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Abstract: In many parts of the Asia, particularly in the arid regions of the middle east the date palm i.e., *Phoneix dactylifera L.* is considered a significant plant both culturally and economically. Over the past decade numerous biotechnological tools have been applied to revolutionize the date palm research and its cultivation process. In this comprehensive review, we provided the in depth overview of the cutting edge developments in the date palm biotechnology, mentioning the important areas such as genomics, genetic engineering, in vitro propagation, omics technologies, and the integration of the artificial intelligence and machine learning (AI-ML).Due to these advancements, in the date palm production how the date palm production lead the production of superior date palm cultivars with the improved yield, fruit quality and resilience to biotic and abiotic stresses. Also it explores the application of the biotech tools in the enhancing pest and disease management strategies, increasing date palm productivity and developing the date palm based bio-factories for the production of high value compounds. This review highlights the current challenges faced by the date palm industries, including the 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.

Keywords: date palm; genomics; genetic diversity; genome editing; pest resistance; disease resistance; in vitro propagation; Ai-ML; precision agriculture
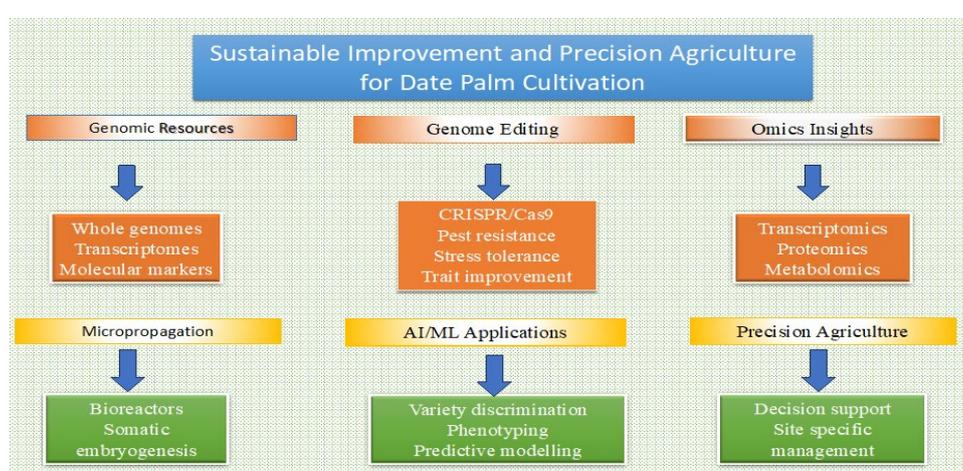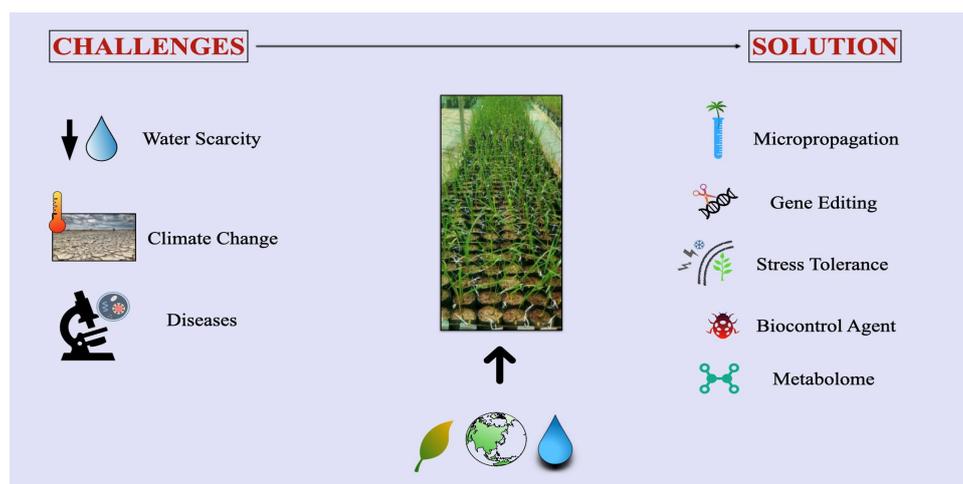
Graphical Abstract: The sustainable improvement and precision agriculture in the DP cultivation will pave way for the arid and semi-arid area development in countries which are suffering from the fertile soil erosion.

1. Introduction

The date palm (*Phonix dactylifera L.*) is a highly revered and versatile fruit crop that has been an integral part of the cultural and economic landscape of the Middle east, North Africa, and the parts of Asia for centuries. Dates, the sweet and nutritious fruit of the date palm (DP), are not only a staple food item but also a significant source of income and employment in many producing countries [1,2]. Beyond there culinary uses, DP also provide the raw materials for various products, including construction materials, furniture, and handicrafts, further underscoring their multifaceted importance [3–5].

