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INTEGRATING PHYSIOLOGICAL STRESS MECHANISMS AND ADVANCED IRRIGATION TECHNOLOGIES FOR SUSTAINABLE RAPESEED PRODUCTION

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ABSTRACT

Rapeseed (*Brassica napus* L.) is an important crop globally for its dual purpose of food and energy production, and precision irrigation has emerged as a transformative approach to improving water-use efficiency, yield, and the sustainability of rapeseed production. In this review, the physiological mechanisms governing rapeseed's response to water stress are discussed with respect to root architecture, osmotic adjustment, and hormonal regulation, specifically abscisic acid (ABA) signalling. The focus is on how advanced technologies such as IoT-enabled monitoring, AI-based decision-making tools, and precision irrigation systems enable optimized resource use and address the impacts of climate variability. Deficit irrigation and fertigation are investigated as sustainable practices that conserve water while maintaining quality and productivity. However, there remains limited knowledge about crop-specific adaptations of irrigation technologies and environmental impacts associated with irrigation and socio-economic barriers to adoption. The solutions to these challenges are identified through interdisciplinary research and scalable solutions, which ultimately realize the full potential of precision irrigation to revolutionize the rapeseed crop. This review highlights the need for adaptive planning and innovative pathways to mitigate tensions among productivity, resource conservation, and climate resilience for global food security and sustainable agricultural systems.

Keywords: Physiological mechanisms, Modern irrigation methods, Agronomic practices, Water use efficiency, Rapeseed (*Brassica napus* L.), Sustainable farming.

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1. INTRODUCTION

Rapeseed, especially its variant canola, plays a key role in global food security and is valued for edible oil production and supplying bioenergy needs. However, rapeseed oil is nutritionally beneficial because it contains a balanced ratio of omega-3 and omega-6 fatty acids and is preferable for cooking and food products (Friedt et al., 2018). Rapeseed oil is also a primary feedstock for biodiesel, with Europe producing 38% of global production. Rapeseed plays a dual role in food and energy; thus, it is of great importance in promoting sustainable agricultural practices and rural economies (Friedt et al., 2018).

The problem of water scarcity, exacerbated by climate change, significantly affects rapeseed yields and global food production, as water is essential for plant growth. Drought stress harms rapeseed (*Brassica napus* L.)

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at all growth stages, particularly during the reproductive phase, by reducing photosynthesis rate and stomatal conductance, resulting in reduced yields and poor oil quality (Raza et al., 2017). Research has shown that efficient irrigation can improve production. For example, some varieties, such as ES Hydromel, are drought-resistant and show improved production by efficient irrigation (Shafighi et al., 2022). About 70 percent of the world's freshwater is estimated to be used for agricultural production. As the global population grows, food demand is expected to double. Hence, water must be used wisely to sustain crop production. The increasing problems of water stress and climate variability stress the need for sustainable irrigation and water management for food production and other human needs.

Precision irrigation is a transformative technique for managing water delivery, reducing water waste and increasing efficiency and production in the cultivation of rapeseed under drought stress. This approach uses technologies such as soil moisture sensors and Geographic Information Systems (GIS) to efficiently deliver irrigation water only where and when crops need it, thereby conserving water resources (Kumar et al., 2023). By using automatically controlled water management systems through real-time data input can decrease water usage by half and boost crop production by as much as 30% (Askaraliev et al., 2024). Moreover, these systems reduce the effects of climate change by conserving water and improve agricultural productivity, especially in arid areas with water scarcity (Lakhiar et al., 2024). Precision irrigation enhances yield and supports sustainable development goals that promote the proper use of resources in addressing climate change and ensuring food security (Lakhiar et al., 2024).

Some prominent research gaps in integrating advanced irrigation technologies with the needs of rapeseed and sustainable farming include an inadequate understanding of the physiological processes and a lack of strong, sustainable frameworks. The current research presents qualitative data on water consumption, along with underdeveloped assessments of the environmental implications of irrigation for rapeseed cultivation systems (Ferreira et al., 2024). Furthermore, the possibilities of IoT and AI in irrigation management are recognized. However, the limitations of their application and the requirement for their adaptation to specific crops are evident (Ghareeb et al., 2023). The current literature demonstrates a need for research into sustainable improvement of crop productivity through advances in rapeseed production factors, including irrigation and nutrient management (Ahmad et al., 2023).

This review addresses critical gaps in coupling advanced irrigation technologies to the specific physiological needs of rapeseed production under water-deficient conditions. It aims to describe the physiological mechanisms that determine the rapeseed response to declining water availability, including root system development, osmotic regulation, and hormonal signaling, including abscisic acid (ABA). It also investigates recent technological advancements in irrigation, including precision irrigation systems, IoT-enabled real-time monitoring, and AI-based decision-making tools, with a view to advancing water-use efficiency and crop productivity. In addition, this study focuses on sustainable irrigation practices, including deficit irrigation and fertigation that help achieve the balance between conservation and yield optimization.

2. PHYSIOLOGICAL AND AGRONOMIC RESPONSES OF RAPESEED TO WATER AVAILABILITY

Oilseed crops, including rapeseed (*Brassica napus* L.), are critically sensitive to water stress, with important effects from the flowering and seed development perspective on reproductive structures, seed size, and oil quality (Fig. 1). During flowering, drought stress reduces chlorophyll content across oilseed species, reducing biomass production and seed yield (Teymoori et al., 2020). This stress also alters the physiological responses of oilseed crops and oil content by downregulating fatty acid biosynthesis and upregulating degradation pathways (Li et al., 2021). Drought-tolerant genotypes across oilseed species, such as Nap9 and ES Hydromel in rapeseed, have shown better drought tolerance, maintaining higher seed yield and oil quality under stress (El Idrissi et al., 2023). Seed weight, oil content, and other key yield components are especially vulnerable to water stress in all oilseed crops. Vital efforts are needed to protect oilseed crop yield and quality from the damaging consequences of drought with effective water management strategies across diverse production systems (Sehgal et al., 2018).

2.1. Impact of Water Stress on Key Growth Stages and Yield Components

The flowering and seed-filling stages are susceptible to water deficits across oilseed crops because of their important role in reproductive development, and they undergo significant physiological and metabolic disruptions. Water deficit during flowering causes pollen sterility and reduced pod set and, thus, seed yield and quality in various oilseed species (Aini & Lalonde, 1997). For example, water stress at these stages reduces seed-bearing pods and yields in rapeseed, while similarly affecting soybean pod formation during R3-R6 stages and sunflower disk floret fertility during anthesis, decreasing yields dramatically under drought conditions. In sunflowers, drought during the reproductive stage can reduce achene number and oil concentration by 30-50%,

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comparable to yield losses in rapeseed. Consequently, water deficits during seed formation reduce seed size, protein and chlorophyll content, and oil accumulation across oilseed crops (Flasiński & Rogozińska, 1985). Accumulation of proline, a stress marker common to both rapeseed and sesame, indicates metabolic responses to drought, thereby complicating plant reproductive success under water-limited conditions. Water availability during these critical stages is important for optimal productivity and quality in all oilseed crops (Flasiński & Rogozińska, 1985). Agronomic traits in oilseed crops are greatly affected by water stress, leading to reduced seed weight, fruit/pod number, and oil content, decreased yield, and altered fatty acid composition. In addition, genetic analyses have revealed candidate genes for drought tolerance linked to these traits and are implicated in potential pathways to breed more drought-tolerant varieties across oilseed species (Salami et al., 2024). Water stress and agronomic traits interact, underscoring the need for management strategies to mitigate drought impacts on oilseed crop production (Raza et al., 2017).

