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Advancing date palm cultivation in the Arabian Peninsula and beyond: Addressing stress tolerance, genetic diversity, and sustainable practices

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ABSTRACT

Date palm (*Phoenix dactylifera* L.) cultivation in the Arabian Peninsula is crucial for regional agriculture and global markets. The Arabian Peninsula is dominant in date production, contributing approximately 34 % of the global output. Recent advancements in agricultural technologies have improved fruit yield and quality, expanding date palm cultivation globally. However, sustainability challenges persist due to various abiotic stresses, such as salinity, temperature extremes, drought, soil factors, and biotic stresses, including diseases and pests. This review examines key environmental factors affecting date palm cultivation, with a focus on soil salinity, water scarcity, and climate change-related stresses. The genetic diversity among date palm varieties is emphasized, highlighting the need for breeding programs aimed at improving stress tolerance and yield. Biotechnological advancements, such as genetic transformation and genome editing, are discussed for their potential to enhance crop resilience and productivity. Additionally, remote sensing techniques are explored for their application in precision agriculture, particularly in the mapping and monitoring of date palm health and soil conditions. The significant role of artificial intelligence in accurately mapping date palm trees using multi-platform remotely sensed data is also reviewed, illustrating its potential to enhance geospatial databases and support sustainable management practices. The review concludes with recommendations for optimizing cultivar selection and management strategies tailored to local conditions, emphasizing the need for ongoing research to advance date palm cultivation on a global scale.

1. Introduction

The date palm (*Phoenix dactylifera* L.), a dioecious monocot species within the Arecaceae family, has been cultivated since approximately 4000 BC, making it one of the earliest domesticated perennial plants (Al-Karmadi and Okoh, 2024; Hadrami and Hadrami, 2009; Krueger et al., 2023; Rahman et al., 2022). The Arecaceae family comprises over 2500 species and 200 genera, contributing significantly to global nutrition, health, and economies. Date palms can reach heights of 21–23 m, with leaves extending 4–6 m and consisting of up to 150 leaflets (Jaradat, 2016). The fruit of the date palm is highly valued for its high sugar content (60–80 % by dry weight), low-fat levels (0.04 g), low salt levels, fiber, and absence of cholesterol, making it a vital agricultural product, especially in hot and humid climates (Al-Karmadi and Okoh, 2024). Historically central to the culture and economy of the Arabian Peninsula, the date palm remains a crucial nutritional and economic resource (Gros-Balthazard et al., 2023, 2017), in arid and semi-arid regions where few other crops can thrive due to its resilience to extreme environmental conditions. For centuries, dates have been a staple food in the Middle East and North Africa (MENA) region, deeply

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embedded in the social and cultural fabric in Arab countries where they symbolize generosity and hospitality (Al-Muaini et al., 2019; Alotaibi et al., 2023; Ibrahim El-Juhany, 2014). The date palm's ability to flourish in extreme environments and produce fruit with minimal inputs underscores its importance in the MENA region, especially during periods of food scarcity (Chao and Krueger, 2007).

In 2022, global date production reached 9.74 million tons, cultivated across 1.27 million hectares (FAO, 2019). The Arabian Peninsula dominates date production, contributing approximately 34 % of the global output. The leading date-producing countries in the Arabian Peninsula include Saudi Arabia, Iraq, the United Arab Emirates, and Oman (Fig. 1). In Iraq, the area under date palm cultivation expanded from 2222 ha in 2014–4582 ha in 2022, with production increasing from 9764 tons to 30,000 tons during the same period. The total area harvested for date cultivation in the Arabian Peninsula in 2022 was 529,692 ha, representing 42 % of the total harvested area worldwide (FAO, 2019). Regional variations in dominant date palm cultivars are shaped by climate, soil characteristics, and societal preferences. There is considerable diversity in the number of date palm cultivars across different countries, with over 5000 cultivars identified globally (Jaradat, 2015). In Saudi Arabia, approximately 34 million date palm trees represent 15 dominant cultivars, while in the UAE, around 40 million date palms are spread across the country, with eight dominant cultivars specific to certain geographic locations (Alotaibi et al., 2023).

Recent advancements in farming technologies, such as drip irrigation, precision farming, fertigation, and climate-smart practices, have expanded the cultivation area of date palms, enhancing both fruit yield and quality globally (Al-Muaini et al., 2019; Mohammed et al., 2023). These technologies improve water-use efficiency by delivering precise amounts of water directly to plant roots (drip irrigation), enhancing nutrient delivery and uptake through controlled fertigation, and optimizing farming practices through precision farming techniques. Climate-smart practices and climate control technologies like greenhouses and shade nets regulate temperature, reducing heat stress on date palms and enhancing resilience to climatic stresses. Automation in farming equipment boosts harvesting efficiency and reduces labor costs. Additionally, farm management techniques like pruning, integrated pest management (IPM), and soil fertility management improve productivity and crop characteristics. Pruning enhances airflow and sunlight penetration, boosting fruit yield and quality. IPM integrates biological and chemical pest control methods to minimize crop damage and environmental impact, while soil fertility management, involving soil testing and balanced fertilization, ensures optimal growth conditions. However, sustainability in date palm cultivation continues to face challenges, mainly due to environmental and soil conditions. Key challenges include abiotic factors such as extreme temperatures, wind, and drought, as well as soil attributes like texture, salinity, pH, organic matter content, and nutrient levels (Ait-El-Mokhtar et al., 2020; Chao and Krueger, 2007; Krueger et al., 2023) Additionally, biotic stresses, including diseases and pests, threaten date palm cultivation worldwide (El Bouhssini and Faleiro, 2018; Haldhar et al., 2017).

Among the abiotic factors, salinity is a significant concern, especially in regions that rely on saline groundwater for irrigation (Akensous et al., 2022; Al Kharusi et al., 2019; Kharusi et al., 2017). Salt accumulation in soils can harm physiological processes, reducing yield and compromising fruit quality. It is crucial to implement effective management strategies such as choosing salt-tolerant cultivars and improving irrigation practices to mitigate these effects and sustainably enhance productivity (Akensous et al., 2022; Alhammadi and Kurup, 2012.; Hammami et al., 2023). Drought stress further exacerbates challenges in date palm cultivation, impacting water availability, nutrient uptake, and overall growth (Akensous et al., 2022; Ali-Dinar et al., 2023; Arab et al., 2016; Du et al., 2021b). Although date palms have evolved physiological adaptations such as enhanced root systems and osmotic adjustment mechanisms to survive prolonged water scarcity (Akensous et al., 2022; Du et al., 2021b; Kruse et al., 2019a), optimizing irrigation techniques

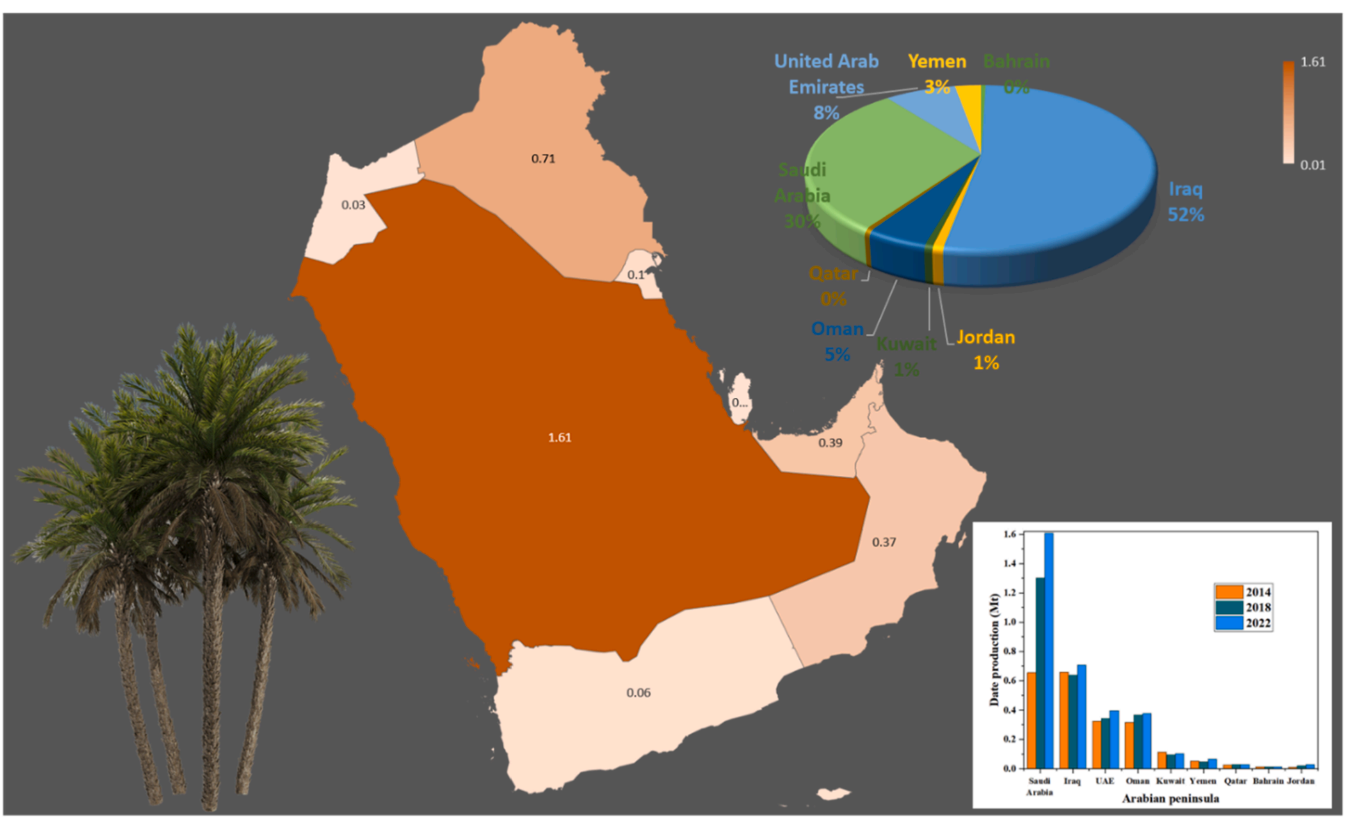

Fig. 1. Date production in the Arabian Peninsula: (a) Distribution of production in million tons by country, (b) Harvested area represented as percentage of total area (FAO, 2019), and (c) Dynamics of date production (Mt) in 2014, 2018, and 2022.

and integrating water-efficient practices are essential to minimize yield losses and ensure long-term sustainability.

Soil properties, including texture, pH, and nutrient availability, play a critical role in the growth and yield of date palms (Alnaim et al., 2022a; Haj-Amor et al., 2017). Understanding these soil-plant interactions is vital for implementing targeted soil management practices that optimize nutrient uptake efficiency. Climatic conditions, like temperature extremes and humidity levels, also profoundly affect date palm physiology, flowering, and fruit development (Dehghanisanij et al., 2023; Du et al., 2021b). These factors significantly constrain agricultural enhancement in arid regions where date palm farming is concentrated globally. The susceptibility of these areas to climate change further complicates the effects of soil and environmental factors on date palm cultivation (Patlakas et al., 2019). These complexities underscore the importance of genetic diversity studies, propagation techniques, and biotechnological advancements in enhancing date palm cultivation, resilience, and productivity.

