



The sustainable improvement and precision agriculture in the date palm cultivation-A Review

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Summary

In many parts of Asia, especially in the regions which are arid in nature, present in the Middle East, the date palm, i.e. *Phoenix dactylifera* L., is a significant plant both culturally and economically. In the last decade, many biotechnological tools have been applied to revolutionize date palm research and its cultivation process. In this comprehensive review, we provided an in-depth overview of the cutting-edge developments in date palm biotechnology, mentioning the critical areas such as genomics, genetic engineering, in vitro propagation and incorporation of artificial intelligence and machine learning (AI-ML). These advancements in date palm production led to the production of superior date palm cultivars with improved harvest, fruit traits, and resilience to biotic and abiotic stresses. Also, it explores the application of biotech tools in enhancing pest and disease management strategies, increasing productivity, and developing Date palm-based bio-factories for the synthesis of high-value compounds. This review highlights the current challenges faced by the date palm industries, including limited water resources, genetic erosion, pests and disease and the need for improved postharvest handling and processing. It examines how these tools, coupled with AI-based approaches, can be leveraged to address these challenges and ensure the long-term sustainability of date palm cultivation.

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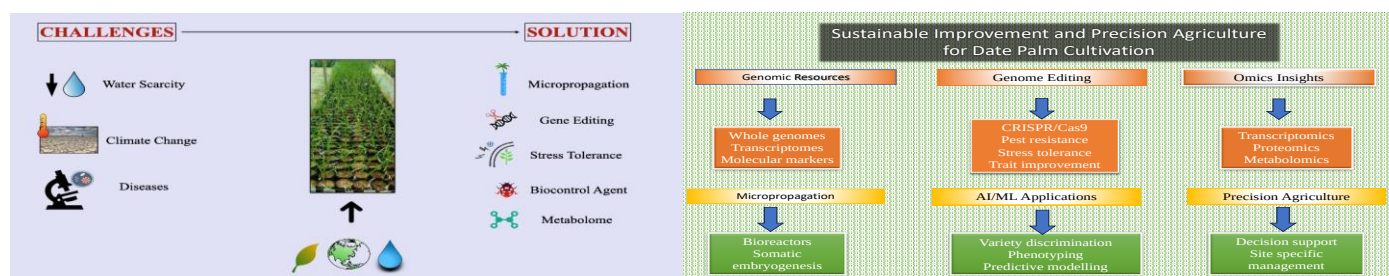
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Keywords: Date palm, Genetic Diversity, Pest Resistance, AI-ML, Precision Agriculture



Graphical Abstract: The sustainable improvement and precision agriculture in date palm cultivation will pave the way for arid and semi-arid area development in countries which are suffering from soil erosion

Introduction

The Date palm (*Phoenix dactylifera* L.) is a highly revered and versatile fruit crop that has been an integral part of the cultural and economic landscape of Middle Eastern countries, North America, and other parts of Asia for many centuries. Fruit from the date palms is sweet and nutritious and also plays a vital role in terms of generating a source of income and employment in many date palm cultivating countries (Soomro et al. 2023; Singh & Ramkesh 2021). Beyond their culinary uses, date palm also provides the raw materials for various products, including construction materials, furniture, and

handicrafts, further underscoring their multifaceted importance (Al-kuthi et al. 2019; Jonoobi et al. 2019; El Hadrami et al. 2012).

Global date production has steadily increased over the past decades, reaching over 8 million metric tons in 2022 (Fig.1) (Sparchia et.al.2023; Wakil et al.2015). However, the date palm industries face numerous challenges, such as limited water resources, pests and diseases, genetic erosion and the need for improved postharvest handling and processing (El-Juhany & Loutfy 2010; Abul Soad et al.2017). In response to these challenges, researchers have increasingly turned to the powerful tools of biotechnology to increase the overall productivity, sustainability and resilience of date palm cultivation (Abdul Aziz et al.2017; Haldhar et al. 2017; Kardrostami et al. 2022; Hazzouri et al. 2020).

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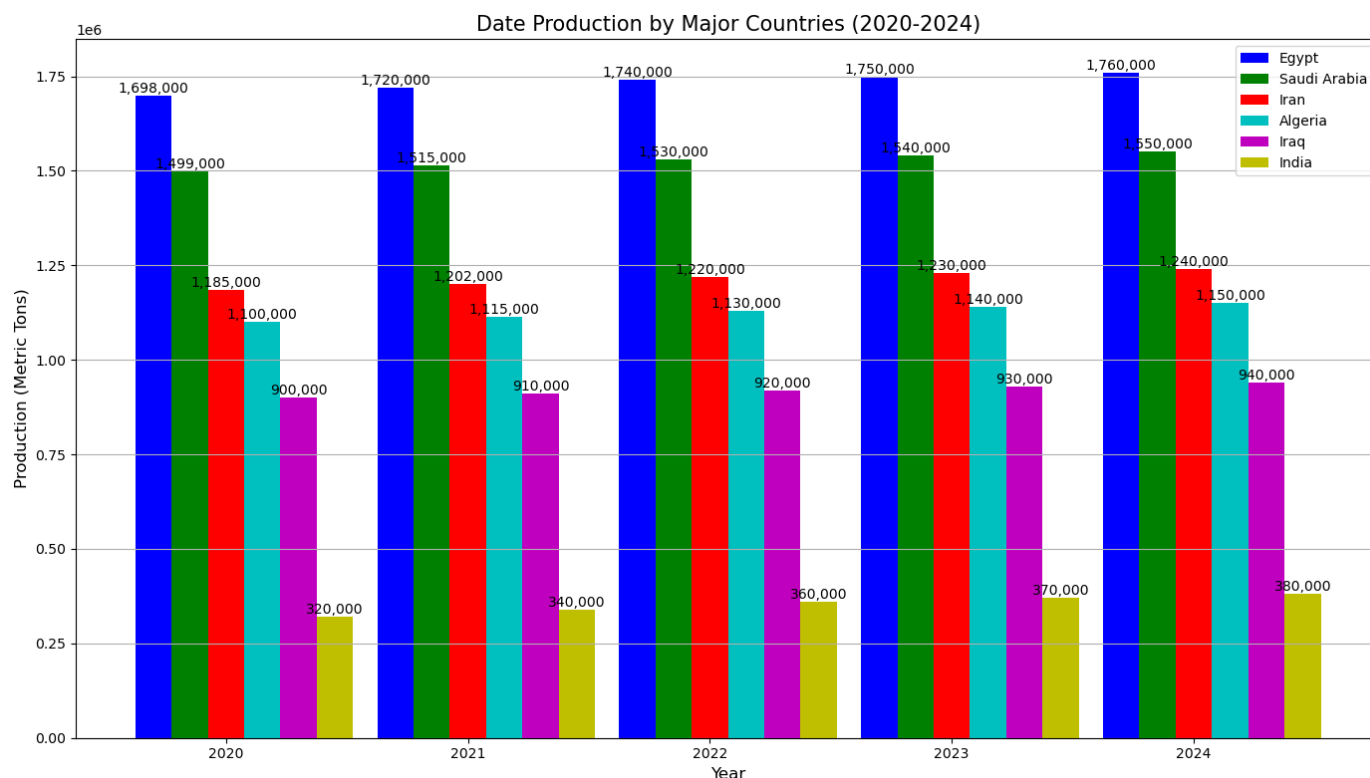


