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Understanding the response of fruit crops to drought stress and irrigation needs under climate change conditions

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Abstract

Climate change has significantly altered weather patterns, increasing the frequency and intensity of drought events and posing serious challenges to agricultural production, particularly fruits. Water scarcity and increased evapotranspiration demands, posing critical challenges to global agriculture and threatening the sustainability of fruit production. Understanding the response of fruit crops to drought stress and their specific irrigation needs is essential for developing resilient and sustainable cultivation systems. This work aims to consolidate existing research and provide a comprehensive analysis of strategies to mitigate the impacts of water scarcity on fruit crops. The paper focuses on the following key areas: (1) evaluating the growth and performance of fruit crops across diverse environments and cultivation methods; (2) assessing the water needs of fruit crops, including evapotranspiration rates, crop coefficients, and strategies for efficient water use; (3) identifying and recommending the most effective irrigation methods; (4) exploring advanced tools for real-time monitoring of plant water status; and (5) comparing and evaluating existing models for quantifying plant water requirements under drought conditions, with an emphasis on their potential integration into decision support systems (DSS). By addressing these critical aspects, it aims to provide actionable insights and foster the adoption of innovative irrigation and water management strategies to support sustainable fruit crop production in the context of climate change.

Key words: climate, fruits, irrigation, evapotranspiration, decision

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INTRODUCTION

Climate change is one of the most pressing challenges facing agriculture, affecting productivity, resource availability, and food security. Its detrimental effects on global food production have been widely acknowledged (IPCC, 2023). Over recent decades, global temperatures have risen significantly, with Europe experiencing pronounced thermal anomalies. According to the World Meteorological Organization (WMO, 2023), the last decade ranks as the warmest decade on record. Climate projections indicate that for every degree of temperature increase, extreme rainfall events could escalate by approximately 7% (IPCC, 2023). As climate change increasingly affects agricultural systems, fruit production must adapt to shifting temperature patterns, irregular rainfall, and extreme weather events (Osorio-Marin et al., 2024). Achieving resilience in fruit production requires a combination of improved cultivation techniques, technological innovations, and sustainable resource management to maintain productivity and quality under changing climatic conditions (IPCC, 2023; Osorio-Marin et al., 2024).

Environmental factors, particularly abiotic stresses, significantly impact these traits, often disrupting reproductive processes and reducing fruit set and quality. Water availability is a critical determinant of fruit crop productivity, and prolonged droughts pose significant threats to yield stability, and overall agricultural sustainability (Hsiao, 1973; Blum, 2011; Seleiman et al., 2021; Pacheco-Labrador et al., 2024; RECROP COST, 2024). A comprehensive synthesis of current knowledge on climate change impacts, particularly drought stress and water scarcity, is essential (Manzoor et al., 2024). To mitigate the adverse effects of climate change, fruit crops require system level analyses that integrate genomic and physiological approaches (Chavez et al., 2003; Čereković et al., 2013; Čereković et al., 2014; Čereković et al., 2015). Genetic variability among cultivars plays a crucial role in determining resilience to water scarcity and extreme temperatures (Čereković et al., 2013; Čereković et al., 2014). To sustain commercial fruit production under increasingly harsh climatic conditions, growers must have access to plant material capable of withstanding extreme drought while maintaining yield and quality. A key strategy for adapting fruit production to climate change is the selection and development of climate-resilient cultivars. These aim to ensure that crops can withstand extreme weather conditions highlighting the urgent need for development of new fruit cultivars that can thrive in modern agroecosystems while demonstrating greater resistance to environmental stressors (Čereković et al., 2013; Čereković et al., 2014; Čereković et al., 2015; Gitea et al., 2019; Sugiura and Yokozawa, 2004; Abdoussalami et al., 2023; Vujadinović Mandić et al., 2023; Meza et al., 2023; Manzoor et al., 2024). Using advanced genetic techniques, temperature resistance, and superior fruit quality under stress (Hsiao and Acevedo, 1979; Farooq et al., 2009; Tian et al., 2021; Farooq et al., 2022), not only protect global food production, but also sustain regions vulnerable to climate change. Integrating traditional agricultural knowledge with modern breeding strategies is crucial for creating sustainable solutions (Kumari et al., 2022; Karagatiya et al., 2023). Additionally, the use of climate-resilient rootstocks that improve tolerance to extreme weather conditions plays a vital role in maintaining stable yields (Cimen and Yesiloglu, 2015). However, genetic improvement is a long-term strategy that depends on access to diverse genetic resources suited for marginal conditions (Osorio-Marin et al., 2024). Since elite germplasm often lacks the genetic diversity for effective adaptation, breeders are increasingly turning to traditional and underutilized cultivars to enhance resilience and ensure long-term sustainability of fruit production.