Genetic diversity within date palm populations is crucial for breeding programs to develop cultivars with improved traits such as disease resistance, yield, and fruit quality (Jaradat, 2015). This diversity is influenced by environmental factors, including soil quality, climate, and geographical location, which shape the genetic stability of date palm cultivars. Site-specific conditions, such as soil salinity, temperature extremes, and drought stress, can drive genetic adaptations in date palms, promoting resilience to these challenges and resulting in locally adapted cultivars. These environmental pressures play a critical role in shaping the genetic makeup of date palms, contributing to the genetic diversity observed across different regions. The distribution of this genetic diversity varies across oases, regions, and localities and is influenced by historical, geographical, ecological, and anthropogenic factors (Chaluvadi et al., 2014; Ferreira et al., 2024). Traditional conservation practices in oases help preserve and enhance genetic resources, ensuring the sustainability and resilience of date palm cultivation in the face of evolving environmental challenges (Jaradat, 2015).

Traditional propagation methods, such as seed and offshoot propagation, pose inherent challenges, including extended time to fruiting, variability in offspring traits, and limited availability of offshoots in some cultivars (Bekheet, 2013). In response, modern biotechnological approaches, such as micropropagation and genetic transformation, offer promising alternatives. These methods expedite propagation, ensure genetic uniformity, and preserve desirable traits critical for sustainable agriculture. Biotechnological innovations, including genome editing technologies like CRISPR-Cas9, hold immense potential for precise genetic modifications aimed at enhancing disease resistance, stress tolerance, and overall crop performance in date palms (Ramesh et al., 2024; Sattar et al., 2017). Furthermore, DNA barcoding and genetic conservation efforts through in vitro preservation and cryopreservation play vital roles in safeguarding the genetic integrity and biodiversity of date palm germplasm (Araújo de Oliveira et al., 2021; Bekheet, 2011, 2017a, 2017b; Hamza et al., 2024).

Despite the importance of date palm cultivation in the Arabian Peninsula, there is a lack of comprehensive reviews addressing key environmental factors, genetic diversity, and the application of remote sensing techniques. While advancements in biotechnological methods, such as genetic transformation and genome editing, show promise for enhancing resilience in date palms, their practical applications remain underexplored. Additionally, the role of artificial intelligence in accurately mapping date palm trees using multi-platform remotely sensed data needs further investigation. This review aims to provide a comprehensive analysis of key factors influencing date palm cultivation in the Arabian Peninsula, focusing on environmental stress tolerance, genetic diversity, and the application of biotechnological advancements, including remote sensing techniques. By integrating current knowledge and outlining future research directions, this review focuses on providing critical insights into sustaining and optimizing date palm cultivation, highlighting its pivotal role in global agriculture and economic development.

2. Factors influencing date palm cultivation in the Arabian Peninsula

2.1. *Effect of Soil quality on date palm cultivation*

2.1.1. *Salinity issues*

Salinity significantly challenges global agricultural productivity and food security in arid regions (Allbed et al., 2014; Serret et al., 2020). These areas experience reduced rainfall and increased evaporation rates, which impair the salinity problem. In semi-arid and arid regions, freshwater scarcity often necessitates reliance on saline groundwater, accumulating salts in the soil (Kharusi et al., 2019; Shin et al., 2022). Excessive groundwater extraction can induce seawater intrusion in coastal areas, further elevating soil and groundwater salinity levels (Alfarrah and Walraevens, 2018). This secondary salinization poses a significant challenge for date palm orchards. While date palms can tolerate soil salinity levels up to 7.68 g/Kg (Haj-Amor et al., 2017), higher levels significantly reduce fruit production's quantity and quality. An increase in soil salinity adversely affects their vegetative growth, mainly due to the accumulation of toxic Na^+ ions in the plant cytosol, which disrupts membrane proteins (Sabeem et al., 2022). A study by Sabeem et al. found that salinity significantly impacts the growth of *Phoenix dactylifera* seedlings during seed germination. At a salinity level of 5.76 g/kg, seed germination was reduced by 50 % (SG50), indicating the plant's ability to tolerate relatively high salinity compared to many other species. However, as salinity exceeded 8.19 g/kg, growth sharply declined, likely due to reduced osmotic potential in the soil and the resulting water deficit. Prolonged exposure to high salinity also leads to tissue degeneration in seeds, rendering them non-viable over time (Ramoliya and Pandey, 2003).

Salinity stress adversely impacts the physiological processes of date palms, including CO_2 fixation and water regulation, leading to stunted growth (Table 1). Salinity reduces all gas exchange parameters (Kharusi et al., 2017; Yaish and Kumar, 2015). It also decreases xanthophyll formation, which is critical for stress responses, and hampers the optimal functioning of photosystem I and II, disrupting electron transport chains (Degl'Innocenti et al., 2009). Additionally, salinity induces oxidative stress and causes nutritional imbalances, reducing leaf and root dry mass and overall plant vigor, as observed in the 'Khalas' cultivar seedlings (Ali-Dinar et al., 2023).

The relationship between date palms and water is crucial for their ability to tolerate salinity. Tolerant cultivars exhibit accelerated growth and root development, higher water content, and enhanced accumulation of osmoprotectants. These adaptations include the additional casparian strip layers formation, facilitating water uptake and ion balance under saline conditions (Alotaibi et al., 2023). Essential nutrients like nitrate and potassium ions play pivotal roles in signalling stomatal closure, thus mitigating salinity stress by supporting proper physiological functions and reducing the accumulation of toxic sodium and chloride ions (Hazzouri et al., 2020). While the salt resistance mechanisms in various species are well-documented, those specific to date palms are still under investigation. One of the salt tolerance mechanisms in date palms is ion exclusion (Yaish and Kumar, 2015). It is hypothesized that date palms' adaptation to salinity involves biochemical pathway modifications that manage osmotic stress, exclude and secrete Na^+ or Cl^-, and facilitate their accumulation in specific tissues (Fig. 2) (Yaish and Kumar, 2015). Sperling et al. (2014) found that the 'Mejhoul' cultivar's photosynthetic tissues can exclude Na^+ ions, allowing efficient photosynthesis to continue even under saline conditions. Similar observations were made in 'Umsila' seedlings exposed to salinity (Kharusi et al., 2019, 2017).

Ion exclusion in date palms is supported by stable membrane structures and high levels of both enzymatic and non-enzymatic antioxidants and detoxifying agents (Kharusi et al., 2019, 2017). Planting

Table 1
Effect of salinity on date palm cultivation.

Salinity level	Growth stage	Type of variety	Salt stress effects	References
0, 300 mM NaCl	Seedlings	Khalas	Reduced photosynthesis, altered gene expression	(Yaish et al., 2017)
0, 240 mM NaCl	Seedlings	Umsila, Zabad	Reduced growth, photosynthesis	(Ait-El-Mokhtar et al., 2019)
5, 10, 15 dS m^{-1}, of salt water	Trees	Ajwat, Naghal, Shagri, Jabri, Sukkari,	Na^+ exclusion, K^+ retention, decreased osmotic potential	(Dghaim et al., 2021)
50, 100, 150 mM NaCl	Seedlings		Increased proline, antioxidant activity, altered gene expression	(Bouhouch et al., 2021)
50, 300 mM NaCl	Seedlings	Khalas	Reduced photosynthesis, altered gene expression, DNA methylation	(Al-Harrasi et al., 2018)
0, 300 mM NaCl	Seedlings	Khalas	Reduced growth, altered root structure, enhanced stress metabolites	(Jana et al., 2019)
< 1, 12–15, 18–20 dS m^{-1}	Trees (4-year-old)	-	Reduced water use	(Abdelhadi et al., 2020)
5, 15 dS m^{-1}	Trees	Lulu Khalas	Reduced growth, water use	(Al-Muaini et al., 2019)
4, 8, 12, 16 g/L NaCl	Seedlings	Deglet Nour	Reduced germination, increased protein, antioxidants	(Bouhouch et al., 2021)
3.2–4.5 dS m^{-1}	Trees	-	Increased transpiration, salt accumulation	(Zemni et al., 2022)

salt-tolerant cultivars is a viable strategy for mitigating salinity issues. For instance, Omani cultivars like 'Umsila' and 'Manuma', which resemble wild types and have lower fruit quality, exhibit higher salinity tolerance compared to domesticated cultivars such as 'Khalas' (Al-Muaini et al., 2019). These resilient cultivars can thrive in soils with electrical conductivity of up to 25 dS/m (Kharusi et al., 2017). While wild date palm cultivars such as 'Umsila' and 'Manuma' exhibit superior salinity tolerance, they often produce lower fruit yields and quality compared to domesticated varieties like 'Khalas.' To address this, advanced biotechnological tools offer promising solutions to enhance these resilient cultivars' productivity and fruit quality. Techniques such as CRISPR-Cas9 genome editing can introduce specific genetic modifications that enhance traits like fruit size, sugar content, and overall yield without compromising their inherent salt tolerance (Kordrostami et al., 2022). Additionally, marker-assisted selection (MAS) can accelerate the breeding process by identifying and selecting desirable traits at the genetic level, ensuring that the best qualities of both wild and domesticated cultivars are combined (Hadrami et al., 2011). Furthermore, the application of transgenic approaches could allow for introducing genes responsible for high fruit productivity and quality into these salt-tolerant wild varieties (Saker, 2011).

