances, algae extracts, chitosan, and advanced engineered materials like metal-organic framework (MOF) composites are employed to improve soil health. These amendments operate based on underlying principles that influence soil function, crop productivity, and soil carbon dynamics.

The application of these amendments leads to improvements in soil physicochemical properties, enhances nutrient cycling and nutrient-use efficiency, and strengthens plant resilience to both biotic and abiotic stresses. Organic nutrient-based amendments primarily enrich the soil and contribute to the

buildup of organic matter, impacting soil carbon inputs and resulting in short- to medium-term increases in soil organic carbon stocks (Oyebiyi et al., 2026).

3.8.2.4. Precision agriculture and site-specific management

Precision Agriculture (PA) technologies have a profound impact on the economic sustainability and data management practices of smallholder farms (Fig. 5). By integrating advanced data tools with traditional farming methods, PA aims to enhance productivity and optimize resource utilization. The adoption of Precision Agriculture offers significant benefits; however, targeted interventions such as financial support, training, and improved data access are essential to facilitate its widespread adoption among smallholder farmers.

These technologies enable more efficient use of inputs such as water, fertilizers, and pesticides, which can reduce costs and minimize environmental impacts while increasing crop yields. Nonetheless, challenges remain, including high initial investment costs, limited technical knowledge, and restricted access to relevant data.

Utilizing real-time reporting systems enhances farmers' ability to adapt to climate variations. Techniques such as precision pest control, tailored fertilization, and variable-rate irrigation contribute to increased production stability and resource efficiency. In large-scale oilseed production systems, where data-driven interventions can mitigate climate-related risks through timely and informed decision-making, these technologies are particularly advantageous.

Therefore, in climate-resilient oilseed farming, precision agriculture is a vital component of sustainable intensification, balancing increased production with environmental stewardship (Basso & Antle, 2020; Benos et al., 2021).

3.8.3. Technological innovations

3.8.3.1. Remote sensing and GIS for monitoring crop health

Geographic Information Systems (GIS) and aerial sensing technologies, such as remote sensing, are valuable tools for assessing the performance of oilseed crops under climate-induced stress conditions. These methods enable the continuous monitoring of vegetation indices, soil moisture levels, and indicators of agricultural stress through data collected from satellite imagery, unmanned aerial vehicles (drones), and multispectral sensors. Early detection of issues such as insect infestations, nutrient deficiencies, or drought stress allows for timely management interventions, thereby reducing production losses caused by extreme environmental events (Hunt & Daughtry, 2018; Shrestha & Vanneschi, 2018).

GIS technology enhances risk assessment and supports precision agriculture by integrating agronomic, climatic, and geographic data. These technologies facilitate climate-smart management practices in oilseed cultivation, including identifying vulnerable zones, optimizing irrigation schedules, and predicting yield outcomes. By promoting proactive rather than reactive farm management strategies, remote sensing contributes to increased crop resilience (Lin & Habib, 2021; Pei et al., 2022).

3.8.3.2. Climate-smart irrigation systems

Oilseed crops significantly benefit from climate-smart irrigation techniques such as drip, sprinkler, and deficit irrigation. By precisely delivering water to the crop root zone, these systems reduce evaporation losses and help maintain optimal soil moisture levels, even in water-scarce conditions. This targeted approach ultimately enhances water use efficiency. In regions experiencing water scarcity, drip irrigation is particularly valuable for increasing water productivity and ensuring yield stability (Luo et al., 2020; Shaglouf et al., 2019).

Furthermore, deficit irrigation involves intentionally applying moderate water stress during growth stages that are less sensitive to moisture deficits, thereby conserving water without compromising crop development. When combined with climate forecasting tools and soil moisture sensor technology, smart irrigation systems enable oilseed crops to better withstand prolonged dry spells and irregular rainfall patterns. Consequently, these practices are vital components of climate-resilient agriculture (Du et al., 2020; Wairich et al., 2021).

3.8.3.3. Use of bio-stimulants and seed priming agents

The exogenous application of biostimulants, such as seaweed extracts, humic substances, amino acids, and microbial formulations, enhances plant physiological functions that contribute to increased stress tolerance. In oilseed crops, the use of biostimulants elevates chlorophyll concentration, antioxidant enzyme activity, and nutrient uptake, thereby enabling plants to better withstand heat, drought, and salinity stresses. Their application promotes sustainable agricultural intensification by reducing dependence on synthetic agrochemicals (Paparella et al., 2015).

Seed enhancement techniques, including hydration priming, osmotic conditioning, and biopriming, improve germination performance, seedling vigor, and early-stage stress resilience. Primed oilseed seeds demonstrate faster and more uniform establishment under adverse climatic conditions, leading to improved crop stand establishment and increased yield stability in stress-prone environments (du Jardin, 2015).

3.8.3.4. Development of climate-adaptive planting schedules

Climate-adaptive planting schedules involve adjusting sowing dates based on climate forecasts, rainfall variability, and temperature projections. By aligning critical crop growth stages with favorable environmental conditions, oilseed crops can reduce their exposure to extreme heat, frost, and drought

stress, thereby minimizing climate-related yield losses. The application of decision-support systems and long-term climatic data allows farmers to identify the optimal planting windows for various oilseed crops across different agro-ecological regions. This adaptive scheduling enhances the synchronization between crop phenology and prevailing climate patterns, leading to improved yield stability and more efficient resource use in the face of changing climatic conditions (Lobell & Gourdji, 2012; Paparella et al., 2015).