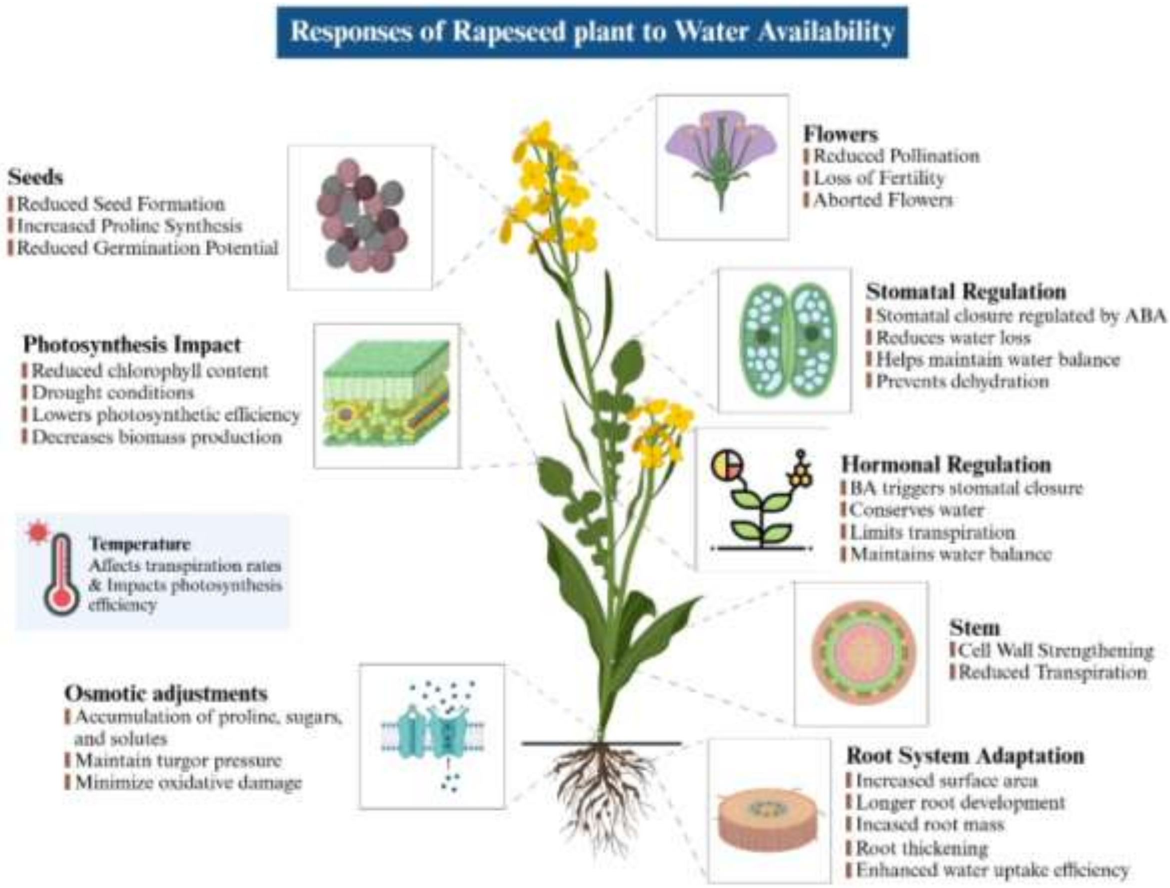

Fig. 1: Physiological Responses of Rapeseed Plants to Water Availability.

Oilseed crops are highly sensitive to water stress, as their phenological cycles are triggered prematurely, resulting in delayed maturity and reduced harvest index. In rapeseed, drought stress is especially detrimental during reproductive stages, including flowering and pollination, and causes early flowering and hastened silique ripening, shortening the time from flowering to maturity (Dogra et al., 2020). Similarly, soybean under drought shows accelerated senescence and reduced seed-filling duration, whereas sunflower exhibits diminished head diameter and altered achene development. Stress reduces yield components such as the number of pods per plant in rapeseed, pods per node in soybean, and seed weight in multiple oilseed crops, causing a decline in harvest index as grain yield declines steeply than biological yield (Abbasian & Rad, 2011).

2.2. Physiological Mechanisms of Rapeseed Under Water Stress

Oilseed crops under drought stress exhibit adaptive root system modifications, with rapeseed showing increased root length and surface area that facilitate deeper water uptake, thereby improving drought tolerance. Sunflower develops deeper taproots (up to 2m), while safflower produces extensive lateral roots for soil

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exploration. Q2 are drought-resistant genotypes with improved root architecture and metabolic responses, including the accumulation of beneficial metabolites that facilitate the absorption of more water from deeper soil layers (Zhi et al., 2024). However, high irrigation rates can cause waterlogging in all oilseed crops, inhibit root respiration and metabolic processes, and reduce growth. In soybean, waterlogging severely impairs nitrogen fixation in root nodules. Physiological stress caused by waterlogging induces the development of aerenchyma and adventitious roots as adaptations, but these adaptations might not reduce the adverse reproductive health and plant vigor impacts (Srivastava et al., 2024). Increasing rooting depth will enhance drought resilience across all oilseed species, whereas excessive irrigation can impair root function and reduce crop productivity.

Water stress is mitigated in oilseed crops through osmotic adjustments by the accumulation of compatible solutes such as proline in rapeseed, glycine betaine in sunflower, and trehalose in sesame, which maintain cell turgor and minimize oxidative damage (Fig. 1). As an osmolyte, proline stabilizes cellular structures and prevents electrolyte leakage which is crucial for maintenance of osmotic balance under drought conditions (Alagöz et al., 2023). More importantly, proline enhances antioxidant capacity by reducing reactive oxygen species (ROS), a process also known as detoxification.

Stomatal movements in oilseed crops are regulated by increased ABA levels under drought stress to balance water conservation and photosynthesis efficiency (Fig. 1). Rapeseed, soybean, and sunflower exhibit rapid stomatal closure to reduce transpirational water loss as an essential response to water deficit conditions (Margay et al., 2024), triggered by ABA accumulation. Peanut shows higher baseline ABA levels and faster stomatal closure than rapeseed under drought. ABA receptors and protein phosphatases and kinases orchestrate this process, resulting in transcriptional changes to increase drought tolerance (Hsu et al., 2021). Moreover, ABA stimulates the generation of reactive oxygen species (ROS) (mainly hydrogen peroxide) in guard cell mitochondria that triggers stomatal closure (Postiglione & Muday, 2023). ABA also modulates stomatal responses (and root traits) through its interaction with other hormones, including auxin, thereby improving drought resilience (Sharma et al., 2023). Consequently, ABA is an important hormone coordinating physiological drought responses across all oilseed crops, including rapeseed.

2.3. Genotypic Variability and Water Use Efficiency in Rapeseed

Physiological responses of drought-tolerant and drought-sensitive genotypes across oilseed crops show substantial differences in their stomatal conductance, photosynthetic efficiency, and yield stability. In rapeseed, drought-tolerant genotypes like Nap9 show higher seed yield and oil content, while in sunflower, drought-resistant cultivars like SF0049 maintain higher leaf water potential and photosynthetic rates. These tolerant varieties across oilseed species exhibit higher root length and leaf relative water content, which are important for maintaining physiological functions under water deficit (El Idrissi et al., 2023). Physiological traits such as canopy temperature, relative water content, and stomatal conductance are significantly correlated with seed yield in both rapeseed and soybean, making them potential selection criteria for drought tolerance across oilseed crops (Pasban Eslam et al., 2017). Taken together, these results highlight physiological performance as a key factor in discriminating among oilseed genotypes' drought responses and guide breeding for increased resilience (Fang et al., 2022).

Drought-tolerant oilseed crop genotypes exhibit higher water-use efficiency (WUE), achieved through diverse physiological and metabolic processes that reduce transpiration rates without compromising growth and productivity. In rapeseed, genotype Q1 decreased in root surface area and volume less than the sensitive genotype Q8, allowing Q1 to take up and maintain more water during drought, while similar root architecture adaptations occur in drought-tolerant safflower and peanut varieties (Zhi et al., 2024). Specific metabolic pathways (galactose metabolism, TCA cycle, etc.) were activated in rapeseed Q2 and comparable osmolyte accumulation mechanisms appear in drought-tolerant sesame genotypes to increase stress resilience (Zhi et al., 2024). Newly developed tissue-cultured canola genotypes showed superior performance under various irrigation regimes (Morsi et al., 2023), indicating potential for yield maintenance under declining water availability across oilseed crops. Quantitative trait loci (QTL) for WUE have been identified in genetic analyses of several oilseed species, suggesting the presence of specific alleles that positively affect WUE and seed yield, underpinning the selection of drought-resistant varieties (Raman et al., 2021). These findings reveal that water-use optimization during growth in drought-tolerant oilseed crop genotypes results from complex interactions among physiological adaptations and conserved genetic factors.