Global date production has steadily increased over the past decades reaching over 8 million metric tons in 2022 (Figure 1) [6,7]. However, the DP industries face numerous challenges such as limited water resources, pests and diseases, genetics erosion and the need for improved postharvest handling and processing [8,9]. In response to these challenges researchers have increasingly turned to the powerful tools of biotechnology to enhance the productivity, sustainability and resilience's of DP cultivation [10–12]
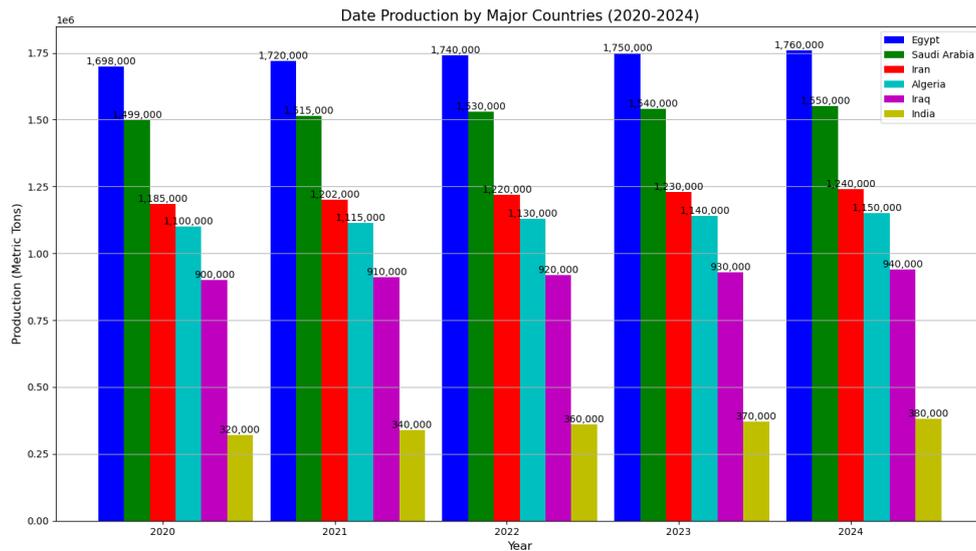
Figure 1. Global Dates production in the major date producing countries along with the India's global production.

In this comprehensive review, we explore the recent advancements in the DP biotechnology that have significantly impacted various aspects of the industry. We cover key research areas including the genomics, genetic engineering, in vitro propagation and the integration of artificial intelligence (AI) and machine learning. We highlighted how these innovations have led to the development of superior DP cultivars, improved pest and disease management strategies, and enhanced DP productivity and product quality.

Furthermore, highlighted the role of AI-ML into the enhancement of effective and efficient methods of the in vitro propagation protocols for developing the predictive models for trait improvements. Additionally, this review discusses the current challenges faced by the DP industry and how biotechnological tools, coupled with the AI based approaches can be leveraged to address these challenges and ensure the long-term sustainability of the DP cultivation.

All these insights have the potential applications in the enhancements of DP traits, the developments of molecular markers and the construction of the comprehensive metabolic models for the targeted metabolic engineering and the production of the valuable compounds. Overall, this review aims to provide a comprehensive understanding of the current state of the DP 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.
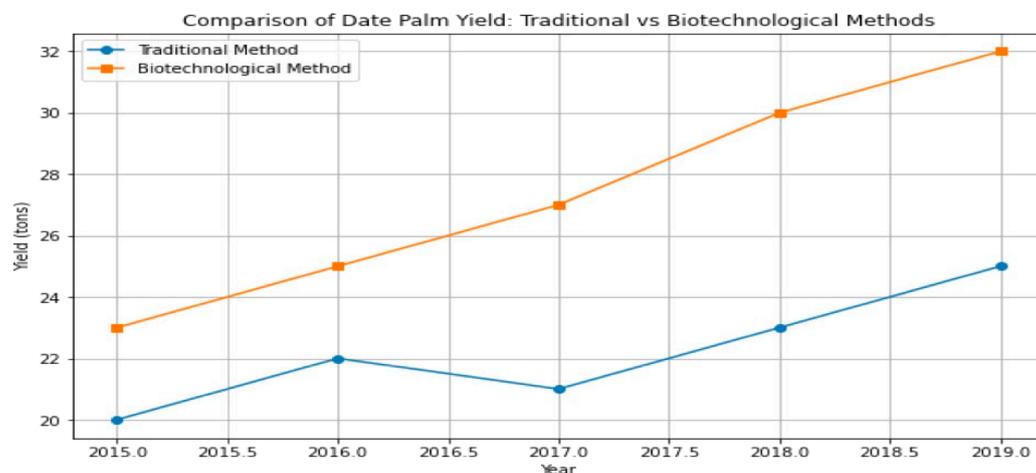

Figure 2. Date palms cultivated using traditional and biotechnological methods from 2015 to 2019.