3.8.4 Sustainable resource management

3.8.4.1. Water conservation techniques

Conservation of climate-resilient oilseed production, particularly in dry and semi-arid regions, is vital for ensuring sustainable agriculture in arid and semi-arid agro-ecosystems. Enhancing soil moisture retention can be achieved through practices such as mulching, rainwater harvesting, and contour farming, which help minimize surface runoff. These farming practices increase water availability during periods of moisture deficit and mitigate the adverse effects of irregular rainfall conditions (Jahantigh & Jahantigh, 2025; Xing & Wang, 2024).

Effective water management supports healthy crop growth while reducing pressure on limited freshwater resources. Implementing water-saving techniques enhances the resilience of oilseed production systems to drought and changing climate conditions, especially when combined with smart irrigation systems and improved crop management practices (Rockström et al., 2010).

3.8.4.2. Soil health improvement practices

To better withstand climatic stress conditions, soil health improvement strategies aim to enhance soil structure, fertility, and biological activity. Management practices such as the use of cover crops, balanced nutrient application, and the addition of organic amendments increase soil water retention and improve nutrient cycling, thereby strengthening soil resilience. Healthy soils promote vigorous root growth and enhance plant resistance to external stresses. Maintaining soil health is crucial for optimizing oilseed crop yields in the face of climate change. Effective soil management is a vital component of climate-resilient agricultural systems, as soils rich in organic carbon and diverse microbial communities help buffer against temperature fluctuations and moisture stress (Xing, Wang, et al., 2025; Xing, Xie, et al., 2025).

3.8.4.3. Integrated pest and disease management

Climate change influences the dynamics of pest and disease infestations in oilseed crops by increasing their severity, frequency, and geographic distribution. To effectively reduce crop losses while minimizing environmental risks, Integrated Pest and Disease Management (IPDM) employs an integrated approach that combines organic control agents, resistant cultivars, cultural practices, and the judicious use of pesticides (Das, 2024; Tanveer et al., 2025).

By maintaining ecosystem homeostasis and decreasing dependence on chemical control methods—which may become less effective under changing weather conditions—IPDM enhances the resilience of agroecosystems. Adaptive pest and disease management strategies are essential for sustaining stable oilseed crop yields in the face of climate-driven pest challenges (Sharma, 2023).

3.8.5. Policy and socioeconomic interventions

3.8.5.1. Incentives for adopting climate-resilient practices

Farmers are encouraged to cultivate oilseeds using climate-resilient practices through policy measures such as subsidies, crop insurance schemes related to climate change, and targeted financial aid programs. These strategies help mitigate the financial risks associated with adopting sustainable farming methods and innovative technologies. Additionally, supportive legislative frameworks are essential to facilitate smallholder farmers' access to new ideas and technologies, thereby promoting the adoption of climate-smart agriculture. By enhancing the resilience of the agricultural sector and ensuring the safety of edible oils, these incentives contribute to the long-term sustainability of agriculture (Safdar et al., 2024; Sahoo et al., 2025b).

3.8.5.2. Farmer education and capacity-building

The successful implementation of climate-resilient technologies in oilseed production systems relies heavily on programs that promote farmer education and capacity building. Through training initiatives, agricultural extension services, and digital platforms, farmers can acquire essential knowledge on risk mitigation strategies, climate-smart practices, and sustainable oilseed management (Erick et al., 2025; Grigorieva et al., 2023).

Moreover, techniques such as agroforestry, intercropping, crop rotation, cover cropping, conservation agriculture, and water harvesting schemes are integral components of climate-smart agriculture. Achieving food security and combating climate change are closely linked to the adoption of such practices. Consequently, education plays a vital role in bridging scientific research and practical application on farms (Bhatnagar et al., 2024b; Ghosh, 2019).

3.8.5.3. Public–private partnerships and innovation hubs

Public–private partnerships (PPPs) foster coordinated efforts among government agencies, research organizations, and the private sector to promote climate-resilient innovations in oilseed production. Through collaborative initiatives, these partnerships support the development and dissemination of improved technologies, strengthen quality seed systems, and implement targeted capacity-building programs tailored to oilseed-based agroecosystems (Mangeni, 2019).

Furthermore, innovation platforms established within PPP frameworks encourage knowledge sharing, entrepreneurship, and the scaling up of climate-smart agricultural solutions. By effectively bridging scientific research and market implementation, PPPs enhance the adoption of new technologies and contribute to the long-term sustainability of climate-resilient oilseed farming systems (Raj Paroda, 2024).