2.4. Water Availability, Nutrient Uptake and Biochemical Responses

Oilseed crop growth and yield are severely impaired by water stress, due to reduced mobility and uptake of essential nutrients such as nitrogen and phosphorus. When plants cannot simultaneously access water and nutrients from the soil under drought conditions, nutrient acquisition is hindered across species. In safflower, nutrient uptake decreases by 20-30% under moderate drought, while sunflower exhibits greater resilience in maintaining phosphorus acquisition compared to rapeseed. Optimized irrigation methods, including partial root zone drying (PRD) and patchy fertilizer placement, enhance root system activity in diverse oilseed crops, allowing plants to access more water and nutrients and grow better (Wang et al., 2007). In soybean, split-root irrigation systems maintain nitrogen fixation under moderate drought stress. Moreover, Zn quantum dot biochar application can alleviate drought stress and improve nutrient uptake in rapeseed and other oilseed crops under water-limited conditions (Alotaibi et al., 2024). This suggests that applying effective irrigation strategies can notably enhance nutrient absorption across the oilseed crop spectrum when undergoing water stress (Alotaibi et al., 2024).

Oilseed crops exhibit significant biochemical adaptations under water-deficient conditions to mitigate oxidative stress and maintain metabolic homeostasis. Activities of antioxidant enzymes, including superoxide dismutase (SOD), ascorbate peroxidase (APX) and glutathione reductase (GR) are enhanced across species, with sunflower showing 40-60% higher baseline APX activity than rapeseed. These responses are especially pronounced in drought-tolerant cultivars which have higher potential for antioxidative responses than drought-sensitive varieties (Abedi & Pakniyat, 2010). Soybean varieties like Clark and Williams-82 exhibit distinct patterns of antioxidant enzyme upregulation compared to Brassica species. The synthesis of compatible solutes, such as proline in rapeseed, glycine betaine in sunflower, and trehalose in sesame, also plays a significant role in osmotic adjustment and in reducing oxidative stress (Bhuiyan et al., 2019). Together, these biochemical strategies improve growth and yield in drought-affected oilseed crops.

For oilseed crops growing under stress, physiological traits, including leaf relative water content (LRWC), root-to-shoot ratio, and stomatal conductance, play critical roles in drought response by supporting survival and minimizing water loss. In drought conditions, LRWC typically decreases across species but at different rates, with sunflower maintaining 5-10% higher LRWC than rapeseed under comparable stress. Stomatal conductance declines to reduce transpiration and save water, with peanut showing more rapid stomatal closure than rapeseed (Pasban Eslam et al., 2017). Oilseed plants allocate more resources to root development to increase water uptake, resulting in larger root-to-shoot ratios, with safflower developing particularly extensive root systems. Drought-tolerant rapeseed genotypes like P287 have higher LRWC and less stomatal density, tending to retain more water and recover more after stress (Zhu et al., 2021). Similar adaptations are observed in drought-resistant sunflower and sesame varieties. Additionally, physiological adjustments like increased abscisic acid levels help regulate stomatal closure to minimize water loss at critical growth stages across the oilseed crop spectrum (Fang et al., 2022). Together, these traits collectively increase drought resilience in oilseed crops, enabling plant survival in water-limited conditions.

3. ADVANCES IN IRRIGATION TECHNOLOGIES FOR RAPESEED

New innovations in irrigation systems have greatly enhanced water supply in agriculture, especially for oilseed crops including rapeseed, soybean, sunflower, and sesame, by being able to supply specific needs without excess (Fig. 2). New technologies like smart irrigation techniques and precision water management (PWM) work on real-time data obtained from the sensor system and can save up to 25% more water as compared to the existing technique (Devendiran et al., 2023). These technologies increase efficiency by enabling precise water application to various oilseed crops, thereby increasing yield and quality and reducing the costs of over-irrigation (Table 1) (Ranwa et al., 2024). In addition, using IoT and machine learning in irrigation practices enables adaptation based on the current environmental climate to sustainable farming methods, besides addressing issues arising from climate change. While rapeseed and sunflower respond differently to soil moisture fluctuations, these smart systems can be calibrated for crop-specific thresholds.

Precision irrigation technologies enhance the ability to cultivate diverse oilseed crops according to their unique water requirements by optimizing efficient water delivery throughout plant development periods (Fig. 2). Modern irrigation systems combine soil moisture sensors with Internet of Things applications to control operations while maintaining resource optimization by minimizing human errors (Korlepara et al., 2024). For deep-rooted oilseed crops like sunflower, these systems can monitor moisture at different soil depths, while more shallow-rooted species like sesame benefit from surface moisture monitoring. Research by Hangeprojections indicates that these automated systems enhance agricultural yields and conserve vast amounts of water in regions experiencing agricultural water scarcity (Nambiar & Bhuvaneswari, 2023). The combination of solar-powered water pumps equipped with moisture sensors for irrigation supplies plants with precisely what they need using optimal environmental conditions (Uddin et al., 2012). These enhanced irrigation techniques are essential for meeting the varied requirements of different oilseed crops, given both changing weather and mounting water resource limitations (Lakhiar et al., 2024).

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Table 1: Advanced Irrigation Technologies: Roles, Benefits, AI Integration, and Key Insights

