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Case Study **Open Access**

Germplasm Flow and Regional Adaptation of Yellow Pitaya: The Role of Genetic Variation in Cultivation Expansion

Zhonggang Li [1], Yeping Han [2]
1 Tropical Specialty Crops Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572026, Hainan, China
2 Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China
Corresponding author: yeping.han@jicat.org

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Abstract Yellow pitaya (yellow dragon fruit, *Selenicereus megalanthus*) is a tropical fruit crop with high nutritional value and economic potential. This study reviews the origin and domestication process of yellow pitaya, the global flow of germplasm resources, and the role of genetic diversity in regional adaptation and cultivation expansion. Global germplasm dissemination and hybrid breeding have greatly enriched the genetic diversity of yellow pitaya, laying the foundation for adaptability in different ecological regions. This study focused on analyzing the environmental adaptation mechanism of yellow pitaya in its native Mesoamerica, as well as regional adaptation cases in newly introduced areas such as the Indochina Peninsula, and explored the contribution of genetic variation to adaptation to different climates in terms of stress resistance, flowering and fruiting, and growth cycle. In addition, we summarized the progress of adaptive breeding and variety selection of yellow pitaya, and analyzed the main constraints facing the current germplasm utilization (such as self-incompatibility, pest and disease stress, and narrow genetic basis). We also looked forward to the prospect of expanding the opportunities of the yellow pitaya industry by expanding the cultivation area (such as greenhouse cultivation) and strengthening genetic improvement (such as polyploid breeding and molecular breeding). Finally, suggestions were made for future research directions, including the establishment of an international germplasm resource sharing platform, the development of genomic selection and biotechnology applications, etc., to promote the sustainable cultivation and industrial development of yellow pitaya.

Keywords Yellow pitaya; Germplasm resources; Genetic diversity; Regional adaptability; Breeding

1 Introduction

Yellow pitaya (commonly known as yellow-skinned pitaya) belongs to the genus *Pitaya* of the Cactaceae family. Its fruit is rich in vitamins, dietary fiber and antioxidants, and has important nutritional value and health benefits (Wang et al., 2019; Lin et al., 2023). As a tropical fruit crop that has emerged in recent years, yellow pitaya has attracted much attention in the global fruit market. In the past decade, the pitaya industry in my country has developed rapidly, with a significant increase in planting area and output, and has become one of the world's largest pitaya producers. The crystal-clear and sweet flesh of the yellow pitaya and the sesame-like black seeds make it very popular in the market. At the same time, its adaptability to cultivation potential has attracted the attention of agricultural departments in various countries.

The research and development and cultivation of yellow pitaya involve multiple disciplines, including fruit tree genetic breeding, horticultural cultivation, plant physiological ecology, and pest and disease control. At present, the Chinese yellow pitaya industry is still facing many challenges, such as the narrow genetic basis of varieties, unclear regional adaptability, self-incompatibility affecting yield, and threats from pests and diseases (Luo et al., 2025). In order to solve these problems, in-depth research on the diversity of yellow pitaya germplasm resources and genetic variation is crucial to improve its adaptability and stress resistance. In addition, in the context of global climate change, exploring the feasibility and adaptation mechanism of yellow pitaya cultivation in new regions is also of great practical significance.

This study systematically combed the research progress at home and abroad in the past five years, focusing on the origin and domestication of yellow pitaya, germplasm resources and global dissemination, genetic diversity and adaptive role, adaptive mechanism of Central American origin, adaptive breeding and selection, regional adaptation case study, constraints on germplasm utilization, expansion of cultivation opportunities and future prospects. It aims to clarify how genetic variation promotes the successful cultivation of yellow pitaya in different regions and provide a scientific basis for future breeding and cultivation.

2 Origin and Domestication of Yellow Pitaya

2.1 Native distribution and domestication centers

Yellow pitaya originated in tropical America. According to historical records, pitaya plants are native to southern Mexico and Central America, including tropical rainforests and dry forests in countries such as Nicaragua, Colombia, and Venezuela (Shah et al., 2023). These areas have high temperatures and moderate rainfall throughout the year, and the altitude ranges from a few meters to nearly 1,840 meters, which breeds rich wild germplasm resources of the genus Pitaya. Yellow pitaya, as a yellow-skinned and white-fleshed species in the genus Pitaya, is believed to have originated mainly in countries around the Andes Mountains in South America, such as Bolivia, Ecuador, Colombia, and Peru (Chen et al., 2023). In the place of origin, wild pitaya plants often grow as epiphytic vines on the edge of forests or in rock crevices, showing climbing, multi-branching characteristics and the ability to adapt to barrenness and drought.

2.2 Historical pathways of early cultivation and trade

The domestication and cultivation of yellow pitaya has a relatively short history. After the Age of Discovery in the 16th century, European explorers first introduced pitaya from Central and South America to Asian colonies (Hernández and Salazar, 2012). According to literature reports, as early as the Shunzhi period of the Qing Dynasty (around 1645 AD), the Dutch had introduced *Hylocereus serrata* (a type of pitaya) to Taiwan as a garden ornamental plant. However, due to problems such as self-incompatibility of the strains introduced at that time, commercial production was not formed. In the mid-19th century, French missionaries brought pitaya to their colonies in Indochina (Vietnam, Laos, Cambodia), and pitaya began to take root in Southeast Asia. In the late 20th century, with the selection and spread of new strains, the planting area of pitaya in Asia expanded rapidly (Trindade et al., 2023). In particular, in the 1980s, Vietnam introduced new self-fertile red-fleshed pitaya varieties from Colombia and other places, and introduced these varieties to Taiwan in 1983, thus starting the process of pitaya industrialization in Taiwan.