3.8.6. Case studies and lessons in climate-resilient oilseed farming

3.8.6.1. Regional success stories

Global efforts to stabilize vegetable oilseed production have underscored the importance of integrating high-yield cultivars with advanced digital technologies and climate-conscious farming practices. In 2020, the worldwide oil palm area spanned approximately 24.134 million hectares, with a production of 73.168 million metric tons (USDA). Five countries—Indonesia, Malaysia, Nigeria, Thailand, and Colombia—account for over 90% of the global fresh fruit bunches (FFB) production. Although small-scale oil palm cultivation exists in many countries, the global market is predominantly dominated by two nations: Indonesia, with around 11.950 million hectares and 43.5 million metric tons, and Malaysia, with 5.4 million hectares and 1.85 million metric tons (USDA). Combined, Indonesia and Malaysia contribute over 85–90% of the world's crude palm oil (CPO) production.

Regarding global palm oil consumption, Indonesia leads with an annual intake of approximately 15.025 million metric tons, followed by India, with around 8.755 million metric tons in 2020 (USDA) (Sudhakar & Ram, 2023).

High oleic sunflower contains four times more oleic acid than conventional sunflower, with the oil comprising 84% oleic acid. In 2019, oleic sunflower production totaled approximately 3.8 million tons, representing about 7% of global sunflower production. France has been a pioneer in oleic sunflower cultivation for nearly 20 years; since 2010, over 60% of its sunflower production has been shifted to oleic varieties, reaching 76% in 2019. Additionally, oleic sunflower cultivation expanded rapidly in Ukraine and Russia, reaching 420,000 hectares by 2018 (Inovia, 2020).

Resilience in sunflower and groundnut farming has been strengthened through intercropping with legumes and the application of biofertilizers. These practices, combined with community-led soil moisture conservation initiatives, have improved soil health, enhanced water efficiency, and reduced pest risks. Furthermore, local seed systems and participatory breeding programs have ensured that crop varieties are well-adapted to specific environmental conditions (Scavo et al., 2020; Vanlauwe et al., 2015).

Soybean producers have demonstrated high adaptability to heatwaves and pest pressures by integrating genomic breeding with digital decision-making tools and employing integrated pest management (IPM). These examples illustrate that climate resilience is most effective when technological innovations are tailored to local economic and environmental contexts (Bhati et al., 2021; Y. Li et al., 2022).

3.8.6.2. Key Lessons for scaling innovation

Developing successful climate-resilient programs requires an entire system—not just technology. Personalization and Participation: Since solutions that succeed in one location may not be effective

elsewhere, they must be tailored to address local soil and climate hazards. Programs that involve farmers in the development and testing of new technologies tend to achieve significantly higher long-term adoption rates (Baraj et al., 2024; Favretto & Stringer, 2024).

3.8.6.3. Economic and institutional support:

Financial support is essential; as advanced technologies such as precision agriculture can be costly. Government investments in digital infrastructure, crop insurance, and accessible financing are often vital for successful scaling of these technologies (Adamkulova et al., 2025).

3.8.6.4. Knowledge and collaboration:

To achieve effective scaling, it is crucial to continue training, utilize digital advisory services, and strengthen extension networks. Additionally, collaborations among the public sector, private enterprises, and researchers are vital for facilitating farmers' access to markets and ensuring the efficient distribution of essential inputs and seeds (Mishra et al., 2024; Priya et al., 2025).

3.8.7. Challenges and future directions

3.8.7.1. Technological and infrastructure constraints

A well-developed infrastructure integrated with advanced technological capabilities significantly influences the successful adoption of climate-resilient technologies in vegetable oilseed farming. Reliable electricity, digital infrastructure, and technical skills are essential prerequisites for devices such as automated irrigation systems, remote sensing, and decision support tools. However, these resources are often scarce in rural and agricultural areas dominated by smallholder farmers (Nxumalo & Chauke, 2025). Additionally, limited access to these resources hampers the scalability and impact of digital transformation within climate-smart agricultural systems. The technical complexity involved in maintaining and calibrating this sophisticated equipment can also lead to inconsistent operation and reduced sustained use (Mollel et al., 2025).

3.8.7.2. Economic and financial barriers

For small and marginal oilseed farmers, the substantial capital investment required remains a significant barrier to adopting climate-resilient technologies. Implementing genetically improved seed varieties, climate-smart irrigation systems, precision agricultural machinery, and soil health management practices often demands considerable financial resources (Olabanji & Chitakira, 2025). Additionally, farmers are discouraged from transitioning to innovative approaches due to limited access to financial incentives, crop insurance, and credit facilities. The perceived economic risks associated with new technologies further inhibit adoption, particularly in emerging economies, where structural constraints in oilseed agriculture lead to persistently narrow profit margins (Mosha & Ngulube, 2025).

3.8.7.3. Genetic improvement and regulatory challenges

Despite significant advances in genomics-assisted breeding and genome editing technologies that enable the rapid development of climate-resilient oilseed varieties, their adoption at the field level remains limited. This delay is primarily due to the complex interactions among genetic factors, environmental conditions, and crop management practices, which necessitate extensive multi-location trials across diverse agro-climatic regions before new varieties can be approved. Additionally, unclear regulatory frameworks and societal concerns regarding genetically edited crops continue to hinder large-scale commercialization. Establishing harmonized biosafety policies and fostering transparent communication about the potential risks and benefits are essential steps toward building public trust and accelerating the acceptance of advanced breeding technologies (Lassoued et al., 2018; Sinha et al., 2021).