In cases where adaptive cultivars are unavailable, shifts in the geographical distribution of fruit production may become necessary. Adaptation strategies must consider the diverse vulnerabilities of different fruit species and cultivars to water stress, as well as regional climatic and geographic variations.

Microclimate management within orchards and controlled environments is a crucial strategy for mitigating the adverse effects of climate change on fruit production. Techniques such as windbreaks, shade nets, and protective tunnels help buffer temperature extremes, minimize the impact of strong winds, and reduce excessive sunlight exposure (Meza et al., 2023). In greenhouse and high-tunnel systems, climate control technologies regulate temperature and humidity, alleviating plant stress and preventing yield losses (Gavillan et al., 2015). To enhance crop resilience, the development of drought tolerant cultivars should be complemented by agronomic practices such as mulching, cover cropping, and organic amendments, which improve soil water retention and promote healthier, more sustainable soils (Grigorieva et al., 2023). Soil health and fertility management are also essential for enhancing resilience. Increasing organic matter through composting and cover cropping improves soil structure, enhances water-holding capacity, and strengthens root systems (Wolf et al., 2023). Conservation tillage and crop rotation further support soil stability, prevent erosion, and reduce vulnerability to extreme weather events such as heavy rainfall and droughts (Michler et al., 2019). Agroforestry and crop diversification offer additional resilience by integrating multiple plant species within fruit orchards. Intercropping enhances biodiversity, reduce environmental stress, and improve economic stability, creating more sustainable agricultural ecosystems (Osorio Marin et al., 2024). Agroforestry techniques, such as planting fruit trees alongside nitrogen-fixing plants, improve soil fertility and provide additional protection against climate extremes, such as droughts and excessive rainfall (Osorio Marin et al., 2024).

Given the escalating challenges of climate change, it is essential to evaluate and optimize current irrigation methods and water management strategies to ensure their effectiveness in mitigating water scarcity impacts on fruit production. Identifying effective strategies for improving water management will be crucial in strengthening the resilience and sustainability of fruit production systems. The irrigation management involves different irrigation methods (surface and subsurface), to compensate for water losses due to evapotranspiration and insufficient natural precipitation. Evapotranspiration (ET_c) is a key determinant of the water requirements of fruit orchards, as it accounts for both soil evaporation and plant transpiration (Allen et al., 1998). The rate of ET_c depending on climate conditions, soil properties, and orchard management. To estimate water use of fruit crops, crop coefficients (K_c) are applied to reference evapotranspiration (ET_0), adjusting for species-specific water demands at different growth stages (Allen et al., 1998). By utilizing climate parameters measured at meteorological stations, it is possible to determine accurate ET_0 values, which serve as the basis for calculating plant water needs (Srdić et al., 2023; Playán et al., 2024). Integrating precise ET_0 estimation, crop specific K_c values, and adaptive irrigation strategies are essential for optimizing water use. Optimized irrigation strategies, play a vital role in climate adaptation by maximizing water-use efficiency. Techniques like regulated deficit irrigation and partial rootzone drying further enhance water use efficiency (WUE) while maintaining yield (Galindo et al., 2018). However, their effectiveness depends on factors such as crop type, growth stage, and environmental conditions. While deficit irrigation is widely used in fruit production to improve WUE and fruit quality, it must be carefully tailored to each crop's phenological stages to prevent yield loss (Ruiz-Sánchez et al., 2018; Galindo et al., 2018).