2.3 Genetic consequences of domestication events

Currently, the cultivated pitaya in the world mainly includes three cultivated populations: red-skinned white-fleshed species (*Hylocereus undatus*), red-skinned red-fleshed species (*H. polyrhizus* or *H. costaricensis*), and yellow-skinned white-fleshed species (*S. megalanthus*). Among them, *H. undatus* is native to Mexico and Central America, *H. polyrhizus* is native to Mexico and other places, and *S. megalanthus* is native to North and South American countries around the Andes Mountains (Alves et al., 2021). As the latter, yellow-skinned pitaya is mainly collected by local people for consumption in its natural state. It has not yet undergone a long process of human selection and domestication and is considered to be still in a "semi-domesticated" state. This is reflected in its cultivation characteristics. For example, the yellow-skinned pitaya still retains wild characteristics such as hard thorns on the skin and relatively concentrated flowering period, which need to be improved through breeding to adapt to modern agricultural production.

3 Germplasm Resources and Global Dissemination

3.1 Classification and characteristics of germplasm types

The germplasm resources of yellow pitaya have significant diversity and regionality (Figure 1). Wild pitaya plants in Central and South America have rich species and intraspecific variation, including variations in morphological traits such as plant size, stem fleshiness, fruit color and flavor, as well as differences in adaptation to environmental factors (such as drought resistance and barrenness resistance). These wild resources are an important basis for improving cultivated varieties. In recent years, through field collection and introduction and preservation, research institutions in various countries have accumulated a certain scale of pitaya germplasm banks. For example, agricultural research units in Guangxi and Hainan, China have widely introduced dozens of pitaya germplasm resources from Central America and Southeast Asia, including red meat, white meat and yellow skin types (Ding et al., 2024). Studies on the ploidy and genome of these resources show that pitaya germplasm has natural polyploidy on the basis of diploid, which provides a special way for genetic improvement.

Figure 1 Two types of yellow peel pitayas. (A) *H. megalanthus*; (B) *H. undatus* (Adopted from Shah et al., 2023)

3.2 Pathways of germplasm flow across regions

With the development of international trade and agricultural exchanges, yellow pitaya germplasm has achieved global dissemination. Since the 19th century, European colonists and missionaries first spread pitaya to Southeast Asia. Vietnam is one of the earliest and most successful Asian countries to accept pitaya germplasm. As early as around 1860, pitaya took root in Vietnam and developed rapidly in the second half of the 20th century. At present, Vietnam has become one of the major producers of pitaya in the world, with a rich variety of types (Trindade et al., 2023). China introduced pitaya cultivation from Taiwan and Southeast Asia in the early 1990s, and initially tried it in southern provinces such as Guangdong and Guangxi. Since then, through multiple germplasm exchanges and introduction trials, more than a dozen provinces and regions across the country, including Hainan, Yunnan, Fujian, Sichuan and even Shaanxi, have begun to plant pitaya, among which Hainan, Guangdong, Guangxi and Yunnan have become the main production areas. Many of the common cultivars in China, such as the red-fleshed "Red Dragon", "Big Red", the white-fleshed "Vietnam White", and the yellow-skinned "Qilin Fruit (Jindu No. 1)", are selected from foreign germplasms through hybridization or natural mutation. It can be said that the development of China's dragon fruit industry depends largely on the introduction and secondary innovative use of global germplasm resources.

In addition to Southeast Asia, yellow pitaya has also been introduced and cultivated in other parts of the world: for example, Australia began to commercially cultivate red-skinned dragon fruit in the late 20th century and cultivated varieties suitable for the local climate (Adnan et al., 2011); Israel introduced multiple pitaya germplasms from Central America in the 1980s, and through hybridization breeding, successfully cultivated a number of excellent varieties adapted to Mediterranean climate conditions, and established dragon fruit orchards in arid areas (Mizrahi et al., 2010); the United States mainly uses greenhouses or orchards in California, Florida and Hawaii to cultivate pitaya on a small scale as an emerging specialty crop to supply the market. Due to climate restrictions, traditional open-field cultivation is rare in Europe, but in recent years, subtropical regions such as southern Spain and Sicily, Italy have also begun to try to plant it, and have achieved certain success. These introduction experiments show that as long as suitable germplasm is selected and cultivation measures are adjusted, yellow pitaya has the potential to grow in a wider range of regions around the world.