2. Advances in DP Genomics

The availability of high-quality genome sequences has been a crucial enabler for the rapid progress in the DP biotechnology [13]. In 2011, a team of researchers from Qatar published the first draft genomes sequences of the DP, providing the in depth understanding of the genetic makeup and the identification of the valuable trait [14]. After that several research groups have further refined and expanded the genomic resources available for date palms leading to the significant advancements in our knowledge of the crops genetics [15,16].

2.1. Genetic linkage Maps and Marker-Assisted Selection

One of the key achievements in the DP genomics has been the development of the dense genetic linkage maps and high throughput genotyping platforms. Researchers have utilized the variety of molecular markers such as simple sequences repeats (SSRs) [17–19], single nucleotide polymorphisms (SNPs) [20,21], and diversity arrays technology (DArT) markers [22,23], 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 important traits such as fruit quality, yield and biotic and abiotic stress tolerance as shown in Table 1 [24,25].

Table 1. Major genomic resources developed for the DP.

Resource	Findings
Draft genome sequence	First draft genome assembly of the khalas DP variety. [21]
High density genetic map	Genetic map with 1,892 SNP & 173 SSR markers across 18 linkage groups [26].
Genome-wide SNP array	Identification of the sex chromosome (Ref). Localized the gender segregating region in DP to LG12, estimated size of the region approx. 5-13Mb. [16]
Pan-genome analysis	Identified 158278 gene families across 62 DP accessions. Explored the polymorphism for DP genetic diversity. Possible selective sweeps within the species and gene network associated with the fruit traits. [27]

Based on such genome resources DP breeders have increasingly adopted marker -assisted selection (MAS) to accelerate the development of improved cultivars (Figure 3) [28]. 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 [29,30]. This approach has led to the development of new DP varieties with enhanced characteristics such as higher yields, larger fruit size, and improved shelf life.
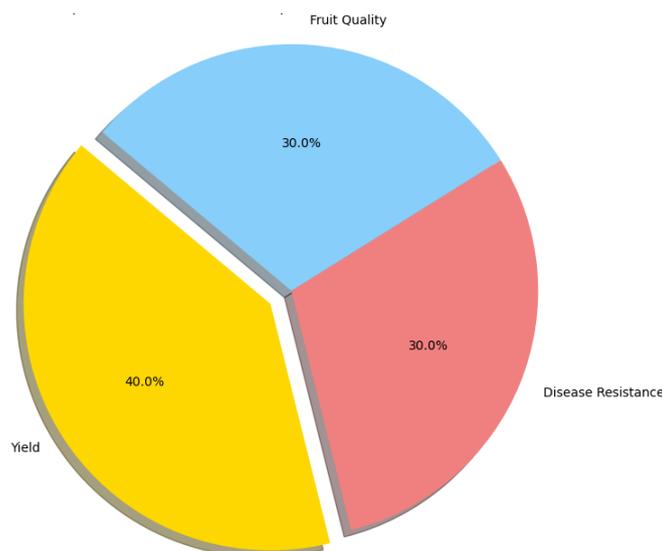
Figure 3. The distribution of MAS's impact on yield, disease resistance, and fruit quality in date palm cultivation, highlighting the significant role MAS plays in improving these critical areas.

2.2. Exploitation of Genetic Diversity and Domestication History

Recent advancements in the next generation sequencing (NGS) technologies have significantly enhanced our understandings of the genetic diversity and domestication history in the DP. The NGS-based genotyping has allowed researchers to analyze genetic variation within and among the DP 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 [31,32]. Leveraging this genetic diversity, GWAS have identified specific genomic regions and candidate genes associated with the important agronomic traits, such as fruit yield, quality, and stress tolerance. These discoveries have been pivotal for marker assisted breeding and genetic engineering efforts aimed at improving the DP cultivars. Additionally, breeders have integrated genomic selection approaches, which utilizes the genome wide molecular markers to predict the breeding value of individuals. This integration has led to the significant improvements in the rate of genetic gain, with some studies reporting up to 30 % increase in the fruit yield and 20 % improvements in the fruit size compared to conventional breeding methods (Figure 2) [33]. Collectively, these advancements underscore the transformative impact of genomics on the DP research and breeding, paving the way for sustainable development and conservation of this culturally and economically important crop.