2.1.2. *Draught Stress*

Date palms possess several anatomical features that enhance their tolerance to hyper-arid conditions (Safronov et al., 2017a). These features include a thick, waxy outer layer and compound leaves with numerous spines that protect the growing tip (Hazzouri et al., 2020). Date palms rely on deep root systems, especially during drought, as they draw moisture from lower soil layers. In sandy loam soils, which are well-drained and capable of retaining moisture, date palms can reach depths of up to five meters or more, allowing them to access moisture even during prolonged dry periods. However, extended drought can lead to reduced photosynthesis, leaf damage, and altered fruit quality (Alotaibi et al., 2023). Additionally, their deep root system allows them to access water from various soil depths, which helps to minimize evaporation, improve water uptake, and contribute to the drought tolerance of *P. dactylifera* (Shin et al., 2022). However, extended periods

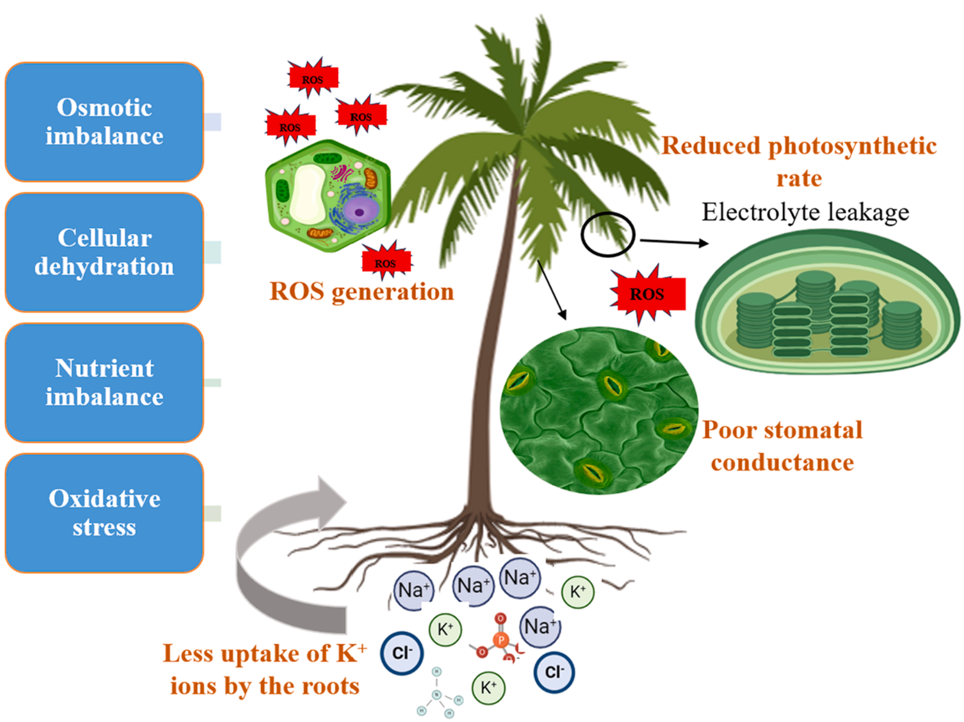

Fig. 2. Impact of salinity on date palm.

of drought can severely affect the growth and productivity of date palms in arid regions (Fig. 3). These conditions significantly impact various aspects of date palm cultivation, including biomass, physiological traits, and overall growth performance. A study by Ali-Dinar et al. (2023) in Saudi Arabia assessed drought effects on four date palm cultivars (Khalas, Barhee, Hilali, and Ashrasee) grown in sandy loam soil with sphagnum peat moss compost, irrigated by solar-powered drip systems. The plants were subjected to varying drought levels (100 %, 80 %, 60 %, and 40 %). Results showed that severe drought (40 % and 60 %) reduced leaf development, biomass, photosynthesis, and mineral content (potassium and calcium) while increasing proline, a stress biomarker. Moderate drought (80 %) had minimal effects. The study also revealed that Khalas and Barhee were more drought-tolerant than Ashrasee, highlighting cultivar-specific responses to drought stress.

Mature Mazafati date palms, those between 10 and 12 years old, exhibit reduced growth in water-scarce environments, often leading to prematurely dropping of young flowers and fruits (Alikhani-Koupaei et al., 2018a). This sensitivity is primarily due to the greater vulnerability of fruit cellular expansion to water deficits compared to cellular division, as well as the inhibition of cell growth caused by low turgor pressure. Furthermore, drought conditions significantly reduce the number of plant leaflets and dry biomass in female offshoots of the Ruziz, Sukary, and Barhee cultivars (Al-Khateeb et al., 2020). Physiologically, drought stress reduces water content and photosynthetic efficiency, while increasing internal carbon dioxide concentration, which indicates inefficient CO_2 utilization during photosynthesis (Fig. 4). Stomatal closure and metabolic impairment further decrease photosynthetic capacity, leading to reduced leaf hydration and net CO_2 assimilation (Du et al., 2021b).

Drought also profoundly impacts the nutritional and biochemical profiles of date palms. In the Mazafati variety, nutrient uptake, including essential minerals such as calcium, iron, and zinc, is significantly hampered under water deficit conditions. The reduction in water flow disrupts mineral absorption, with increased hydroxide concentrations further obstructing iron assimilation in the roots (Alikhani-Koupaei et al., 2018a). Biochemically, drought induces notable changes, such as increased fructose and glucose derivatives in seedlings (Elango et al., 2022). While carbohydrates act as osmoprotectants against drought-induced oxidative stress, drought conditions also lead to a decline in ascorbate content and an accumulation of amino acids like alanine (Akensous et al., 2022). Additionally, secondary metabolism is triggered, producing increased phytochemicals and a reduction in glutathione levels (Hazzouri et al., 2020). Yaish (2015) observed that date seedlings accumulate proline in response to abiotic stresses, indicating that proline production is a common stress marker associated with improved drought and salt tolerance. Both non-enzymatic and enzymatic antioxidants, including peroxidase and polyphenol oxidase, are elevated under drought conditions, enabling date palms to mitigate oxidative stress and endure prolonged water deficits (Akensous et al., 2022; Hazzouri et al., 2020).

Date palms are highly resilient, thriving in semi-arid and arid regions due to their evolved mechanisms for withstanding various abiotic stresses. For example, to maintain osmotic balance under stressful conditions, date palms accumulate solutes such as glycine betaine, proline, and sugars within their cells (Akensous et al., 2022; Alotaibi et al., 2023). These solutes help lower the osmotic potential, prevent water loss, and maintain turgor pressure (Singh et al., 2015). This accumulation is facilitated by abscisic acid (ABA), which plays a crucial role in stress signaling and response. ABA also regulates the expression of genes related to stress tolerance and triggers stomatal closure to reduce transpiration (Akensous et al., 2022).

Under stress, date palms produce increased quantities of reactive oxygen species (ROS), which can impair photosynthesis, cause cell death, and damage DNA (Awad et al., 2019). To mitigate these damages, date palms activate antioxidant enzymes such as superoxide dismutase, peroxidase, and catalase and accumulate antioxidant metabolites like ascorbic acid and glutathione (Harkousse et al., 2021). Stress tolerance in date palms involves the differential expression of various genes related to stress signaling, osmotic adjustment, hormone biosynthesis, and antioxidant defense (Safronov et al., 2017b). Transcription factors are key in regulating these stress-responsive genes (Hazzouri et al., 2020).

Genetic diversity within date palm populations significantly influences their ability to adapt to extreme environmental conditions (Jaradat, 2016). Identifying genetically diverse and stress-tolerant varieties can inform breeding programs to develop more resilient date palm cultivars. Several gene families, including aquaporins, dehydrins, and heat shock proteins, are implicated in stress tolerance in date palms. These genes encode specialized proteins that protect cells from dehydration during high temperatures, facilitate water transport, and stabilize and protect cellular structures from degeneration under stress (Movahedi et al., 2015).

Fig. 3. Date palm trees in drought stress (Arab News, 2018).

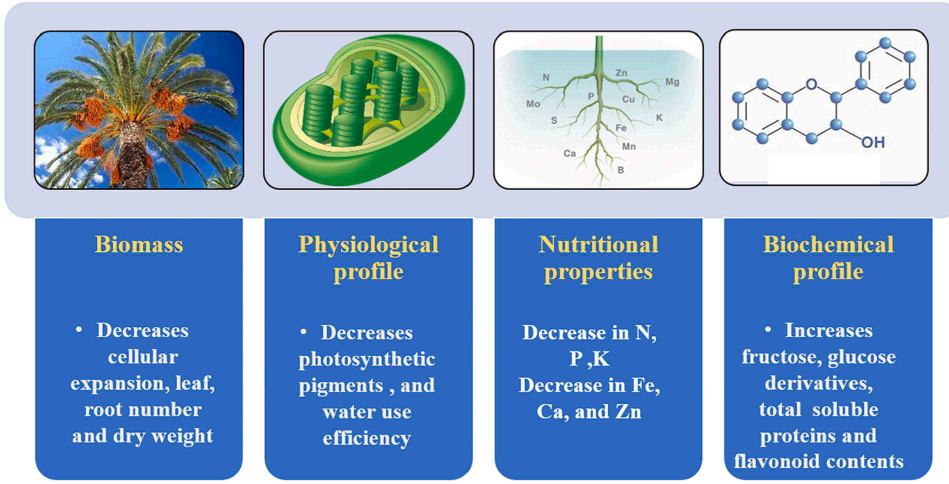

Fig. 4. Effect of drought stress on date palm.

2.1.3. *Soil properties*

Date palms require adequate nutrients for optimal growth, with their needs varying based on soil type and environmental conditions (Alotaibi et al., 2023; Kharusi et al., 2017; Zaid et al., 2011). On average, date palms need 650 g of nitrogen, 650 g of phosphorus, and 870 g of potassium per tree annually (Al-Qurashi et al., 2016). Soil characteristics, such as organic matter content, pH levels, texture, and cation exchange capacity, play critical roles in influencing nutrient availability and uptake (Alotaibi et al., 2023; Ben Mbarek et al., 2019; Dhaouadi et al., 2021).

Soil texture is crucial for date palm growth as it affects properties like porosity, moisture retention, aeration, and drainage efficiency, all of which influence productivity and yield by affecting water and nutrient distribution along with root development (Kavvadias et al., 2024; Saïd and Coquet, 2018). Although date palms can grow in various soil textures, they thrive best in sandy loam soils, which promote improved root growth and drainage (Kavvadias et al., 2024). Additionally, date palms grow well in soils with high alkalinity and calcium content, common in arid regions where the pH is typically slightly above 7.0 due to the presence of alkaline cations like Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} (Labaied et al., 2020). However, these conditions can limit the nutrient availability of phosphorus, necessitating the use of slow-release phosphorus fertilizers and soil additives to counteract the negative effects of $CaCO_3$. Date palms also thrive in hot summers with minimal rain and low humidity (Chao and Krueger, 2007; Erskine et al., 2004). Given the frequent water shortages in these regions, proper irrigation management is essential to ensure sufficient water availability (Dhaouadi et al., 2021; Haj-Amor et al., 2018, 2017). Advanced irrigation technologies can enhance water use efficiency, especially since sandy soils require more water than loamy soils due to their lower water-holding capacity (Baiamonte et al., 2020; Dhehibi et al., 2018; El-Hendawy et al., 2008).

Improving soil structure by adding organic matter and soil amendments can enhance water retention and create a more favorable environment for nutrient uptake. The intricate root system of date palms plays a vital role in nutrient absorption, which can be influenced by soil conditions and root health (Al-Karaki, 2013). Using organic fertilizers can improve water and nutrient retention in such poor sandy soils (Alotaibi et al., 2023). Sandy soils typically have low WHC due to their large particle size, but organic fertilizers, being hydrophilic, can retain moisture and reduce water loss by filling the spaces between soil particles, thus enhancing water availability to plants (Vengadaramana, 2012). Additionally, organic fertilizers increase the soil's cation exchange capacity (CEC), which improves nutrient retention, particularly for potassium, magnesium, and calcium, and reduces leaching. These fertilizers decompose gradually, providing a sustained release of nutrients, while also stimulating microbial activity that stabilizes nutrients in plant-available forms (Zhao et al., 2021). Proper fertilization programs, including foliar fertilization and regular soil testing, are essential for maintaining soil fertility. Applying nutrients directly to the leaves through foliar fertilization allows for immediate absorption and utilization by the tree, which is beneficial during critical growth stages or periods of stress.

2.1.4. *Soil microbes*

Soil microbes play a critical role in enhancing the resilience of date palms to salinity and drought stresses (Ferreira et al., 2024). These microbes, particularly symbiotic fungi like arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPRs), form beneficial relationships with date palms, helping them thrive in harsh environments (Boutheina et al., 2019).