Figure 1. Global Date production in the significant date-producing countries along with India's global production

In this comprehensive review, we explore the recent advancements in date palm biotechnology that have significantly impacted various aspects of the industry. We cover key research areas, including genomics, genetic engineering, in vitro propagation and the incorporation of AI-ML. We highlighted how these innovations led to the developing of superior date palm cultivars, improved pest and disease management strategies, and enhanced date palm productivity and product quality.

They further highlighted the role of AI-ML in the enhancement of effective and efficient methods of in vitro propagation protocols for developing predictive models for trait improvements. Additionally, this review discusses the present challenges faced by date palm production, as well as how biotechnological tools, coupled with AI-based approaches, can be leveraged to address these challenges and ensure the long-term sustainability of date palm cultivation.

All these insights have potential applications in the enhancements of date palm traits, the development of molecular markers, the construction of comprehensive metabolic models for targeted metabolic engineering, and the production of valuable compounds. Overall, in this review, we propose to postulate a broad understanding of the present state of date palm biotechnology and its potential to shape the future of this culturally and economically important crop while also highlighting the challenges and opportunities that lie ahead.

Advances in date palm genomics

The availability of high-quality genome sequences has been a crucial enabler for the rapid progress in date palm biotechnology (Kardrostami et al. 2022). In 2011, a team of researchers from Qatar published the first draft of the date palm genome sequences, providing an in-depth understanding of the genetic makeup and the identification of the valuable trait (Al-dous et al. 2011). After that, several research groups have further refined and expanded the genomics resources obtainable for the date palm, leading to significant advancements in our knowledge of the crop's genetics (Hadrami A et al. 2011; Mathew L.S et al. 2014)

1. Genetic linkage Maps and Marker-assisted selection

Significant key achievements in date palm genomics have been the development of dense genetic linkage maps and high throughput genotyping platforms. Researchers have utilized a variety of molecular markers, such as simple sequences repeats (SSRs) (Zhao et al. 2012; Mokhtar et al. 2016; Ahmed et al. 2009) single nucleotide polymorphisms (SNPs) (Mathew et al. 2015; Al-Massalleh et al. 2013) and diversity arrays technology (DART) markers (Mandy et al. 2021; Ahmed et al. 2021), to construct the detailed genetic maps of the date palm genome. These maps have enabled the identification of quantitative trait loci (QTLs) associated with economically significant characteristics such as fruit quality, harvest and biotic and abiotic stress tolerance, as shown in Table 1 (Al-Khayriso et. al 2018; Mandy et al. 2021)

Table 1. Primary genomic resources developed for the date palm

Resource	Findings
Draft genome sequence	First draft genome assembly of the Khalas date palm variety (Al- Massalleem et al. 2013)
High-density genetic map	Genetic map with 1,892 SNP & 173 SSR markers across 18 linkage groups (Ibrahimi et al. 2023)
Genome-wide SNP array	Identification of the sex chromosome. Confined the gender segregating region in date palm to LG12, the estimated size of the area is approximately 5-13Mb (Mathew L.S et al. 2014)
Pan-genome analysis	We identified 158278 gene families across 62 date palm accessions. We explored the polymorphism for date palm genetic diversity. Possible selective sweeps within the species and gene network associated with the fruit traits (Hazzours et al. 2015)

Based on such genome resources, date palm breeders have increasingly adopted marker-assisted selection (MAS) to accelerate the development of improved cultivars (Fig.3) (Hadrami et al. 2011; Haldhar et al. 2021). By using molecular markers linked to desirable traits, breeders can more effectively select for these traits and pyramid the multiple beneficial alleles in their breeding programs (Lalrinmawii et al. 2023; Mandey et.al 2021). This approach has led to the development of new date palm varieties with enhanced characteristics such as higher yields, larger fruit size, and improved shelf life.

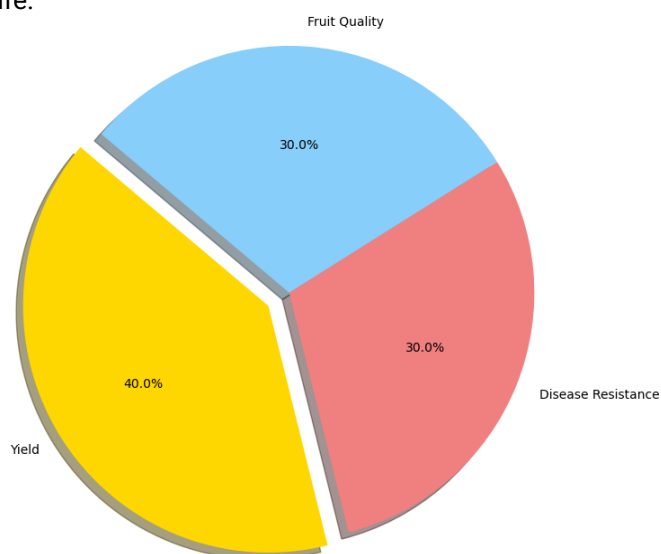


Figure 3. The distribution of MAS's impact on yield, disease resistance, and fruit quality in date palm cultivation highlights the significant role MAS plays in improving these critical areas