3.3 Institutional roles in germplasm collection and sharing

The global flow of germplasm has greatly promoted the exploration and utilization of genetic diversity of yellow pitaya. For example, through SSR molecular marker analysis of 32 pitaya germplasms collected in Okinawa, Japan, it was found that there were significant allele differences between materials from different sources, and the germplasms could be divided into 6 genetic groups, which roughly corresponded to their species classification (Nashima et al., 2021). For another example, ISSR analysis of 76 yellow-skinned pitaya genotypes in Colombia showed that the species had high genetic diversity locally (He average value 0.34), and the intra-population variation accounted for 75% of the total variation, indicating that there was still gene exchange between geographically separated populations of yellow-skinned pitaya (Morillo et al., 2022). These studies confirm the importance of global germplasm exchange: the process of introducing and cultivating different regions is itself a process of recombining genetic diversity and expanding the gene pool. Through global introduction and hybridization, breeders are able to integrate the excellent traits of different strains into new cultivated varieties, thereby cultivating new yellow pitaya varieties with higher yield, higher quality and wider adaptability.

However, global germplasm flow also brings biosafety risks, such as the risk of pests and diseases spreading with seedlings (Derviş and Özer, 2023). In recent years, the stem blight disease (caused by the fungus *Neoscytalidium dimidiatum*), which seriously harms pitaya, has broken out in many newly introduced areas and is believed to be related to the transportation of seedlings (Serrato-Diaz and Goenaga, 2021). In this regard, while promoting germplasm exchange, countries need to strengthen quarantine inspection and disease prevention and control research.

4 Genetic Diversity and Its Role in Adaptation

4.1 Types of genetic variation in yellow pitaya populations

Genetic diversity is the cornerstone for crops to adapt to different environmental conditions and achieve sustainable development. For yellow pitaya, rich genetic variation enables it to have the potential to grow and bear fruit under different climates and cultivation systems (Morillo et al., 2022). Studies have shown that pitaya germplasm resources are highly diverse at the morphological, cytological and molecular levels. For example, in terms of floral traits, analysis of the floral morphology of pitaya germplasm collected in China found that the flower size, perianth morphology, style length and other indicators of different strains were significantly different, and the Simpson diversity index of floral phenotypes reached 0.22~0.60, indicating that the floral organ characteristics among germplasms are extremely diverse (Huang et al., 2021). At the same time, there is a correlation between floral traits of different germplasms and fruiting ability: the position relationship between stigma and anther, pollen quantity, etc. are significantly correlated with fruit setting rate and fruit size, which are important indicators to pay attention to during breeding. These findings mean that by utilizing the genetic variation of floral traits, it is possible to breed new varieties with large pollen quantity, strong self-pollination ability and excellent fruiting performance.

4.2 Genomic tools for assessing genetic diversity

Diversity is also obvious at the genomic level. Korean scholars used simplified genome sequencing to analyze the genetic relationship of 47 pitaya germplasms. The results showed that materials from different sources were clearly clustered into three major groups, corresponding to white flesh, red flesh and yellow skin species. Chinese researchers used flow cytometry to detect the chromosome ploidy of 42 pitaya germplasms and found that there were both diploids and a few natural tetraploids or mixed ploidy conditions, suggesting that pitaya has variation mechanisms such as chromosome doubling. Ploidy variation can lead to changes in plant phenotype and physiology, such as stem fleshiness, fruit size and stress resistance, and therefore has potential application value in breeding. In addition, molecular markers (such as SSR, AFLP, etc.) are used to evaluate the genetic diversity of pitaya germplasm. Okinawa University used 16 newly developed pairs of SSR markers to analyze 32 local pitaya gene pools, and obtained 612 alleles per locus and an expected heterozygosity of 0.500.85, indicating a high level of variation within the genome (Nashima et al., 2021). Most varieties can be distinguished by a small number of core SSR markers, reflecting the effectiveness of marker-assisted identification of germplasm.

4.3 Relationship between genetic diversity and environmental resilience

The role of genetic diversity in regional adaptability is mainly reflected in the differences in the response of different genotypes to environmental factors, which makes the species as a whole have a wider ecological range. In pitaya, some varieties are drought-resistant and heat-resistant, and are suitable for fruiting in high temperature and drought environments; others are more resistant to low temperatures or shade and humidity, and can survive in cooler or rainy environments (Lin et al., 2023; Huang et al., 2024). For example, the red-fleshed pitaya variety

‘Dahong’ has strong resistance to high temperatures and sunburn, and is suitable for open-field cultivation in the tropics; while the white-fleshed variety ‘Vietnam White’ is relatively shade-tolerant and can bloom and bear fruit normally under weak light conditions in the greenhouse, so it is often used in facility cultivation. Another example is that yellow-skinned pitaya germplasm is generally sensitive to soil drought, but some materials from the Andes region have better tolerance to low temperatures than ordinary varieties, which provides material for improving the cold resistance of pitaya. A study compared the metabolite differences between red-fleshed pitaya and white-fleshed pitaya and found that the red-fleshed type accumulated more pigment secondary metabolites such as betacyanin, which may be related to its antioxidant and UV resistance, while the white-fleshed type is more active in certain carbohydrate metabolic pathways (Lin et al., 2021). These differences are all manifestations of genetic diversity, reflecting the specific adaptive characteristics formed by different strains under long-term natural selection or artificial selection.