No.	Technology	Role	Benefits	AI Technologies	AI Language	Key Insights and Impact	References
1	IoT-Enabled Soil Moisture Sensors	Real-time monitoring of soil moisture	Reduces water waste and improves irrigation precision	Predictive analytics, rule-based models	Python, Node-RED	Sensors enable water-saving decisions tailored to soil needs.	(Afzal et al., 2025)
2	AI-Based Decision Support Systems (DSS)	Predicts irrigation needs under variable climatic conditions	Optimizes water usage, increases yield	Neural networks, decision trees	TensorFlow, PyTorch	Integrates multi-source data for informed irrigation strategies.	(Nakhaei et al., 2023)
3	Wireless Sensor Networks (WSNs)	Monitor environmental parameters remotely	Enables large-scale environmental monitoring	Clustering algorithms, regression models	MATLAB, R	Efficient for large-scale real-time soil and weather monitoring.	(Othman & Shazali, 2012)
4	Smart Drip Irrigation Systems	Automated water delivery based on crop needs	Saves water, increases water-use efficiency	Fuzzy logic, sensor-driven algorithms	Embedded C, Python	Tailors water delivery to crop growth stages.	(Bhavsar et al., 2023)
5	Geographic Information Systems (GIS)	Mapping and spatial analysis of water distribution	Enhances resource allocation and reduces wastage	Spatial data analysis	QGIS, ArcGIS	Identifies and mitigates water stress zones in fields.	(Boken et al., 2004)
7	IoT-Integrated Weather Stations	Collects localized weather data	Improves predictive irrigation scheduling	Machine learning-based forecasting	Python (SciPy, NumPy)	Real-time updates optimize water allocation efficiency.	(Selvam & Al-Humairi, 2023)
8	AI-Driven Predictive Models	Forecasts soil moisture and water needs	Ensures timely irrigation	Random Forest, LSTM, KNN	TensorFlow, Scikit-learn	Supports long-term water resource management.	(Ashoka et al., 2024)
9	Robotics in Irrigation	Automates water distribution and system maintenance	Reduces human labor, ensures precision in large farms	Path optimization	ROS, Python	Robots autonomously manage irrigation schedules in large setups.	(Duckett et al., 2018)
10	Solar-Powered Automated Sprinklers	Sustainable power source for irrigation systems	Saves energy, reduces carbon footprint	Sensor-based water regulation	Arduino IDE, Embedded C	Cost-efficient and eco-friendly irrigation for remote areas.	(An et al., 2019)
11	Cloud-Based Irrigation Management	Remote monitoring and control of irrigation systems	Facilitates remote access, reduces operational costs	IoT-cloud integration, anomaly detection	AWS IoT, Google Cloud IoT	Farmers can monitor and optimize irrigation remotely.	(Tyagi et al., 2017)
12	Negative Pressure Irrigation (NPI)	Maintains soil moisture through pressure differentials	Reduces water usage by 23%, improves root health	Basic mechanistic modeling	N/A	Suitable for arid regions with limited water availability.	(Jin et al., 2022)
13	Real-Time Remote Sensing	Provides aerial or satellite imagery for water stress analysis	Identifies dry zones, optimizes water allocation	Image recognition, CNNs	OpenCV, TensorFlow	Enables early detection of drought-prone zones.	(Ahmad et al., 2021)
14	AI-Optimized Sprinkler Systems	Dynamically adjusts water spray patterns	Reduces water wastage, maximizes coverage	Gradient Boosting, Reinforcement Learning	PyTorch, TensorFlow	Adapts spray behavior to crop-specific needs and environments.	(Hussain et al., 2024)
15	Capillary-Based Irrigation Systems	Uses soil capillarity to distribute water	Minimizes energy use, ensures uniform wetting patterns	N/A	N/A	Ideal for energy-scarce regions with consistent water requirements.	(Semananda et al., 2018)
16	Machine Learning for Water Needs	Predicts water requirements based on historical and real-time data	Reduces over-irrigation, improves crop yield	SVM, LSTM	TensorFlow, R	Enhances accuracy in water delivery predictions.	(Glória et al., 2021)
17	Optimized Subsurface Irrigation Systems (OPSIS)	Distributes water effectively using soil capillary properties	Reduces operational costs, increases soil health	Heuristic modeling	MATLAB	Prevents soil nutrient leaching by optimizing water flow.	(Gunarathna et al., 2017)
18	Fuzzy Logic Controllers	Makes irrigation decisions under uncertain conditions	Improves water allocation efficiency	Fuzzy logic	MATLAB, Python	Provides robust solutions for unpredictable environmental changes.	(Abu & Yacob, 2013)
19	Satellite-Based Irrigation Monitoring	Tracks and monitors irrigation status on large scales	Facilitates macro-level irrigation planning	Remote sensing algorithms	ENVI, ERDAS Imagine	Supports wide-area agricultural water management strategies.	(Foster et al., 2020)
20	AI-Integrated Crop Models	Simulates crop responses to water availability	Helps in strategic planning, optimizes water productivity	Predictive modeling, RNNs	Keras, TensorFlow	Enables long-term crop and water resource planning.	(Patil, 2024)
21	Dynamic Neural Networks for Irrigation	Predicts soil moisture content dynamically	Enables adaptive irrigation scheduling	Dynamic Neural Networks	PyTorch, TensorFlow	Adjusts irrigation schedules in real-time based on weather and soil conditions.	(Adeyemi et al., 2018)

22	Precision Fertigation Systems	Combines water and nutrient application tailored to crop stages	Increases nutrient uptake, reduces waste	Predictive algorithms	Python, Excel	Synchronizes water and fertilizer delivery with crop needs.	(Xing & Wang, 2024)
23	IoT-Powered Micro-Irrigation	Manages small water applications through sensor networks	Saves water, enhances root absorption	IoT automation	Python, Raspberry Pi	Highly efficient for precision farming in arid areas.	(Kulkarni et al., 2023)
24	Data-Driven Irrigation Optimization	Uses data analytics to identify irrigation patterns	Optimizes water productivity, reduces waste	Regression models, k-Means Clustering	R, Python	Aligns irrigation schedules with climatic and soil requirements.	(Bwambale et al., 2023)

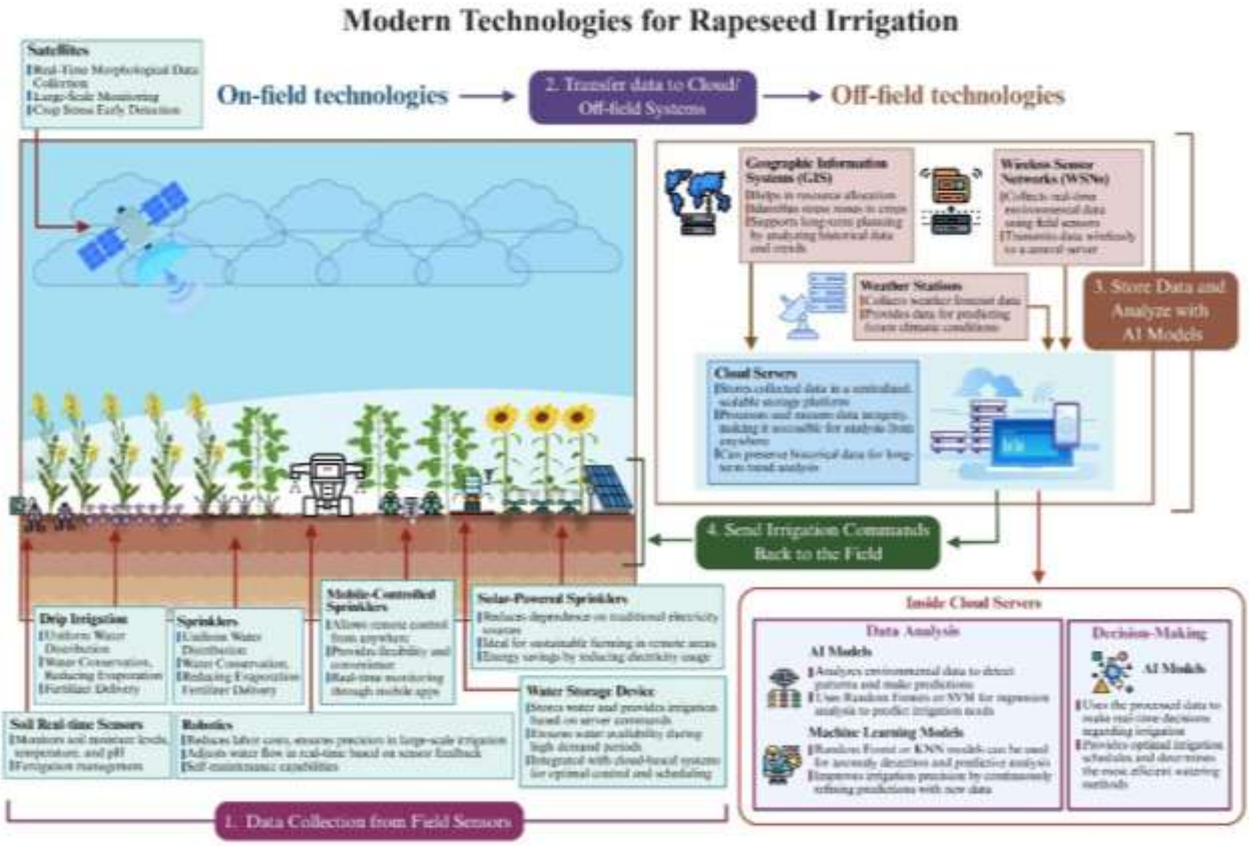

Fig. 2: Modern Irrigation Technologies for Rapeseed Farming: Integrating On-field and Off-field Systems.

3.1. Site-Specific Drip and Subsurface Irrigation Systems

Subsurface drip irrigation (SDI) and conventional drip irrigation practices reduce evaporation and runoff losses in localized water delivery and improve water use efficiency across oilseed crops, including rapeseed, soybean, and sunflower. Studies show that adapting drip irrigation schedules can decrease water consumption by 20-35% across oilseed crops while increasing productivity by 11-28% compared to traditional practices (Kumar et al., 2021). In addition, fertigation combined with SDI effectively applies nutrients alongside water, with soybean showing 85% increased nitrogen uptake and safflower demonstrating improved protein quality, meaning wastage is eliminated and crops can withstand drought conditions (Callau-Beyer et al., 2023). For instance, real-time irrigation planning for various oilseed crops has shown water productivity increases of 23% and evaporation reductions of 16% when implementing such targeted irrigation (Dai & Chen, 2023).