AMF colonize the roots of date palms (Outamamat et al., 2021), extending the plant's ability to access water and nutrients, especially in saline or dry soils. These fungi improve the absorption of essential nutrients like phosphorus and maintain physiological functions under stress conditions. In saline environments, AMF reduces the uptake of toxic ions like Na^{+} and Cl^{-}, thus preventing ionic imbalance and toxicity in plants (Ait-El-Mokhtar et al., 2020). Furthermore, they enhance water uptake efficiency (Benhiba et al., 2015), critical in arid regions where drought stress is common. AMF produces easily extractable glomalin-related soil protein (EE-GRSP) that influences organic carbon storage in soil (Fig. 5).

Similarly, PGPRs like *Pseudomonas* and *Bacillus* species contribute to plant growth by producing phytohormones, such as indole-3-acetic acid, and by regulating ethylene levels through 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity, which mitigates stress-induced ethylene production (Lau et al., 2022). These bacteria also induce systemic resistance, strengthening plant defense mechanisms against environmental stresses (Triwidodo and Listihani, 2020). Microbes enhance the uptake of essential nutrients (e.g., nitrogen, phosphorus, and iron), synthesizing osmolytes like soluble sugars and proline to improve drought tolerance, and producing exopolysaccharides to maintain soil structure and moisture (Huang et al., 2014; Rolli et al., 2015;Upadhyay and Singh, 2015). Indirectly, microbes improve soil properties, foster root surface expansion for better nutrient and water absorption, and suppress pathogens that exacerbate stress conditions (Ngumbi and Kloepper, 2016; Poudel et al., 2021).

The use of microbial bioinoculants, which include formulations of beneficial fungi and bacteria, offers a sustainable strategy for enhancing salinity and drought tolerance in crops (Nader et al., 2024). These bioinoculants not only improve soil fertility but also enhance plant

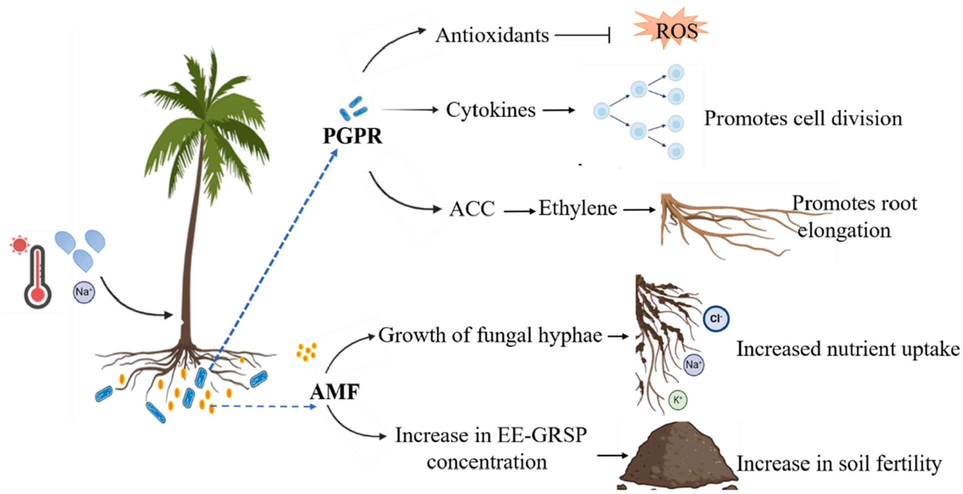

Fig. 5. Role of soil microbes in alleviating stress in date palm.

resilience by reducing oxidative damage caused by reactive oxygen species (ROS) under stress. Incorporating microbial diversity into date palm cultivation practices can enrich soil organic matter, promote root growth, and reduce dependency on chemical fertilizers and irrigation.

2.2. Water availability

Date palm cultivation relies heavily on efficient irrigation systems to meet water requirements, which are crucial for sustainable agricultural practices and water management (Al Hamedi et al., 2023; Dhaouadi et al., 2021; Haj-Amor et al., 2016; Mohammed et al., 2021a; Shin et al., 2022). The Arabian Peninsula's arid climate and scarce water resources present significant challenges for date palm cultivation. With minimal rainfall, groundwater aquifers are the primary freshwater source (Al-Muaini et al., 2019). However, the over-extraction of these aquifers is leading to rapid depletion, threatening the sustainability and expansion of date palm cultivation during the fruiting season when water demand is high (Dhaouadi et al., 2021). Water demand across various sectors now exceeds available freshwater resources, leading to aquifer depletion and an increased risk of saltwater intrusion, which risks freshwater supplies for irrigation (Dagar and Kumar Yadav, 2017).

Various irrigation methods have been employed globally to optimize water use and enhance yield. Traditionally, flood irrigation has been prevalent, involving the application of large water volumes at intervals, typically weekly in summer and less frequently in winter (Haj-Amor et al., 2018; Mohammed et al., 2021a). Although common, this method requires substantial water resources. Bubbler irrigation, a modified form of drip irrigation, offers greater water efficiency by delivering water directly to the root zone through bubblers or emitters placed near the trees (Mohammed et al., 2021a). This method has demonstrated superior water distribution and uniformity, significantly conserving water compared to flood irrigation. Surface drip irrigation, another advanced method, applies water directly to the soil surface via tubing, minimizing evaporation losses and ensuring precise water application (Alnaim et al., 2022a; Mohammed et al., 2021b). Subsurface drip irrigation (SSDI), which places the irrigation system below the soil surface, further optimizes water use by reducing evaporation and enhancing nutrient uptake efficiency (Alnaim et al., 2022a; Dehghanisanij et al., 2023).

Unlike traditional methods, SSDI delivers water directly to the root zone at controlled depths below the soil surface, minimizing losses due to evaporation and runoff (Mohammed et al., 2020). This approach improves water use efficiency by ensuring that water reaches the active root zone where it is most needed, promoting optimal growth and productivity of date palms. SSDI has been noted for its ability to enhance yield, quality, and water use efficiency in date palm cultivation, which is crucial for regions with limited water resources like Saudi Arabia and the UAE (Singh et al., 2022). As date palm agriculture expands, adopting efficient irrigation systems like SSDI becomes imperative for sustainable water management and agricultural productivity enhancement. In the UAE, solar energy-powered SSDI systems have been implemented, as depicted in Fig. 6. Research has shown that SSDI can substantially improve the yield and quality of date palm fruits compared to surface irrigation methods (Al-Muaini et al., 2019; Alnaim et al., 2022). By maintaining a consistently moist root zone without wetting the foliage, SSDI reduces the risk of diseases and pests that thrive in humid conditions, which is crucial for the health and longevity of date palms (Salah, 2018). Moreover, the precise control over water application provided by SSDI allows for better management of salinity levels in the root zone, preventing salt accumulation and improving soil health over time (Zemni et al., 2022).

The quality of irrigation water is crucial for successfully cultivating date palms (Carr, 2013). Groundwater sources in the region often exhibit high salinity levels, and excessive use of saline water for irrigation can lead to soil salinization, which impairs nutrient absorption and reduces crop yields. Moreover, agricultural and industrial activities contribute to the contamination of water sources with pollutants, further degrading water quality and posing significant risks to plant health and fruit safety. To mitigate these challenges, ongoing research is exploring sustainable practices, including the use of treated wastewater and desalination techniques (Alharbi et al., 2024; Hammami et al., 2023).

2.3. Climatic condition influencing date palm cultivation

2.3.1. Extreme temperatures

Date palms thrive in arid to semi-arid climates, where they experience long, hot, dry summers and comparatively mild winters. However, extreme temperature fluctuations can challenge their growth (Chao and Krueger, 2007). The ideal temperature range for date palm growth is between 28°C and 41°C from May to October, with tolerance up to 50°C and short-term frost down to 5°C (Chao and Krueger, 2007; Shabani and Kumar, 2013).

High temperatures, often exacerbated by climate change, can induce heat stress, disrupting essential physiological processes such as photosynthesis and respiration and ultimately reducing fruit yield and quality (Alabdulkader et al., 2016). In addition to daytime temperatures, night temperatures play a significant role in fruit development. Night temperatures around 18°C are essential for maintaining water balance, as high nocturnal temperatures can exacerbate moisture loss from the fruit, leading to shriveling. In their natural environment, date palms are adapted to high diurnal temperature fluctuations, often exceeding 45°C

Fig. 6. Solar energy-powered subsurface drip irrigation system in UAE (ICARDA 2006–2023).

during the day. Despite these extreme conditions, date palms optimize their photosynthesis and respiration to counteract heat stress and prevent metabolic disruption (Kruse et al., 2019a). However, if nighttime temperatures are too high, this acclimation process is less effective, leading to excessive water loss from fruit, which can impair fruit quality. Prolonged periods of temperatures exceeding 35°C during pollination and fruit development can also result in fruit shriveling (Kruse et al., 2019a). Those authors also found that the optimum leaf temperature for date palms ranges between 20°C and 33°C in winter and between 28°C and 45°C in summer. While date palms can tolerate extreme temperatures as high as 60°C and short periods of freezing, their optimal growth occurs around 32°C (Safronov et al., 2017b). However, extreme temperatures can impair cell division and growth, with freezing temperatures hindering these processes and excessively high temperatures causing heat stress that affects physiological functions like photosynthesis and respiration. Long, hot summers with low humidity are crucial for preventing fruit cracking and disease (Al-Khayri et al., 2018). Most cultivars perform best under hot, arid conditions. Maintaining low humidity during flowering and fruit maturation is essential for better fruit quality, as high humidity levels can increase the risk of inflorescence rot and fungal diseases (Senthil Kumar and Yaashikaa, 2019). Safronov et al., (2017a) emphasized that maintaining optimal growth temperatures and managing environmental stressors are crucial for successful date palm cultivation.

Climate change significantly impacts date palm cultivation with extreme temperature variations and altered precipitation patterns. High temperatures increase evapotranspiration rates, exacerbating water stress, especially in the water-scarce Arabian Peninsula (Alabdulkader et al., 2016). Saudi Arabia, with its arid climate, is highly vulnerable to climate change. Projections suggest that temperatures could gradually rise by up to 6°C by 2100 under high-emission scenarios, with incremental increases averaging 0.2–0.3°C per decade depending on global mitigation efforts. This rise would significantly increase crop irrigation demands, estimated to grow by 602–3122 million m^3, potentially causing yield losses of 5 % to over 25 % for various crops. This would critically affect agriculture and food production by reducing water availability and directly impacting crop yields (Zatari, 2011).

