Research Perspective Open Access

Research on Varietal Improvement and Cultivation Techniques for Dragon Fruit (Pitaya)

Min Dong
Jiaxing Realzen Ecological Agriculture Technology Co., Ltd, Jiaxing, 314200, Zhejiang, China
Corresponding email: 13357168001@189.cn
International Journal of Horticulture, 2024, Vol.14, No.6 doi: 10.5376/ijh.2024.14.0041
Received: 25 Oct., 2024
Accepted: 10 Dec., 2024
Published: 24 Dec., 2024

Preferred citation for this article:
Dong M., 2024, Research on varietal improvement and cultivation techniques for dragon fruit (pitaya), International Journal of Horticulture, 14(6): 414-425 (doi: 10.5376/ijh.2024.14.0041)

Abstract This study explores the main varieties of dragon fruit and their improvement techniques, analyzes cultivation management strategies, and explores the potential for applications in digital farming and precision management to provide scientific support for dragon fruit cultivation. It aims to meet the growing market demand for high-quality fruit. The study finds that dragon fruit improvement methods, including hybrid breeding, mutation breeding, molecular marker-assisted selection (MAS), and gene editing, have significantly enhanced dragon fruit's performance in disease resistance, fruit quality, and stress tolerance. Additionally, optimized cultivation techniques, such as water and fertilizer management, flowering management, and post-harvest preservation, play a crucial role in ensuring high yield and quality. Intelligent management tools such as the Internet of Things (IoT), drone monitoring, and data analysis drive dragon fruit cultivation toward precision and efficiency. The integration of varietal improvement and precision cultivation techniques not only enables future dragon fruit production to better adapt to climate change, improving production efficiency and economic benefits, but also provides a reference for achieving sustainable agriculture and reducing resource waste.
Keywords Dragon fruit; Varietal improvement; Cultivation techniques; Digital management; Precision agriculture

1 Introduction

Dragon fruit, also known as pitaya, belongs to the Cactaceae family and is native to the tropical and subtropical regions of southern Mexico, Central America, and northern South America. This fruit is cultivated extensively in tropical and subtropical regions worldwide, including the United States, particularly in Florida, southern California, and Hawaii. The adaptability of dragon fruit to various ecological conditions, ranging from very dry to extremely wet regions, has facilitated its widespread cultivation (Goenaga et al., 2020; Xu and Wang, 2024).

The economic importance of dragon fruit has surged in recent years due to its increasing popularity among consumers seeking healthy and diverse food products (Goenaga et al., 2020). The fruit's high economic value is evident in its significant contribution to the income of local farmers in regions like Guizhou, China, where it has also played a role in poverty alleviation (Li et al., 2022). The global fruit market has recognized dragon fruit as a valuable crop, with its demand steadily rising due to its nutritional benefits and exotic appeal (Trivellini et al., 2020; Attar et al., 2022).

The nutritional value of dragon fruit is substantial, with studies highlighting its high antioxidant activity, total phenolic content, and the presence of bioactive compounds such as flavonoids and betacyanins (Paśko et al., 2021; Attar et al., 2022). These attributes not only enhance its market demand but also underscore the need for advancements in cultivation techniques and varietal improvement to meet the growing consumer demand (Tel-Zur, 2022; Oltehua-Lopez et al., 2023).

This study will summarize recent advances in the varietal improvement and cultivation techniques of dragon fruit, exploring new developments in breeding programs, including hybrid variety development and the application of molecular tools for genetic improvement. Additionally, it will examine innovative cultivation practices aimed at enhancing yield and fruit quality, addressing challenges such as postharvest diseases and environmental stress.

This study provides insights into the future directions for dragon fruit cultivation, ensuring its continued economic and nutritional importance in the global market.

2 Varieties and Breeding of Dragon Fruit

2.1 Main varieties and their characteristics

Dragon fruit, also known as pitaya, is categorized into several varieties based on skin and flesh color. The primary varieties include red-skinned red-fleshed (*Hylocereus polyrhizus*), red-skinned white-fleshed (*Hylocereus undatus*), and yellow-skinned white-fleshed (*Selenicereus megalanthus*) (Figure 1) (Perween et al., 2018; Goenaga et al., 2020; Attar et al., 2022). Representative dragon fruit varieties cultivated in Puerto Rico include NOI-13, NOI-14, NOI-16, N97-15, N97-17, N97-18, N97-20, N97-22, American Beauty, Halley's Comet, and Purple Haze, featuring various types such as red-skinned red-fleshed, red-skinned white-fleshed, and yellow-skinned white-fleshed. Each variety is distinct not only in appearance but also in its cultivation requirements and market appeal.