2.3. Genome Editing Applications

The advent of CRISPER-Cas9 has enabled the precise targeting and modification of specific genes in DP, opening up the new possibilities for the trait improvements [34,35]. The use of genome editing tools to enhance the traits like quality of fruit, shelf life and tolerance toward stress has demonstrated the potential of this approach for DP varietal developments (Table 3). These advancements in the DP genomics have been instrumental in addressing the industries 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 a 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.[36]	High throughput screening for genetic variations	Over 100 polymorphic bands identified in various genotypes	Population structure analysais (Soma clonal Variation détection -Germplasm management)	Low marker specificity - Dominant markers complicate heterozygosity analysis-
AFLP studies [37,38]	Multi locus fingerprinting for comprehensive diversity assessment	Up to 300 polymorphic markers detected per study. Shannon-Weaver diversity index ranging from 0.24 to 0.48 across population.	Evolutionary history reconstruction Identification of unique genetic signatures Marker assisted selection	Technically demanding and expensive Requires specialized equipment and analysis software
Microsatellite Markers [39]	Highly polymorphic loci for accurate cultivar identification and genotyping.	Able to distinguish >90% of cultivars with high accuracy Unique markers identified for specific cultivars like Medjool and Zahed.	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 [40]	Targeting functional regions for the 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 (CDDP) [41,42]	Cost effective genotyping platform for large population studies.	Efficient analysis for pre designed primer set for conserved genomics regions.	Rapid diversity assessment in germplasm collection. Population genetic analysis and gene flow studies	Limited marker resolution compared to highly polymorphic techniques May not capture rare or novel variations
Next - Generation Sequencing (NGS) [43]	Unprecedented depth and details for SNP population genomics	Over 100,000 SNPs identified in single date palm genomes.	Fine grained evolutionary history reconstruction. GWAS for complex traits. Identification of candidate genes for breeding programs	High Cost and computational requirements-Complex data analysis pipelines

3. Pest Management

Genetic engineering has helped in the management of pest and the disease related to DP. One striking advancement is the making of the cultivars with the improved tolerance to both abiotic and biotic stresses (Table 3). For example, in an important study, gene providing resistance to major DP pests like the red palm weevil (*Rhynchophorus ferrugineus*) and Dubas bug (*Ommatissus lybicus*) were effectively transferred [44].
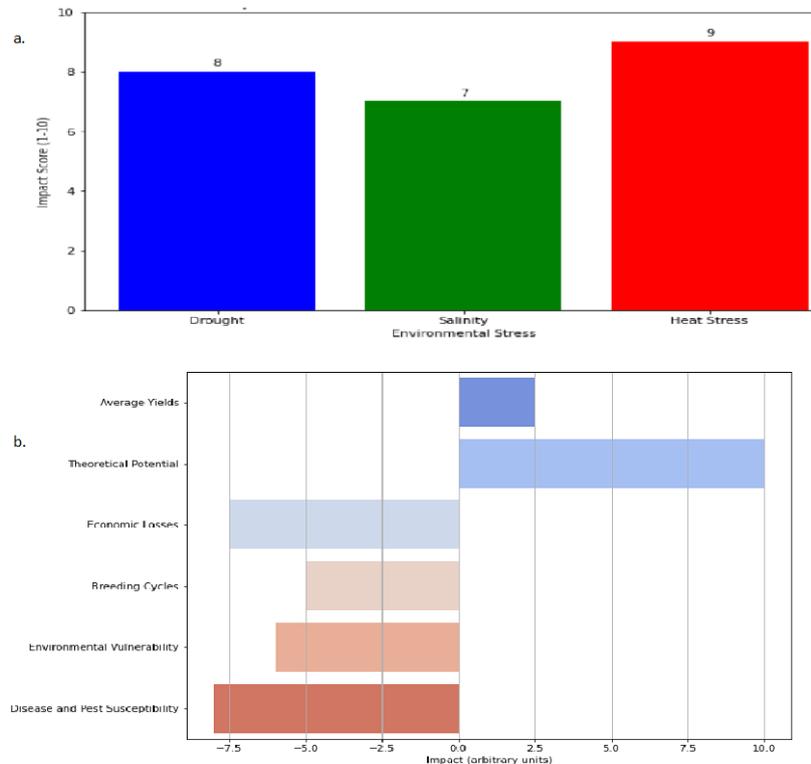

Figure 4. Multifaceted issues facing date palm production: Impact of environmental vulnerability and disease and pest susceptibility on DP cultivation: (a) This bar chart illustrated the environmental stresses on the DP production and represents the severity of drought, salinity and heat stress on the 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 DP production and mitigate food insecurity in vulnerable regions [45–47]. (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 [48,49].

In terms of use of pesticides, one such studies were carried out in in the Kingdom of Saudi Arabia (KSA), 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 [50].