2. Exploitation of the genetic diversity and domestication history

Recent advancements in technologies such as next-generation sequencing (NGS) have significantly enhanced our understanding of the genetic diversity and domestication history in the date palm. The NGS-based genotyping has allowed researchers to analyse genetic variation within and among the date palm cultivars on an

unprecedented scale. This has provided critical insights into their complex domestication processes and phylogenetic relationships, revealing the distinct genetic differentiation between Middle Eastern and North African populations (Flowers et al. 2019; Gros-Balthazard et al. 2017). Leveraging this genetic diversity, GWAS have identified specific genomic regions and candidate genes related to significant agronomical characteristics, such as fruit yield, quality and stress tolerance. Such discoveries have been pivotal for marker-assisted breeding and genetic engineering works aimed at improving the date palm cultivars. Additionally, breeders have integrated genomic selection approaches, which utilizes genome-wide molecular markers to predict the breeding value of the individuals. This integration led to substantial developments in the rate of genetic gain, with some studies reporting up to a 30 % increase in the fruit yield and 20 % improvements in the fruit size compared to conventional breeding methods (Figure 2) (Mathew et al. 2015). Collectively, these advancements underscore the transformative impact of genomics on date palm research and breeding, paving the way for sustainable development and conservation of this culturally and economically important crop.

3. Genome Editing Applications

The advent of CRISPR-Cas9 has enabled the precise targeting and modification of specific genes in date palm, opening up new possibilities for trait improvements (Sattar et. al. 2017; Sebastian et al. 2023). The use of genome editing tools to enhance traits like quality of fruit, shelf life and tolerance toward stress has demonstrated the potential of this approach for date palm varietal developments (Table 3). These advancements in date palm genomics have been instrumental in addressing the industry's challenges, from improving productivity and resilience to conveying genetic diversity. The continued integration of these genomics tools with other genetic approaches and precision farming holds great promise for the future of the date palm industry (Table 4).

Table 2. Key findings using Molecular tools in the date palm

Techniques	Key Findings	Data Points	Applications	Limitations
RAPD & ISSR Studies. (Hassanzadeh et al. 2019)	High throughput screening for genetic variations	Over 100 polymorphic bands identified in various genotypes	Population structure analysis (Soma clonal Variation detection - Germplasm management)	Low marker specificity - Dominant markers complicate heterozygosity analysis-
AFLP-studies (El- Assar et al. 2005; Saboari et al. 2021)	Multi-locus fingerprinting for comprehensive diversity assessment	Up to 300 polymorphic markers were detected per study. Shannon-Weaver diversity index ranging from 0.24 to 0.48 across the population.	Evolutionary history reconstruction Identification of unique genetic signatures Marker-assisted selection	Technically demanding and expensive Requires specialised equipment and analysis software
Microsatellite Markers.(Zahid et al. 2022)	Highly polymorphic loci for accurate cultivar identification and genotyping.	Able to distinguish >90% of cultivars with high accuracy Unique markers were identified for specific cultivars like Medjool and Zahid.	Breeding program development Cultivar traceability and certification Gene Mapping and QTL Analysis	Costly compared to other techniques Labor intensive for large-scale genotyping.
SCoT Polymorphism. (Saboari et al. 2020)	Targeting functional regions for insights into gene expression and adaptation	Potential for Marker-Assisted selection of stress tolerance traits	-Early-stage technology with limited data availability Development of specific primers needed for targeted loci	N/A
Conserved DNA-derived polymorphism (CDDATE PALM).(Hasan et al.2022; Ghazzawy et al. 2021)	Cost-effective genotyping platform for extensive population studies.	Efficient analysis for pre-designed primer set for conserved genomic regions.	Rapid diversity assessment in germplasm collection. Population genetic analysis and gene flow studies	Limited marker resolution compared to highly polymorphic techniques It may not capture rare or novel variations
Next - Generation Sequencing (NGS). (Ibrahimi et al. 2024)	Unprecedented depth and details for SNP population genomics	Over 100,000 SNPs were identified in single Date palmgenomes.	Acceptable-grained evolutionary history reconstruction. GWAS for complex traits. Identification of candidate genes for breeding programs	High Cost and computational requirements-Complex data analysis pipelines

Pest Management

Genetic engineering has helped in the management of pests and diseases related to date palm. One striking advancement is the making of the cultivars with the improved tolerance to both biotic and abiotic stresses

(Table 3). For example, in a study, genes providing resistance to major date palm pests like the red palm weevil (*Rhynchophorus ferrugineus*) and the Dubas bug (*Ommatissus lybicus*) were effectively transferred (Abdel-Banat et al. 2024; Haldhar et al. 2022).