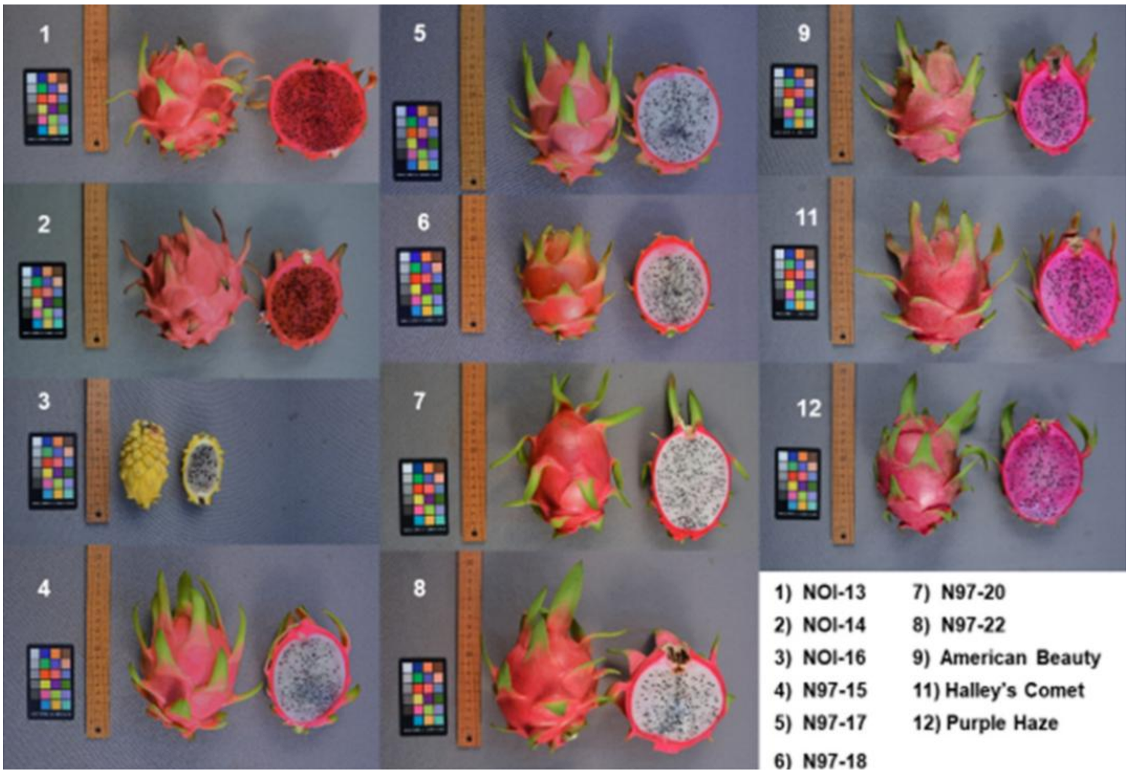

Figure 1 Representative fruit of 11 dragon fruit cultivars grown in Puerto Rico (Adopted from Goenaga et al., 2020)

The red-fleshed varieties, such as *Hylocereus polyrhizus*, are noted for their higher antioxidant capacity and total phenolic content compared to white-fleshed varieties like *Hylocereus undatus*. These red-fleshed fruits also contain higher levels of quercetin, a predominant phenolic compound, which contributes to their health benefits. On the other hand, white-fleshed varieties tend to have a higher content of volatile compounds, which can influence their flavor profile (Attar et al., 2022). In terms of yield, certain cultivars like N97-17 and N97-15 have shown significantly higher fruit production, while others like Cosmic Charlie have lower yields but higher soluble solids content, indicating a sweeter taste (Goenaga et al., 2020). The yellow-skinned white-fleshed variety, *Selenicereus megalanthus*, is less common but valued for its unique flavor and texture (Perween et al., 2018). The peel of *Selenicereus megalanthus* is bright yellow with prominent spiky protrusions on the surface. The flesh is white, delicate in texture, and evenly distributed with black seeds. This variety has a high sweetness level, typically around 24.2 Brix (Figure 2).

Figure 2 The appearance, internal structure, and sugar content measurement of *Selenicereus megalanthus*

2.2 Main breeding objectives for dragon fruit

The primary breeding objectives for dragon fruit include increasing yield and quality, enhancing disease resistance, and improving stress tolerance. High-yielding cultivars such as N97-17 and N97-20 have been identified, which produce significantly more fruit per hectare (Goenaga et al., 2020). Additionally, breeding efforts focus on extending the shelf life of the fruit to reduce post-harvest losses and improve marketability (Perween et al., 2018).Improving fruit texture and sweetness is crucial to meet consumer preferences. Varieties with higher soluble solids content, such as NOI-16 and N97-18, are particularly sought after for their sweetness (Goenaga et al., 2020). Enhancing the nutritional content, including increasing the levels of antioxidants and phenolic compounds, is also a key objective to boost the health benefits of the fruit (Huang et al., 2021; Attar et al., 2022). The red-fleshed varieties, in particular, are targeted for their higher nutritional value and bioactive compounds (Huang et al., 2021).

2.3 Challenges in breeding

Breeding dragon fruit presents several challenges. One of the primary issues is the long breeding cycle, which can extend up to several years before new cultivars are ready for commercial production. The genomic complexity of dragon fruit, with its diverse genetic background, adds another layer of difficulty in achieving consistent breeding outcomes (Perween et al., 2018). Additionally, ensuring adaptability in various cultivation conditions, from dry to wet regions, is essential but challenging due to the plant's sensitivity to environmental changes (Perween et al., 2018; Goenaga et al., 2020). These challenges necessitate ongoing research and development to optimize breeding strategies and improve the resilience and productivity of dragon fruit cultivars.

3 Techniques in Varietal Improvement of Dragon Fruit

3.1 Hybrid breeding

Hybrid breeding is a crucial technique in the varietal improvement of dragon fruit, aimed at enhancing both the quality and stress tolerance of the fruit. This method involves the cross-breeding of different dragon fruit varieties to combine desirable traits from each parent. For instance, the study on the yield and fruit quality traits of various dragon fruit cultivars grown in Puerto Rico highlights significant differences in fruit number, weight, and soluble solids among cultivars, indicating the potential for selecting superior hybrids for improved yield and quality (Goenaga et al., 2020). Additionally, transcriptome analysis of wild and cultivated pitahaya has identified differentially expressed genes related to drought stress, suggesting that hybrid breeding can also target stress tolerance by selecting for genes that enhance drought resistance (Oltehua-Lopez et al., 2023).