3.8.7.4. Research gaps and emerging opportunities

Progress in developing climate-resilient oilseed crops has been steady; however, significant gaps remain in understanding how these crops respond when subjected to multiple simultaneous abiotic and biotic stresses (Rejeb et al., 2014). A major obstacle to the development of adaptable, sustainable, and scalable solutions is the limited number of multi-environment studies that evaluate integrated genetic, agronomic, and technological strategies. The integration of phenomics, genomics, and climate modeling technologies offers a promising approach to accelerating the breeding of oilseed varieties with enhanced stress tolerance. Furthermore, advancements in artificial intelligence, machine learning, and large-scale data analytics provide innovative methods for predicting the impacts of climate change on crop yields, optimizing crop management practices, and maximizing resource use in oilseed production systems (Walter et al., 2017).

3.8.7.5. The role of interdisciplinary approaches

An interdisciplinary collaboration among plant breeders, agronomists, climatologists, researchers, and policymakers is essential to address the challenges of climate change in oilseed production systems (Howden et al., 2007). The application of global warming modeling within crop simulation and agronomy represents a novel approach that enables the assessment of climatic impacts and the identification of optimal adaptation strategies at the regional level (Peng et al., 2020). Research conducted under socioeconomic conditions can elucidate farmer practices, identify constraints to adoption, and evaluate policy impacts. Furthermore, interdisciplinary approaches foster inclusive innovation platforms that enhance the scalability, sustainability, and practical effectiveness of climate-resilient oilseed farming systems by strengthening the connections between research institutions, extension agencies, and farming communities (Amadu et al., 2020; R. K. Varshney et al., 2021b).

3.8.7.6. Recommendations for policymakers, researchers and farmers

Policymakers should proactively promote long-term investments in risk-sharing plans tailored to oilseed production through mechanisms such as incentives and legislation. Building capacity in technical skills is essential and serves as a crucial prerequisite not only for the broader dissemination of climate-

resilient agricultural practices but also for the effectiveness of extension services and farmers' training programs. Researchers should focus on developing oilseed rape cultivars with tolerance to specific stressors by utilizing improved breeding techniques, high-throughput phenotyping, and climate-informed selection strategies. To enhance resilience and productivity, farmers are encouraged to adopt integrated production systems that incorporate sustainable irrigation and environmentally friendly agricultural practices (Lipper et al., 2014b; Rockström et al., 2017).

3.8.8. Novelty impact statement

This systematic review introduces innovative, systems-based approaches that integrate digital technologies, advanced breeding techniques, and sustainable agronomic practices to enhance the climate resilience of vegetable oilseed farming. By leveraging cutting-edge tools such as genomics-assisted breeding, CRISPR gene editing, remote sensing, and precision irrigation, it offers novel solutions to mitigate the adverse impacts of climate change on oilseed yield and quality. The comprehensive synthesis of these approaches provides a transformative framework for developing resilient, resource-efficient, and environmentally sustainable oilseed production systems, ultimately contributing to global food security and rural livelihoods.

3.8.9. Aligning the study with the United Nations' sustainable development goals

This systematic review directly supports multiple UN Sustainable Development Goals, including Goal 2 (Zero Hunger) by promoting resilient and sustainable oilseed crop production; Goal 13 (Climate Action) through climate-smart innovations that reduce greenhouse gas emissions and adapt to climate variability; and Goal 15 (Life on Land) by advocating for soil health management and conservation agriculture. By fostering sustainable agricultural practices, advancing technological innovation, and strengthening farmer capacity, the study contributes to building equitable, climate-resilient, and environmentally responsible food systems aligned with global sustainability commitments.

Conclusion

To enhance the resilience of vegetable oilseed agricultural systems, this systematic review emphasizes the significance of modern methodologies such as technology-driven farming, climate-smart irrigation (CSI), genomics-assisted breeding (GAB), and sustainable agronomy practices. While precision agriculture improves input efficiency and helps mitigate climate-induced yield fluctuations, advanced breeding technologies enable the development of oilseed cultivars with increased resistance to drought, heat, salinity, and emerging biotic stresses. Collectively, these innovations offer valuable strategies to mitigate the adverse effects of climate change on oilseed production.

For long-term climate resilience, integrated approaches that combine digital technologies, recommended agronomic practices, and genetic modifications are more effective than individual interventions. Sustainable soil and water conservation techniques—such as conservation agriculture and efficient

irrigation—contribute to improved soil health, stable oilseed yields, and enhanced ecosystem services. These system-based strategies ensure that oilseed-based agricultural systems remain sustainable amid changing climatic conditions, promote resource use efficiency, and reduce environmental impacts.

Climate-resilient vegetable oilseed agriculture is essential for ensuring food security, fostering sustainable farming, and producing environmentally friendly edible oils amidst global climate change. Future progress will depend on sustained investments in digital farm infrastructure, transdisciplinary research, and adaptive policy frameworks. To translate scientific innovations into practical, scalable solutions, strong collaboration among researchers, farmers, and policymakers is crucial. Ultimately, climate-resilient oilseed farming should be regarded as a long-term sustainability strategy rather than merely a short-term adaptation measure.