Fruit responses to climate change

Throughout the vegetation cycle, fruit development is continuously affected by climatic fluctuations, (Hsiao, 1973; Blum, 2011). Drought, in combination with rising temperatures, adversely affects fruit yield throughout the year (Čereković et al., 2013; Čereković et al., 2014; Čereković et al., 2015) especially during critical growth stages (e.g., flowering, flower initiation, and fruit development), can lead to poor pollination, fruit drop, reduced fruit size, and lower sugar content, negatively impacting both productivity and marketability (Čereković et al., 2013; Čereković et al., 2014; Čereković et al., 2015). In many perennial fruit crops, flowering induction occurs before, after, or in parallel with harvest, emphasizing the critical need for optimal irrigation throughout the growing season. Winter dormancy conditions play a significant role in preparing plants for the next growing season where rising temperatures present additional challenges, particularly in the context of shifting seasonal climate patterns. A key concern is that mild winters can compromise the accumulation of winter chilling units required for dormancy release, which is crucial for fruit yield production (Salama et al., 2021). Warmer winters result in insufficient chilling hours, affecting deciduous fruit crops and potentially interrupting dormancy or accelerating early vegetation growth, making plants more susceptible to late spring frosts (RECROP COST, 2024; Rousssos, 2024). These conditions can disrupt flowering and fruiting stages, leading to reduced and unstable yields. In crops requiring vernalization, delayed or inadequate flowering due to insufficient chilling, combined with an increased risk of early bloom, heightens vulnerability to late-season frost damage in temperate regions (Kaufmann and Blanke, 2019; Drepper et al., 2020).

The severity of drought stress largely depends on climate conditions, irrigation practices, and soil moisture capacity (Blum, 2011) where responses to drought stress require system level analyses that integrate both genomic and physiological approaches (Chavez et al., 2003) to mitigate stress.

Under natural conditions, plants may experience either gradually developing water shortages, lasting from days to weeks or months, or short-term water deficits, occurring over hours or days (Chavez et al., 2003; Kul et al., 2020). The short-term physiological responses to drought stress include stomatal closure and root osmotic adjustment, while long-term adaptations involve leaf osmotic adjustment, a reduction in transpiration area, and modifications in shoot and root growth patterns. A summary of these short-term and long-term drought response mechanisms is presented in Figure 1.