A specific case study of hybrid breeding involves the improvement of red-skinned red-fleshed and yellow-skinned white-fleshed dragon fruit varieties. The nutritional analysis of red-purple and white-fleshed pitaya species grown in Turkey provides insights into the biochemical differences between these varieties, with red-fleshed fruits showing higher antioxidant capacity and phenolic content compared to white-fleshed ones (Attar et al., 2022). This information is valuable for hybrid breeding programs aiming to combine the high nutritional value of red-fleshed varieties with the desirable traits of other varieties. Furthermore, the study on dragon fruit cultivation in India mentions the popularity and commercial potential of red-fleshed and white-fleshed pitaya, underscoring the economic benefits of developing superior hybrids (Perween et al., 2018).

3.2 Mutation breeding

Mutation breeding involves the use of physical or chemical mutagens to induce genetic variations, which can lead to the development of new dragon fruit varieties with desirable traits. This technique has been employed to introduce novel characteristics that are not present in the existing gene pool. For example, the study on dragon fruit cultivars in Puerto Rico demonstrates significant variability in fruit yield and quality among different cultivars, suggesting that mutation breeding could further enhance these traits by creating new genetic variations (Goenaga et al., 2020). Additionally, the transcriptome analysis of pitahaya reveals numerous differentially expressed genes, indicating the potential for mutation breeding to target specific genes associated with stress tolerance and other beneficial traits (Oltehua-Lopez et al., 2023).

An example of mutation breeding is the development of disease-resistant dragon fruit varieties through radiation-induced mutation. This method involves exposing plant tissues to radiation to induce mutations that may confer resistance to diseases. The study on the nutritional analysis of pitaya species in Turkey highlights the importance of disease resistance in maintaining fruit quality and yield, as healthier plants are more likely to produce high-quality fruits (Attar et al., 2022). Moreover, the transcriptome analysis of pitahaya identifies genes related to hormone-mediated signaling pathways, which are known to play a role in plant defense mechanisms. By targeting these pathways, radiation-induced mutation can potentially enhance disease resistance in dragon fruit varieties (Oltehua-Lopez et al., 2023).

3.3 Molecular breeding and marker-assisted selection (MAS)

Marker-assisted selection (MAS) has revolutionized the breeding of dragon fruit by enabling the selection of disease-resistant and high-quality varieties through the integration of molecular markers and genomic information. MAS allows for the indirect selection of traits, making the breeding process more efficient and precise. This technique is particularly useful for traits with low heritability, such as abiotic stress resistance and horizontal disease resistance, which are challenging to improve through conventional breeding methods (Torres, 2010; Singh et al., 2015; Pathania et al., 2017). By utilizing molecular markers linked to resistance genes, breeders can identify and select resistant individuals early in the breeding process, thereby streamlining the development of new cultivars (Torres, 2010; Migicovsky and Myles, 2017). The application of MAS in dragon fruit breeding has been facilitated by advancements in genomic tools, including the development of a draft genome for *Hylocereus undatus*, which provides valuable insights into the genetic basis of important traits (Chen et al., 2021; Tel-Zur, 2022).

MAS has been successfully employed to improve various traits in dragon fruit, including sweetness, stress tolerance, and coloration. For instance, the use of molecular markers has enabled the selection of hybrids with enhanced sweetness by targeting genes involved in sugar metabolism (Chen et al., 2021; Tel-Zur, 2022). Additionally, MAS has been used to develop dragon fruit varieties with improved stress tolerance by selecting for genes associated with drought and heat resistance (Oltehua-Lopez et al., 2023). The coloration of dragon fruit, which is primarily determined by betalain biosynthesis, has also been improved through MAS by identifying and selecting for genes involved in the betalain biosynthetic pathway (Chen et al., 2021). These advancements demonstrate the potential of MAS to accelerate the breeding of high-quality dragon fruit varieties with desirable traits.

3.4 Gene editing technology

Gene editing technologies, particularly CRISPR/Cas9, have opened new avenues for the precise modification of key genes in dragon fruit to achieve desired traits. CRISPR/Cas9 allows for targeted modifications at specific genomic loci, enabling the precise editing of genes involved in important traits such as disease resistance, fruit quality, and stress tolerance (He et al., 2017; Chen et al., 2021). This technology has the potential to overcome the limitations of traditional breeding methods by directly altering the genetic makeup of dragon fruit, thereby accelerating the development of improved varieties. The application of CRISPR/Cas9 in dragon fruit breeding is still in its early stages, but it holds great promise for the future of varietal improvement.

An example of the application of CRISPR/Cas9 in dragon fruit breeding is the targeting of genes involved in sugar synthesis to enhance fruit flavor. By precisely editing genes that regulate sugar metabolism, researchers can increase the sugar content of dragon fruit, resulting in sweeter and more flavorful fruits (Chen et al., 2021). This approach not only improves the sensory qualities of dragon fruit but also enhances its marketability and consumer appeal. The successful application of CRISPR/Cas9 in modifying sugar synthesis genes in dragon fruit demonstrates the potential of gene editing technologies to achieve specific breeding goals with high precision and efficiency.

4 Advances in Varietal Improvement of Dragon Fruit

4.1 Genetic diversity of dragon fruit varieties

Dragon fruit (Pitaya) exhibits significant genetic diversity, particularly among its different varieties, which include red-skinned white-fleshed, red-skinned red-fleshed, and yellow-skinned white-fleshed types. Studies have shown that red-fleshed varieties generally have higher antioxidant capacities and total phenolic content compared to white-fleshed varieties (Attar et al., 2022). Additionally, metabolomic analyses have revealed that red-skinned cultivars with different pulp colors (red, pink, and white) exhibit distinct primary metabolite profiles, including variations in glucose, fructose, and sucrose levels during fruit maturation (Hua et al., 2018). Genetic diversity studies using SSR markers have identified significant genetic variation among different germplasm accessions, indicating a rich genetic pool that can be utilized for breeding programs (Pan et al., 2017).