Abbreviations

CPO
crude palm oil
CRISPR
Clustered Regularly Interspaced Short Palindromic Repeats
CSI
climate-smart irrigation
eO_3
Elevated tropospheric ozone
FFB
fresh fruit bunches
GAB
genomics-assisted breeding
GIS
Geographic Information Systems
GS
Genomic Selection
IPDM
Integrated Pest and Disease Management
IPM
integrated pest management
MAS
Marker-Assisted Selection
MOF
metal-organic framework
PA
Precision Agriculture
PPPs

Public–private partnerships
SDGs
sustainable development goals
SOTA
state-of-the-art
UN
United Nations
USDA
United States Department of Agriculture

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Data availability

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Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures

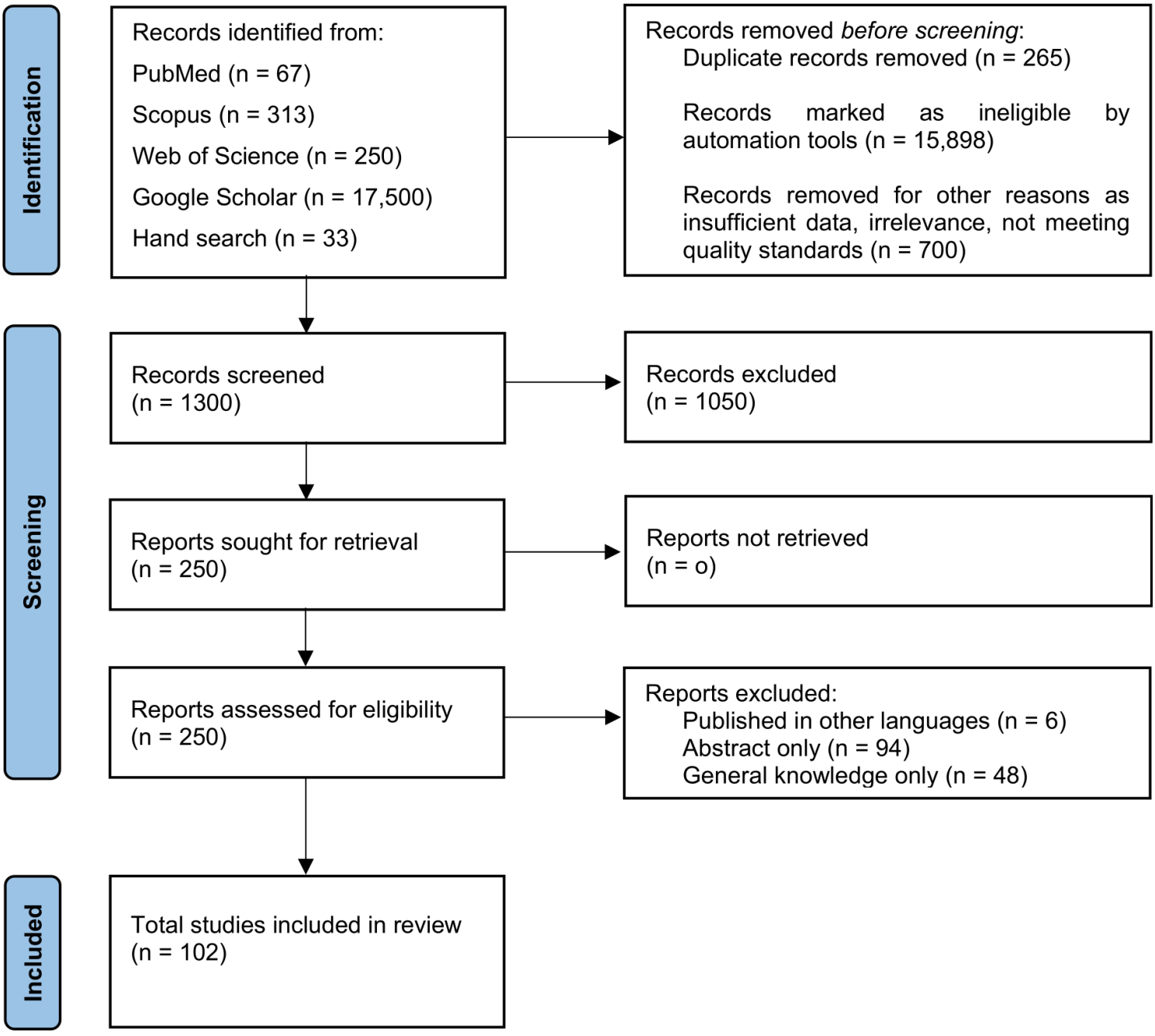


Figure 1

PRISMA flow diagram including searches of databases (2007-2026)