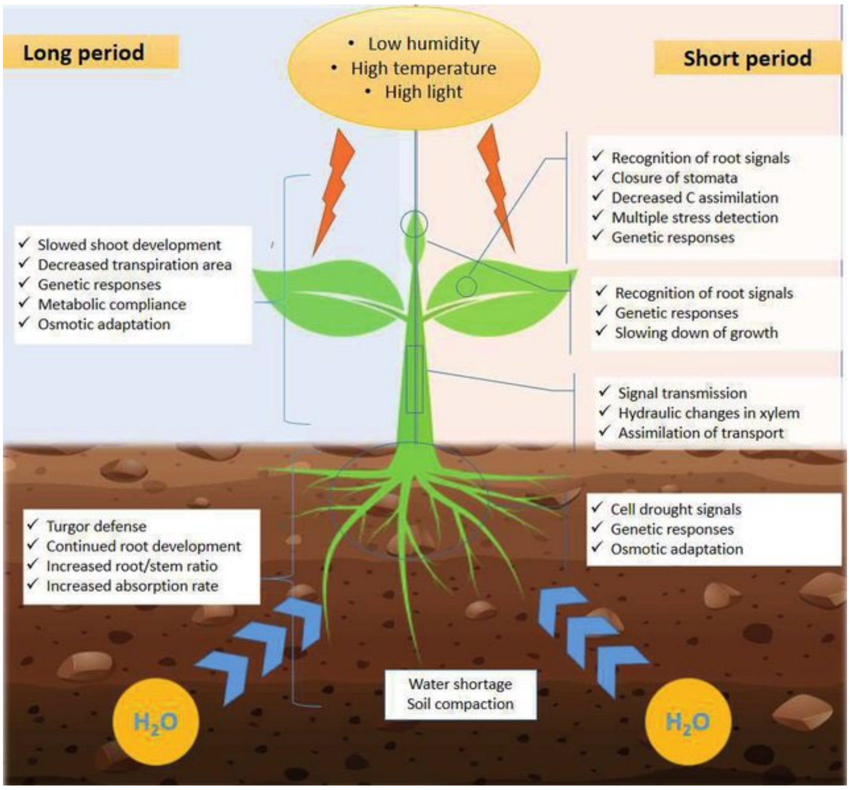

Figure 1. Plant mechanisms of drought stress tolerance. Short term responses (right) and long-term responses (left) (Kul et al., 2020)

Plant responses to drought stress can be broadly categorized into three main strategies: (a) short-term physiological adjustments, primarily involving stomatal regulation and changes in leaf movement and positioning; (b) acclimation to a specific water availability level, achieved through solute accumulation, osmotic potential adjustments, and morphological modifications; and (c) long-term adaptation to drought conditions, characterized by anatomical changes that enhance water retention and stress tolerance (Kozlowski et al., 1991; Yang at al., 2021; Sato et al., 2024)

In cases of rapid dehydration, plants may adopt a drought escape strategy, accelerating their life cycle to complete reproduction before severe stress occurs. Flowering time is a key trait in this response, as earlier flowering may enable plants to set seed before water availability becomes critically low (Kazan and Lyons, 2016). One of the primary responses of plants to drought stress is stomatal closure, a defense mechanism that reduces water loss through transpiration. However, this also limits carbon dioxide uptake, leading to decreased photosynthesis, reduced carbohydrate and energy production, and ultimately slower growth and development. As a result, leaf area, water potential, and osmotic potential decline, while turgor loss disrupts normal physiological functions (Čereković et al., 2013; Čereković et al., 2014; Čereković et al., 2015).

The perennial fruits nature and complex reproductive processes further heighten their susceptibility to climatic changes. Certain functional traits related to physiological adaptation can help predict a fruit crop's drought resistance. In particular, traits associated with leaf plasticity, such as leaf area, specific leaf area, and leaf dry matter content, play a crucial role in resilience to unfavorable drought conditions (Čereković et al., 2013; Čereković et al., 2014). Prolonged drought stress triggers visible symptoms such as leaf curling, an initial defense response to minimize water loss. However, with continued dehydration, leaf area can be significantly reduced, leading to stunted growth that extends to other plant parts, including stems, roots, and fruit (Čereković et al., 2013; Čereković et al., 2014). In fruit-bearing plants, drought stress shortens growth stages, reducing biomass accumulation and leading to smaller fruit, lower sugar content, and increased susceptibility to sunburn, posing significant challenges for sustainable production in water-limited environments (RECROP COST, 2024).