Water savings of up to 50% have been reported with smart irrigation systems equipped with soil moisture sensors, evapotranspiration controllers, and rain sensors across oilseed crops (Touil et al., 2022). Various irrigation methods prove effective: NPI reduces water consumption by 23% in rapeseed, magnetically treated water increases water use efficiency by 13.9% in sunflower, and SDI lowers canopy temperatures up to 2.5°C in soybean compared to conventional methods (Zhao et al., 2019). In addition to saving water, these methods yield steady crops with higher yields and quality; they stabilize soil moisture retention, which increases nutrient uptake, with sesame achieving optimal seed yield (485kg/fed) at 80% ETc. These efficiency gains support the integration of IoT and AI in irrigation systems for precise water management and real-time monitoring, essential for adapting to ecological

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conditions and promoting sustainable agricultural practices (Tace et al., 2023). The implications of these technological advances in irrigation management for oilseed crops offer significant opportunities for efficiency gains and yield increases, aligning with broader goals of sustainable agriculture and resource conservation.

In addition to the subsurface irrigation system's efficient soil moisture management capacity, technologies like the Optimized Subsurface Irrigation System (OPSIS) can be utilized for various oilseed crops based on soil capillary property to distribute water effectively, reducing energy requirements and operational cost (Gunarathna et al., 2017). Furthermore, subsurface irrigation systems include soil moisture sensors and weather data to manage irrigation schedules tailored to different root architectures—from safflower's deep roots (8-10 feet) to other oilseed crops' more moderate depths, preventing over-irrigation and poor soil aeration (Nambiar & Bhuvaneswari, 2023). Subsurface drip irrigation helps maintain soil aeration, essential for root respiration and plant health, particularly beneficial for soybean's nitrogen-fixing nodules.

3.2. Integration of IoT Sensors and Automation in Irrigation

Real-time monitoring of soil moisture and environmental parameters through IoT-based sensors plays a crucial role in oilseed crops, including rapeseed, soybean, sunflower, and sesame, where soil moisture sensors and environmental sensors are essential for making irrigation decisions. These sensors are integral to systems designed to monitor—and sometimes maintain—key parameters such as soil moisture, temperature, humidity, and nutrient levels, with calibration options for different crop-specific thresholds. The precise data collected can be used to tailor irrigation practices to the specific needs of each oilseed crop, as referenced in Table 1 (Zhang et al., 2024; Al Kalaany et al., 2025). Similar to the use of IoT in farming, also known as smart farming, these technologies control and optimize irrigation schedules more effectively, conserving resources while increasing yields across various oilseed varieties (Ercan Oğuztürk, 2025). IoT systems, for example, can utilize predictive analytics to forecast weather conditions using algorithms like Random Forest, enabling adjustments to irrigation patterns based on predictions. This ensures that soil moisture levels remain optimal for plant growth, with different set points programmed for drought-sensitive crops like rapeseed versus more drought-tolerant oilseeds like safflower. Furthermore, real-time environmental monitoring is conducted using wireless sensor networks (WSNs), which are crucial for precision agriculture, as referenced in Table 1. Data collected from these networks is analyzed to inform decisions on irrigation and other agricultural practices (Zhang et al., 2025). IoT is also integrated with cloud computing and mobile applications to provide farmers with easy access to this data, allowing them to remotely log in to their irrigation systems and efficiently monitor and control them, thereby reducing labor costs and improving farm efficiency (Morchid et al., 2024; Srikanthnaik, 2024). Additionally, the accuracy of these IoT sensors is supported by high R^2 values in various studies, ensuring reliable data collection essential for effective crop management and protection against groundwater contamination by nutrients (Kumari et al., 2025; Le et al., 2023). Precision monitoring through IoT-based sensors underscores its technological strength as a sustainable solution for water resource management, leading to enhanced oilseed cultivation yields with environmentally friendly irrigation practices (Dong et al., 2024; Lakhiar et al., 2024).

Automated irrigation scheduling, along with IoT systems, delivers the use of real-time data and advanced decision-making tools to deliver water to oilseed crops precisely. These systems use multiple IoT technologies, machine learning algorithms, and sensor networks to monitor and respond to the unique needs of different oilseed crops. Moreover, fuzzy logic controllers are integrated to refine irrigation decisions. Their integration is based on the fact that sensor data are processed by linguistic control rules to cater to specific scenarios to deliver water correctly, with parameters adjusted for different oilseed crop growth stages (Benzaouia et al., 2023). Moreover, real time monitoring and control are implemented in these systems, where users may remotely manage the irrigation using mobile applications and web interfaces and change the irrigation schedules in a very timely manner refer to Table 1 (Khriji et al., 2021). Integrating IoT and machine learning in automated irrigation systems offers an important advancement in precision agriculture in managing water with speed and precision, based on the real time needs of diverse oilseed crops.

Several case studies of the successful adoption of IoT systems for oilseed crop farming are presented, with significant resource use and yield improvements demonstrated. Similar benefits have been observed in soybean farms in Brazil and sunflower cultivation in Spain. Further, the implementation of IoT based farmland monitoring systems to collect real time environmental variables data allows farmers to optimize resource utilization and improve yield across various oilseed crops. Similarly, a study points out IoT platforms such as Blynk, which makes use of real time monitoring of soil moisture and environmental conditions for accurate irrigation management in both rapeseed and other oilseeds. The effectiveness of this approach has been to keep the soil moisture at the optimum level, which is good for crop health and yield (Wasatkar et al., 2023). The Smart Farm project shows how IoT can contribute to the highest crop yield and promote sustainability by integrating many different sensors to report soil moisture, temperature, and crop status as a knowledge base for informed decisions and elevated productivity across oilseed crops (Wasatkar et al., 2023). Furthermore, IoT based sensors have demonstrated substantial water usage reduction, like automated sprinklers reducing 24% water in rice cultivation, with similar systems showing 18-30% water savings in various oilseed crops (Roy & Aslekar, 2022). Collectively, these case studies show how IoT systems in oilseed crop farming can bring about measurable changes in resource use and yield, helping create more sustainable and efficient agricultural practices.

3.3. Decision Support Systems (DSS) for Optimized Water Management

Decision support systems (DSS) based on advanced machine learning and other AI technologies predict irrigation needs and optimize water management for oilseed crops under highly variable climatic conditions. These systems bring together sets of disparate data, such as soil moisture, temperature, weather forecasts, and more, to make precise irrigation recommendations for diverse crops including rapeseed, sunflower, soybean, and safflower. AI-driven smart irrigation systems utilize deep neural networks to embrace the detailed correlation between soil moisture and ambient temperature for autonomous valve control, with different threshold parameters programmed for drought-tolerant oilseeds like safflower versus more sensitive crops like rapeseed (Alex et al., 2024). Furthermore, AI aided irrigation systems use IoT and sensor networks for scheduling irrigation precisely. Machine learning algorithms like regression and deep learning CNNs and RNNs are used to predict climate using predictive climate modeling, thus enabling us to predict climate trends patterns and therefore enables informed decision making and to adapt agricultural strategies to reduce the effects of climate change for various oilseed production systems (Huntingford et al., 2019). Moreover, AI based soil monitoring and real time decision making in irrigation enhance the process of water management, thus, leading to efficient utilization of natural resources, improved crop yield and reduced footprint for all oilseed crops (Elshaikh et al., 2024). Using the UNet-ConvLSTM model, AI is integrated into remote sensing technologies to capture spatial and temporal features, thereby improving prediction accuracy of agricultural water management with applications extending from rapeseed to soybean and other oilseed crops (Ye et al., 2024). Using weather history patterns, soil moisture levels and crop traits, AI systems can calculate in advance irrigation requirements, prior to the onset of rainfall, reducing water waste and effectively using available resources, with specific models calibrated for different oilseed crop water requirements (Goel et al., 2024). The application of AI systems requires attention to both infrastructure integration and data privacy concerns which demand strategic approaches for complete adoption (Ashoka et al., 2024; Mushtaq et al., 2024). Overall, AI based DSS possesses strong potential especially through predictive modeling and on real time data analysis to optimize water management and climate adaptation in oilseed crop cultivation.