Technology such as Integrating sensor technology into pest management has also shown promise. The high infestation rates in sensor-equipped settings stem from the disparity between 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 prompt response treatments has proven highly effective in reducing weevil damage and providing a cost-efficient alternative to preventive treatments [51,52]. Thus, genetic engineering, advanced monitoring, and targeted pest control measures offer a comprehensive strategy for managing pests and diseases in DP.

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

Agent	Target Pest	Mechanism of Action
Beauveria bassiana [53,54]	Red palm weevil	Entomopathogenic fungus
Metarhizium anisopliae [55]	Dubas bug	Entomopathogenic fungus
Bacillus thuringiensis [56]	Various pests	Bacterial toxins
Trichogramma spp. [57,58]	Date moth	Egg parasitoid

4. Salinity Stress Management

Salinity stress poses a significant challenges to DP cultivation, affecting the fruit yield and quality(Figure 4). To deal with this challenges different steps are being considered such as use of nano-fertilisation and Disper Osmotic in alleviating the salinity stress in the two dates palm cultivars such as "Khastawi"and "Zahdi". This study was conducted 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 treatment s significantly increased fruit bunch weight with the highest values observed at the 1 g/L and 2 g/L concentration, respectively [59].Overall the results demonstrate that nano fertiliser and disperse osmotic application mitigate the adverse effects of salinity, stress on date productivity with a significant improvement, observed in food yield and quality parameters. These finding suggest the potential of the strategies for sustainable DP cultivation in saline environment.

Table 4. Techniques used in the Environmental Stress in DP.

Technique Used	Environmental Stress	Experiment Details	Plant Material
RNA Sequencing (RNA-seq) [60]	High Salt Levels (Salinity)	Studied gene activity in Deglet Beida seedling roots after exposure to salt stress.	Seedling Roots
RNA-seq [61]	High Salt Levels (Salinity)	Analyzed gene activity in both leaves and roots of Khalas seedlings after salt stress.	Seedling Leaves & Roots
Small RNA Sequencing (Small RNA-seq) [62]	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 [63]	Abscisic Acid (ABA) Treatment	Compared gene activity in leaves of seedlings treated with ABA, a stress hormone, to untreated controls.	Seedling Leaves
RNA-seq & Methylomics [64]	High Salt Levels (Salinity)	Investigated changes in DNA methylation and gene activity in Khalas seedling roots due to salt stress.	Seedling Roots
Proteomics Analysis [65]	Water Depletion (Drought) & High Salt Levels (Salinity)	Analyzed protein profiles in 18-month-old palms grown in tissue culture and subjected to drought and salt stress.	Tissue Culture
Metabolomics Analysis [66]	High Salt Levels (Salinity) & Silicon	Analyzed metabolite levels in leaves and roots of seedlings after treatment with salt and silicon.	Seedling Leaves & Roots

RNA-seq & Metabolomics Analysis [67]	Mild Heat, Water Depletion (Drought), & Combined Stress	Analyzed genes and metabolites in seedlings subjected to mild heat, drought, and combined stress conditions.	Seedlings

4. Genome Editing for Trait Improvement

More, the emergence of editing technique, such as CRISPER-Cas 9 has revolutionized the precision and efficiency of the date, 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 [68,69].

5. Advancements in In Vitro Propagation and Micropropagation

In vitro propagation and micro propagation techniques have been instrumental in addressing the challenges associated with the conventional vegetative propagation of the date palms (Figure 6). Traditional of based propagation is often slow, labor intensive and limited in scale, hence hampering the rapid dissemination of improved date palm cultivars
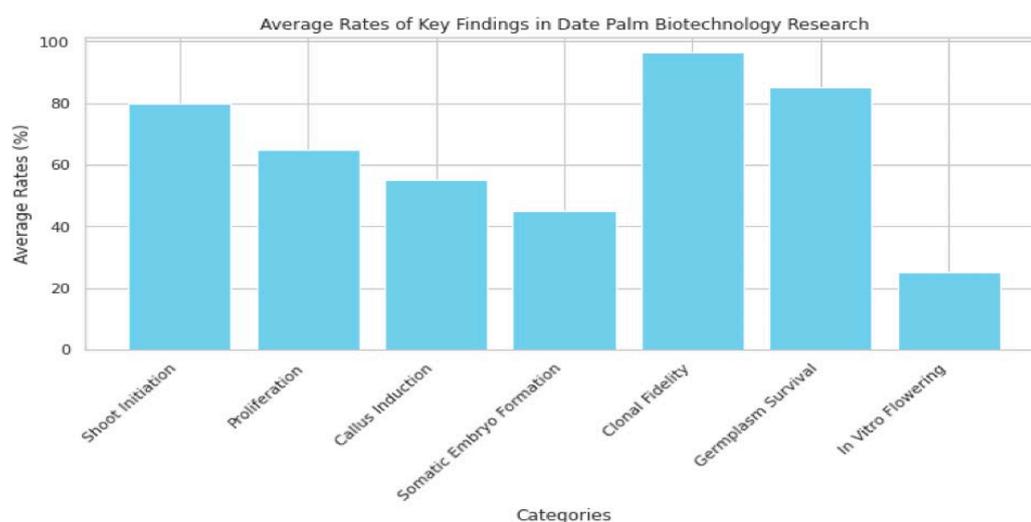

Figure 5. Most of the key findings in the DP research has been focused on the its clonal fidelity and germplasm survival.