4.2 Primary goals in varietal improvement

The primary goals in the varietal improvement of dragon fruit include enhancing fruit quality, extending shelf life, and improving disease resistance and stress tolerance. Enhancing fruit quality involves improving texture and sweetness, which are critical for consumer acceptance. For instance, cultivars such as N97-20 and NOI-13 have been noted for their higher individual fruit weight and soluble solids content, which are indicators of better fruit quality (Goenaga et al., 2020). Extending shelf life and improving disease resistance are also crucial, as these factors directly impact the commercial viability of the fruit. Genetic studies have identified genes related to drought stress and hormone-mediated signaling pathways, which could be targeted to develop more resilient varieties (Oltehua-Lopez et al., 2023).

4.3 Application of genetic improvement techniques

Various genetic improvement techniques have been employed to enhance dragon fruit varieties. Traditional breeding methods, such as hybrid breeding and interspecific crosses, have been used to produce improved hybrids with desirable traits (Tel-Zur, 2022). Marker-assisted selection (MAS) has also been utilized to identify and select for specific genetic markers associated with beneficial traits. Modern techniques like gene editing are being explored to precisely modify genes involved in key pathways, such as betalain biosynthesis, which is responsible for the red coloration in some dragon fruit varieties (Xi et al., 2019; Chen et al., 2021). Transcriptome analyses have further clarified the genetic mechanisms behind traits like flesh coloration, providing valuable insights for targeted breeding (Fan et al., 2020).

4.4 Successful cases

Several newly developed superior dragon fruit varieties have shown promising performance in production. For example, cultivars N97-17, N97-20, N97-22, and NOI-13 have demonstrated significantly higher fruit yields and better fruit quality traits compared to other cultivars (Goenaga et al., 2020). In another instance, interspecific hybrids produced through embryo rescue procedures have been successfully released to farmers, offering improved fruit traits and resilience. The study by Tel-Zur (2022) investigated autopolyploid hybrids of dragon fruit, showing that hybridization can significantly increase the diversity of fruit morphology and color. These hybrids exhibited high fertility, indicating that in dragon fruit breeding, both intraspecific and interspecific hybridization can effectively improve fruit quality and yield (Figure 3). This genetic diversity holds important significance for the commercial cultivation and breeding of dragon fruit. The development of a high-density genetic map and the identification of key regulatory genes involved in betalain biosynthesis have also paved the way for the creation of new varieties with enhanced nutritional and aesthetic qualities (Chen et al., 2021).

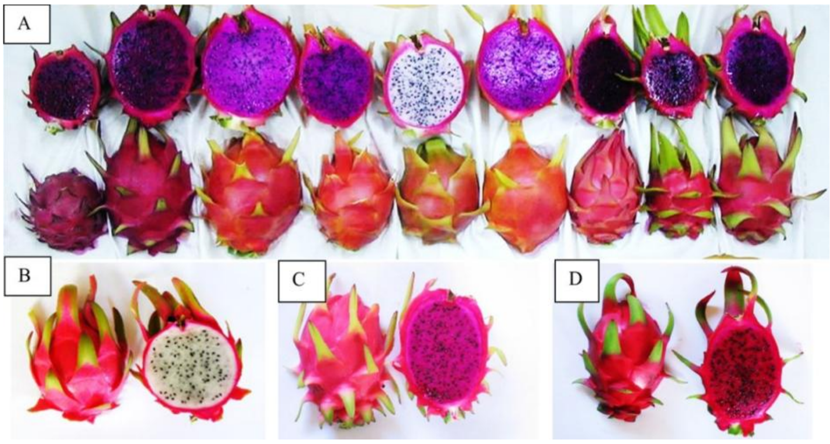

Figure 3 Fruit diversity in homoploid diploid hybrids (Adopted from Tel-Zur, 2022)
Image caption: The homoploid diploid crosses resulted in hybrids with a high fertility level. A. Assorted hybrid fruits from different cross combinations. B. Intraspecific hybrid S-107 (*H. undatus* × *H. undatus*). C. Interspecific hybrid J-21 (*Hylocereus monacanthus* × *H. undatus*). D. Interspecific hybrid 34-07 (*H. monacanthus* × *H. undatus*) (Adopted from Tel-Zur, 2022)

5 Cultivation Techniques for Dragon Fruit

5.1 Seedling selection and propagation methods

Selection of high-quality dragon fruit seedlings is crucial for ensuring robust plant growth and high yield. Ideal seedlings should be disease-free, exhibit vigorous growth, and have a well-developed root system (Figure 4). Common propagation methods for dragon fruit include cutting and grafting. Cutting is the most widely used method due to its simplicity and high success rate. Cuttings of 25 cm length treated with Indole-3-butyric acid (IBA) have shown significant improvement in rooting percentage, root number, and length, making it an efficient propagation technique (Elobeidy, 2006). However, the cutting method may result in genetic uniformity, which can be a disadvantage in terms of disease resistance. Grafting involves joining a scion of a desired cultivar onto a rootstock, which can enhance disease resistance and improve growth rates. This method, while effective, is more labor-intensive and requires skilled labor (Tel-Zur, 2022).

Figure 4 Selection and cutting propagation of dragon fruit seedlings

5.2 Cultivation environment and soil management

Dragon fruit thrives in tropical and subtropical climates, with optimal growth occurring at temperatures between 20 °C and 30 °C. The plant requires a well-drained soil with a pH range of 5.5 to 7.0. High humidity levels and adequate sunlight are essential for optimal growth and fruit production (Goenaga et al., 2020; Trivellini et al., 2020). Soil management is critical for dragon fruit cultivation. The soil should be rich in organic matter and have good drainage to prevent waterlogging, which can lead to root rot. Regular soil testing and amendments, such as the addition of compost or well-rotted manure, can help maintain soil fertility and structure (Perween et al., 2018).