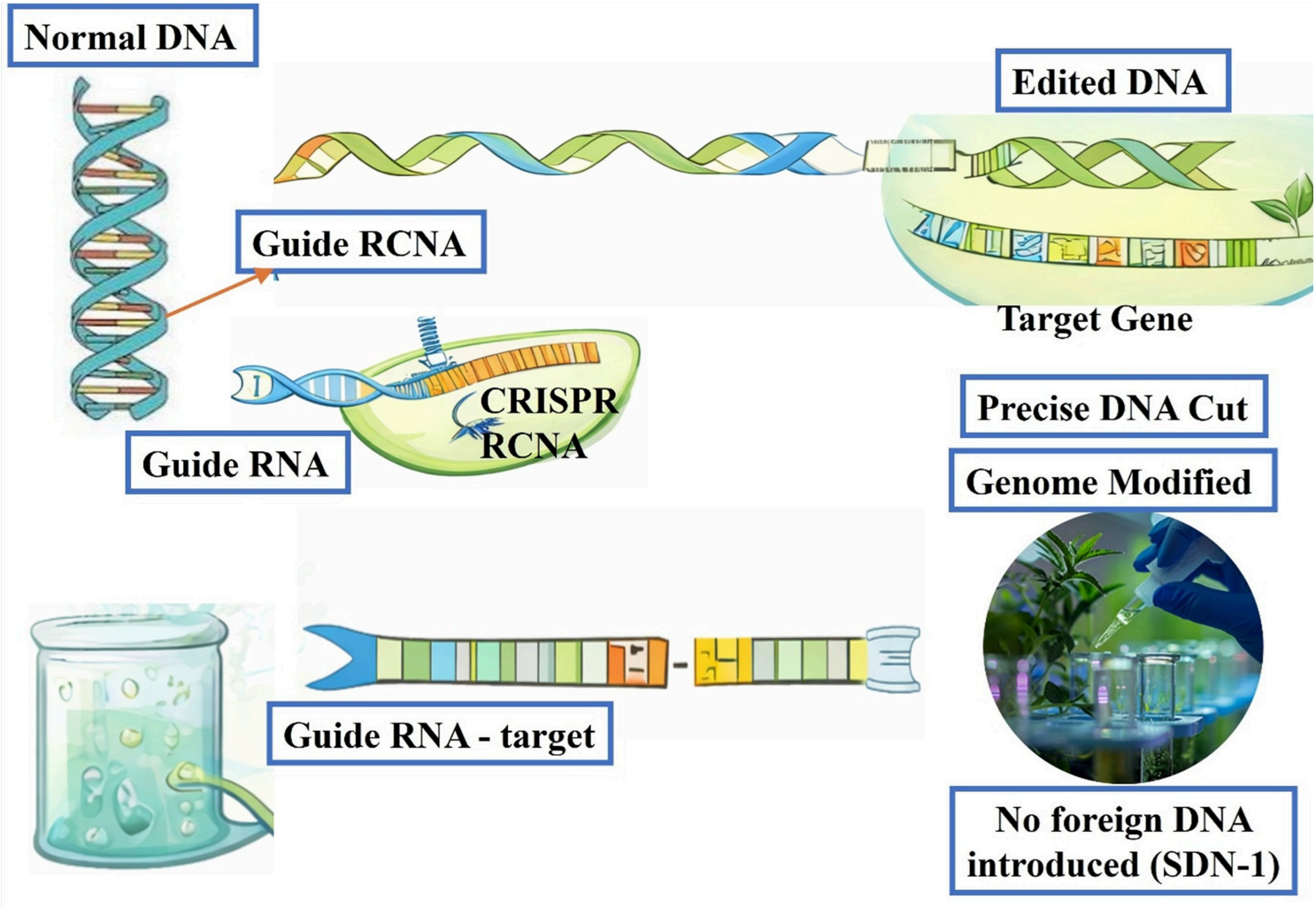


Figure 2

CRISPR/Cas9 gene editing for stress tolerance

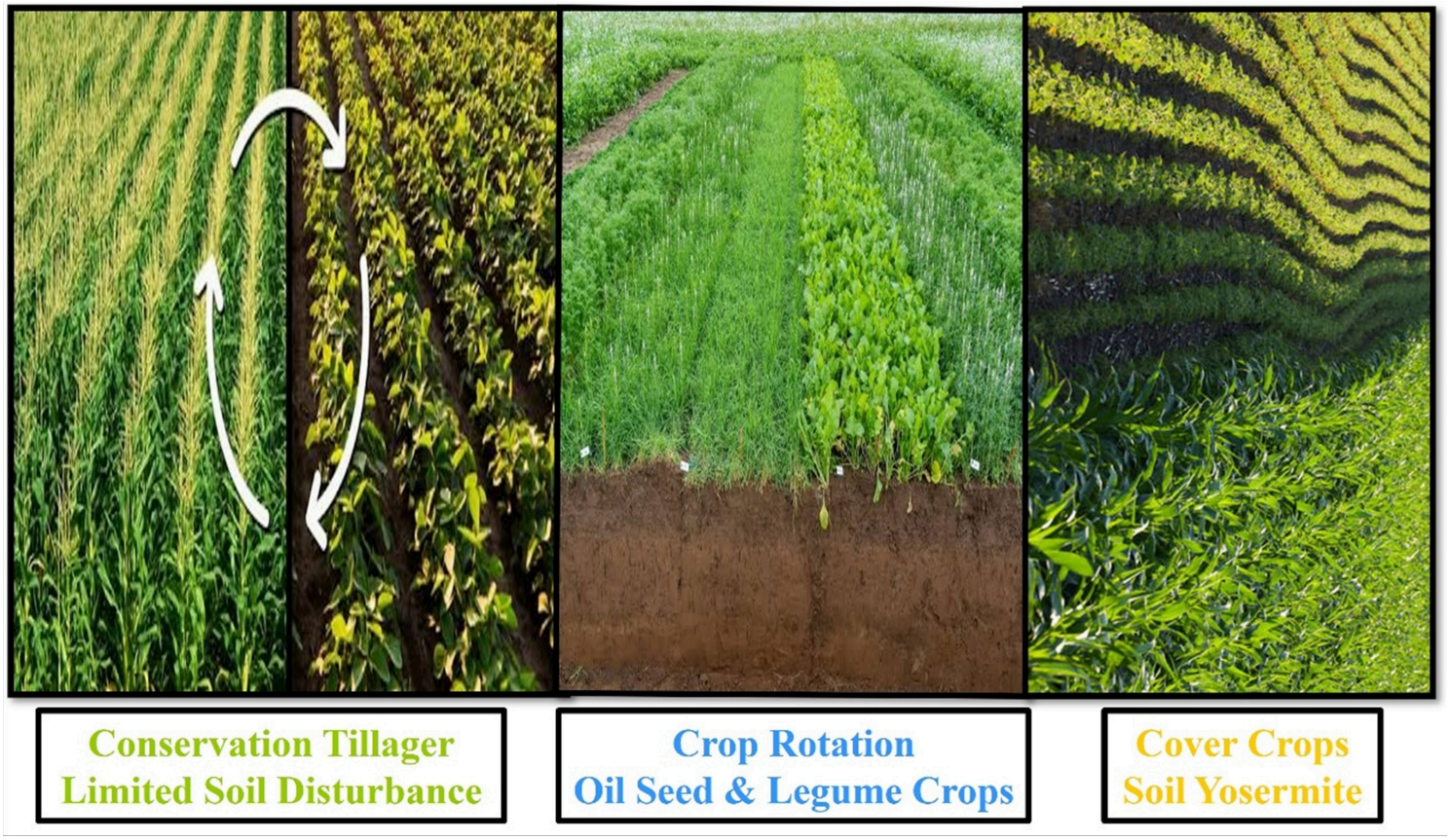