It is worth mentioning that self-incompatibility is also an aspect of the genetic characteristics of pitaya. Some red-fleshed pitaya varieties have difficulty in self-pollination and must be cross-pollinated to ensure yield. However, through multiple generations of artificial selection, some self-compatible strains (such as the red-fleshed strain introduced from Vietnam) have been bred. The genetic control of self-incompatibility involves multiple loci, and the accumulation of corresponding variations has led to different types of pitaya in this important reproductive trait, providing convenient self-pollinating varieties for production. This shows that genetic variation makes it possible for pitaya to adapt to different cultivation modes (artificial pollination or natural fruiting).

5 Mesoamerican Regional Adaptation Mechanism

5.1 Climatic factors influencing local adaptation

The tropical environment of Central America, where the yellow pitaya originated, has shaped its unique physiological and ecological adaptation mechanism. The typical ecological characteristics of the origin are high temperature, seasonal drought and strong light, which have enabled the dragon fruit plants to evolve a series of adaptive strategies to survive and reproduce in adversity.

Yellow pitaya has fleshy stems and crassulacean acid metabolism (CAM) photosynthesis mechanism, which is an important physiological basis for drought adaptation. The fleshy stem is rich in mucilage, which can store water in the tissue and maintain water balance under drought conditions (Lee and Chang, 2024). CAM photosynthesis absorbs CO_2 by opening stomata at night and closing stomata during the day to reduce transpiration, thereby reducing water loss during hot and dry days. Studies have confirmed that pitaya is a typical non-facultative CAM plant, which mainly uses the CAM pathway to fix carbon regardless of sufficient water supply or drought stress (Wang et al., 2019). This mechanism enables it to survive in arid environments with an annual rainfall of only 350 mm (Shah et al., 2023). However, persistent severe droughts still interfere with pitaya photosynthesis, reducing the net CO_2 absorption rate. This may be related to drought-induced chlorophyll oxidation damage and destruction of photosynthetic machinery. But in general, thanks to CAM metabolism, yellow pitaya is more tolerant to water deficit than C_3 and C_4 plants, and its biomass produced per unit water consumption is higher, and it is considered to be a crop with high water use efficiency. Pitaya native to Central America often grows on tree crowns or climbing rocks, and relies on CAM metabolism to survive in high temperature and exposure environments. This adaptation continues to work when introduced to areas with similar dry and hot climates (such as the Mediterranean coast).

5.2 Genotype-by-environment interaction in yellow pitaya

Yellow pitaya has low requirements for soil and nutrient conditions and shows characteristics of adapting to poor soils. In its native habitat, pitaya is commonly found in sandy soil or limestone areas with low humus content, and obtains limited nutrients through a well-developed root system and symbiotic microorganisms (Gong et al., 2024). Studies have isolated endophytic strains with phosphorus solubilization, potassium solubilization and nitrogen fixation functions from the rhizosphere of pitaya, such as *Trichoderma* and Bacillus, which can increase the effective phosphorus and potassium content in the soil and promote the growth of pitaya plants. This shows that pitaya may rely on rhizosphere growth-promoting bacteria to provide nutrients and improve its adaptability in a barren environment. In the wild environment of Central America, pitaya also often coexists with large trees, and its aerial roots are attached to the surface of tree trunks rich in mosses and algae, absorbing nutrients and water from rainwater and air. This epiphytic lifestyle is also an adaptation to resource-scarce environments.

5.3 Role of local selection and farmer preferences

Yellow pitaya has formed a complete set of mechanisms to adapt to dry and hot climates and barren environments in its native Central America, including CAM photosynthesis, efficient water use, nutrient acquisition promoted by rhizosphere bacteria, flexible phenology, and biochemical mechanisms of self-protection. This set of "adaptation strategy packages" makes yellow pitaya often show tenacious vitality when introduced to similar environments. For example, in Sicily, Italy, which has a Mediterranean climate, the introduced pitaya grows well under high temperature and low rainfall conditions in the greenhouse, and each plant has a considerable annual fruit yield, which has been proven to be adapted to local production (Trivellini et al., 2020). This shows that making full use of the inherent adaptation mechanism of yellow pitaya and combining it with appropriate agricultural measures can achieve its successful cultivation in non-origin environments.

6 Breeding and Selection for Adaptation

6.1 Key agronomic traits targeted in breeding programs

In response to the demand for yellow pitaya cultivation in different regions, adaptive breeding has been gradually carried out in recent years. The core goal of breeding is to enable new varieties to adapt to the climate and cultivation conditions of the target environment through genetic improvement, while having excellent yield and quality. Since yellow pitaya is introduced over a wide area and the environment varies significantly from place to place, the traits of concern in breeding in different regions are different. For example, in hot and arid areas (such as the dry and hot valleys in the northwest), the focus of breeding is on breeding varieties that are drought-resistant and heat-resistant and have a high self-flowering fruiting rate; while in rainy and humid areas (such as the southern monsoon area), it is necessary to cultivate disease-resistant and waterlogging-resistant varieties. For greenhouse protected cultivation, the varieties are also required to have strong adaptability to weak light and potted environments (Liu, 2020).