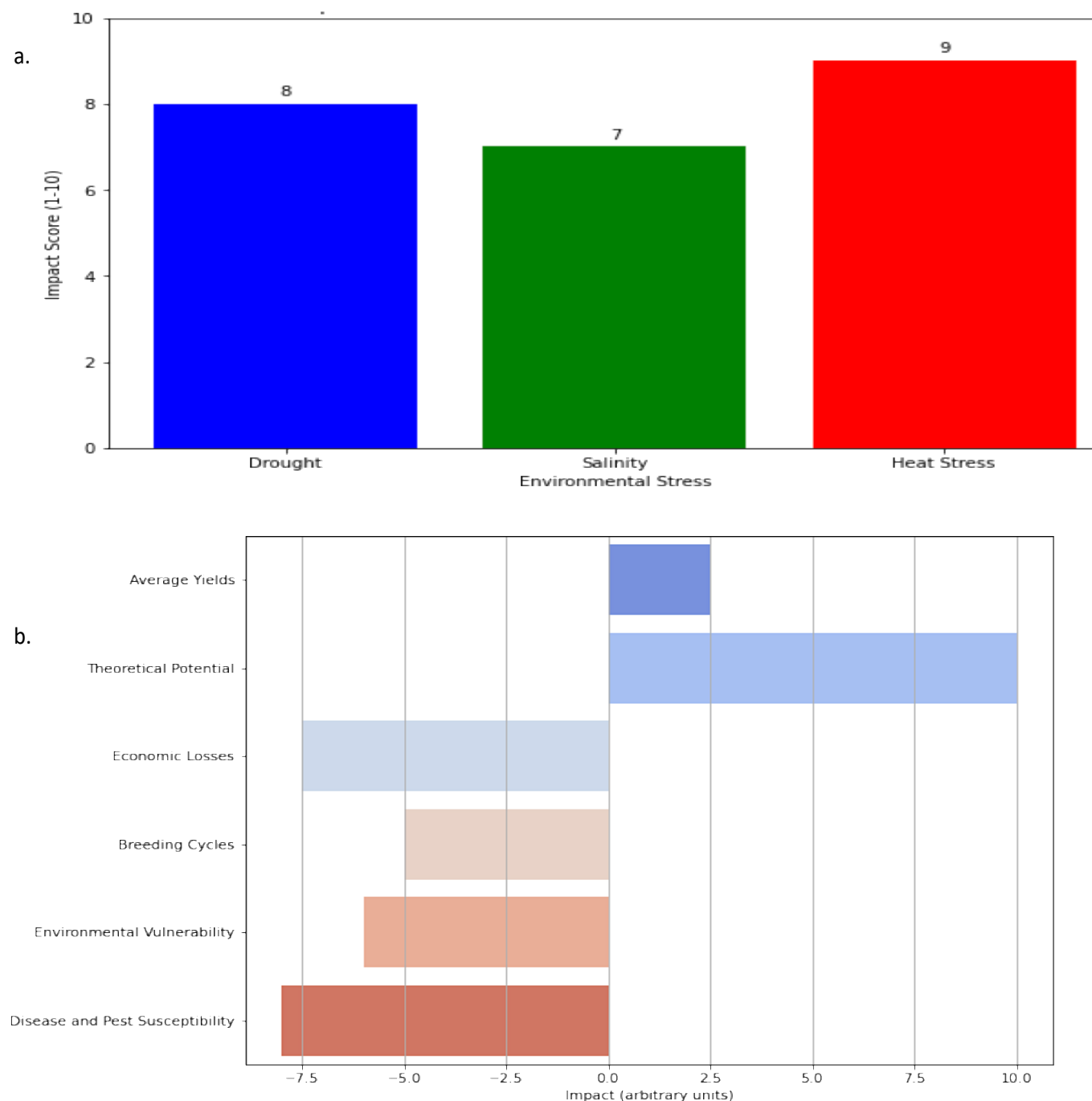


Figure 4. Multifaceted issues facing date palm production: Impact of environmental vulnerability and disease and pest susceptibility on date palm cultivation: (a) This bar chart illustrates the ecological stresses on date palm production and represents the harshness of the drought, salinity and thermal stress on the scale of 1-10, highlighting the significant challenges these environmental factors pose to date palm cultivation. It underscores the urgency of addressing these stresses to ensure the sustainability of date palm production and mitigate food insecurity in vulnerable regions (Kassem et al. 2020; Naveed et al. 2023; El-Bouhssini & Mustapha. 2018). (b): This bar chart illustrates the impact of current challenges in date palm cultivation, highlighting the significant gap between average yields and their theoretical potential, the economic losses due to this gap, and the negative impact of protracted breeding cycles (Shabani et al.2012; Bourg et al. 2023).

In terms of the use of pesticides, one study from the Kingdom of Saudi Arabia (KSA), the trunk injection with “Emamectin benzoate” proved highly effective against red palm weevil (RPW) infestations, achieving 90.6% recovery for apical infestations and 100% success for trunk infestations. However, imidacloprid and deltamethrin showed lower efficacy (Nasracui et al. 2024)

Technology such as Integrating sensor technology into pest management has also shown promise. The higher

level of infestation rates in the sensor-equipped settings stems from the disparity between the detected infections and preventive treatment. Aligning weevil control with sensor data can prevent significant damage, as weevils prefer previously affected palms. Combining seismic sensor monitoring with swift response treatment has proven highly applicable to the reduction of weevil damage and providing a cost-effective substitute to preventive treatments (Mendel et al. 2024). Thus, genetic engineering, advanced monitoring, and targeted pest

control measures offer a comprehensive strategy for managing pests and diseases in date palm.

Table 3. Biopesticides and Biological Control Agents for Date palm Pests

Agent	Target Pest	Mechanism of Action
<i>Beauveria bassiana</i> (Gindin et al.2016; Dembilio et al. 2010)	Red palm weevil	Entomopathogenic fungus
<i>Metarhizium anisopliae</i> (khudhairs et al. 2016)	Dubas bug	Entomopathogenic fungus
<i>Bacillus thuringiensis</i> (Elsharkawy et al. 2022)	Various pests	Bacterial toxins
<i>Trichogramma spp.</i> (El-Shafie et al. 2018; Abdel-galil et al. 2018)	Date moth	Egg parasitoid

Salinity stress management

Salinity stress poses a significant challenge to date palm cultivation, affecting the fruit yield and quality (Fig.4). To deal with these challenges, different steps are being considered, such as the use of nano-fertilisation and disper osmotic in alleviating the salinity stress in the two dates palm cultivars such as "Khastawi" and "Zahdi". This research was piloted over two growth seasons, and various parameters were assessed to determine the impact on fruit quality and productivity(ref). Moreover, both nano fertiliser and Disper osmotic treatments

significantly increased fruit bunch weight, with the highest values observed at the one g/L and two g/L concentrations, respectively (Altemimy et al. 2019). Overall, the results demonstrate that nano fertiliser and dispersed osmotic application mitigate the adverse effects of the salinity stress on date palm productivity, with a significant improvement observed in food yield and quality parameters. These findings suggest the potential of the strategies for sustainable date palm cultivation in saline environments.