Figure 3

Crop management and agronomic practices

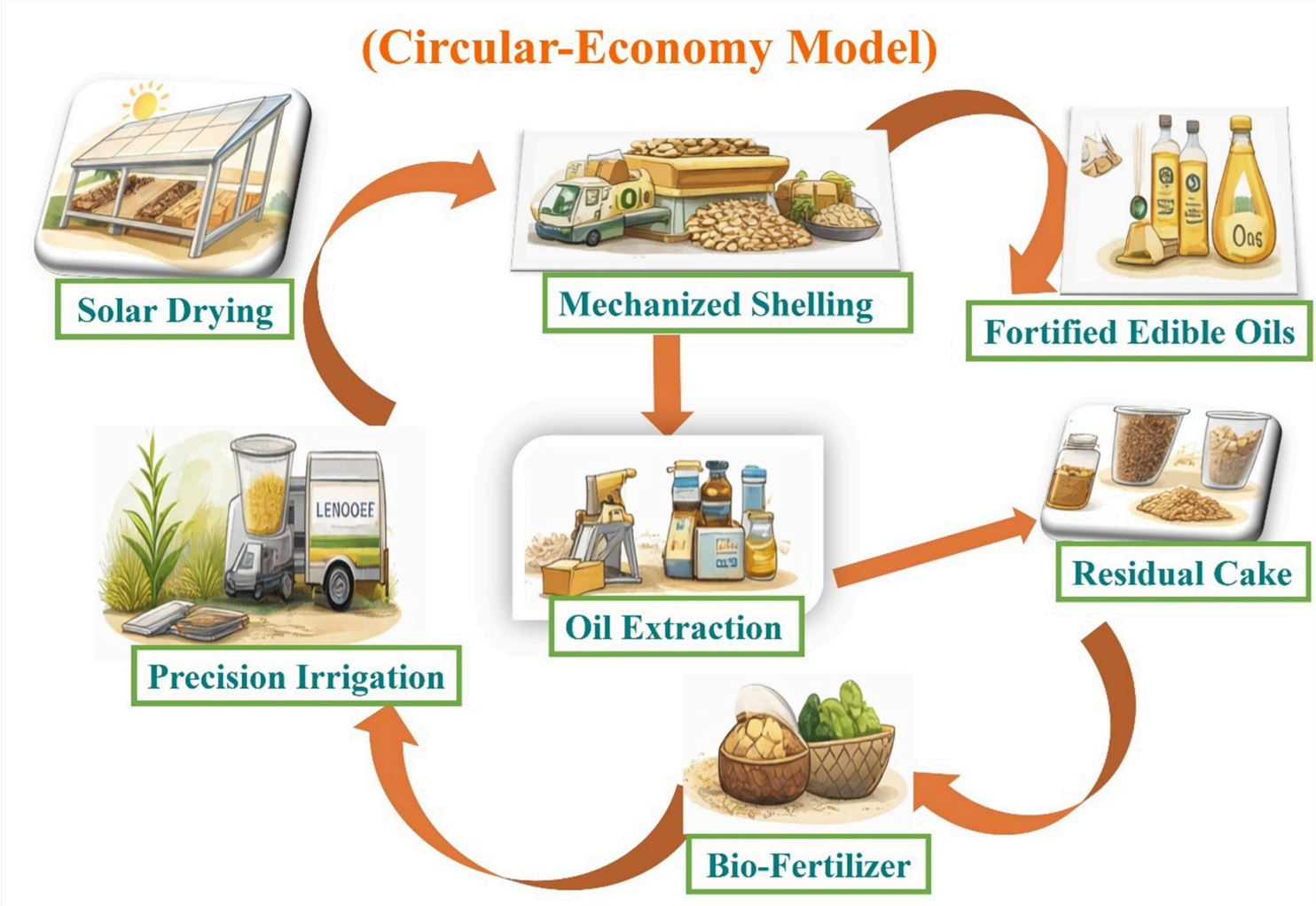


Figure 4

Post-harvest and value added innovations