2.3.2. Humidity

Humidity is critical in date palm cultivation, mainly during the flowering and fruit maturation (Chao and Krueger, 2007; Shah, 2014). Maintaining low humidity levels is crucial to ensure optimal fruit quality, as high humidity can lead to inflorescence rot and increase susceptibility to fungal diseases, which negatively impact fruit development and maturation. Moreover, humidity is a key factor in the development and proliferation of arthropod pests in date palm plantations (Latifian, 2014). For example, diseases such as leaf spot and Khamedje disease and pests like the lesser moth, date scale, show greater injury severity in environments with higher humidity, typically found in denser plantings, areas near river sites, or regions with intercropping (Latifian et al., 2012). These conditions create favorable microclimates for pest development. Furthermore, the microclimate within the tree itself, influenced by factors such as canopy structure and light interception, also contributes significantly to pest development. For instance, canopy porosity affects airflow and moisture retention, both of which influence pest populations (Latifian et al., 2012). Pathogens such as *Fusarium oxysporum* (causing Bayoud disease and Fusarium wilt), *Thielaviopsis punctulata* (responsible for diseases like black scorch and trunk rot), and various other fungal pathogens thrive in humid conditions, posing significant challenges to date palm health and productivity (Chellappan et al., 2023; El Bouhssini and Faleiro, 2018; Nishad and Ahmed, 2020).

Date palm farmers in Saudi Arabia face significant challenges due to widespread pests, pathogens, and diseases. Date palms are vulnerable to various pests, such as the red palm weevil, longhorn beetles, dust mites, fruit flies, scale bugs, and several fungal pathogens (Al-Dosary et al., 2016). Various pests affecting date palms in the Arabian Peninsula are illustrated in Fig. 7 (ICARDA project report, 2006–2023). The red palm weevil, a non-native pest, threatens young and mature trees by invading trunks and disrupting the vascular system. The larvae of the weevil burrow into the trunk, feeding on the soft tissues and creating tunnels that undermine the structural stability of the tree (El-Shafie, 2014). Trees affected by pests often show symptoms such as wilting leaves and yellow discoloration, which can ultimately lead to the tree's death (Ziedan et al., 2022). Managing humidity levels is therefore crucial not only for maintaining fruit quality but also for mitigating the spread of pests, pathogens, and diseases that can devastate date palm plantations.

3. Genetic diversity in date palms

Genetic diversity in date palms refers to the variety of genetic traits found across different species, cultivars, and populations. This diversity can be assessed through morphological, physiological, biochemical, and molecular analyses (Jaradat, 2016, 2015). Several methods are used to measure genetic diversity within plant populations, including the assessment of polymorphism levels, allelic richness, gene diversity, and heterozygosity (Avolio et al., 2012). Despite the recognized importance of genetic diversity, only a fraction of the total genetic diversity in date palms has been thoroughly characterized, assessed, and utilized for breeding and crop enhancement. Intensive artificial selection and clonal propagation practiced in oasis agroecosystems have significantly altered the genetic structure of date palms (Hasan et al., 2021a). This selection process, both within and among cultivars, has been the primary force shaping genetic diversity patterns, favoring individuals who are more likely to thrive and reproduce through seedlings or offshoots.

The distribution of genetic diversity in date palms is uneven, varying among oases, populations, and localities (Jaradat, 2016). This variation is influenced by a combination of historical, geographical, ecological,

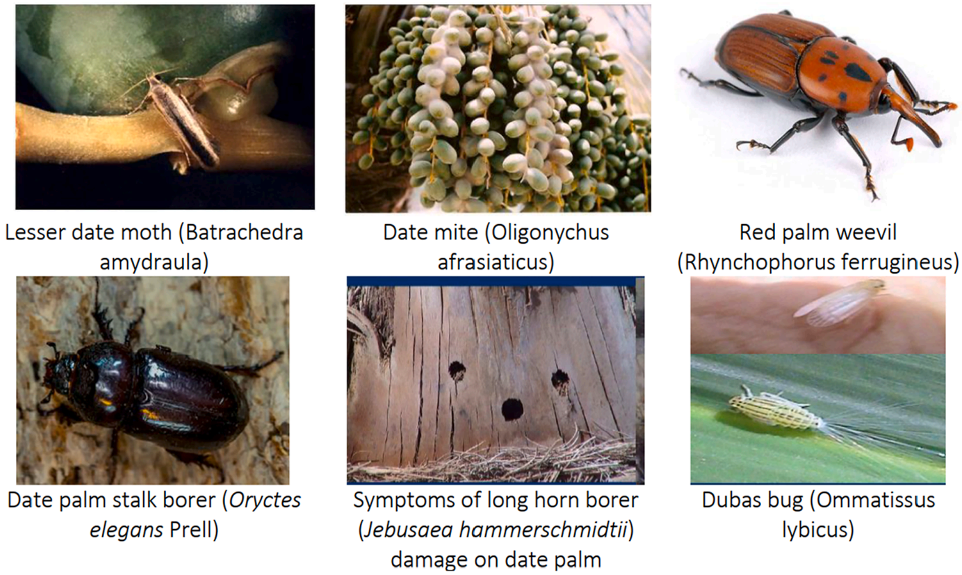

Fig. 7. Various pest affecting date palm cultivation (ICARDA 2006–2023).

and human factors, which collectively shape fruit quality traits. Traditional oases are crucial in maintaining and enriching date palm genetic resources through various conservation practices (Hassan et al., 2021b). Accurate identification and differentiation of cultivars require numerous morphological markers alongside biochemical and molecular markers (Agarwal et al., 2008). The stability of certain morphometric traits within cultivars has been utilized for the precise identification and classification of cultivars based on fruit characteristics. Accurate estimation of genetic diversity is essential for the long-term improvement of date palms and for enhancing their resilience to various stresses (Hassan et al., 2021b). These estimates typically include features of the trunk and crown, fruiting characteristics, and fruit quality, all of which are critical for effectively managing and improving date palm plantations. Preserving and utilizing the genetic diversity in date palms allows breeders to select for traits that improve resistance to environmental stresses. Populations with greater genetic diversity have a higher potential to harbor traits that enhance tolerance to various abiotic stresses, such as drought, salinity, and heat (Jaradat, 2015).

3.1. Molecular markers in genetic diversity studies

Molecular markers are valuable tools in modern plant breeding and genetics. They provide an accurate and efficient way to identify genetic diversity, map genes, and select desirable crop traits (Idrees and Irshad, 2014). Unlike conventional morphological markers, which are based on observable traits that can be influenced by environmental conditions, molecular markers directly link to the plant's genetic makeup, allowing for more accurate and reliable genotype selection. These markers enable the early identification of valuable traits, such as disease resistance or drought tolerance, long before they appear physically, thus speeding up the breeding process. This is advantageous in long-lived crops like date palms, where traditional breeding methods can be time-consuming. Numerous studies have highlighted the effectiveness of molecular markers in evaluating genetic diversity related to stress tolerance in date palms. Markers such as SSR, AFLP, RAPD, and ISSR are frequently utilized to detect genetic variations associated with stress-resistant traits (Hamza et al., 2011). Among these, ISSR markers have proven particularly useful for assessing genetic diversity in plants exposed to stress (Khalil, 2013). A study by Suhim et al. (2017) investigated the oxidative responses and genetic stability of the Barhi cultivar of date palm under varying salinity levels in irrigation water, employing ISSR markers. The analysis revealed that higher concentrations of NaCl (200, 300, and 400 μM) resulted in more polymorphic fragments compared to the control treatment, whereas the DNA profile remained consistent between the control and the 100 μM NaCl treatment.

Maryam et al. (2016) utilized microsatellite markers containing simple sequence repeats (SSR) to identify the gender of date palms, which are dioecious and slow to flower, using 12 SSR primers. Similarly, Ismail et al. (2008) identified sex-specific DNA markers using Randomly Amplified Polymorphic DNA (RAPD) and Inter-Simple Sequence Repeats (ISSR). They found three female-specific and two male-specific markers using RAPD, and five markers using ISSR. The Sequence Characterized Amplified Regions (SCAR) technique utilizes SCAR markers to amplify specific DNA fragments associated with male or female traits. In addition, the Simple Sequence Repeats (SSR) technique identifies polymorphic microsatellite loci linked to gender-specific traits (Awan et al., 2017).

The SSR markers are widely regarded as the most effective molecular markers for studying genetic diversity in date palms due to their high polymorphism and co-dominant nature. SSR markers have been successfully employed to differentiate between date palm varieties across a wide geographical range. For instance, studies in Libya (Racchi et al., 2014), Qatar (Elmeer et al., 2011; Ahmed and Al-Qaradawi, 2010; Elmeer and Mattat, 2015), and Iraq, Iran, and Africa (Arabnezhad et al., 2012) have utilized SSRs to reveal significant genetic variability and relationships among local genotypes. In Saudi Arabia, Al-Faifi et al. (2016) leveraged SSRs for the classification of indigenous date palms. SSR analysis has also been applied in Tunisia and Algeria (Zehdi et al., 2005, 2012; Akkak et al., 2009), as well as in Oman, Bahrain, Iraq, and Morocco (Al-Ruqaishi et al., 2008). These studies collectively demonstrate the widespread application of SSR markers in understanding the genetic diversity and structure of date palm cultivars across different regions (Table 2).

Amplified Fragment Length Polymorphism (AFLP) markers have also been employed in genetic diversity studies, though to a lesser extent compared to SSRs. AFLP markers have been used to analyze date palm genotypes in the UAE (Al Kaabi et al., 2007), Tunisia (Rhouma et al., 2007), the United States (Devanand and Chao, 2003), Egypt (El-Assar et al., 2005), and Iraq (Jubrael et al., 2005). These studies demonstrate the utility of AFLP markers in assessing genetic variation within and between date palm populations across diverse environments. Furthermore, The RAPD and ISSR markers have also been used in several studies to assess the genetic diversity of date palms. RAPD markers have been applied in Egypt (Said et al., 2003), Saudi Arabia (Al-Khalifah and

Table 2
List of molecular markers in genetic diversity studies of the date palm.

Markers type	Genotypes studied	Geographical location	Cultivar	Reference
SSR	11	Qatar	Khakas, Shaishi, Barhi, Hilali, Sukari, Khanaizi, Shahil, Khasab, Razaiz, Lulu and Phahel	(Elmeer et al., 2011)
SSR	15	Qatar	Barhee, Khadraway, Thuri, Zahidi, Hatamy, Helaly, Sheshy, Succary, Abu Main, Barhee, Naboot Saif, Khanezy, Khush Zabad, Sultana, and Anbara	(Ahmed and Al-Qaradawi, 2010)
SSR	32	Saudi Arabia	Ajwa, Anbra, Barhi, Bintzamil, Dekhaini, Ghur, Hatmi, Hilali, Halawa, Kashkash, Khalas, Khenaizy, Khesab, Khodry, Meneifi, Nabtatali, Nabtatsaif, Quatarah, Rabeaa, Rushodia, Ruthana, Ruzeiz, Safri, Sari, Segae, Shahal, Shaishi, Sukkari, Sullaj, Thawee, Wannana, Wesaili.	(Al-Faifi et al., 2016)
SSR	59	Qatar	Khalas (17), Shishi (10), Barhi (7), Hillali (6), Khnaizi (8), Gar (4), Tanazel (1), Nabetseif (1), Jabri (2), Marzaban (1), Iraqi (1), Deqlah (1).	(Elmeer and Mattat, 2015)
SSR	10	UAE	Aboumaan, Barhee, Hilali, Jech Ramli, Khalas, Maktoumi, Rziz, Sakii, Succary, and Sultana	(Al Kaabi et al., 2007)
AFLP	13	Saudi Arabia	Ajwa, Barney, Bareem, Nabtet Saif, Nabtet Sultan, Om-Hammam, Om-Kobar, Rabeeha, Shehel, Shishi, Sugai, Succary Asfar, and Sukkary Hamra.	(Al-Khalifah and Askari, 2003)
RAPD	5	Saudi Arabia	Barhi, Nabtet Ali, Rothanah, Ajwa and Succary	(AI-Moshileh et al., 2004)
RAPD	10	Bahrain	-	(Roy et al., 2008)

Askari, 2003; AI-Moshileh et al., 2004), and Bahrain (Roy et al., 2008), while ISSR markers have been utilized in Tunisia (Zehdi et al., 2002), Ethiopia (Takele et al., 2021), and Iran (Sharifi et al., 2018). These markers have proven useful for identifying genetic differences in date palm populations in regions where SSR and AFLP markers are less frequently used (Table 2).