5.3 Water and fertilizer management strategies

Effective water and fertilizer management are key to maximizing dragon fruit yield and quality. Dragon fruit plants require moderate irrigation, with the frequency depending on the soil type and climatic conditions. Over-irrigation should be avoided as it can lead to root diseases (Goenaga et al., 2020; Trivellini et al., 2020). A balanced fertilization plan is essential for healthy plant growth. The application of nitrogen (N), phosphorus (P), and potassium (K) in a balanced ratio is recommended. Nitrogen promotes vegetative growth, phosphorus supports root development and flowering, and potassium enhances fruit quality and disease resistance. Regular foliar feeding with micronutrients can also be beneficial (Perween et al., 2018; Goenaga et al., 2020).

5.4 Flowering management and artificial pollination

Dragon fruit (pitaya) exhibits unique flowering characteristics that necessitate specific management practices to optimize fruit set rates. The flowering phase of dragon fruit is marked by nocturnal blooming, with flowers typically opening in the evening and remaining receptive for a limited period. Studies have shown that the stigma of pitaya flowers is most receptive to pollen during the early hours of the night, with the highest pollen germination rates observed around 7 p.m. (Li et al., 2020; Li et al., 2022b; Moreira et al., 2022). This narrow pollination window underscores the importance of timely pollination to ensure successful fruit set.

Artificial pollination has been demonstrated to significantly enhance fruit set and quality compared to natural pollination. Manual cross-pollination, in particular, has been found to produce larger and higher-quality fruits than self-pollination or natural pollination (Hu et al., 2011; Moreira et al., 2022). The process involves transferring pollen from one flower to the stigma of another, which can be done using a brush or similar tool. This method not only increases the fruit set percentage but also improves the average fruit weight and commercial value of the produce (Hu et al., 2011; Li et al., 2020).

Moreover, the synchronization of stigma receptivity and pollen activity is crucial for successful pollination. Research indicates that pollination within six hours after blooming yields the best results in terms of fruit setting percentage and fruit size. Pollen collected and used within this timeframe maintains higher viability, which is essential for effective fertilization. Storing pollen for more than 24 hours at low temperatures significantly reduces its germination rate and, consequently, the fruit set rate (Li et al., 2020; Li et al., 2022b).

5.5 Harvest and post-harvest management

Determining the optimal maturity for harvesting dragon fruit is critical to ensure the best quality and shelf life. The maturity of dragon fruit can be assessed by several indicators, including skin color, fruit size, and the development of scales on the fruit surface. Typically, dragon fruit is harvested when the skin color changes from green to a vibrant red or yellow, depending on the variety. Harvesting techniques also play a vital role in maintaining fruit quality. It is recommended to use clean, sharp tools to cut the fruit from the plant, leaving a small portion of the stem attached to prevent damage and reduce the risk of post-harvest diseases (Goenaga et al., 2020; Trivellini et al., 2020). Handling the fruit with care during harvesting and transportation is essential to minimize bruising and mechanical injuries, which can lead to spoilage.

Post-harvest management practices are crucial for extending the shelf life of dragon fruit. One of the primary challenges is the control of post-harvest diseases, which can cause significant economic losses. Common pathogens include fungi such as *Penicillium spinulosum*, *Phoma herbarum*, and *Fusarium proliferatum*, which can be effectively managed using fungicides like tebuconazole and prochloraz. Additionally, maintaining optimal storage conditions, such as low temperatures and high humidity, can help preserve fruit quality and extend shelf life (Li et al., 2022a). Innovative approaches to utilizing dragon fruit by-products, such as peels, can also contribute to sustainable post-harvest management. The peels are rich in pectin and dietary fiber, which can be extracted and used in various applications, including bioplastics and natural dyes, thereby reducing waste and adding value to the fruit (Taharuddin et al., 2023).

6 Digitalization and Precision Management in Dragon Fruit Cultivation

6.1 Smart irrigation and environmental monitoring

The application of the Internet of Things (IoT) in dragon fruit cultivation has revolutionized traditional farming practices by enabling real-time monitoring of soil and climate data. This technology allows for precise control over irrigation schedules, ensuring that the plants receive the optimal amount of water, which is particularly beneficial given the varying water requirements of dragon fruit across different ecological conditions (Goenaga et al., 2020; Trindade et al., 2023). By integrating sensors that measure soil moisture, temperature, and humidity, farmers can make data-driven decisions to enhance crop yield and quality. This approach not only conserves water but also improves the overall efficiency of the cultivation process, making it more sustainable and cost-effective (Figure 5) (Trivellini et al., 2020; Trindade et al., 2023). Trivellini et al. (2020) experimented with management methods for *Hylocerius* species, from propagation to greenhouse cultivation, combined with smart irrigation and environmental monitoring technology. By adjusting water supply based on real-time monitored greenhouse data (such as soil moisture, temperature, and light intensity), growers can better understand the microclimate conditions affecting plant growth. This enables precise cultivation practices, such as trellis building, pruning, and flowering control, further optimizing growth conditions and fruit quality for dragon fruit.