Table 4. Techniques used in the Environmental Stress in date palm

Technique Used	Environmental Stress	Experiment Details	Plant Material
RNA Sequencing (RNA-seq) (Radwan et al. 2015)	High Salt Levels (Salinity)	We studied gene activity in Deglet Beida seedling roots after exposure to salt stress.	Seedling Roots
RNA-seq (Yaish et al. 2015)	High Salt Levels (Salinity)	We analysed gene activity in both the leaves and roots of Khalas seedlings after salt stress.	Seedling Leaves & Roots
Small RNA Sequencing (Small RNA-seq) (Mueller et al. 2024)	High Salt Levels (Salinity)	Identified genes targeted by microRNAs (miRNAs) and studied gene activity in Khalas seedling leaves and roots after salt stress.	Seedling Leaves & Roots
RNA-seq. (Al-Harrasi et al. 2018)	Absciscic Acid (ABA) Treatment	Gene activity in leaves of seedlings treated with ABA, a stress hormone, was compared to that of untreated controls.	Seedling Leaves
RNA-seq & Methylomics (El-Rabey et al. 2015)	High Salt Levels (Salinity)	We investigated changes in DNA methylation and gene activity in Khalas seedling roots due to salt stress.	Seedling Roots
Proteomics Analysis (Jana et al. 2019)	Water Depletion (Drought) & High Salt Levels (Salinity)	Analysed protein profiles in 18-month-old palms grown in tissue culture and subjected to drought and salt stress.	Tissue Culture
Metabolomics Analysis (Safronov et al. 2017)	High Salt Levels (Salinity) & Silicon	We analysed metabolite levels in the leaves and roots of seedlings after treatment with salt and silicon.	Seedling Leaves & Roots
RNA-seq & Metabolomics Analysis (Sattar et al. 2017)	Mild Heat, Water Depletion (Drought), & Combined Stress	Analysed the genes and metabolites in seedlings subjected to mild heat, drought and combined stress conditions.	Seedlings

Genome Editing for Trait Improvement

Moreover, the emergence of editing techniques, such as CRISPR-Cas 9, has revolutionized the precision and efficiency of data and palm genetic improvement. Researchers have leveraged these tools to target and modify specific genes responsible for the desirable traits, such as food, quality, riling of the fruit and post-harvest shelf life. This precise, targeted approach to trade improvement has the potential to overcome the limitation

of conventional reading and generate palm cult with enhanced commercial value (Razzaq, et al: 2019; Khan et al.2012).

Advancements in In Vitro Propagation and Micropropagation

In vitro propagation and micropropagation techniques have been instrumental in addressing the challenges associated with the conventional vegetative propagation of date palms (fig.6). Traditional of based propagation is

often slow, labour-intensive and limited in scale, hence hampering the rapid dissemination of improved date palm cultivars.

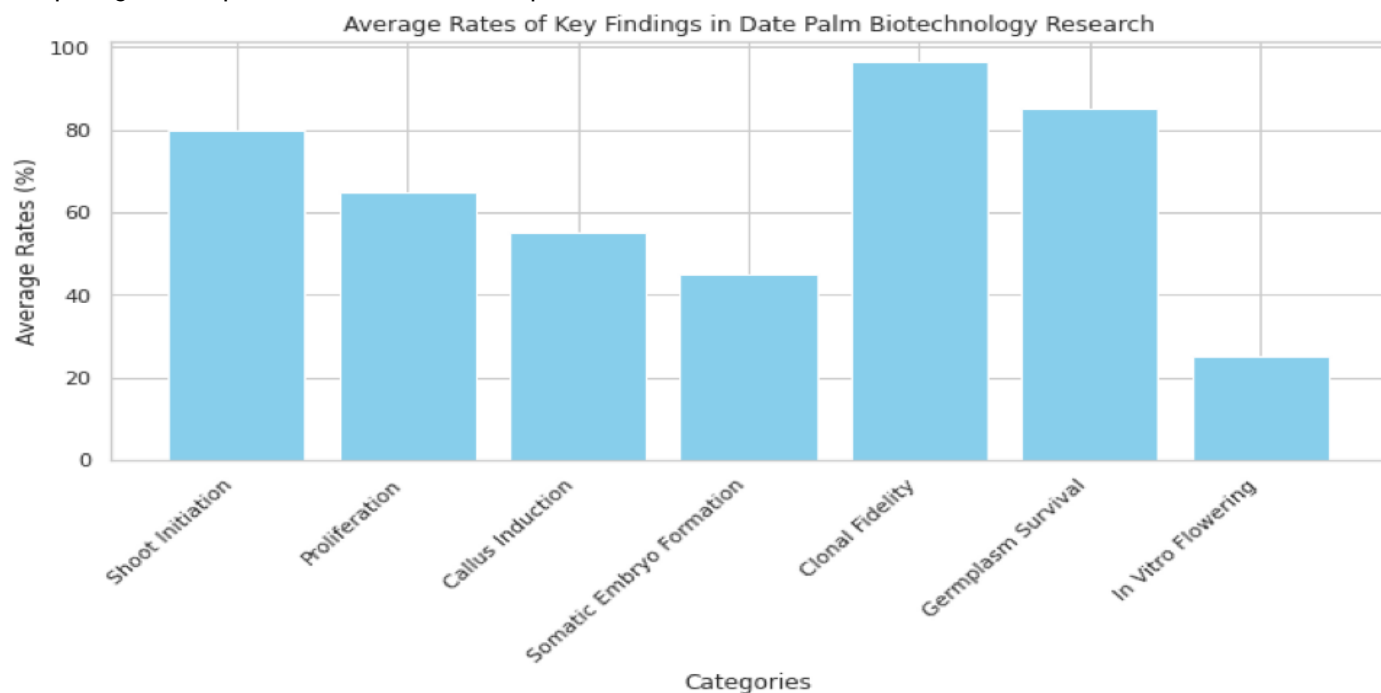


Figure 5. Most of the key findings in the date palm research have been focused on its clonal fidelity and germplasm survival

Significant development has been made in terms of developing highly efficient in vitro propagation protocols for Date palms using various explant sources, such as shoot tips, lateral buds, and somatic embryos. Till now, continuous progress has been made in the protocol

upgradation optimized the media composition, growth regulator, concentrations, and culture conditions to achieve high rates of shoot multiplication and root formation, enabling mass production of the type disease-free date palm plantlets (Table 5)