To cope with drought, plants employ a combination of stress tolerance mechanisms, including stomatal closure, osmotic adjustment and relative water content. These adaptations enhance water uptake and minimize water loss, allowing plants to maintain higher water potential under drought conditions (Chavez et al., 2003). Stomatal closure is the most immediate response to water deficit, reducing transpiration to conserve water (Hsiao, 1973; Guerfel et al., 2009; Čereković et al., 2013; Čereković et al., 2014). However, this defense mechanism also restricts CO_2 assimilation, leading to reduced photosynthesis and decreased carbohydrate production, which ultimately limits plant growth (Chaves et al., 2009). Osmotic adjustment is a physiological mechanism that enables plants to maintain turgor and cell volume under drought stress by decreasing osmotic potential through the accumulation of solutes within cells (Chaves et al., 2003; Blum, 2011). A crucial indicator of plant water status is leaf water potential, which declines under drought stress and is closely associated with growth inhibition (Čereković et al., 2013; Čereković et al., 2014. As water potential (ψ_l) declines in the surrounding environment, solutes such as proline and sugars accumulate in plant cells, helping to retain water, delay dehydration, sustain growth, and support photosynthesis during drought conditions (Blum, 2017; Lopez-Galiano et al., 2019; Seleiman et al., 2021). However, osmotic adjustment is typically a slow process, and rapid-onset drought may not allow sufficient time for its development (Chaves et al., 2003). Studies on perennial plants have shown that in such cases, reductions in osmotic potential are primarily due to dehydration, with osmotic adjustment playing only a minor role in maintaining turgor (Blum, 2017). Relative water content (RWC) serves as an important indicator of drought stress, reflecting the plant's water status at full turgor. Under drought conditions, RWC exhibits greater fluctuations compared to irrigated plants (Čereković et al., 2014).

Climate adaptation and water management in fruit crop cultivation

Fruit crops are cultivated across diverse climatic zones, each presenting unique environmental challenges and advantages. The growth and productivity of fruit crops are influenced by temperature, rainfall patterns, soil conditions, and environmental stressors, requiring region-specific adaptation strategies (Osorio Marin et al., 2024). In Mediterranean climates, characterized by warm, dry summers and mild winters, citrus, olives, and grapes dominate production. However, challenges such as water scarcity, drought, and heat stress necessitate efficient irrigation systems like drip irrigation, alongside adaptive management practices such as mulching and shade nets. Conversely, high-latitude temperate regions with cold winters are well-suited for deciduous orchards, including apples, pears, cherries, and certain grape and berry varieties. Key challenges in these areas include frost risk, shorter growing seasons, and low winter temperatures, requiring protective measures such as frost mitigation techniques and the selection of late-blooming cultivars. In subtropical and warm-temperate climates, where deciduous orchards such as peaches, plums, and apricots thrive alongside grapes and berries, heat stress and variable rainfall patterns pose major concerns. Adaptation strategies in these regions include evaporative cooling, soil moisture conservation, and the use of drought-resistant rootstocks. Meanwhile, tropical climates, characterized by high temperatures and humidity, support crops like bananas, pineapples, mangoes, and papayas. Here, sustainable production is challenged by irregular rainfall, excess moisture, disease prevalence, and heat stress, necessitating techniques such as high-density planting, controlled pruning, and protective netting. In arid regions, where water scarcity and extreme temperatures prevail, drought-tolerant crops like figs, olives, and dates require innovative irrigation solutions and specialized cultivation strategies to ensure sustainable yields.

Fruit crops progress through length of four main growth stages, initial (L_{ini}), crop development (L_{dev}), mid-season (L_{mid}) late season (L_{late}), each requiring distinct water management approaches (Allen et al., 1998). The duration of each stage varies based on climatic conditions, elevation, latitude, and cultivar-specific traits. Crops require a specific accumulation of growing degree days (GDD) to mature, and increasing temperatures accelerate GDD accumulation, shortening the overall crop cycle (McMaster and Wilhelm, 1997). FAO 56 (Allen et al., 1998) provide crop growth stages baseline estimates, but projected temperature increases of +2°C to +4°C are expected to shorten growth cycles by 7-15%. Table 1. presents FAO 56 crop growth stage duration and suggested updated projections for key fruit crops under changing climatic conditions, when the temperature may increase 3°C. and how this impact may affect the crop growth cycle of key fruit crops. The analysis is based on phenological stages (Initial, Development, Mid, End) and examines how total duration in days is expected to shift due to climate change. Fruits were evaluated by examining their typical duration in each growth stage under current climate conditions and shortening of the cycle under +3°C was estimated. The extent of reduction varies by crop and is presented as a percentage range, based on changes in growing degree days (GDD) accumulation and known physiological responses. The average reduction in crop cycle ranges from 7% to 15%, primarily due to quicker accumulation of GDD. Fruits in temperate or Mediterranean climates (e.g., olives, citrus, grapes) show more significant shifts, whereas tropical (e.g., banana, pineapple) less pronounced changes, with pineapple notably stable due to its CAM physiology. Deciduous trees in low latitudes may face challenges related to insufficient chilling despite overall faster development.