Several Decision Support Systems (DSS) case studies show significant yield improvements and water savings across oilseed crops. The use of improved production technologies in rapeseed farming in Assam, India, through Front Line Demonstrations (FLDs), increased yields by as much as 18.03 to 26.90% for the past 5 years, with benefit-cost ratios of 1.94 to 2.97, showing the potential of DSS to bridge the yield gap (Sharma et al., 2023). Similar yield increases have been observed in soybean (15-22%) and sunflower (16-25%) production systems using comparable DSS approaches. A real-time self-organizing algorithm for irrigation planning was developed in China, enhancing water productivity by 23% and reducing soil surface evaporation by 16%, providing evidence of the application of DSS across oilseed crops (Dai & Chen, 2023) and realizing water use optimization. Moreover, optimally scheduled drip irrigation and fertigation for oilseed crop cultivation using the developed block maximized yield by 18% and reduced water use by 35.4% compared to existing methods (Kumar et al., 2021). DSS technologies' scalability and worldwide adoption pose several challenges. The high costs, reliability issues, and the requirement for custom-designed solutions limit the adoption of a few applications, particularly for smaller-scale oilseed producers (Shamshiri et al., 2024). Besides, the maturity of innovative farming technologies is low and still fragmented because of a mix of technological complexity and infrastructure development (Ali & Zhang, 2023). In addition, future directions for DSS in oilseed crop farming include combining advanced technologies, such as CRISPR for genetic improvement, with digitalization of existing technologies to improve precision in crop management across the oilseed spectrum (Shamshiri et al., 2024). These challenges must be addressed by reducing costs, increasing reliability, and developing scalable, extendable solutions for all agricultural inputs, from the smallest local farm in Ethiopia to the largest in China. With continuously increasing research and development in oilseed crops, notably in China, which leads the world in research output (Zheng & Liu, 2022), there is a solid foundation for promoting DSS technologies and achieving cost-effective, sustainable oilseed crop agricultural production.

4. INTEGRATING IRRIGATION WITH OTHER AGRONOMIC PRACTICES

Fertigation and direct delivery of fertilizer by irrigation improve nutrient use efficiency and oilseed crop growth through delivery to the root zone, thereby minimizing nutrient losses and enhancing uptake efficiency (Fig. 3). Drip fertigation is especially highly effective for providing water and nutrients to various oilseed crops, with sunflower showing 12-15% higher nutrient recovery compared to conventional methods, resulting in precise and

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uniform distribution that meets the crops' requirements in real time while reducing fertilizer losses by up to 30% over traditional methods. The application of this technique is handy in water-scarce areas, as it enhances crop yield and quality and increases nutrient uptake and nutrient-water use efficiency across the oilseed spectrum (Paramesha et al., 2022). Agronomic practices, including mulching, conservation tillage, and crop rotation, enhance soil moisture retention and reduce evaporation losses in oilseed crop cultivation (Fig. 3). For instance, mulching helps conserve soil moisture, reduces weed growth, and regulates soil temperature, thereby improving the efficiency of soil nutrient use for both rapeseed and soybean production (Tahir et al., 2022). Conservation tillage and crop rotation also help retain soil moisture and cycle more nutrients, which better uses water and increases crop resistance in diverse oilseed systems (Xin et al., 2023). The application of straw mulching and reduced slow-release fertilizer in Southwest China has been found to enhance rapeseed yield and oil content substantially while reducing water consumption, with similar benefits observed in sesame and peanut production, as well as improving water use efficiency for oilseed crops by up to 28.71% (Fig. 3) (Feng et al., 2020). Combined with fertigation, these practices synergistically improve resource use efficiency for cultivating various oilseed crops under different climatic conditions (Fig. 3) (Feng et al., 2020). Generally, combining these agronomic practices with fertigation provides a comprehensive approach to enhancing nutrient and water use efficiency, thus promoting crop growth and productivity in oilseed crop production.

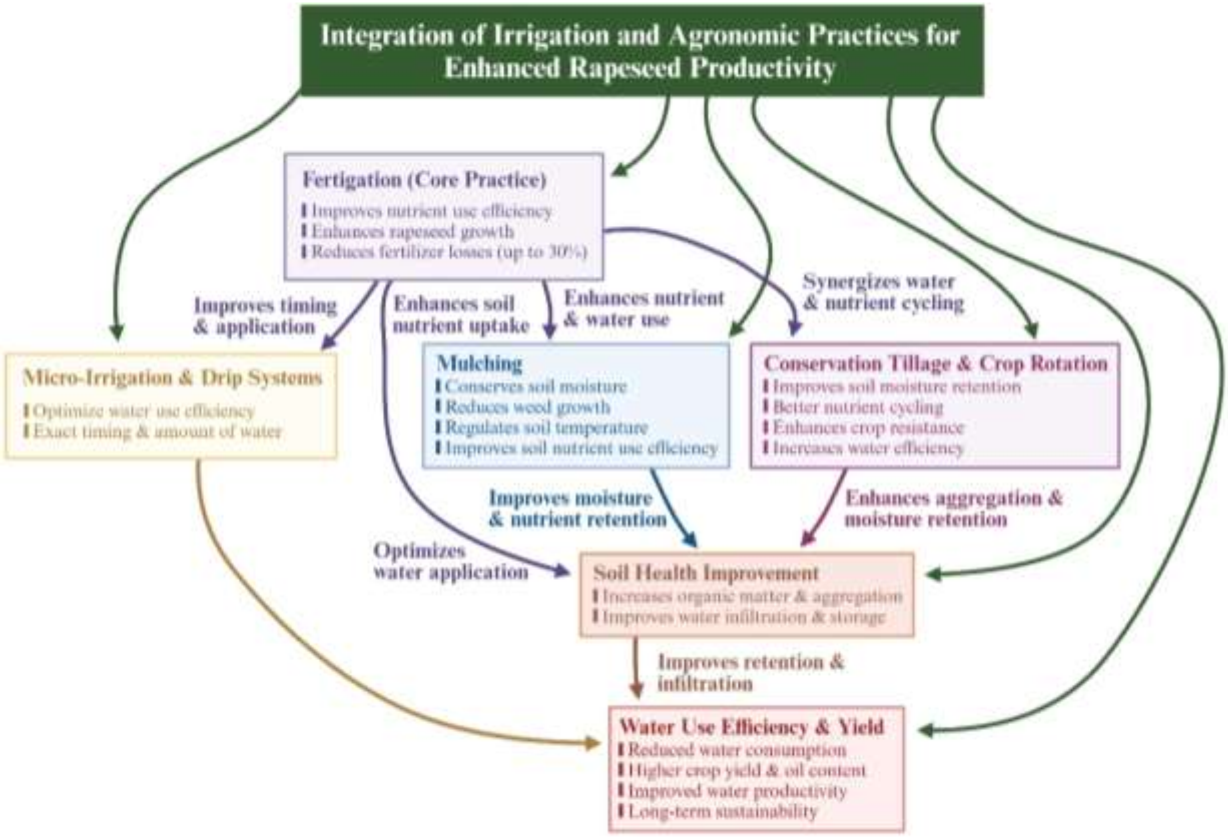

Fig. 3: Integration of Irrigation and Agronomic Practices for Enhanced Rapeseed Productivity.