6.2 Traditional vs. modern selection techniques

Conventional hybrid breeding is one of the main means. Through hybridization, the excellent traits of different parents can be recombined to obtain offspring with better comprehensive traits. For example, Taiwanese and Vietnamese breeders used red-fleshed self-incompatible varieties to cross with white-fleshed self-compatible varieties to breed a new "two-color" pitaya variety that has both red flesh and self-pollination, successfully combining the advantages of the two types. Shaanxi Yangling Vocational and Technical College and other institutions recently reported red-fleshed × white-fleshed hybrid offspring varieties such as "Qin Honglong", which are both adapted to the local climate and have the characteristics of large fruit and high yield. These results show that through distant or close hybridization, it is possible to break through the limitations of a single strain and integrate multiple target traits such as stress resistance, self-compatibility, high yield, and large fruit (Huang et al., 2021).

Ploidy breeding is also an exploratory direction for pitaya breeding. Polyploid plants often show characteristics such as enlarged organs and enhanced stress resistance. Chinese researchers successfully induced pitaya tetraploid materials by treating bud tips with colchicine, and used them to cross with diploids to produce triploid seedless varieties (Ding et al., 2024). Although there are no commercial polyploid varieties available yet, studies have shown that tetraploid pitaya is superior to diploid in terms of stem thickness, flower and fruit size, and is more tolerant to high temperature and drought (presumably based on the polyploidy rules of other crops). This provides ideas for breeding varieties for special purposes.

In terms of mutation breeding, some studies have used physical or chemical mutagenesis to create new variations of pitaya. For example, irradiating pitaya seeds with carbon ion beams has been shown to effectively produce mutant plant populations. The experiment found that after treatment with carbon ion beams at a dose of 15~30 Gy, the survival rate of pitaya seedlings decreased, and some traits mutated, some of which may have breeding value

(Wu et al., 2021). The team of Guangxi Academy of Agricultural Sciences in China reported obtaining mutant strains with stronger growth and shorter internodes through carbon ion mutagenesis screening. Methods such as radiation mutagenesis are expected to break the bottleneck of pitaya genetics and provide more materials for the breeding of new varieties.

Molecular breeding and gene editing are currently in their infancy. With the establishment of pitaya genome sequencing and transformation system, it is possible to use MAS (marker-assisted selection) and genome editing technology for targeted improvement. In recent years, the draft of pitaya whole genome sequencing has been published, laying the foundation for the discovery of key genes related to disease resistance, stress resistance, and fruit quality (Li et al., 2025). For example, the structural genes and regulatory genes that control anthocyanin synthesis in pitaya have been found, which can be used to guide the breeding of new varieties with brighter flesh color and stronger antioxidants (Lin et al., 2021). In terms of disease resistance, Taiwanese scholars cloned disease-resistant transcription factor genes such as pitaya WRKY33, and after being transferred into pitaya, they significantly improved its resistance to stem blight (Luo et al., 2025). These research advances mean that in the future, pitaya varieties that are more tolerant to specific adversities can be cultivated through genetic engineering. Although there is no commercial application of genetically modified pitaya at present, molecular breeding is undoubtedly a powerful tool to improve breeding efficiency.

6.3 Integration of local and exotic germplasm in breeding

Regional trials and selection of varieties are also important links in adaptive breeding. For different ecological zones, the agricultural department has established pitaya variety comparison test gardens to evaluate the regional adaptability of introduced and cultivated varieties. For example, the experiment in Rongjiang, Guizhou showed that the growth results of multiple introduced varieties in the local area were close to the level of the best production areas in Guizhou Province, proving that the climate in Rongjiang is suitable for promoting pitaya cultivation (Huang et al., 2024). For another example, Guangxi set up points in southern, central and northern Guangxi to test the yield and cold resistance of different varieties. The results showed that some varieties can be moved north to areas with an annual minimum temperature of around 0°C for planting, and they can safely overwinter by covering and protecting them in winter. Through regional trials and screening, various regions have selected the main varieties suitable for their own environments. For example, Hainan mainly uses the early-maturing, high-sugar red meat "Dahong", while the western Guangdong region promotes high-yield and stable soft-branch white meat varieties. These practices reflect the principle of "selecting good varieties according to local conditions" and accelerate the renewal of varieties in yellow pitaya production.

In the process of adaptive breeding, breeders also attach importance to maintaining genetic diversity to prevent the risk of single varieties. Some units have established core germplasm banks to classify and preserve germplasms with different genetic backgrounds, and carry out reincarnation selection to improve specific traits while retaining the diversity of the population as much as possible (Morillo et al., 2022). In addition, it is also very important to strengthen germplasm exchanges and joint breeding between different institutions. Research institutes in Guangxi, Guangdong and Vietnam have exchanged hybrid offspring materials many times, promoting the sharing of excellent genes. Internationally, some scholars have suggested establishing an international dragon fruit research alliance and germplasm sharing platform to integrate the breeding forces of various countries and avoid duplication of work. These measures are expected to accelerate the breeding of new yellow pitaya varieties that are more adaptable to a wide range of environments.