Table 1. FAO 56 and updated suggested crop growth stage durations based on temperature increase

Crop	Climate Region	L_{ini} days	L_{dev} days	L_{mid} days	L_{late} days	Total Current	Projected (+3°C)	Change (%)
Citrus	Mediterranean	60 → 50	90 → 80	120 → 100	95 → 85	365	315–330	-10 to -15%
Deciduous orchard	High latitude	20 → 15	70 → 60	90 → 75	30 → 25	210	175–190	-10%
Deciduous orchard	Low latitude	20 → 15	70 → 60	120 → 105	60 → 50	270	230–240	-10%
Olives	Mediterranean	30 → 25	90 → 75	60 → 50	90 → 75	270	225–245	-10 to -17%
Grapes	Mid latitude wine	30 → 25	60 → 50	40 → 35	80 → 70	210	180–195	-7 to -10%
Grapes	Low latitude	20→18	40→35	120→105	60→55	240	210–220	-8 to -12%
Grapes	California, USA	20→18	50→45	75→65	60→55	205	180–190	-7 to -12%
Grapes	High latitude	20→18	50→45	90→75	20→19	180	155–165	-8 to -14%
Banana (1st year)	Tropical	120 → 110	90 → 80	120 → 110	60 → 50	390	350–360	-8 to -10%
Banana (2nd year)	Tropical	120 → 110	60 → 50	180 → 160	5 → 5	365	325–340	-7 to -11%
Pineapple	Tropical	60	120	600	10	790	N/A	Less affected
Pistachios	Mediterranean/ Arid zones	20 → 15	60 → 50	30 → 25	40 → 35	150	125–135	-10 to -17%
Walnuts	Temperate continental	20 → 15	10 → 8	130 → 110	30 → 25	190	160–175	-8 to -16%

Fruit orchard and protected cultivation irrigation management

Effective irrigation management is essential for sustaining fruit production while optimizing water use efficiency. Traditional rainfed cultivation is no longer sufficient in many regions due to increased climate variability. Instead, modern irrigation methods tailored to crop type, soil characteristics, and climate conditions are required (Nikolaou, et al., 2020). In open field fruit production, irrigation scheduling is based on phenological stages, ensuring that water is applied at critical periods such as flowering, fruit set, and ripening. Farmers utilize soil moisture sensors, tensiometers, and evapotranspiration models to determine irrigation needs (Allen et al., 1998). Drip irrigation is widely preferred for its efficiency in delivering water directly to the root zone, minimizing evaporation and weed growth. Other methods include furrow irrigation for deep-rooted crops, sprinkler irrigation for overhead watering (used in apples and peaches), and traditional flood irrigation, which remains in use for certain crops like citrus and date palms despite its inefficiencies (Allen et al., 1998). As fruit approaches maturity, irrigation strategies must be adjusted to enhance quality. For instance, reducing water supply before harvest improves sugar accumulation and flavor in grapes (Perez Alvarez et al., 2021), while maintaining moderate soil moisture helps prevent fruit cracking in berries (Manzoor et al., 2024). Post-harvest soil moisture monitoring is especially important due to the control of flower initiation for the next season (Čereković et al., 2014).