Several conservation agriculture (CA) strategies can be implemented to address issues like cold soils and surface soil compaction in oilseed crop farming, including rapeseed, sunflower, and soybean systems. These strategies aim to enhance water productivity, boost yield per unit of water used, and improve long-term soil health and water-holding capacity. Research shows that CA practices, such as minimum tillage, direct drilling, and the use of cover crops, significantly enhance soil water retention and reduce evaporation, making them essential for both rainfed and irrigated oilseed systems (Hobbs et al., 2008). In addition to improving water use efficiency, these practices enhance soil health by increasing organic matter and additional soil aggregation that improves water infiltration and retention under the forces of gravity, leading to higher amounts of water infiltration for root uptake and water maintained in the soil profile as water storage (Kumar et al., 2016). Modern irrigation methods like micro-irrigation and subsurface drip systems, coupled with real-time soil moisture monitoring for irrigation scheduling, can further improve water use efficiency in oilseed production by exactly matching the timing and amount of water applied to the conditions (Hobbs et al., 2008). Finally, the application of synthetic and natural fertilizers with crop residue improves soil structure and nutrient availability to improve crop yields and soil carbon sequestration across all oilseed crops (Stagnari et al., 2019). Additionally, these practices play an important role in soil as a carbon sink, reducing the impacts of climate change (García-Tejero et al., 2020). In addition, a permanent mulch cover of the soil surface leads to better soil porosity and hydraulic conductivity and, therefore, better water retention and lower soil erosion in diverse oilseed production systems (Stagnari et al., 2019). Taken together, these strategies enhance water productivity and crop yield and ensure that oilseed farming systems as a whole are sustainable and resilient even to environmental stress and change.

4.1. Sustainable Irrigation Practices for Rapeseed

Sustainable irrigation practices for oilseed crops, including rapeseed, involve implementing precision irrigation systems, soil amendments, and advanced forecasting models to optimize crop growth, water use efficiency, and environmental sustainability (Fig. 4). Precision Irrigation Systems (PIS) are crucial for enhancing water use efficiency and reducing environmental footprints across oilseed crops. By supplying water precisely according to real-time data, these systems can mitigate the adverse effects of climate change on oilseed production (Lakhiar et al., 2024). Transitioning to modern irrigation technologies that improve water-energy-food (WEF) nexus metrics is particularly important for oilseed crops in water-scarce, dry, and temperate regions. This approach aims to maximize crop yield per unit of water, energy, and land used (Taguta et al., 2022). For example, in sunflower cultivation, these technologies have shown potential to increase water use efficiency by up to 25% compared to conventional methods. Irrigation equilibrium indicators (IEIs) help achieve a sustainable balance among climate, water, food, and energy factors, optimizing agricultural yield and economic returns for oilseed crops (Batisha, 2024). This holistic approach is particularly beneficial for diverse oilseed production systems, from rapeseed in temperate climates to drought-tolerant oilseeds like safflower in arid regions. Advanced irrigation scheduling techniques, such as Bi-directional Gated Recurrent Unit (Bi-GRU) networks, are being employed to accurately predict water requirements based on soil moisture, weather, and crop-specific data. These systems can reduce water waste and improve productivity across various oilseed crops, with studies showing potential water savings of 15-30% in soybean and rapeseed production (Katta et al., 2024). Soil amendments like biochar, zeolite, and compost, combined with foliar nutrition, significantly improve water retention capacity and boost plant resilience under deficit irrigation conditions. These practices are essential for sustainable oilseed farming in arid regions, with research demonstrating up to a 20% improvement in water-use efficiency for crops such as sesame and peanut (El-Ghamry et al., 2024). The integration of these strategies results in sustainable irrigation models that optimize water use, yield, and quality while contributing to climate change mitigation. These approaches improve both economic and environmental outcomes for oilseed crop farming, including rapeseed, sunflower, and soybean production systems.

4.2. Deficit Irrigation Strategies

Deficit irrigation strategies are effective for reducing water use in oilseed crops, including rapeseed, without significantly compromising yield and quality. This approach applies water below full crop requirements during non-critical growth stages, thereby optimizing plant physiological responses to water stress and promoting water-use efficiency. Partial root zone irrigation (PRZI) can save 20-30% of irrigation water while maintaining yield in oilseed crops. This technique enhances guard cell signal transduction and optimizes stomatal control, reducing soil evaporation (Chai et al., 2016). Combining deficit irrigation strategies (DIS) with superabsorbent polymer (SAP) hydrogels under micro-sprinkler systems has shown promising results across oilseed crops. In Indian mustard, a close relative of rapeseed, this approach increased seed yield and water productivity compared to rainfed conditions, significantly improving net returns and benefit-to-cost ratios (Rathore et al., 2019). Recent findings suggest that deficit irrigation strategies result in substantial water savings and improved economic outcomes for oilseed crop cultivation, including rapeseed. However, careful management is crucial for successful implementation. These strategies show potential for widespread adoption in water-limited agricultural systems across various oilseed crops (Laita et al., 2024).

4.3. Climate-Smart Irrigation Practices

In response to climate change and increasing rainfall variability, along with changes in seasonal water availability, dynamic irrigation schedules are increasingly being developed to effectively address uncertainty. Machine learning paradigms with k-means clustering and long short-term memory networks are implemented to create dynamic models for predicting soil moisture dynamics and constructing irrigation schedules (Agyeman et al., 2023). These models are important for managing external perturbations and disturbances to apply irrigation

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efficiently and only when needed (Adeyemi et al., 2018). Additionally, constructing simulation and optimization frameworks establishes the foundation for identifying irrigation parameters that optimize crop net margins while minimizing irrigation water usage, preventing waterlogging, and maintaining optimal soil moisture throughout the entire production season (Fontanet et al., 2022). Stochastic dynamic programming and fuzzy random simulations can further enhance the option to handle water resources with uncertain cases like variable seasonal inflow and rainfall by optimizing water allocation between different growth stages and agricultural sub-areas (Xu et al., 2015). These approaches are particularly valuable for drought-sensitive oilseed crops like rapeseed and soybean, while also benefiting more drought-tolerant species like sunflower. Advanced irrigation scheduling techniques not only enhance water use but also help oilseed crops develop climate resilience by ensuring that water is available when needed most, accommodating the varying sensitivities of different species during critical reproductive stages (Hafeez et al., 2022).