7 Case study: Regional Adaptability (e.g. Southeast Asia)

7.1 Germplasm introduction history and initial challenges

Southeast Asia is one of the most successful regions for the introduction of yellow pitaya, with Vietnam and Thailand being particularly typical. Taking Vietnam as an example, dragon fruit has expanded rapidly in the country since the late 20th century, and its current planting area and output are among the highest in the world (Trindade et al., 2023). The climate in Binh Thuan Province and Tien Giang Province in the central and southern coastal areas of Vietnam is hot and rainy, which is very suitable for the growth of dragon fruit. Through trellis cultivation and artificial pollination, growers have achieved an average annual output of tens of thousands of tons of commercial fruit. It is reported that the area of dragon fruit cultivation in Vietnam has maintained a rapid growth trend in recent years, with an average annual growth rate of more than 10% between 2015 and 2020, and the industry prospects are widely optimistic (Zeng et al., 2021). However, studies have pointed out that the scientific research support for dragon fruit in Vietnam is relatively lagging, and investment in breeding of improved varieties and disease prevention is insufficient. For example, pitaya stem blight and canker diseases occur frequently in Vietnam, causing losses in production, and the corresponding prevention and control technologies and research and development of disease-resistant varieties need to be strengthened. In addition, market fluctuations and climate factors (such as extreme high temperatures or floods) also bring uncertainty to the industry. In response to these problems, the Guangxi Academy of Agricultural Sciences and other institutions cooperated with Vietnam to conduct research and proposed that an international germplasm resource sharing platform and scientific research cooperation alliance should be established to jointly cultivate new varieties suitable for Vietnam and surrounding areas, and at the same time strengthen cultivation management training to improve the industry's risk resistance. Vietnam's experience shows that even if a region has superior natural conditions, it may face challenges after scale expansion if it lacks scientific and technological support and diversified operations.

7.2 Performance and selection in local Agroecological zones

Thailand is also a case of successful adaptation of pitaya in Southeast Asia. Some areas in central and northeastern Thailand use orchard intercropping and family courtyards to grow pitaya. With abundant local sunshine and labor resources, the pitaya industry has developed. The Thai agricultural sector actively introduced excellent varieties from Vietnam and Taiwan, such as the red-fleshed "Big Red" and the white-fleshed "Big Mac", and at the same time selected some strains suitable for local tastes and climate. Thai farmers focus on organic cultivation and extending the fruiting period. By adjusting watering and fertilization, pitaya can be evenly available almost all year round to meet the needs of tourism and exports. It is reported that some planting areas in Thailand have controlled light to induce off-season flowering, so that pitaya can also bear fruit in the traditional off-season, thereby improving economic benefits (Trivellini et al., 2020). These measures show that pitaya has a strong responsiveness to artificial cultivation regulation, which is another manifestation of its regional adaptability (Figure 2) (Al-Qthanin et al., 2024).

7.3 Cultivar development and market integration outcomes

In addition to Vietnam and Thailand, Malaysia, the Philippines and other countries have also gradually expanded the scale of pitaya cultivation. Malaysia has accumulated certain experience in controlling pests and diseases, such as reducing the incidence of stem blight by more than 60% through pruning and clearing the garden (Dutra et al., 2025). The Philippines uses volcanic ash soil to grow pitaya, and the fruit has a unique flavor and is branded. In Southeast Asia, countries have also carried out experience exchanges, such as establishing a dragon fruit industry association to hold annual seminars to share information on new varieties and new technologies. These cross-regional collaborations have further promoted the adaptation and promotion of dragon fruit in Southeast Asia.

8 Constraints and challenges of germplasm utilization

8.1 Genetic bottleneck and low pollination rate

Most of the widely planted yellow pitaya varieties are derived from a few introduced materials and have a high degree of homogeneity. Some main varieties (such as the Vietnamese white-fleshed variety) account for too large a proportion of the planting area. Once they encounter an unfavorable environment or a new pathogen, they may fail as a whole. For example, many places use red-fleshed pitaya varieties introduced from Vietnam. These varieties are highly similar in genetics and have similar disease resistance spectra. Therefore, when stem blight or other diseases break out in the region, all plots are often infected at the same time, resulting in heavy losses. The narrow genetic base also limits the space for further breeding improvements. For some traits (such as cold resistance), the currently available allelic variation is limited, which slows down breeding progress. Therefore, it is necessary to introduce and create more germplasm variation, including distant hybridization of wild relatives, new alleles obtained by mutagenesis, etc., to broaden the genetic background (Ding et al., 2024).

Figure 2 Three different *Selenicereus* species of pitaya (A) *S. undatus* (B) & (C) *S. costariscensis* and (D) represent *S. megalanthus* (Adopted from Al-Qthanin et al., 2024)

Bird's nest fruit has different degrees of self-flowering failure. This means that when there is no foreign pollen or artificial assisted pollination, the fruit setting rate is very low, thus affecting the yield. To overcome this problem, pollination trees or artificial pollination need to be configured in production, which increases labor costs and management difficulties. Although some new self-compatible varieties have been selected through breeding, these new varieties may not be comprehensively superior to traditional varieties in terms of fruit quality or other traits, so their promotion is subject to certain restrictions. In addition, in terms of pollinators, the main pollinating insects and bats in the origin may be missing in the new area, resulting in a low natural pollination rate. How to cultivate varieties with strong self-pollination ability and high quality, or improve agricultural measures to increase the natural fruit setting rate, is one of the key challenges to improving production efficiency.