Table 5. In vitro propagation for Date palm

Explant type	Optimal media	Key growth regulators	Multiplication rate
Shoot tips (Al-Mayahi & Ahmed Madi 2014.)	MS + supplements	BAP,2iP, NAA	Up to 8-fold
Lateral buds (Zayed & Zeinab 2017)	½ MS + additives	TDZ, IBA	Up to 12-fold
Somatic embryos (Hussain et al 2012)	DCR media	2,4-D, BAP	Up to 20-fold

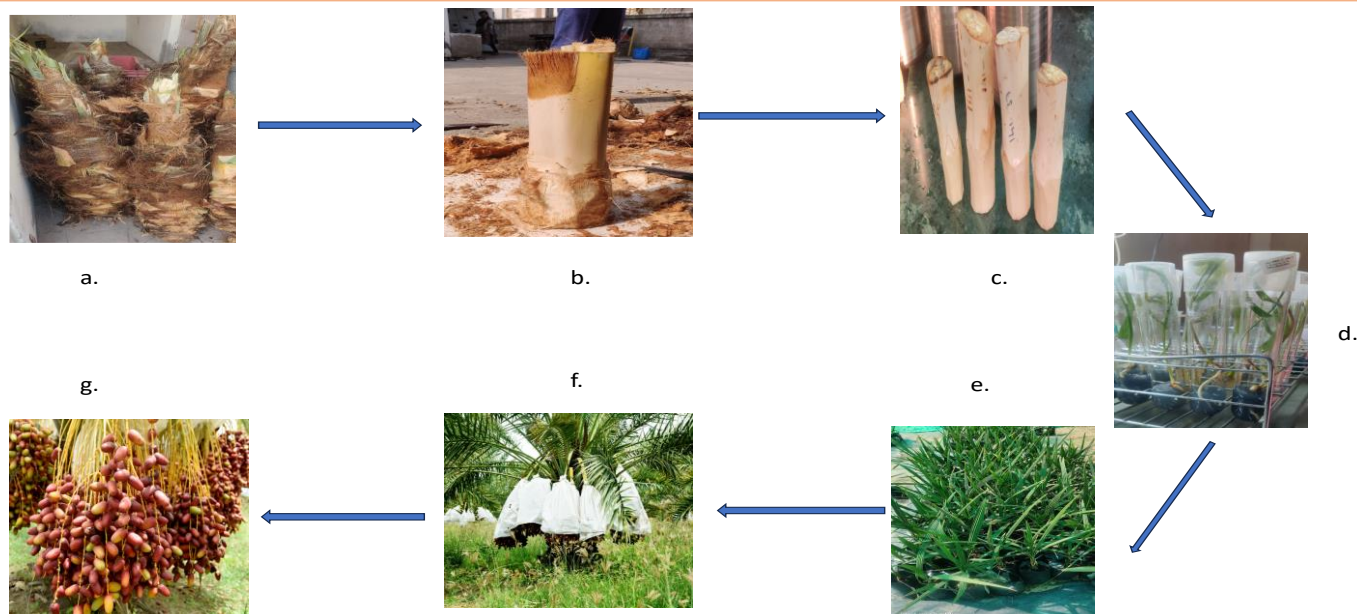


Figure 6. In vitro micropropagation of the local variety of India's date palm in the Kutch area. (a) Local date palm offshoot (b)(c), shoot tip after the removal of outer leaves. (d) Rooted Plantlets in specialised MS medium. (e) After the acclimatization in free-living condition. (f)(g) Fully matured plant with the fruits in Mundra, IN

Bioreactor-Based Systems

The application of bioreactor based micropropagation has significantly enhanced the scalability and cost-effectiveness of the date palm *In vitro* propagation. Utilizing the liquid media and automated control of environmental parameters, these advanced systems have demonstrated an increase in the proliferation and growth rates of the date palm cultures by up to 40 % while reducing labour costs by approximately 50 % (Murthy et al. 2023; Lee et al. 2023).

In terms of the liquid-based bioreactors, in particular, they have shown a 30- 50 % increase in biomass accumulation, and the automation in this system minimizes the contamination risks, leading to higher yields and consistent quality of the plantlets. These reliable. *In vitro* techniques are pivotal for the rapid dissemination of the improved date palm cultivars and the conservation of endangered germplasm. As genetic engineering has enabled the development of date palm-based biofactories for producing high-value compounds such as vaccines, therapeutics proteins, and industrial enzymes, thereby diversifying economic opportunities and contributing to sustainable plant-based production platforms (Niego et al. 2023).

This technological advancement is projected to significantly impact the global market, with plant-derived bioactive compounds expected to reach USD 4.3 billion by 2025 (Dhanaraju et al. 2022). Genetic modification, including enhanced pest resistance and improved drought and salt tolerance, is crucial for increasing yield and making date palm cultivation viable in arid regions. As genetic engineering and editing tools like CRISPR-Cas9 evolve, they will play a critical role in the development of superior date palm cultivars, driving the industry towards greater productivity, sustainability and resilience.

Challenges and AI-Powered Solutions

Even though a significant advancement in the date palm *in-vitro* propagation, this industry still faces many challenges, included the limited explant availability and its quality, high rates of somaclonal variation, recalcitrance to *in vitro* regeneration, challenges in acclimatization and field establishment, and the need for scaling up and automation. The application of AI, that is, AI-ML algorithms, has the potential to revolutionize various aspects of date palm micropropagation, from the optimization of the culture conditions to the production of plant regeneration potential. The AI-based models can be used to analyse the complex interaction between different media components, growth regulators, and environmental factors and predict the optimal conditions for improved shoot, multiplication route formation, and acclimatization. These models can significantly reduce the time and resources required for protocol development and optimization and will increase the rate of innovation for date palm *in vitro* propagation. Moreover, AI-powered computer vision and image analysis techniques have been employed to monitor and evaluate the development and growth of these palm cultures in real time. By analysing these high-resolution images of the cultures, these systems can detect any

sign of somaclonal variations. Identify the optimal harvest time for the plantlets and monitor the transition from *in vitro* to *ex-vitro* conditions. This automated and data-driven approach could help to ensure genetic fidelity and the successful establishment of the regenerated date palm.