In tunnel and greenhouse fruit production, irrigation management must balance soil moisture, fruit quality, and humidity control to prevent fungal diseases. Since tunnels provide partial environmental control, irrigation scheduling is adjusted according to temperature fluctuations, substrate type, and crop growth stages. Drip irrigation is the preferred method, ensuring efficient water delivery while minimizing humidity buildup. Fertigation, which combines irrigation with nutrient application, is commonly used to support plant nutrition and optimize yield. Overhead irrigation is rarely applied in tunnels due to the risk of increasing disease pressure. Soil moisture sensors, tensiometers, or manual monitoring help determine the right timing and amount of water needed. Drip irrigation is the most commonly used method in tunnels, as it delivers water directly to the root zone, minimizing evaporation and reducing the risk of excessive humidity build up inside the structure. This method is particularly effective for strawberries and raspberries, ensuring efficient water use while maintaining consistent soil moisture (García-Tejero et al., 2018). In some cases, fertigation which combines irrigation with nutrient delivery is applied to support optimal plant nutrition. As fruit approaches maturity, irrigation strategies need to be carefully adjusted. Reducing water supply before harvest enhances fruit flavor, sugar content, and firmness, particularly in crops like berries. However, adequate moisture levels must still be maintained to prevent stress-related issues.

Greenhouse production offers even greater control over irrigation, often integrating automated climate monitoring systems and advanced moisture sensors. Drip irrigation is the preferred method in greenhouse fruit cultivation, as it delivers water directly to the root zone, reducing evaporation and preventing excessive humidity. This system is commonly used for strawberries (Yuan et al, 2004). For crops grown in containers or soilless substrates, nutrient-rich irrigation (fertigation) is often applied to supply essential nutrients along with water, ensuring balanced growth. In some cases, ebb-and-flow systems or hydroponic irrigation methods are used to optimize water efficiency by recycling excess water.

As fruits mature, irrigation strategies must be adjusted to enhance quality. Reducing water supply before harvest can improve fruit texture, flavor, and sugar content. However, maintaining adequate moisture levels is essential to prevent physiological disorders as the cultivation of fruit crops is deeply influenced by climatic conditions, with each region requiring tailored water management strategies to ensure sustainability. As climate change continues to alter growth cycles and water availability, adaptive irrigation techniques, improved phenological monitoring, and innovative management practices will be crucial in sustaining fruit production across diverse climatic zones.

Precise monitoring of soil plant water status to optimize irrigation scheduling

Efficient water management in fruit production requires precise monitoring of plant water status to optimize irrigation scheduling and enhance water use efficiency. Recent advancements in sensor technology, remote sensing, and data analytics have provided fruit growers with powerful tools to assess real-time water availability and plant responses to water stress. These technologies not only maintain optimal growing conditions but also contribute to sustainable water resource management (Gavilan et al., 2024). Soil moisture sensors play a critical role in tracking water availability in the root zone, ensuring fruit crops receive the right amount of water at key growth stages. Various sensor types, such as tensiometers and time-domain reflectometry (TDR) sensors, provide valuable data for determining the precise moment when irrigation is needed (Milan et al., 2024). While soil moisture sensors provide indirect measurements, plant-based sensors offer direct insights into the physiological status of fruit crops, delivering a more precise assessment of plant hydration and stress levels. Stem water potential sensors (pressure chambers) are used extensively, measuring the tension within plant tissues to assess water availability and where controlled water stress is used to improve fruit quality. Sap flow sensors track water movement within the plant, providing real-time data on transpiration rates, particularly useful when precise water control impacts fruit size and yield through precise water control. Leaf temperature and stomatal conductance sensors using instruments such as infrared thermometers and porometers assess plant temperature and leaf transpiration rates, signaling early signs of water stress before visual symptoms appear (Čereković et al., 2013; Čereković et al., 2014).