Significant progress has been made in developing highly efficient in vitro propagation protocols for date palms, using various explant sources, such as shoot tips, lateral buds and somatic embryo. Till now continuous progress has been done 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 the mass production of the true to type disease, free date plantlets (Table 5)

Table 5. In vitro Propagation for DP.

Explant type	Optimal media	Key growth regulators	Multiplication rate
Shoot tips [70]	MS + supplements	BAP,2iP, NAA	Up to 8-fold
Lateral buds [71]	½ MS + additives	TDZ, IBA	Up to 12-fold

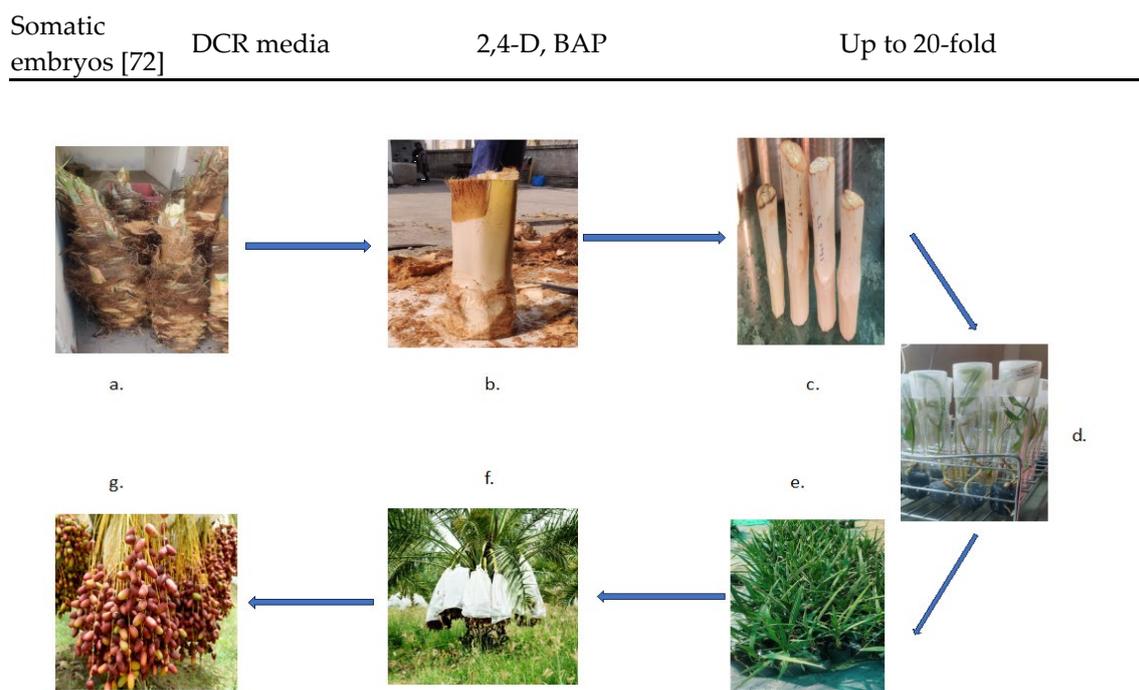| Somatic embryos [72]	DCR media	2,4-D, BAP	Up to 20-fold

Figure 6. In vitro micropropagation of local variety of India's date palm in 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.

6. Bioreactor-Based Systems

The application of bioreactor based micropropagation has significantly enhanced the scalability and cost effectiveness of the DP 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 DP cultures by up to 40 percent, while reducing the labor costs by approximately 50 percent [73,74]. In terms of the liquid-based bioreactors, in particular, have shown a 30- 50 percent increase in the 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 DP cultivars and conservation of endangered germplasm. As genetic engineering has enabled the development of the DP based bio factories for producing the high value compounds such as vaccine, therapeutics proteins, and industrial enzymes, thereby diversifying the economic opportunities and contributing to sustainable plant-based production platforms [75]. 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 [76]. Genetic modification, including enhanced pest resistance and improved drought and salt tolerance are crucial for the increase in yield and making the DP cultivation viable in arid regions. As genetic engineering and editing tools like CRISPR-Cas9 evolve, they will play a critical role in the developing of superior DP cultivars, driving the industry towards greater productivity, sustainability and resilience.