Additionally, researchers have leveraged machine learning algorithms to develop the predictive models for date palm regeneration potential based on various factors such as genotype, ex-plant type and culture condition. These models can help the breeders and propagative to identify the most responsive genotypes and optimize the propagation protocols for recalcitrant cultivars, thereby enhancing the efficiency and scalability of the date palm.

The integration of AI-powered solutions in *in vitro* propagation is still an emerging field. Still, the early results have been auspicious because of these technologies, which continue to evolve and become more accessible. These technological steps hold the potential to address the critical challenges faced by the industry, enabling the far-reaching production of high quality true to type date palm planting materials (Mohammed et al. 2023).

Revolutionizing Agriculture with IoT: Enhanced Efficiency, Yield, and Sustainability

The integration of IoT technologies in agriculture has demonstrated substantial benefits across various domains. In irrigation management, IoT-controlled systems have significantly increased crop yields and improved water use efficiency compared to traditional methods. Over a span of five years, the yield per hectare has consistently risen, while the efficiency of water usage has also seen a marked improvement, indicating a more sustainable approach to farming (Benhmad et al. 2024). Furthermore, IoT solutions in subsurface irrigation have led to remarkable water savings, with a 70% reduction in water usage compared to conventional practices. This not only conserves a vital resource but also reduces costs for farmers (fig.6) (Mohammed et al. 2021). Additionally, the acclimatization of tissue culture plantlets through IoT-controlled environments has resulted in higher survival rates, showcasing the technology's potential to enhance plant health and productivity. Overall, the adoption of IoT in agriculture promises to revolutionize the industry by optimizing resource use, increasing efficiency, and ensuring sustainable growth (Figure 7).

The integration of AI and IoT technologies holds immense promise for revolutionizing date palm cultivation in countries which are majorly working in the date palm industry, especially in Gulf countries and south Asian countries (Gibril et al. 2023; Ahmed et al. 2023). By optimizing irrigation, enhancing subsurface irrigation systems, streamlining tissue culture plantlet acclimatization, and improving cold storage management, AI and IoT offer solutions to critical challenges faced by date palm farmers. However, challenges such as infrastructure limitations, high implementation costs, and data security concerns remain. Constant exploration and improvement in this

field are crucial for enhancing date palm farming practices which would support the agricultural sector.

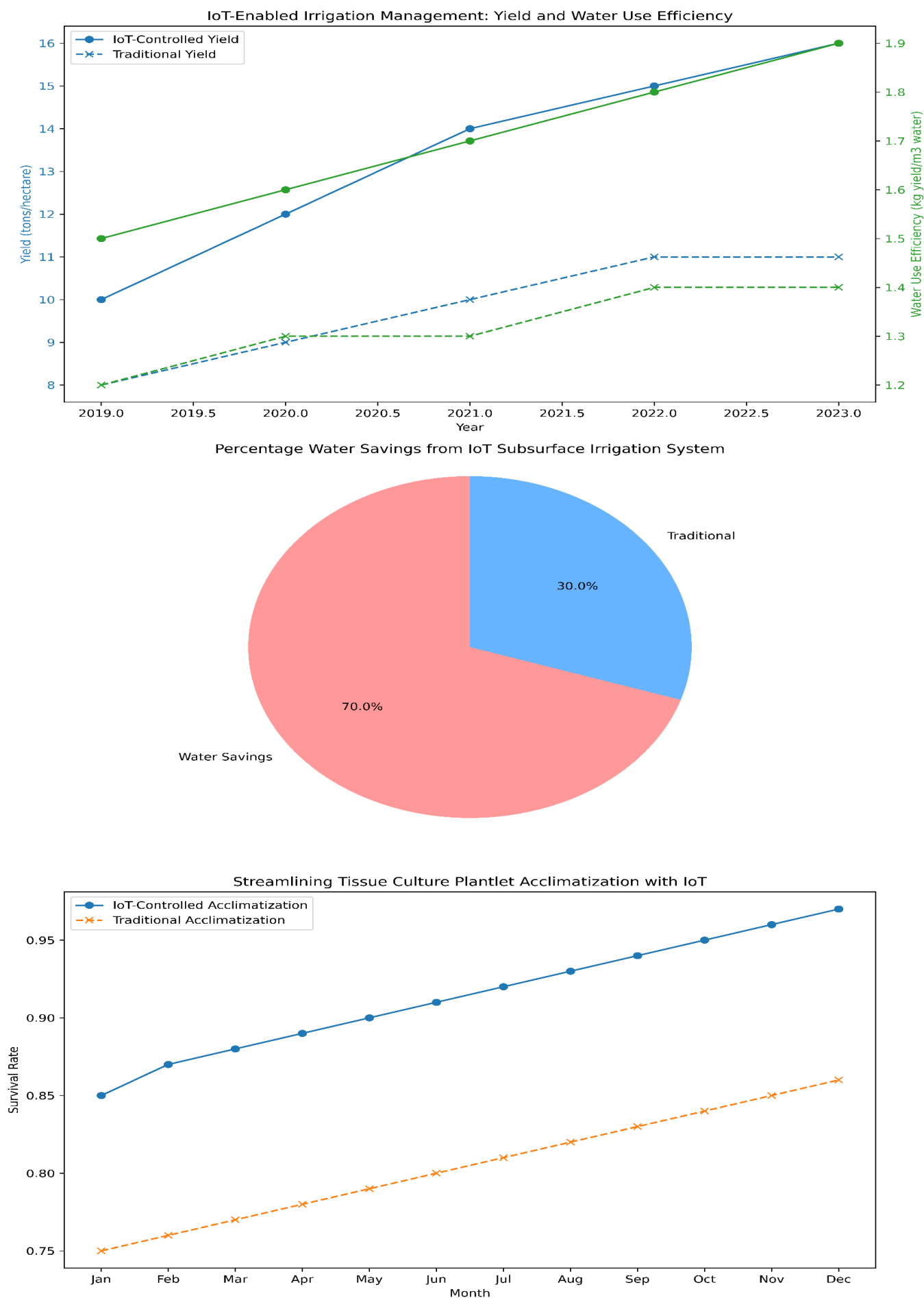


Figure 7. Application of IoT technologies in date palm agriculture (Culman et al. 2020 ; Abrteimel et al. 2022)