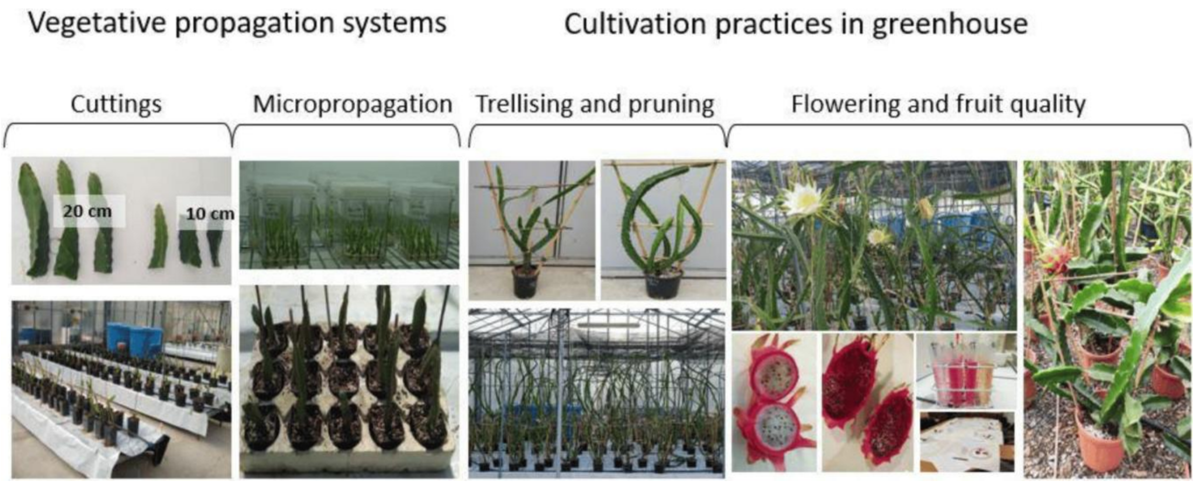

Figure 5 Overview of the whole chain approach, from propagation to the greenhouse cultivation of species belonging to the genus *Hylocerius* spp (Adopted from Trivellini et al., 2020)

6.2 Drones and remote sensing technology

Drones and remote sensing technology have emerged as powerful tools in the monitoring and management of dragon fruit cultivation. These technologies enable farmers to conduct aerial surveys of their fields, providing detailed images and data on plant health, growth stages, and pest and disease conditions. For instance, drones equipped with multi-spectral cameras can detect early signs of stress in plants, allowing for timely intervention and reducing the risk of crop loss (Li et al., 2022a; Tel-Zur, 2022). Additionally, remote sensing can be used for yield estimation, helping farmers to plan their harvests more effectively and optimize their supply chain (Goenaga et al., 2020; Trivellini et al., 2020). The use of drones thus enhances the precision and efficiency of farm management practices, contributing to higher productivity and better quality produce.

6.3 Data-driven precision management

Data collection and analysis play a crucial role in optimizing various aspects of dragon fruit cultivation, including fertilization and pest control. By leveraging data from IoT devices, drones, and other monitoring tools, farmers can gain insights into the specific needs of their crops and tailor their management practices accordingly. For example, data on soil nutrient levels and plant health can inform precise fertilization schedules, ensuring that plants receive the right nutrients at the right time (Oltehua-Lopez et al., 2023; Taharuddin et al., 2023). Similarly, data on pest and disease prevalence can guide targeted pest control measures, reducing the reliance on broad-spectrum pesticides and minimizing environmental impact (Paśko et al., 2021; Li et al., 2022a). This data-driven approach not only enhances the efficiency and sustainability of dragon fruit cultivation but also improves the quality and yield of the produce, meeting the growing demand for this exotic fruit (Goenaga et al., 2020; Nishikito et al., 2023; Trindade et al., 2023).

7 Future Directions for Varietal Improvement and Cultivation Techniques of Dragon Fruit

7.1 Breeding for stress-tolerant varieties

Breeding for tolerance to environmental stresses such as high temperatures and drought is crucial for the sustainable cultivation of dragon fruit, especially in the face of climate change. Advances in genome editing technologies, such as CRISPR/Cas9, offer promising avenues for developing stress-tolerant varieties by targeting specific structural and regulatory genes involved in stress responses (Anwar and Kim, 2020; Zafar et al., 2020; Campa et al., 2023). High-throughput phenotyping (HTP) methods can accelerate the breeding process by providing rapid and accurate data acquisition for drought tolerance traits, thus facilitating the development of drought-resistant cultivars (Kim et al., 2021). Additionally, the use of crop wild relatives (CWRs) can expand genetic diversity and improve adaptability to various abiotic stresses, providing a valuable resource for breeding programs (Kapazoglou et al., 2023).

7.2 Sustainable cultivation management

Promoting eco-friendly cultivation techniques is essential to reduce the reliance on pesticides and chemical fertilizers. Integrating sustainable practices such as organic farming, the use of biofertilizers, and integrated pest management (IPM) can enhance soil health and reduce environmental impact. The development of transgenic plants with improved stress tolerance can also contribute to sustainable cultivation by reducing the need for chemical inputs (Wang and Qin, 2017; Anwar and Kim, 2020). Moreover, the application of new breeding techniques, including cisgenesis and CRISPR/Cas genome editing, can optimize the development of varieties with enhanced resistance to pathogens and abiotic stresses, further supporting sustainable cultivation practices (Campa et al., 2023).

7.3 Integrated innovation in varietal improvement and cultivation techniques

Integrating multiple breeding and cultivation technologies is key to enhancing the yield and quality of dragon fruit. Rapid-cycle breeding and the use of elite germplasm from diverse regions can ensure the continuous improvement of cultivars (Atlin et al., 2017). Molecular breeding approaches, such as marker-assisted selection and genome-wide association studies (GWAS), can identify key genetic components underlying stress tolerance, enabling precise genetic improvements (Wang and Qin, 2017; Hong and Huang, 2024). Combining these advanced breeding techniques with sustainable cultivation practices will lead to the development of superior dragon fruit varieties that are resilient to environmental stresses and have high yield potential (Bhatnagar-Mathur et al., 2008; Cattivelli et al., 2008; Joshi et al., 2016).