8.2 Pest and disease infection and adaptability

Bird's nest fruit is often introduced to a new environment and faces the invasion of pests and diseases in the origin or the infection of new local pests and diseases. Among them, stem blight/ulcer disease is the biggest threat to the current global dragon fruit industry. It is caused by the fungus *N. dimidiatum* and can cause branch ulcer rot and fruit lesions. The disease has been prevalent in many countries in Southeast Asia, East Asia, and the Americas, and has been listed as a major disease that needs to be strictly prevented by the world's plant pathology community (Espinoza-Lozano et al., 2023). Because the pathogen of stem blight has the characteristics of a wide host and strong environmental adaptability, it is called a "destructive disease" (Derviş and Özer, 2023). At present, there are no highly resistant varieties to stem blight, and chemical control has limited effect. Each production area mainly relies on timely pruning of diseased branches and biological control measures to control it (Dutra et al., 2025). In addition to stem blight, fruit rot (such as post-harvest fruit rot caused by *Curvularia lunulata*) also harms the storage and transportation process. In terms of pests, aphids, scale insects, mites, fruit flies, and red fire ants can all affect the growth and results of pitaya (Tang et al., 2020). Since yellow pitaya is an introduced crop, many pest and disease control technologies are still imperfect, and there is a lack of registered special pesticides or integrated control models. This requires scientific research and promotion departments to strengthen the monitoring and research of yellow pitaya diseases and pests, cultivate disease-resistant varieties and develop green control technologies. For example, the application of antagonistic microorganisms such as *Trichoderma* to control ulcer disease has achieved initial results, and some *Trichoderma* strains can inhibit the bacteria by more than 80% (Chen et al., 2020). In the future, these new technologies need to be integrated and applied to reduce the threat of diseases and pests to the industry.

The long-term adaptability of yellow pitaya in many new regions is still under observation. Due to large climate variations in some marginal planting areas (such as high latitudes or high altitudes), pitaya may occasionally encounter extreme low temperatures or abnormal weather, resulting in reduced production or even frost damage and death (Liu et al., 2020). For example, in some years, winter frost occurred in southern my country, and open-field pitaya was severely damaged. Therefore, there are risks in promoting pitaya in these areas, and it is necessary to strengthen protection and select more cold-resistant varieties. For example, in greenhouse cultivation, long-term low light environment may affect the photosynthesis and flowering of pitaya, which needs to be solved by supplementary lighting and other technologies. In addition, pitaya is sensitive to excessive soil moisture and is prone to root rot in areas with high annual precipitation and poor drainage. Therefore, it is necessary to improve cultivation facilities (such as high-bed cultivation and rain shelter trellises). All of these require us to conduct in-depth research on the physiological response mechanism of yellow pitaya to environmental stress (cold, flooding, low light, etc.) and screen materials with stronger tolerance to cope with possible climate change in the future.

8.3 Quality improvement and sustainable planting

For yellow pitaya to gain a foothold in the global fruit market, it is necessary to continuously improve the fruit quality, including taste, nutrition and storage and transportation performance. At present, some varieties have insufficient sugar content or bland flavor, and are not competitive enough in the high-end market. In addition, the skin of pitaya is thin and the ripening effect is not significant. The shelf life of the fruit after picking is relatively short. Generally, it can be stored at room temperature for about 2 weeks before it begins to soften and rot (Luo et al., 2025). This poses challenges to long-distance transportation and export. Improving fruit quality through genetic means, such as increasing the sugar-acid ratio, increasing the content of aromatic substances, enhancing the toughness and antioxidant capacity of the peel, is an important direction of quality breeding (Lin et al., 2021). At the same time, it is also necessary to develop post-harvest preservation technology (such as low-temperature controlled atmosphere storage and edible coating preservation) (Hu et al., 2020). Only by overcoming the bottlenecks of quality and preservation can yellow pitaya obtain a higher market premium and the industry become more competitive.

Bird's nest fruit cultivation is a labor-intensive industry, which requires a lot of manpower from scaffolding, pruning to artificial pollination. Due to rising labor costs in some areas, the profit margin of pitaya cultivation has been squeezed. How to reduce production costs through mechanization and intelligent means is a practical problem facing the industry. For example, the development of pollination machines, automatic fertilization and irrigation systems, and pest and disease monitoring Internet of Things are expected to reduce dependence on labor. Another example is the promotion of "grass cultivation" and "organic planting", which can reduce the use of herbicides and fertilizers and achieve a win-win situation for environmental and economic benefits. In addition, long-term land use and continuous cropping also bring the risk of accumulation of soil-borne diseases. It is necessary to explore crop rotation and intercropping patterns or soil improvement methods to ensure the sustainable production capacity of the land.