Computer Vision and Image Analysis

The recent progressions in computer vision and deep learning have significantly improved the accuracy and effectiveness of date palm propagation and monitoring. Specifically, the models in deep learning, such as “Convolutional neural networks” (CNN) and the vision transformers, have been effectively employed for disease detection, tree inventory, and segmentation tasks. For instance, a study utilizes deep learning models, including the Segformer and UperNet-Swin transformers, to segment date palm trees from the UAV-based and aerial images. These models demonstrated a high accuracy, with the mean intersection over union (mIoU) values varying from 85% to 86.3% and the mean F1 -scores between 91.6% and 92.4%. The Segformer model, in particular, outperformed CNN-based models in both accuracy and computational efficiency, making it a valuable tool for the large-scale mapping of the date palm trees (Khan et al.2012)

Another research applied deep learning techniques for disease detection in the date palm, using a transfer learning approach with the Inception-ResNet network. This method achieved high accuracy in classifying palm leaves into categories such as healthy, white scale, and brown spots’ use of pre-trained models allowed for rapid and effective adaptation to the specific characteristics of the date palm diseases, demonstrating the potential of AI in enhancing the agriculture management practices (Jaradat et al.2016).

Moreover, the application of CNNs for individual palm tree detection in RGB imagery has proven its effectiveness in terms of supporting tree inventory efforts. A study conducted in the Alicante province of Spain employed CNNs to map the *Phoenix dactylifera* and *Phoenix canariensis* palms, attaining a mean average precision of 0.861. Such a method enabled the creation of a comprehensive spatial inventory of palm trees, facilitating long-term monitoring and management (Diaz Rodriguez et al.2023).

These advancements highlight the transformative potential of AI and computer vision in agricultural practices, particularly for the propagation and monitoring of date palms. Integration of these technologies can significantly enhance the precision, efficiency, and scalability of agricultural operations, providing valuable insights for farmers and researchers.

Integration with Precision Agriculture

The integration of AI-ML has yielded promising results in the various aspects of date palm biotechnology. However, several challenges still need to be addressed, such as the inclusion of the availability of high-quality datasets for the machine learning algorithms, interpreting and validating model outputs, and the need for interdisciplinary collaboration among biotechnologists, computer scientists and agriculture experts. The ethical and accountable improvement and employment of AI-powered solutions in agriculture will be a crucial step to ensure long-term sustainability and social acceptance. Despite the remarkable advancements, the date palm industry continues to face several challenges that require concentrated research

efforts and innovative solutions. These challenges include climate change water scarcity, genetic erosion and conservation, increasing pests and diseases, postharvest handling and processing, value addition and product diversification.

For instance, climate change impacts, such as rising temperatures, prolonged droughts and increased salinity, pose significant threats to date palm cultivation, particularly in the arid regions. Furthermore, the genetic diversity loss in a date palm germplasm due to new urbanization in the agricultural land, habitat destruction and the prioritization of the few commercially successful cultivars could limit the ability to adapt to changing environmental conditions and market demands. Addressing these challenges would require a sustained interdisciplinary research effort and the integration of emerging biotechnologies such as gene editing, high throughput phenomics, synthetic biology, and advanced computational biology techniques. The responsible and ethical development and its deployment, along with the robust regulatory frameworks, risk assessment protocols and public engagement efforts, are essential. Hence, the synergistic integration of AI-ML and emerging biotechnologies holds great promise for the future of the date palm industry, leading to innovative solutions for addressing complex challenges such as climate adaptation, sustainable intensification, and the development of value-added products from date palm.

Conclusion

A remarkable progress in date palm genomics and biotechnology has opened up new frontiers for this culturally and economically significant crop. The presence of high-quality genome sequences and genetic resources combined with advanced tools such as genome editing, genetic engineering and OMICS technologies has revolutionized our ability to understand and improve the date palm traits.

Genomics-assisted breeding approaches have accelerated the improvement of such elite cultivars with improved yield, fruit quality and resilience to biotic and abiotic stresses. Genetic engineering and precision genome editing techniques like CRISPER- Cas 9 have unlocked novel value-added traits, including pest and disease resistance, enhanced tolerance from abiotic stress and the ability to produce the high-value compounds in the date palm-based bio factories.

Techniques from in vitro propagation methods such as somatic embryogenesis and organogenesis, have addressed the bottlenecks of conventional vegetative propagation, enabling the rapid dissemination of improved cultivars and the conservation of germplasm. Moreover, the integration of OMICS technologies has provided unprecedented insights into the molecular mechanism underlying the key traits, showing the steps for targeted metabolic engineering and the development of date palm-based production platforms for valuable compounds.

The application of AIML algorithms has further revolutionize the numerous features of date palm farming, from optimizing the in vitro propagation protocols and monitoring the cultural growth to

predicting the plant regeneration potential and accelerating the genomic analysis and the breeding programs. These advancements have been remarkable; the challenges related to climate change, water, scarcity, genetic erosion, pests, and the application of AI-ML algorithms have further various aspects of date palm biotechnology, from optimizing in-vitro propagation protocols and monitoring culture growth to predicting plant regeneration potential and accelerating genomics analysis and breeding programs.

As we look forward to the future, the date for industry stands at the cost of a new era where biotech technology, coupled with traditional knowledge and sustainable practices, holds the promise of ensuring food, security, economic prosperity, and environmental stewardship in the arid regions. The advancement highlighted in this review the foundation for a vibrant and resilient palm industry capable of meeting the challenges of the 21st century and beyond.

Contributions from Authors

Conceptualization, Nikhil Pandey (NP); Methodology, NP and PT; Software, Naina Pandey (NAP) PT.; validation, NP and PT; formal analysis, HK, YS and PG.; investigation, NP, PT; resources, HK, YS data curation, NP; Writing - original draft preparation, NP & PT writing – review and editing, NP; visualization, NP, NAP, PT supervision, NP. All the authors have read and agreed to the final version of the manuscript.

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Declaration of Interests

All authors declared no conflicts of interest

Data Sharing

All relevant data are within the manuscript.

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