Acknowledgment

The author expresses deep gratitude to Professor R. Cai, Researcher at the Zhejiang Agronomist College/Institute of Life Sciences for his thorough review of the manuscript and constructive suggestions. The author also extends thanks to the two anonymous peer reviewers for their valuable revision recommendations.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Anwar A., and Kim J.K., 2020, Transgenic breeding approaches for improving abiotic stress tolerance: Recent progress and future perspectives, International Journal of Molecular Sciences, 21(8): 2695.
https://doi.org/10.3390/ijms21082695

Atlin G.N., Cairns J.E., and Das B., 2017, Rapid breeding and varietal replacement are critical to adaptation of cropping systems in the developing world to climate change, Global Food Security, 12: 31-37.
https://doi.org/10.1016/j.gfs.2017.01.008

Attar Ş., Gündeşli M., Urün I., Kafkas S., Kafkas N., Ercişli S., Ge C., Mlček J., and Adámková A., 2022, Nutritional analysis of red-purple and white-fleshed pitaya (*Hylocereus*) species, Molecules, 27(3): 808.
https://doi.org/10.3390/molecules27030808

Bhatnagar-Mathur P., Vadez V., and Sharma K., 2008, Transgenic approaches for abiotic stress tolerance in plants: Retrospect and prospects, Plant Cell Reports, 27: 411-424.
https://doi.org/10.1007/s00299-007-0474-9

Campa M., Miranda S., Licciardello C., Lashbrooke J.G., Costa L., Guan Q., Spök A., and Malnoy M., 2023, Application of new breeding techniques in fruit trees, Plant Physiology, 194(3): 1304-1322.
https://doi.org/10.1093/plphys/kiad374

Cattivelli L., Rizza F., Badeck F., Mazzucotelli E., Mastrangelo A., Francia E., Marè C., Tondelli A., and Stanca A., 2008, Drought tolerance improvement in crop plants: An integrated view from breeding to genomics, Field Crops Research, 105: 1-14.
https://doi.org/10.1016/j.fcr.2007.07.004

Chen J.Y., Xie F.F., Cui Y.Z., Chen C.B., Lu W.J., Hu X.D., Hua Q., Zhao J., Wu Z., Gao D., Zhang Z., Jiang W., Sun Q., Hu G., and Qin Y.H., 2021, A chromosome-scale genome sequence of pitaya (*Hylocereus undatus*) provides novel insights into the genome evolution and regulation of betalain biosynthesis, Horticulture Research, 8.
https://doi.org/10.1038/s41438-021-00612-0

Elobeidy A., 2006, Mass propagation of pitaya (dragon fruit), Fruits, 61: 313-319.
https://doi.org/10.1051/fruits:2006030

Fan R., Sun Q., Zeng J., and Zhang X., 2021, Contribution of anthocyanin pathways to fruit flesh coloration in pitayas, BMC Plant Biology, 20: 361.
https://doi.org/10.1186/s12870-020-02566-2

Goenaga R., Marrero A., and Pérez D., 2020, Yield and fruit quality traits of dragon fruit cultivars grown in Puerto Rico, HortTechnology, 30(6): 803-808.
https://doi.org/10.21273/horttech04699-20

He J., Zhao X., Laroche A., Lu Z.X., Liu H., and Li Z., 2014, Genotyping-by-sequencing (GBS), an ultimate marker-assisted selection (MAS) tool to accelerate plant breeding, Frontiers in Plant Science, 5: 484.
https://doi.org/10.3389/fpls.2014.00484

Hu Z.Y., Liang G.D., Huang H.S., Sun Q., and He C.M., 2011, Effect of artificial pollination and natural pollination on development and production of pitaya, Guangdong Agricultural Sciences, 38(13): 39-41.

Hong W.Y., and Huang W.Z., 2024, Diversity and cultivation of sugarcane: From traditional practices to modern breeding techniques, Molecular Plant Breeding, 15(5): 269-281.
https://doi.org/10.5376/mpb.2024.15.0026

Hua Q., Chen C., Zur N., Wang H., Wu J., Chen J., Zhang Z., Zhao J., Hu G., and Qin Y., 2018, Metabolomic characterization of pitaya fruit from three red-skinned cultivars with different pulp colors, Plant Physiology and Biochemistry, 126: 117-125.
https://doi.org/10.1016/j.plaphy.2018.02.027

Huang Y., Brennan M.A., Kasapis S., Richardson S.J., and Brennan C.S., 2021, Maturation process, nutritional profile, bioactivities and utilisation in food products of red pitaya fruits: A review, Foods, 10(11): 2862.
https://doi.org/10.3390/foods10112862

Joshi R., Wani S., Singh B., Bohra A., Dar Z., Lone A., Pareek A., and Singla-Pareek S., 2016, Transcription factors and plants response to drought stress: Current understanding and future directions, Frontiers in Plant Science, 7: 1029.
https://doi.org/10.3389/fpls.2016.01029

Kapazoglou A., Gerakari M., Lazaridi E., Kleftogianni K., Sarri E., Tani E., and Bebeli P.J., 2023, Crop wild relatives: A valuable source of tolerance to various abiotic stresses, Plants, 12(2): 328.
https://doi.org/10.3390/plants12020328

Kim J., Kim K.S., Kim Y., and Chung Y.S., 2020, A short review: Comparisons of high-throughput phenotyping methods for detecting drought tolerance, Scientia Agricola, 78: e20190300300.
https://doi.org/10.1590/1678-992x-2019-0300

Li J., Shi H., Huang X., Wang Y., Zhao J., Dai H., and Sun Q., 2020, Pollen germination and hand pollination in pitaya (*Hylocereus undatus*), Research Square, preprint.
https://doi.org/10.21203/rs.2.22205/v1