Traditional molecular markers, have played a crucial role in detecting genetic variations linked to stress responses, the advent of next-generation sequencing has transformed this field by enabling whole-genome and organellar genome analyses. These provide deeper insights into genetic diversity, functional gene characterization, and the mechanisms underlying stress resilience. In date palms, the sequencing of full organellar genomes, including mitochondria (715,001 bp) and chloroplasts (158,462 bp), has paved the way for identifying SNPs as robust markers for assessing genetic diversity and cultivar relationships (Hamza et al., 2023). Organelle genomes, with their uniparental inheritance, high copy number, and low recombination rates, have been widely used to investigate genetic differentiation and evolutionary patterns in plants. For instance, whole-genome resequencing studies in date palms have revealed phylogenetic relationships and intraspecific diversity among cultivars, offering valuable insights into stress adaptation mechanisms across regions. Genome-skimming strategies, a cost-effective NGS approach, have further facilitated the exploration of high-copy genomic fractions, including organelle genomes and nuclear ribosomal DNA, enabling large-scale phylogenetic studies (Nevill et al., 2020).

4. Biotechnological approaches for genetic improvement

Genetic variation is fundamental to agricultural advancement and the objectives of plant breeding. Various techniques have been employed to enhance crop traits, including ploidy manipulation, cross-breeding, mutation breeding, interspecific hybridization, transgenic breeding, and genome editing (Sparjanbabu, 2013). Ploidy manipulation, through triploidy, is a promising technique for improving date palm traits. Othmani et al., (2024) reported the creation of triploid date palms by crossing a tetraploid mutant with a diploid male, producing palms with enhanced fruit characteristics, and increased resistance to abiotic stresses. Traditional cross-breeding involves controlled mating to combine desirable traits, but its effectiveness is often limited by the narrow genetic variability of elite germplasms. Mutation breeding, which induces random mutations across genomes using chemical or radiation mutagenesis, expands genetic diversity but requires labor-intensive screening to identify beneficial traits (Holme et al., 2019) (Fig. 8).

Date palm breeding faces unique challenges, including the species' extended generation time and limited genetic variability, complicating efforts to map quantitative trait loci (Chao and Krueger, 2007). Nonetheless, breeding programs for date palms have intensified in response to rising market demands for high-quality, safe date fruits. Traditionally, these programs have focused on increasing yield and improving fruit size, while also managing the extended time required for the first flowering and maximum yield achievement (Hadrami and Hadrami, 2009). Current strategies now emphasize enhancing productivity and ensuring adaptability to diverse environments through effective farm management practices, despite the limited standardization in date palm management and the availability of extension services (Al-Khayri et al., 2021). Disease resistance, mainly against devastating diseases like Bayoud disease, remains a critical objective, requiring intricate cross-breeding and back-crossing methods to stabilize desirable traits (Hadrami et al., 2011). Additionally, breeding efforts are directed toward developing date palms with enhanced tolerance to abiotic stresses such as drought and salinity, utilizing advances in genetic studies and molecular tools to manipulate stress-related genes and improve the resilience of cultivated varieties (Hazzouri et al., 2020).

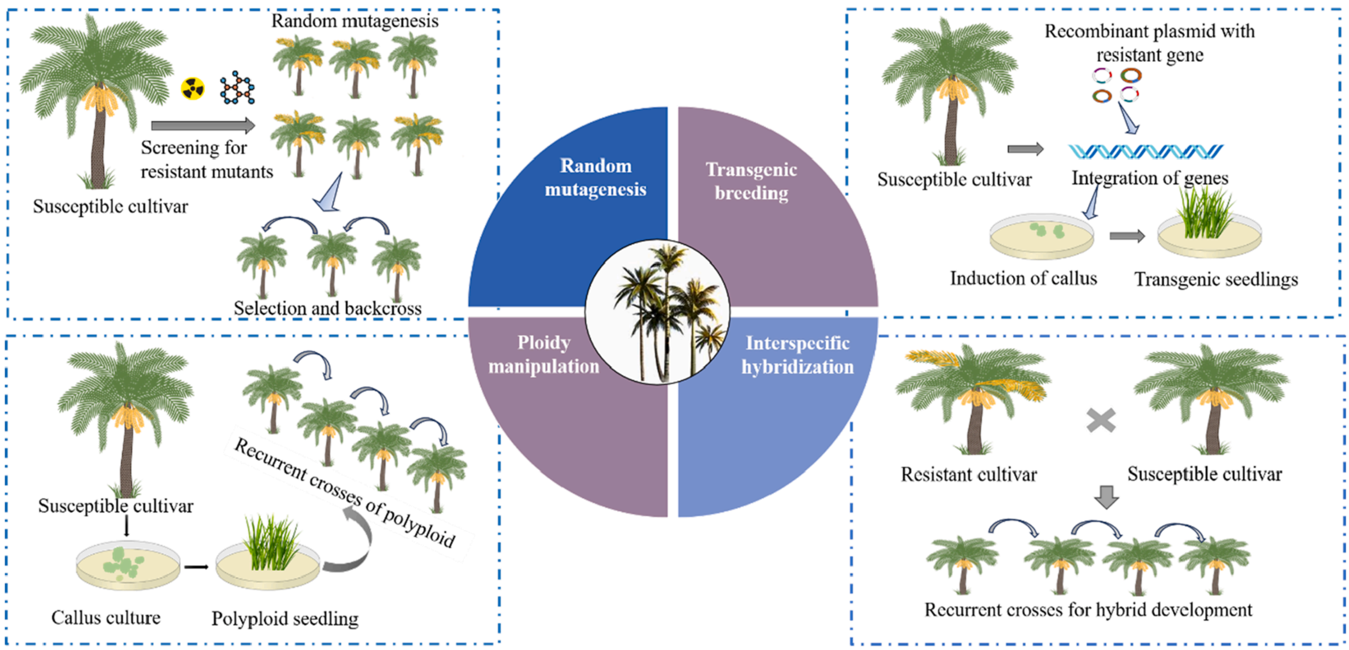

Fig. 8. Plant breeding techniques employed to introduce new traits into an elite crop.

4.1. *Integrating plant breeding with microbial solutions for stress tolerance*

Plant breeding programs for date palms have traditionally focused on selecting cultivars with improved traits such as higher fruit yield, disease resistance, and enhanced tolerance to abiotic stresses. However, an emerging frontier in agricultural research involves integrating plant breeding with microbial solutions (Calvo et al., 2019) to optimize crop performance under stressful conditions like salinity and drought. By combining traditional breeding approaches with microbial solutions, researchers can leverage the benefits of soil microbes such as AMF and PGPR to enhance the stress tolerance of new cultivars. Breeding for traits that favour symbiosis with beneficial microbes can result in cultivars that more efficiently utilize microbial assistance, leading to better nutrient uptake and stress resilience. For instance, breeding date palms to have an enhanced root system architecture can improve their interaction with AMF (Boutheina et al., 2019), increasing the plant's ability to absorb water and nutrients under stressful conditions. Similarly, selecting cultivars that exhibit a higher affinity for specific PGPR strains can further improve stress resilience, as these microbes stimulate root growth and improve soil health through nutrient cycling and the production of phytohormones (Sinclair et al., 2014).

Recent advances in molecular breeding techniques, such as marker-assisted selection allow researchers to identify genetic markers linked to traits that promote effective microbial associations (Su et al., 2019). By selecting for these traits, breeders can develop cultivars that are more responsive to microbial bioinoculants, creating a synergistic approach to stress management. For example, wild date palm varieties that exhibit superior tolerance to salinity and drought due to their natural associations with soil microbes can be crossbred with domesticated varieties. The goal is to produce cultivars that maintain high fruit yield and quality while leveraging the benefits of microbial interactions to withstand environmental stresses.

Integrating plant breeding with microbial solutions also supports the principles of sustainable agriculture. By reducing dependence on chemical fertilizers and increasing the use of bioinoculants, farmers can enhance the resilience of date palm orchards to environmental stresses, such as salinity and drought, while also promoting soil health. This integrative approach can play a key role in ensuring the long-term sustainability and productivity of date palm cultivation in arid regions.

4.2. *Genome editing techniques*

Genome editing techniques like CRISPR-Cas technology, have revolutionized plant breeding by enabling precise genome modifications to achieve desired traits (Schindele et al., 2020). CRISPR-Cas9 uses a guide RNA to direct the Cas9 nuclease to specific DNA sequences, allowing targeted gene editing. The process involves designing a single guide RNA (sgRNA) that matches the target DNA, constructing a plasmid vector with the Cas9 gene and sgRNA, and introducing this vector into plant cells through methods like Agrobacterium-mediated transformation or biolistics (Fig. 9). The edited cells are then propagated and cultured into mature plants, which are evaluated for traits such as disease resistance, improved fruit quality, or stress tolerance (Sattar et al., 2017). CRISPR/Cas9 also allows for precise gene modifications, such as activation or knockout, and can target multiple loci within the complex date palm genome. It has potential applications in early sex determination and combating phytoplasma diseases (Altpeter et al., 2016). However, successful implementation requires careful target selection, effective sgRNA design, appropriate delivery methods, and efficient plant regeneration. This technology enhances traditional breeding and opens new avenues for precise genetic improvements in date palms (Sattar et al., 2017).