7. Challenges and AI-Powered Solutions

Despite the significant advancement in the date palm in-vitro propagation, the 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 have the potential to revolutionize various aspects of DP micropropagation, from the optimization of the culture conditions to the production of plant regeneration potential. The AI based

models can be used to analyze the complex interaction between different media components, growth regulators, and environmental factors and predict the optimal conditions for improved shoot, multiplication route formation and its acclimatization. These models can significantly reduce the time and resources required for protocol development and optimization does accelerating the pace of innovation in the date palm invitro propagation. Moreover, the AI powered computer vision and image analysis techniques have been employed to monitor and evaluate the growth and development of palm cultures in the real time. By analyzing these high-resolution images of the cultures, these systems can detect any sign of somoclonal variations. Identify the optimal harvest time for the plantlets, and monitor the transition from in vitro to ex vitro conditions. These type of automated and data driven approach could help to ensure the genetic fidelity and the successful establishment of the regenerated DP

Additionally, researches have leverage machine learning algorithms to develop the predictive models for DPA 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 DP.

The integration of AI powered solutions in in vitro propagation is still an emerging field, but the early result has been very promising as these technologies continue to evolve and become more accessible. They hold the potential to address the key challenges faced by the industry, enabling the large-scale production of high-quality true to type, date palm planting materials [77].

8. 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 [78]. 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 (Figure 6) [79]. 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 DP industry especially in Gulf countries, South Asian countries [80,81]. By optimizing irrigation, enhancing subsurface irrigation systems, streamlining tissue culture plantlet acclimatization, and improving cold storage management, AI and IoT offer solutions to key challenges faced by date palm farmers. However, challenges such as infrastructure limitations, high implementation costs, and data security concerns remain. Continued research and innovation in this field are crucial for advancing date palm cultivation practices and supporting the agricultural sector.
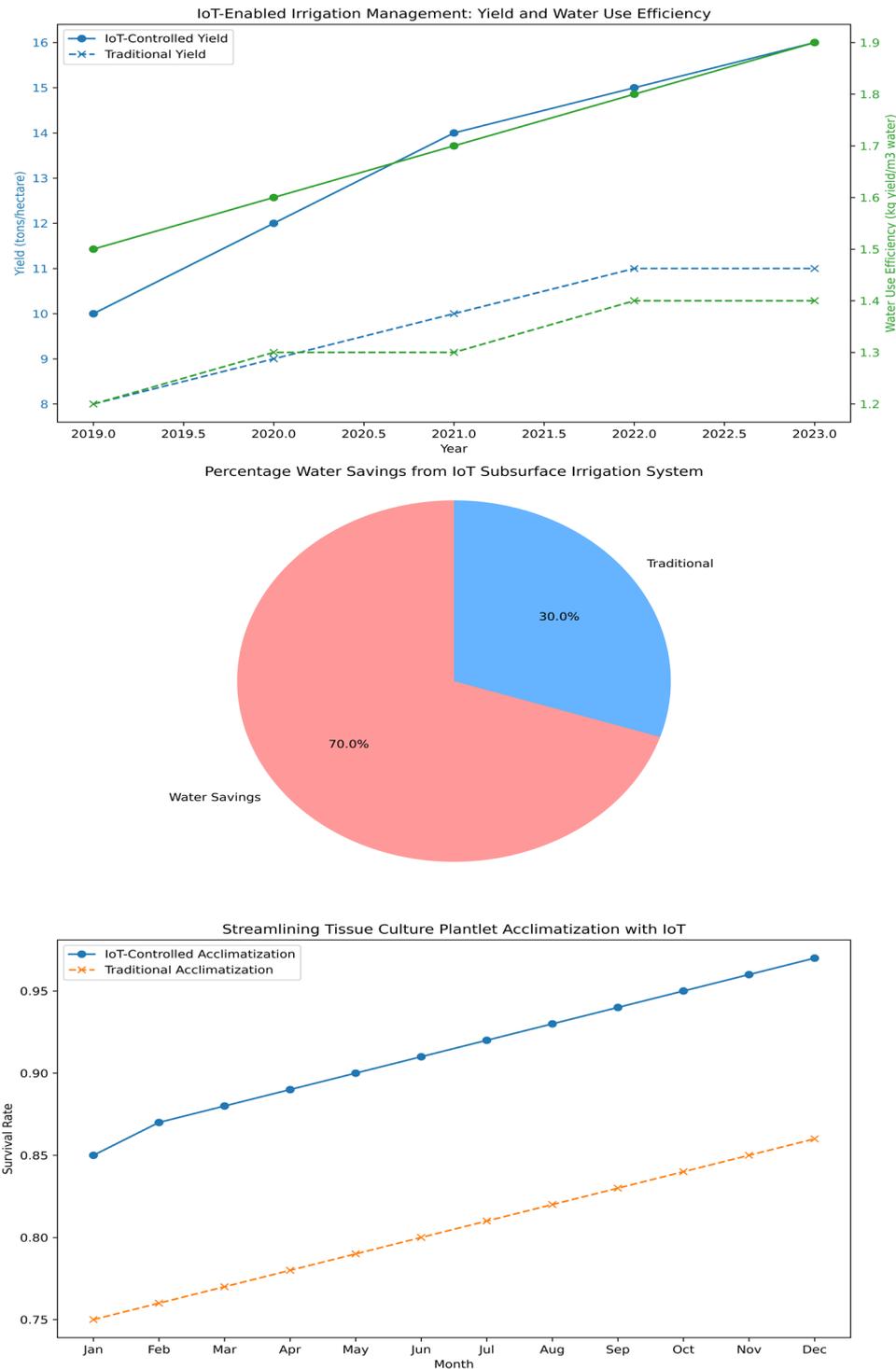
Figure 7. Application of IoT technologies in DP agriculture [82,83].