Li J., Shi H., Dai H., Wang Y., Zhao J., Nguyen C., Huang X., and Sun Q., 2022a, Pollen germination and hand pollination in pitaya (*Selenicereus* spp.), Emirates Journal of Food and Agriculture, 34(5): 369-387.
https://doi.org/10.9755/ejfa.2022.v34.i5.2855

Li Y., Chen H., Ma L., An Y., Wang H., and Wu W., 2022b, Laboratory screening of control agents against isolated fungal pathogens causing postharvest diseases of pitaya in Guizhou, China, Frontiers in Chemistry, 10: 942185.
https://doi.org/10.3389/fchem.2022.942185

Migicovsky Z., and Myles S., 2017, Exploiting wild relatives for genomics-assisted breeding of perennial crops, Frontiers in Plant Science, 8: 460.
https://doi.org/10.3389/fpls.2017.00460

Moreira R., Rodrigues M., Souza R., Silva A., Silva F., Lima C., Pio L., and Pasqual M., 2022, Natural and artificial pollination of white-fleshed pitaya, Anais da Academia Brasileira de Ciências, 94: e20211200.
https://doi.org/10.1590/0001-3765202220211200

Nishikito D.F., Borges A.C.A., Laurindo L.F., Otoboni A.M.B., Direito R., Goulart R.D.A., Nicolau C., Fiorini A., Sinatora R., and Barbalho S.M., 2023, Anti-inflammatory, antioxidant, and other health effects of dragon fruit and potential delivery systems for its bioactive compounds, Pharmaceutics, 15(1): 159.
https://doi.org/10.3390/pharmaceutics15010159

Oltehua-López O., Arteaga-Vázquez M.A., and Sosa V., 2023, Stem transcriptome screen for selection in wild and cultivated pitahaya (*Selenicereus undatus*): An epiphytic cactus with edible fruit, PeerJ, 11: e14581.
https://doi.org/10.7717/peerj.14581

Pan L., Fu J., Zhang R., Qin Y., Lu F., Lili J., Qinglei H., Liu C., Huang L., and Liang G., 2017, Genetic diversity among germplasms of pitaya based on SSR markers, Scientia Horticulturae, 225: 171-176.
https://doi.org/10.1016/J.SCIENTA.2017.06.053

Paśko P., Galanty A., Zagrodzki P., Ku Y.G., Luksirikul P., Weisz M., and Gorinstein S., 2021, Bioactivity and cytotoxicity of different species of pitaya fruits–A comparative study with advanced chemometric analysis, Food Bioscience, 40: 100888.
https://doi.org/10.1016/J.FBIO.2021.100888

Ragimekula N., Varadarajula N.N., Mallapuram S.P., Gangimeni G., Reddy R.K., and Kondreddy H.R., 2013, Marker assisted selection in disease resistance breeding, Journal of Plant Breeding and Genetics, 1(2): 90-109.
https://doi.org/10.1016/B978-0-444-63661-4.00009-8

Perween T., Mandal K.K., and Hasan M.A., 2018, Dragon fruit: An exotic super future fruit of India, Journal of Pharmacognosy and Phytochemistry, 7(2): 1022-1026.

Singh B.D., Singh A.K., Singh B.D., and Singh A.K., 2015, Marker-assisted selection, Marker-assisted plant breeding: principles and practices, 259-293.
https://doi.org/10.1007/978-81-322-2316-0_9

Taharuddin N.H., Jumaidin R., Mansor M.R., Hazrati K.Z., Tarique J., Asyraf M.R.M., and Razman M.R., 2023, Unlocking the potential of lignocellulosic biomass dragon fruit (*Hylocereus polyrhizus*) in bioplastics, biocomposites and various commercial applications, Polymers, 15(12): 2654.
https://doi.org/10.3390/polym15122654

Tel-Zur N., 2022, Breeding an underutilized fruit crop: A long-term program for *Hylocereus*, Horticulture Research, 9: uhac078.
https://doi.org/10.1093/hr/uhac078

Torres A.M., 2009, Application of molecular markers for breeding disease resistant varieties in crop plants, Molecular Techniques in Crop Improvement: 2nd Edition, 185-205.
https://doi.org/10.1007/978-90-481-2967-6_8

Trindade A.R., Paiva P., Lacerda V., Marques N., Neto L., and Duarte A., 2023, Pitaya as a new alternative crop for Iberian Peninsula: biology and edaphoclimatic requirements, Plants, 12(18): 3212.
https://doi.org/10.3390/plants12183212

Trivellini A., Lucchesini M., Ferrante A., Massa D., Orlando M., Incrocci L., and Mensuali-Sodi A., 2020, Pitaya, an attractive alternative crop for Mediterranean region, Agronomy, 10(8): 1065.
https://doi.org/10.3390/agronomy10081065

Wang H., and Qin F., 2017, Genome-wide association study reveals natural variations contributing to drought resistance in crops, Frontiers in Plant Science, 8: 1110.
https://doi.org/10.3389/fpls.2017.01110

Xi X., Zong Y., Li S., Cao D., Sun X., and Liu B., 2019, Transcriptome analysis clarified genes involved in betalain biosynthesis in the fruit of red pitayas (*Hylocereus costaricensis*), Molecules, 24(3): 445.
https://doi.org/10.3390/molecules24030445

Xu J.G., and Wang Z.Z., 2024, Genetic study of pigment synthesis and related genes in dragon fruit, International Journal of Horticulture, 14(5): 297-309.
https://doi.org/10.5376/ijh.2024.14.0031

Zafar S.A., Zaidi S.S.E.A., Gaba Y., Singla-Pareek S.L., Dhankher O.P., Li X., Mansoor S., and Pareek A., 2020, Engineering abiotic stress tolerance via CRISPR/Cas-mediated genome editing, Journal of Experimental Botany, 71(2): 470-479.
https://doi.org/10.1093/jxb/erz476