9 Expansion of Cultivation Opportunities

9.1 Exploration of untapped genetic resources

In addition to traditional tropical regions, some temperate regions have also shown interest in yellow pitaya cultivation. For example, southern European countries along the Mediterranean coast are very suitable for pitaya growth due to hot and dry summers and mild winters. Italy, Spain and other countries have successfully trial-grown pitaya under greenhouses or rain shelters, achieving high yields and quality. Studies have shown that the efficient use of water by yellow pitaya makes it competitive in water-scarce Mediterranean agriculture (Trivellini et al., 2020). Another example is California, USA, where commercial pitaya farms have also emerged in recent years due to its climate being close to that of northern Mexico. It is reported that California farms use greenhouses to cultivate yellow-skinned pitaya, with a considerable output value per hectare per year (Trindade et al., 2023). These successful cases indicate that yellow pitaya cultivation is possible in more subtropical and even temperate regions through facility agriculture. In addition, desert arid regions such as the Middle East and North Africa have also begun to pay attention to pitaya, a drought-resistant crop, to explore new ways of water-saving and high-value agriculture. In short, breaking geographical restrictions and exploring new suitable habitats for yellow pitaya in the world is an important direction for the expansion of the industry.

9.2 Development of facility agriculture

Bird's nest fruit shows unique advantages in greenhouse and shed cultivation. In areas with higher northern latitudes, greenhouses can create a temperature and high light environment close to the tropics, allowing pitaya to grow and bear fruit smoothly. For example, Shandong and Liaoning in northern China have successfully cultivated red-fleshed pitaya using solar greenhouses, realizing "southern fruit and northern planting" (Liu, 2020). Greenhouse cultivation not only expands the planting area, but also extends the supply period. By regulating the temperature, humidity and light in the greenhouse, pitaya can bloom in non-traditional seasons, thereby achieving off-season production and meeting market demand throughout the year. For example, in a greenhouse experiment in Harbin, pitaya still blooms and bears fruit normally in the cold winter with excellent quality through heating and light enhancement. Facility agriculture is also conducive to fine management, such as the application of water and fertilizer integration and sensor monitoring to achieve precise irrigation and fertilization and environmental regulation, and reduce stress and coercion. The smart pitaya demonstration base in Zhanjiang, Guangdong has introduced agricultural meteorological monitoring and automated drip irrigation technology to improve yield and quality. It can be foreseen that with the advancement of facility horticulture technology, yellow pitaya will increasingly enter greenhouses and take root and bear fruit in a wider area.

9.3 Product diversification and processing value-added

The fresh market for yellow pitaya continues to expand, and opportunities are also emerging in its processing and by-product utilization. Processed products such as pitaya juice, fruit wine, and dried fruit are beginning to be popular with consumers (Wang et al., 2019). Red-fleshed pitaya is rich in natural pigment betacyanin, which can be used as a food colorant or nutritional additive, and has application potential in beverages, baking and other industries (Lin et al., 2021). In addition, pitaya peel and seeds are rich in dietary fiber, unsaturated fatty acids and other substances, and are currently often discarded as waste. If developed, pectin can be extracted for functional foods or cosmetics, or seed oil can be pressed to make health oils (Villalobos-Gutiérrez et al., 2019). Some studies have explored the use of pitaya peel mucus to prepare edible packaging films (López-Díaz et al., 2023), turning waste into treasure and increasing added value. With the food industry's preference for natural raw materials, the value of yellow pitaya processing byproducts is expected to be further explored. This will promote the transformation of pitaya cultivation from single fresh fruit sales to the development of the entire industrial chain, increase the value of agricultural products through intensive processing, and drive the expansion of planting scale. For example, when there is a seasonal surplus of fruits such as longan and lychee, the introduction of pitaya processing can stagger production and stabilize the income of fruit farmers. Therefore, expanding the product chain of pitaya is also an important means to promote the expansion of its cultivation.

10 Future Prospects and Research Directions

In the face of global climate change and disease threats, countries should jointly establish a yellow pitaya germplasm resource bank to collect and preserve more wild relatives and local varieties as a strategic reserve for breeding. It is recommended to build an international germplasm sharing platform to achieve orderly exchange of germplasm information and materials under the framework of intellectual property rights. For example, an "International Joint Research Center for Pitaya" can be established, with the participation of scientific research institutions in major producing countries, sharing core germplasm and databases, and achieving global collaborative innovation.

At present, the research on the pitaya genome has just started, and high-quality whole genome sequence maps and QTL positioning of important traits (disease resistance, stress resistance, quality) should be completed as soon as possible. Use genomic selection (GS) technology to shorten the breeding cycle and improve breeding accuracy. At the same time, explore the application of gene editing in pitaya, and conduct genome-directed improvement for restrictive traits such as self-incompatibility and disease susceptibility. Once regulations allow, new gene-edited varieties can be cultivated. For example, editing flowering time-related genes to regulate phenology, editing disease-resistant genes to enhance resistance, etc., will all have great potential.

Introduce Internet of Things and artificial intelligence technologies in pitaya planting management to achieve refined and intelligent production. For example, develop a special pollination robot for pitaya, use machine vision to identify flowers and automatically spray pollination to reduce labor costs; establish a remote monitoring and early warning system for pests and diseases, and use field sensors and algorithm models to timely predict the risk of ulcers and other diseases, and guide early prevention and control. In addition, build a digital model of yield and quality, dynamically adjust water and fertilizer according to environmental parameters, and ensure high and stable yields. The application of smart agricultural technology will significantly improve labor productivity and resource utilization efficiency, making pitaya still competitive when planted on a larger scale.

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Conflict of Interest Disclosure

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

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