4.3. *DNA barcoding in date palm research*

DNA barcoding, also referred to as DNA taxonomy, is a method used to identify plant species through the analysis of a standardized, short region of DNA. It involves extracting DNA from plant samples and analyzing specific gene regions that exhibit variation between species but remain consistent within a species. Steps in DNA barcode library construction is shown in Fig. 10. By comparing these DNA barcodes with a comprehensive database of known plant barcodes, precise species identification can be achieved, thereby facilitating research in biodiversity, conservation, and product authentication (Jeanson et al., 2011). However, the development of robust barcodes for plant species poses challenges, prompting researchers to explore various DNA genes from the plastid genome, such as *matK, rpoC1, erbcl, ropB, trnH-psbA, ycf1*, and

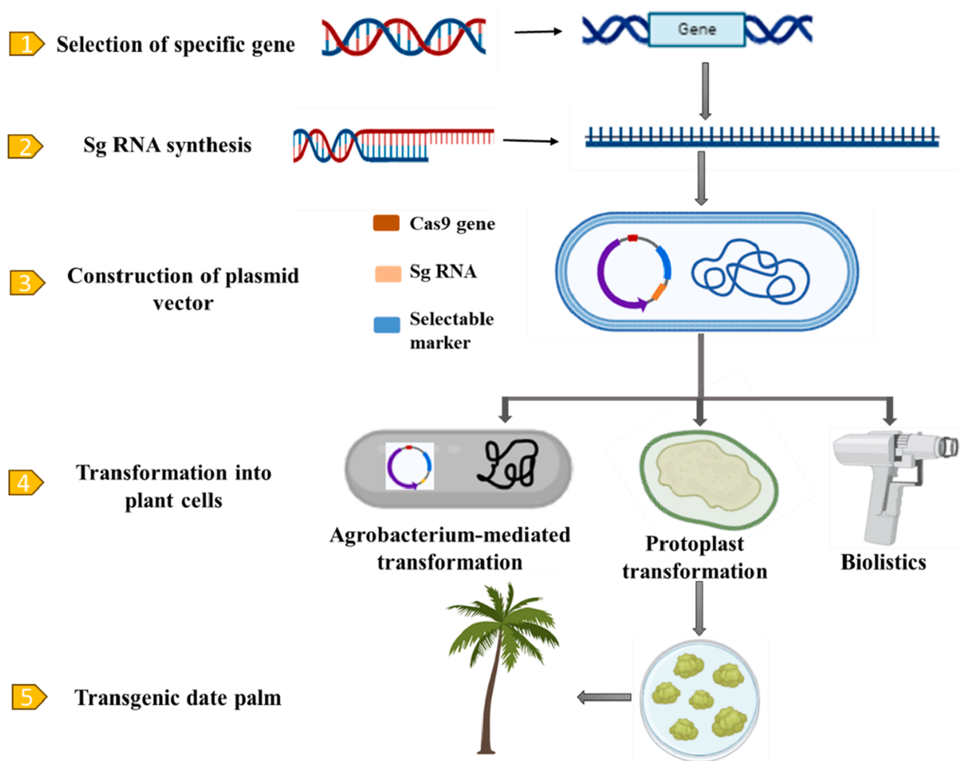

Fig. 9. Schematic representation of CRISPR/Cas9 technology in date palm genome editing.

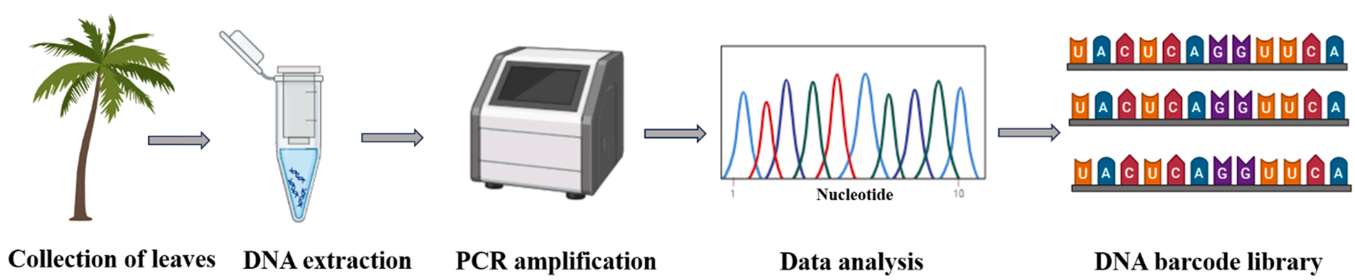

Fig. 10. Steps in DNA barcode library construction.

the nuclear genome (ITS), to improve accuracy (Al-Khayri et al., 2021).

Chloroplast DNA (cpDNA) in each species contains conserved and distinct regions, categorized into non-coding and coding regions. Non-coding regions play critical roles in regulation and structure, providing essential information for molecular systematics, phylogenetics, and species identification through DNA barcoding (Hamza et al., 2023). Coding regions encode proteins crucial for photosynthesis and other chloroplast-specific functions (Hollingsworth, 2011). The use of chloroplast DNA barcodes markers like *mat*K and *rbc*L, enhances species discrimination and supports phylogenetic analyses. *Mat*K, with its high variability, is valuable for species distinction, while *rbc*L's conserved sequences facilitate broader comparisons, collectively enhancing the accuracy and reliability of species identification efforts.

DNA barcoding has revolutionized date palm research by providing a precise method for species identification using specific DNA regions that vary between species but remain stable within species. This approach primarily utilizes chloroplast genome markers such as *mat*K, *rbc*L, *trn*H-*psb*A, and others to discern genetic diversity and phylogenetic relationships. Chloroplast DNA comprises non-coding regions crucial for molecular systematics and coding regions encoding essential photosynthesis-related proteins (Hollingsworth, 2011). For instance, a study by Hani et al. (2020) examined several date cultivars—Bartamoda, Malkaby, Amhaat, Hayani, Sakkoty, and Gondila—using chloroplast markers like *mat*K, *rbc*L, *ycf*5, and *psb*A-*trn*H. Their findings underscored the effectiveness of these markers in phylogenetic tree construction and genetic variation analysis within date palms. Similarly, Naeem et al. (2014) evaluated *mat*K and *rbc*L genes for species differentiation within the Palmae family, with *rbc*L demonstrating higher discriminatory power (90 %) compared to *mat*K (66.6 %), suggesting its potential as a standard barcode for Palmae species identification. Enan, (2020) focused on the atpF-atpH intergenic spacer of chloroplast DNA to assess genetic relationships among 30 date palm varieties. Their study revealed low genetic diversity and minimal genetic differences among the studied cultivars, highlighting the utility of DNA barcoding in elucidating genetic similarities among closely related species. Le et al. (2020) expanded the application of DNA barcoding by comparing five markers (*rbc*L, *mat*K, *trn*H-*psb*A, ITS, ITS2) across various palm species, demonstrating that ITS2 provided superior species resolution compared to plastid markers, thus enhancing identification accuracy for taxonomists and horticulturalists.

5. Genetic conservation of date palm old native varieties

5.1. Invitro preservation of date palm germplasm

Germplasm collections are essential for maintaining genetic diversity and ensuring the future of species and agricultural advancements (Bekheet, 2017a, 2017b). Traditionally, these collections have been preserved in vivo within gene banks as whole plants in the field. However, this method exposes the plants to risks such as pest and pathogen attacks or natural disasters (Abul-Soad et al., 2017). In vitro conservation offers a more secure and efficient alternative using plant tissue culture methods (Al-Bahrany and Al-Khayri, 2012; Araújo de Oliveira et al., 2021; Bekheet, 2011). This technique ensures the regeneration and propagation of genetically stable seedlings, preserving the genetic fidelity of stored material. Advances in tissue culture methods have significantly improved the maintenance of date palm germplasm, minimizing somaclonal variation. Combining tissue culture with molecular biology techniques provides a practical approach for germplasm storage (Abul-Soad et al., 2017). Miniaturizing explants reduces space requirements and labor costs, making this method beneficial for vegetatively propagated crops and offering a reliable solution for long-term conservation.

Two main categories of in vitro gene banks are those utilizing slow growth under cold storage conditions and those employing cryopreservation methods (Al-Bahrany and Al-Khayri, 2012). These methods use various plant materials, such as nodal segments, shoot tips, and rooted shoots. Proper pathogen indexing is crucial to ensure the health and viability of the stored tissues.

5.1.1. Cold storage

Cold storage is an in vitro preservation technique that slows down plant growth under sterile conditions, minimizing genetic changes and preventing contamination (Benelli et al., 2022; Jain, 2012). This method involves modifying culture conditions, such as using growth retardants, osmotic agents like mannitol or sorbitol, and controlling environmental factors like temperature and light intensity (Armijos-González et al., 2024; El-Bahr et al., 2016). These adjustments extend the intervals between subcultures, allowing for long-term storage of clonal plant material, which can range from 1 to 15 years, depending on the species. Cold storage is typically performed under low light or complete darkness, using various plant materials such as shoot tips and nodal segments (Bekheet, 2017a, 2017b). It has been successfully applied to various plants, including cold-tolerant and tropical species, achieving reduced growth and prolonged storage without compromising genetic stability (Bekheet, 2011). Additional techniques, like controlled atmospheres with reduced oxygen levels, further enhance storage capabilities. Although there are challenges, slow-growth in vitro methods offer a promising solution for conserving plant genetic resources effectively (Almusallam et al., 2021). For example, Bekheet et al. (2007) used offshoots from female plants, sterilized their leaves with ethanol and sodium hypochlorite, and cultured the explants on Murashige and Skoog media supplemented with naphthaleneacetic acid and dimethylaminopurine. The cultures were incubated in the dark and re-cultured every six months, with 70 % of shoot buds and nearly all callus cultures remaining viable for up to 12 months.

5.1.2. Cryopreservation

Cryopreservation is a long-term in vitro preservation technique achieved by maintaining samples between −79°C and −196°C (Al-Bahrany and Al-Khayri, 2012; Nguyen et al., 2023). Cell division and metabolism halt at these ultra-low temperatures, preserving cells indefinitely (Bekheet et al., 2007). Cryopreservation ensures the optimal stability of stored germplasm's phenotypic and genotypic characteristics, theoretically enabling infinite conservation without genetic alteration. Its main advantages include minimal need for viability indexing or subculturing, cost-effectiveness, and ease of management. Cryopreservation is vital for preserving vegetatively propagated plant germplasm (Al-Bahrany and Al-Khayri, 2012). Various tissues have been successfully preserved in liquid nitrogen, although there is a risk of injury to sensitive tissues during desiccation. Despite this, cryopreservation presents an attractive alternative to slow-growth methods due to its lower maintenance cost, reduced contamination, and minimized genetic alterations (Bekheet, 2017a, 2017b). For instance, Araújo de Oliveira et al., (2021) employed cryopreservation techniques to preserve date palm pollen by adjusting its moisture content and equilibrating it under various humidity and temperature conditions before storage in liquid nitrogen vapor (LNV) at temperatures ranging from −165°C to −190°C. Their results showed that pollen viability remained stable after 9 months in LNV and even after up to 60 freeze-thaw cycles, indicating that date palm pollen can be effectively cryopreserved for long-term storage.

5.2. DNA banking of date palm

Modern biotechnology tools like DNA technology, play a significant role in characterizing and conserving plant diversity, including date palms (Elshibli and Korpelainen, 2011). PCR allows for the routine amplification of specific genes from genomic DNA, establishing international DNA repositories for long-term storage. DNA banks support barcoding projects by providing access to high-quality DNA storage and comprehensive documentation. This method is crucial for species that are difficult to conserve through traditional means or are highly threatened in the wild. Hodkinson et al. (2007) outlined critical functions of DNA Bank-Net, including plant material collection, DNA extraction, and long-term preservation in liquid nitrogen. However, DNA storage does not facilitate the regeneration of entire plants. For practical preservation, DNA should be stored at −80°C or below to prevent damage, with the purity of extracted DNA being crucial to avoid contamination (Plitta-Michalak et al., 2021). DNA sequencing programs identify genes expressed during critical developmental stages. The date palm genome comprises 18 chromosome pairs (Mathew et al., 2014) and approximately 1.2 billion bp. Yang et al. (2010) reported the chloroplast genome sequence of the elite cultivar Khalas through pyrosequencing.