9. Computer Vision and Image Analysis

The recent advancements in the computer vision and deep learning have significantly improved the precision and efficiency of date palm propagation and monitoring. Specifically, the deep learning models such as convolutional neural networks (CNNs) and vision transformers, have been effectively employed for the 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 UAV-based and aerial images. These models demonstrated a high accuracy,

with the mean interaction over Union (mIoU) values ranging from 85% to 86.3% and mean F1-scores between 91.62% and 92.44%. 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 [84].

Another research applied the deep learning techniques for disease detection in the DP, using a transfer learning approach with the Inception-ResNet network. This method achieved a high accuracy in the classifying of palm leaves into categories such as healthy, white scale, and brown spots' use of pretrained models allowed for rapid and effective adaptation to the specific characteristics of the DP diseases, demonstrating the potential of AI in enhancing the agriculture management practices [85].

Moreover, the application of CNNs for the individual palm trees detection in RGB imagery has proven the effectiveness in terms of supporting the tree inventory efforts. A study has conducted in the Alicante province of Spain employed CNNs to map the *Phoenix dactylifera* and *Phoenix canariensis* palms, achieving a mean average precision of 0.861. This method enabled the creation of comprehensive spatial inventory of palm trees, facilitating long-term monitoring and management [86].

These advancements highlight the transformative potential of AI and computer vision in the 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 the valuable insights for the farmers and researchers.

10. Integration with Precision Agriculture

The integration of AI-ML has yielded promising results in the various aspects of DP biotechnology. However, several challenges remain such as the inclusion of the availability of the high quality of datasets for the machine learning algorithms, interpreting and validating model outputs, and the need for the interdisciplinary collaboration among biotechnologist, computer scientist and the agriculture experts. The ethical and responsible development and deployment of AI powered solution in agriculture will be the crucial to ensure the long-term sustainability and social acceptance. Despite the remarkable advancements the DP industry continues to face several challenges that require a concentrated research efforts and innovative solutions. These challenges include climate change on the water scarcity, genetic erosion and conservation, increasing pest and diseases, postharvest handling and processing, value addition and products diversification.

For instance, climate change impacts such as rising temperatures, prolonged droughts and increased salinity, pose the significant threats to the DP cultivation particularly in the arid regions [87,88]. Furthermore, the loss of genetic diversity in the DP 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 environment conditions and market demands [89]. Addressing these challenges would require a sustained interdisciplinary research efforts and the integration of emerging biotechnologies such as gene editing, high throughput phenomics, synthetic biology, and the advanced computational biology techniques. The responsible and ethical development and its deployment along with the robust regulatory frameworks, risks assessment protocols and public engagement efforts are essential [90]. Hence the synergistic integration of AI-ML and emerging biotechnologies holds a great promise for the future of the DP industry, leading to innovative solutions for addressing complex challenges such as climate adaptation, sustainable intensification and the development of value-added DP products.

Conclusion

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

Genomics-assisted breeding approaches have accelerated the development of elute 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 the pest and disease resistance, enhanced abiotic stress tolerance and the ability to produce the high value compounds in the DP based bio factories.

In vitro propagation techniques 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 the unprecedented insights into the molecular mechanism underlying the key traits, paving the way 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 various aspects of the date palm biotechnology 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, pest, and the application of AI-ML algorithms has further various aspects of DP 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 the future, the date for industry stands at the cost of new era where biotech technology coupled with the 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 challenges of the 21st century and beyond.

Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

Conflicts of Interest: The authors declare no conflicts of interest.

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