Facing the challenges posed by climate change requires the application of modern irrigation techniques, such as satellites, remote sensing, drones, machine learning and sensors. These advanced technologies are revolutionizing water resource management, enabling more efficient use, increasing agricultural productivity and preserving the environment, contributing to reduce in water consumption and optimizing productivity, water control and conservation (Sruthi et al., 2015; Imtiaz et al., 2024; Guebsi et al. 2024). However, modern fruit production increasingly relies on remote sensing technologies to assess water stress over large orchards and fields. Multispectral and thermal imaging drones are equipped with high-resolution cameras, UAVs (unmanned aerial vehicles) capture real-time data on canopy temperature, water deficit, and overall plant health, particularly beneficial for large-scale fruit farms. Satellite based remote sensing platforms such as Sentinel-2 and Landsat provide vegetation indices like the Normalized Difference Water Index (NDWI), helping growers track drought stress trends and irrigation needs over time.

Advanced irrigation systems now integrate Internet of Things (IoT) devices and artificial intelligence (AI) to automate water delivery based on real-time plant data. Automated drip irrigation with AI Algorithms: AI-driven irrigation controllers use soil moisture and weather data to adjust water application dynamically, reducing waste and optimizing fruit quality. This is particularly useful for berry fruits grown in high-tech greenhouses with use of cloud-based decision support systems (DSS) that aggregate sensor data, weather forecasts, and crop models to provide farmers with predictive analytics on water needs (Gavilan et al., 2024). In recent decades, with the rapid development of computer technology and artificial intelligence theory, calculating ET_o using meteorological data has become a regression task that can be solved by various machine learning models. Models such as ANN (Artificial Neural Network), ELM (Extreme Learning Machine), SVM (Support Vector Machine), ANFIS (Adaptive Neuro- Fuzzy Inference System) have been used in many studies (Zhijun et al., 2020; Zhu et al., 2020; Gocić and Amiri, 2021; Elbeltagi et al., 2022; Agrawal et al., 2022) and have shown their effectiveness in evaluating ET_o using only temperature data or a combination composed of different climate parameters.

By combining machine learning, remote sensing, and drones, it will empower farmers, researchers, and policymakers to make informed decisions, optimize water use, and improve agricultural productivity (McCabe et al., 2017; Hadadi et al. 2022). By leveraging these advanced technologies, fruit growers can significantly improve water-use efficiency, ensure sustainable irrigation practices, and enhance crop productivity in response to changing climate conditions.

CONCLUSIONS

The impact of climate change on fruit crop production is becoming increasingly evident, with rising temperatures, erratic precipitation patterns, and prolonged droughts posing severe challenges to sustainable agricultural practices. This study highlights the critical need for effective water management strategies, advanced irrigation techniques, and climate-resilient cultivation methods to mitigate the adverse effects of water scarcity. By integrating traditional agronomic knowledge with modern technologies, such as precision irrigation, remote sensing, and AI driven decision support systems, farmers can optimize water use efficiency, sustain yields, and enhance fruit quality despite challenging environmental conditions. Adaptation measures, including the selection of drought-tolerant cultivars, improved soil management techniques, and climate-smart orchard designs, play a crucial role in ensuring long-term resilience. Strategies such as regulated deficit irrigation (RDI), partial root-zone drying (PRD), and the application of mulching and cover cropping contribute to enhanced water retention, reduced evaporation, and improved plant health. Furthermore, the integration of meteorological data and plant sensors enables real time monitoring of water stress, allowing for precise irrigation scheduling and more sustainable resource allocation. The importance of cross disciplinary collaboration between researchers, policymakers, and farmers to accelerate the adoption of innovative water management solutions is needed. Investments in research and development, supportive policies and financial incentives, are essential to facilitate the widespread implementation of climate-adaptive practices in fruit production. Ultimately, securing the future of fruit cultivation requires a holistic approach that balances productivity with environmental sustainability. By embracing technological advancements, fostering knowledge exchange, and prioritizing water conservation, the agricultural sector can build resilient production systems that ensure food security and economic stability in a rapidly changing climate. Continued research and innovation in irrigation efficiency and precision agriculture will be pivotal in shaping the next generation of climate-resilient fruit farming practices.

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