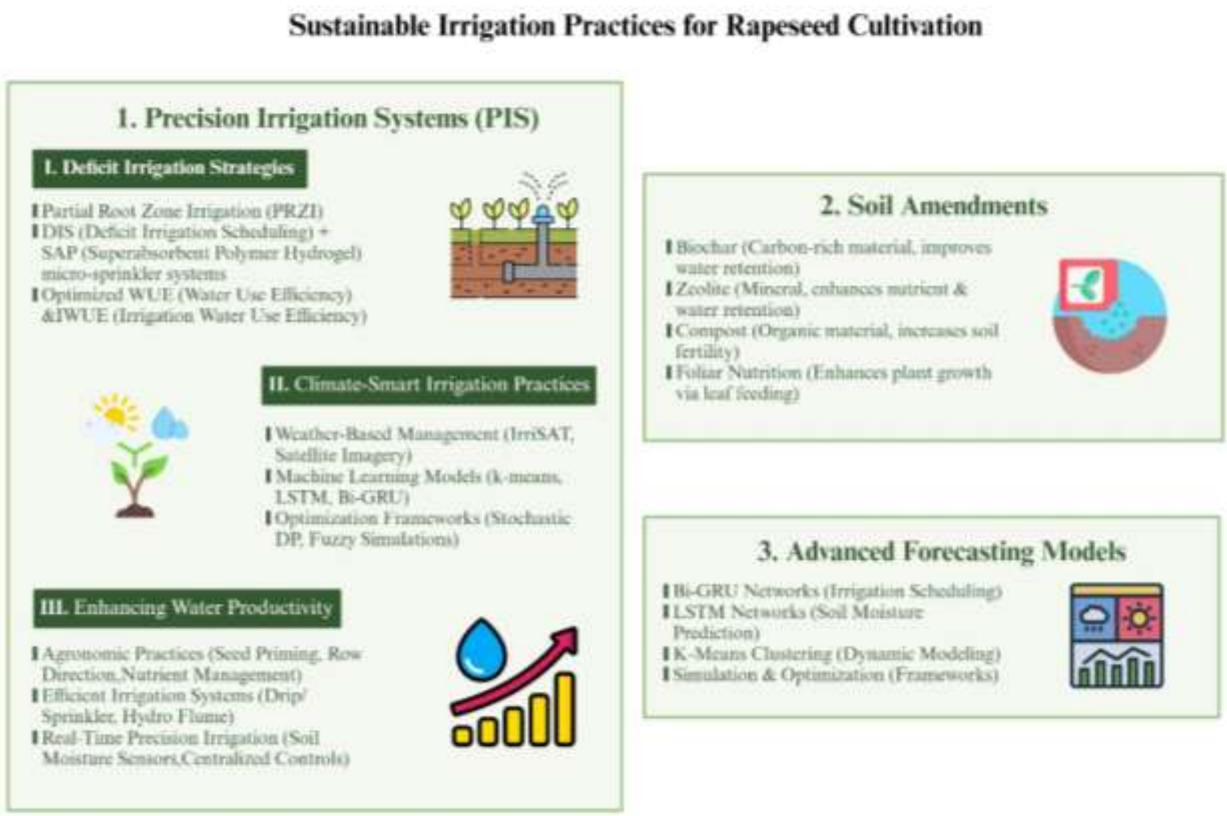

Fig. 4: Sustainable Irrigation Practices for Rapeseed Cultivation.

4.4. Enhancing Water Productivity

Several strategies to enhance water productivity and implement improved irrigation technologies have been identified to achieve higher yields with reduced water inputs across oilseed crops. Optimizing the ratio of crop yield per unit of water consumed (water productivity) is a key performance metric and is enhanced by precision agronomic and water management technologies across various oilseed species. Seed priming, proper row orientation, nutrient management, and drip and sprinkler irrigation systems help minimize water application in all oilseed crops, with sunflower showing 15-20% improved water use efficiency under optimized row spacing compared to conventional methods. These approaches, especially drip and sprinkler irrigation, reduce unproductive water loss and increase soil water holding capacity across diverse oilseed production systems (Molden et al., 2010). Precision irrigation systems (PISs) have proven particularly effective at increasing water-use efficiency and crop yield by adjusting to real-time soil moisture conditions, helping mitigate climate change impacts while improving water productivity across various oilseed crops (Lakhiar et al., 2024). For example, deficit irrigation scheduling (DIS) combined with superabsorbent polymer-hydrogel (SAP hydrogel) under micro-sprinkler systems has increased seed yield and water productivity in Indian mustard, a close relative of rapeseed, under semi-arid conditions (Rathore et al., 2019). Similar approaches have shown promising results in safflower and sesame production with yield increases of 10-15% despite reduced water application. According to research findings, optimizing seed yield and irrigation water productivity in arid environments can be achieved by adjusting watering intervals and row arrangements across oilseed crops. This approach enhances overall seed harvests and irrigation water productivity (IWP) rates while reducing water usage to optimal levels, even with occasional decreases in oil output.

Additionally, real-time precision irrigation systems incorporating soil moisture sensors and centralized controls can save water and increase crop yield by applying water precisely according to the specific needs of different oilseed crops (Korlepara et al., 2024). Integrating optimal water and fertilizer management with advanced irrigation technologies results in significant improvements in oilseed crop cultivation, particularly increased yield and water-use efficiency across various climatic conditions (Feng et al., 2020). In conclusion, the incorporation of these innovative irrigation practices and technologies is essential for realizing sustainable oilseed crop production with lower water inputs, benefiting diverse crops from rapeseed to sunflower, soybean, and safflower.

5. CHALLENGES AND FUTURE DIRECTIONS

There are numerous economic barriers to deploying advanced irrigation systems in oilseed crop farming, including high initial investment costs, limited financial returns, and inadequate government support across production regions. A significant barrier is financial constraints, which affect producers of diverse oilseed crops, including rapeseed, soybean, sunflower, and sesame. For example, in India, canal irrigation efficiency suffers due to frequent, insufficient government funding and low water charge collections, jeopardizing the financial sustainability of Water User Associations (WUAs) that support various oilseed producers (Nigam et al., 2023). This stems from perceived costs and challenges associated with installing and maintaining drip irrigation systems, as observed in Australian oilseed production systems (Greenland et al., 2018). Additionally, the transition to sustainable practices is sometimes hindered by reductions in government subsidies and the need for more labor, as seen in the broader context of sustainable agriculture across oilseed production regions (Jordan & Jordan, 2013). Positive examples can be seen in developing countries where the adoption of solar pumps for irrigating diverse oilseed crops helps reduce long-term costs and dependence on fossil fuels when integrating renewable energy sources (Mohammed et al., 2023). As for the adoption of sustainable irrigation, it is encouraged by policies, subsidies, and incentives applicable to all oilseed crop producers. Therefore, because water rights can be associated with salt rights, adopting policies that require monitoring and management of irrigation and drainage can improve water management for diverse oilseed crops (Oster & Wichelns, 2003). To overcome these barriers, effective government policies and support, such as subsidies for adopting sustainable technologies and educational programs, are essential for the widespread adoption of advanced irrigation systems in oilseed crop farming and beyond (Greenland et al., 2019).

Future research in precision irrigation for oilseed crops will require a greater understanding of the comparative physiological mechanisms by which different species respond to water stress. These efforts can inform the breeding of drought-resistant varieties adapted to precision irrigation across the oilseed spectrum, focusing on root architecture (which varies significantly from sunflower's deep taproot to rapeseed's more moderate rooting depth), osmotic adjustments (with different osmoprotectants dominant in various species), and abscisic acid (ABA)-specific regulation of hormone signaling pathways. Moreover, the scalability and smart irrigation technology that enable crop-specific adaptations of IoT-enabled systems and AI-driven decision support tools need to be investigated for optimal performance in different environments and with diverse oilseed crops with varying water requirements and stress responses. To develop comprehensive frameworks that integrate precision irrigation within sustainable agricultural practices, we also need to perform holistic evaluations of environmental impacts (soil health, water quality, energy consumption, etc.) across production systems for various oilseed crops. Furthermore, socio-economic barriers such as high costs, low levels of digital infrastructure, and farmer awareness play significant roles in increasing accessibility to and adoption of advanced irrigation systems, particularly in regions where lower-value oilseed crops are grown. Finally, bringing together the fields of agronomy, data science, and environmental science holds promise for developing novel, cross-cutting approaches that simultaneously improve productivity, sustainability, and resilience of oilseed crops in a changing climate. Addressing these challenges can open up new possibilities for precision irrigation in oilseed crops and help meet the world's food and energy security challenges.

6. CONCLUSION

Rapeseed cultivation can be revolutionized through precision irrigation to address the dual challenges of water scarcity and climate variability while achieving sustainable agriculture. This review emphasizes the importance of understanding how rapeseed responds to water stress in terms of root system architecture, osmotic adjustment, and hormonal regulation to breed drought-resistant varieties. Advanced technologies, including IoT and AI, along with real-time monitoring systems, hold great promise for improving water-use efficiency and streamlining resource allocation. Sustainable irrigation techniques such as deficit irrigation and fertigation can strike a balance among water conservation, yield enhancement, and quality improvement while aligning with global goals for resource-efficient, climate-resilient agriculture. However, significant gaps remain, including crop-specific adaptations of precision irrigation technologies and comprehensive assessments of their environmental impacts. Addressing these gaps will require interdisciplinary efforts that integrate agronomic expertise, cutting-edge technology, and sustainable management frameworks. Overcoming socioeconomic barriers, such as high costs and low adoption of advanced systems, is equally important for achieving widespread implementation and equitable access. If these strategies advance in tandem with innovations in technology and sustainability, then precision irrigation will position rapeseed farming as a model of efficiency and resilience. These efforts will contribute to global food and energy security while supporting various environmental and socioeconomic goals for a sustainable agricultural future.

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Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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