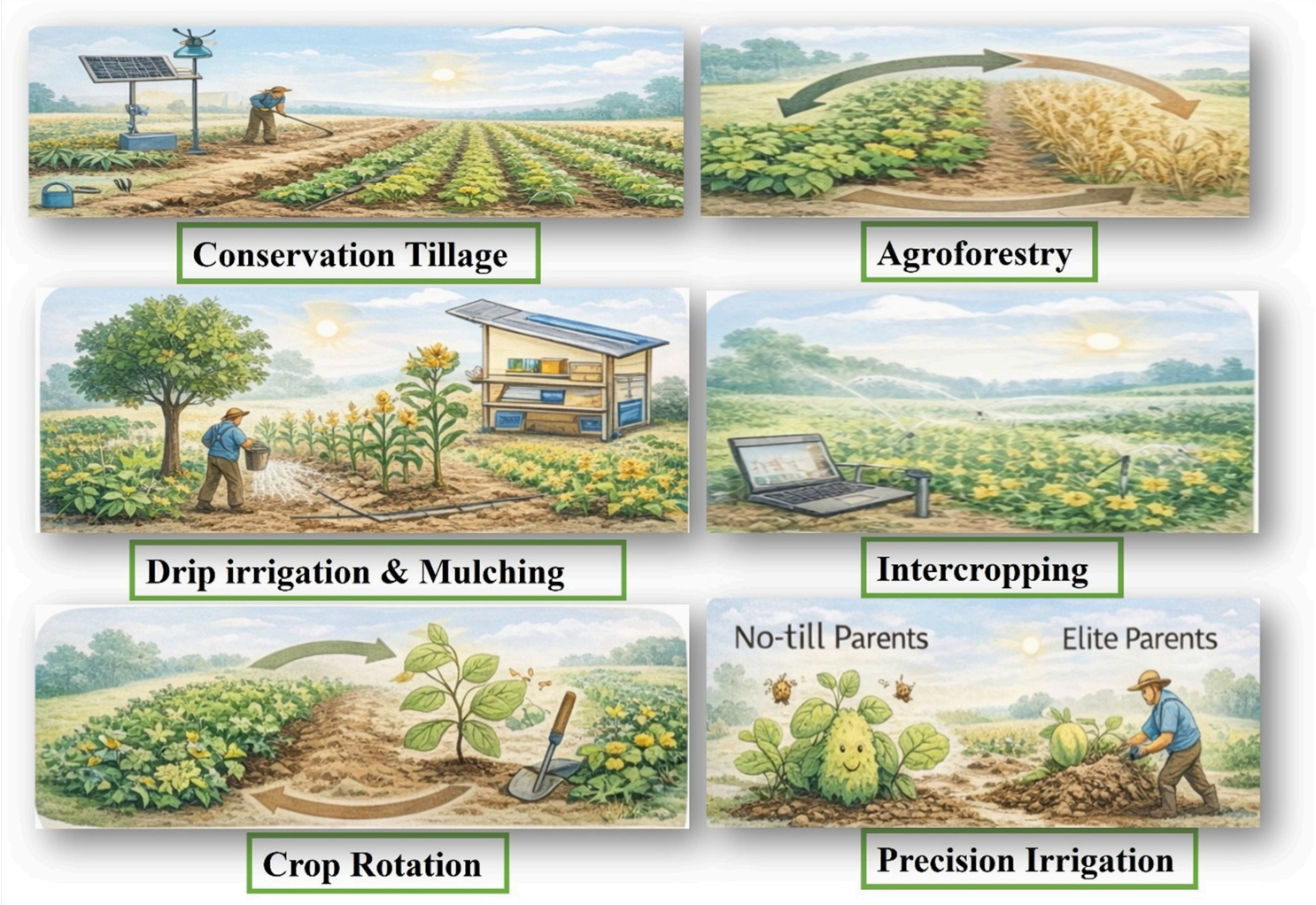


Figure 5

Agronomic and cultural practices

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