Institutions like King Faisal University in Saudi Arabia, the International Center for Biosaline Agriculture in Dubai, UAE, and the Wadi Quriyat Date Palm Research Station in Oman play significant roles in preserving and researching genetic diversity (Jaradat, 2015). This diversity is crucial for supporting sustainable agriculture and enhancing environmental resilience in arid regions. These institutions contribute significantly to ongoing efforts to preserve and utilize the genetic resources essential for date palm cultivation and conservation across the Arabian Peninsula.

Seed bank conservation is a widely used for maintaining seed viability at low temperatures and desiccated conditions (Abul-Soad et al., 2017). While effective for many seeds, 'recalcitrant' seeds like those of date palms cannot withstand desiccation or low temperatures. Their heterozygous nature complicates genetic resource conservation through seed banking, necessitating alternative methods like in vitro tissue culture and cryopreservation for preserving date palm genetic diversity (Abul-Soad et al., 2017).

6. Remote sensing techniques for mapping and health assessment of date palm

Continuous large-scale mapping and monitoring of date palm plantations using traditional field-based techniques can be challenging, considering the enormous number of trees that are distributed over vast agricultural and urban settings. Unlike traditional field surveys, remote sensing techniques have been considered more affordable, faster, and practical means for date palm tree mapping and management. The utilization of remote sensing technologies for mapping tree species has become an alternative to field-based measurements since the mid-1980s

(Zhen et al., 2016). Moreover, remotely sensed data is essential in monitoring crop health and environmental conditions and offers critical insights into optimizing irrigation, detecting stress factors, and enhancing overall crop management (Alqasemi et al., 2021; Mulley et al., 2019).

Remotely sensed data are acquired from different platforms, including satellites, airplanes, and unmanned aerial vehicles. Table 3 highlights the application of various remote sensing technologies in assessing the health of date palm vegetation, soil salinity, and the mapping of date palm trees in arid regions, mainly focusing on the UAE and Saudi Arabia. The spatial, spectral, and radiometric resolutions of remotely sensed data play a major role in accurately mapping date palm trees with different crown sizes and health statuses (Gibril et al., 2023). With the vast and growing volume of remotely sensed data, machine learning techniques have been employed and developed to extract valuable insights and leverage these data sources for various Earth-related applications. Machine learning techniques utilized in mapping and monitoring date palm trees can generally be divided into traditional machine learning methods and deep learning models.

Classical machine learning models, including per-pixel and object-based techniques, have traditionally been used to map date palm trees from remotely sensed data. Among the methods used are maximum likelihood supervised classification (Mihi et al., 2022) spectral indices and thresholding analysis (Shareef and Hasan, 2020) a hybrid per-pixel classification approach (Issa et al., 2019), fuzzy logic (Mazloumzadeh et al., 2010), and DT rule-based object-based image analysis (Al-Ruzouq et al., 2018). Given the variations in remotely sensed data (i.e., differences in sensors, resolutions, seasons, and complex environmental conditions) and the diversity among date palm trees (such as cultivar, crown size, age, overlapping crowns, and the presence of shadows), accurately and automatically mapping individual date palm trees from various sources using traditional machine learning techniques remains a challenge.

In recent years, deep learning techniques have extensively been applied to detecting and mapping date palms using Unmanned Aerial Vehicles (UAV), aerial, and satellite imagery. Unlike traditional machine learning, deep learning is data-driven, learning the relationship between input and output directly from the data. Detection and mapping date palm trees using deep learning techniques are carried out using different computer vision tasks, including object detection, semantics, and instance segmentation. For instance, Culman et al. (2020) employed RetinaNet, an object detection architecture, to detect date palm trees from aerial images. The authors reported that date palm trees with varying appearances achieved a mean average precision (mAP) of 0.861.

Similarly, Ammar et al. (2021) conducted a comparative evaluation of multiple object detection algorithms, including Faster R-CNN, YOLO-V3, YOLO-V4, and EfficientDet-D5, for detecting and geolocating individual date palm trees using UAV-based imagery from farms in Saudi Arabia. YOLO-V4 and EfficientDet-D5 provided the most balanced performance in terms of both accuracy and speed. Jintasuttisak et al. (2022) employed YOLO-V5 to detect date palm trees from UAV images, achieving a mAP of 92.34 %, surpassing the performance of YOLO-V3, YOLO-V4, and SSD300 models. Gibril et al. (2022) evaluated various deep instance segmentation algorithms to enable the mapping of individual date palm trees from large-scale UAV-based images. Recently, Gibril et al. (2024) proposed a deep learning approach to map individual date palm trees and initially evaluated the overall well-beings of date palm trees from UAV-based images.

A group of studies conducted by Gibril et al. (2021), and Gibril et al. (2023) have evaluated different convolutional and transformer-based semantic segmentation architectures to map the plantations of date palm trees in muti-date UAV and aerial images. Such studies are essential for developing and updating geospatial databases of date palms and ensuring consistent monitoring and sustainable management of the dates industry. Recently, Al-Ruzouq et al. (2024) demonstrated the potential of very-high-resolution satellite imagery, with a spatial

Table 3
Remote sensing technologies utilized for the assessment of date palm health, evaluation of soil salinity, and mapping of date palm trees in arid regions.

Country	Technology/ Index	Parameter Assessed	Description / Major Findings	Reference
UAE	Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+)- based SAVI	Vegetation health and greenness anomalies	Date palm vegetative growth declined in the UAE's eastern region due to groundwater salinization, with a decrease in SAVI values indicating salt-affected areas.	(Alhammadi and Glenn, 2008)
Saudi Arabia (Al-Ahsa Oasis)	Landsat NDVI	Spatiotemporal variation in vegetation cover	Significant improvement in the ecological environment of the Al-Ahsa Oasis from with NDVI values increasing, indicating enhanced vegetation cover and ecological conditions.	(Chouari, 2024)
UAE	RGB Vegetation Indices, δ13 C, CT	Salinity effects on biomass, fruit yield,	The water status trait, leaf δ13 C, indicates date palm biomass across salinity levels, but it does not work as well for assessing fruit yield.	(Serret et al., 2020)
Saudi Arabia (Al-Ahsa Oasis)	SAVI, NDSI, SI-T (from IKONOS images)	Soil salinity effects on vegetation indices	SAVI, NDSI, and SI-T indices yielded the best results for assessing soil salinity in dense, uniform vegetation. NDSI and SI-T showed the highest correlation with salinity in less densely vegetated lands and bare soils.	(Allbed et al., 2014)
UAE	Vision Transformers with WorldView−3 (WV−3) Satellite Data	Mapping of date Palm Trees	Evaluated the performance of various vision transformer models (UperNet, SegFormer, Mask2Former, UniFormer) for large-scale mapping of date palm trees using WorldView−3 satellite data. Accurate and extensive	Al-Ruzouq et al. (2024).

(continued on next page)

Table 3 (*continued*)

Country	Technology/ Index	Parameter Assessed	Description / Major Findings	Reference
			mapping of date palm trees to create palm tree inventories and update geospatial databases continuously.	
UAE	U-Net Architecture with ResNet−50 backbone	Large-scale mapping of date palm trees	A U-Net architecture based on a deep residual learning network (ResNet−50) was developed for the semantic segmentation of date palm trees. The model enabled an efficient deep learning architecture for the automatic mapping of date palm trees from VHSR UAV-based images.	Gibril et al., (2021)

resolution of 30 cm, for regional-scale mapping of date palm trees using a spectral-spatial transformer-based deep learning approach. Their study underscored the feasibility and effectiveness of utilizing multispectral satellite data for comprehensive surveys of date palm plantations.

7. Challenges and future directions

Addressing key challenges in date palm cultivation requires innovative and sustainable strategies. To combat soil salinity, the development of salt-tolerant cultivars is crucial, alongside integrating organic and mineral amendments to reduce soluble salt availability. The use of treated wastewater, combined with efficient irrigation systems like drip or subsurface methods, offers a practical solution for managing water scarcity while reducing reliance on saline groundwater. Climate-resilient cultivars, developed using advanced tools such as CRISPR/Cas9, are essential to mitigate the impacts of temperature extremes and altered precipitation patterns on flowering and fruiting stages (Chao and Krueger, 2007; Sattar et al., 2017; Schindele et al., 2020). Improving soil health through increased organic matter and nutrient retention can enhance overall productivity, while genetic diversity in propagation methods can sustain adaptability to local conditions. Future research should prioritize comprehensive pest management strategies, precision irrigation technologies, and the integration of remote sensing to monitor and optimize cultivation practices. These efforts will ensure long-term sustainability and resilience in date palm cultivation under increasingly challenging environmental conditions.

8. Conclusions

Date palm cultivation remains a cornerstone of agricultural practice in arid regions, particularly in the Arabian Peninsula. However, its cultivation faces significant environmental stresses, including soil salinity, water scarcity, and climate variability, all impaired by climate change. Overcoming these challenges requires diverse approaches, including adopting advanced remote sensing technologies, developing genetically improved cultivars, and implementing efficient irrigation systems. By integrating these strategies, the sustainability and productivity of date palm cultivation can be significantly enhanced, ensuring this vital crop's continued economic and cultural importance in the face of evolving environmental conditions. Despite these challenges, the region's extensive genetic diversity and centuries-old cultivation practices provide a resilient foundation for adaptation. Integrating advanced agricultural technologies, sustainable water management practices, and genetic improvement strategies will be critical in enhancing both productivity and sustainability. These approaches promise not only to increase yield and resilience but also to minimize environmental impacts. Preserving and harnessing the genetic diversity of date palms through conservation efforts, combined with leveraging scientific advancements, are essential steps forward. Biotechnological advancements, such as micropropagation, genetic transformation, and genome editing, offer promising solutions to enhance crop productivity, improve genetic diversity, and mitigate environmental impacts. Additionally, remote sensing technologies provide precise tools for monitoring and managing date palm health, further contributing to sustainable cultivation practices. The integration of these approaches holds immense potential for ensuring the resilience of date palm cultivation against global agricultural challenges, securing the future of this vital crop in arid regions.

CRediT authorship contribution statement

Ali El-Keblawy: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Investigation, Conceptualization. **Soumya Koippully Manikandan:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Dharshini Jenifer. A:** Writing – review & editing, Writing – original draft, Data curation. **Nisarga K. Gowda:** Writing – review & editing, Writing – original draft, Data curation. **Fouad Lamghari:** Writing – review & editing, Supervision, Resources, Project administration. **John Klironomos:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation. **Maryam Al Hmoudi:** Writing – review & editing, Writing – original draft, Data curation. **Mohamed Sheteiwy:** Writing – review & editing, Writing – original draft, Data curation. **Rami Al-Ruzouq:** Writing – review & editing, Writing – original draft, Data curation. **Mohamed Barakat A. Gibril:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Vaishakh Nair:** Writing – review & editing, Writing – original draft, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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