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AGRONOMIC MANAGEMENT PRACTICES FOR SUSTAINABLE YIELD AND QUALITY ENHANCEMENT IN DRAGON FRUIT (*HYLOCEREUS SPP.*): A REVIEW

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ABSTRACT

Dragon fruit (*Hylocereus* spp.), tropical cactus crop, it has become a global and national concern due to its adaptability to arid and semi-arid climate, it is having high nutritional value, and rising demand of functional food. Dragon fruit is a relatively well-known tropical fruit, this fruit interests the whole world due to its various look, nutritional and health benefits.es. The scientific name of dragon fruit is *Hylocereus* spp. which has become a promising crop to solve climate change and rural penury. It contains a lot of the essential nutrients viz. vitamins and minerals, carbohydrates, dietary fibres and antioxidant compounds in abundance. The popularity of dragon fruit is based on its high nutritional value and offers great medicinal properties because of its prebiotic effects, various pharmaceutical and medicinal properties like anti-oxidant, anti-cancerous, anti-diabetic, anti-microbial and hepato protective properties. It can withstand extreme environmental conditions, in drought and high temperatures, which makes it suitable to arid and semi-arid areas, and its low water and resource demands enhance its sustainability, but the lack of agronomic uniformity, access to quality planting material and environmental constraints, such as climate variability and pollination limitations, limit its productivity and fruit quality. Traditional methods including the regular reliance on chemical fertilizers and pesticides are contrasted with new sustainable strategies such as organic additional things, high tunnel systems, and agroforestry. To boost yield, fruit quality, and resource efficiency, agronomic improvements such as high-density planting, drip fertigation, organic nutrient management, the use of bio stimulants, and artificial flower induction have been made. The propagation of the dragon fruit is sexually through the use of seeds and asexually through the use of stem cuttings, grafting, and micropropagation. Cold storage, modified packaging, edible coating, and non-thermal methods are all post-harvest strategies which are closely considered to retain quality and minimize spoilage. During the recent years, the genome of the dragon fruit has been published, the biosynthesis of betalains and self-incompatibility of the genome have been investigated as some of the key biological traits. This incorporates progress in cultivation, post-harvest technologies, and bioactivity research and points out any information gaps and future research areas. This integrates advancements in cultivation, post-harvest technologies, and bioactivity research and highlights existing information gaps and future research directions.

Keywords **:** Dragon fruit (*Hylocereus* spp.), Agronomic management practices, Sustainable agriculture, Nutrient management, Propagation techniques, Postharvest technology, Bioactive compounds.

Introduction

The tropical cactus *Hylocereus* spp. (dragon fruit) has achieved significant recognition over the past few years due to its outstanding adaptability to arid and semi-arid conditions, nutritional value, and growing popularity as a functional food. The crop is native to Central and South America, and has been introduced and commercialized in various tropical and subtropical areas, such as Southeast Asia, China, and India, where it has become a valuable horticultural crop (Ortiz-Hernandez and Carrillo-Salazar, 2012; Kakade *et al*., 2025). Its economic profitability, consumer preference to exotic fruits and increasing awareness of its health benefits greatly contribute to its rapid expansion in terms of cultivation (Balaji, 2025).

The fruit is greatly valued due to its special looks, bright coloured skin and pulp, mild sweetness and refreshing taste. Other than being tasty, dragon fruit contains many vital nutrients including vitamins (especially vitamin C and B-complex), minerals (such as calcium, phosphorus, and iron), carbohydrates, and dietary fiber (Sharma *et al*., 2024). It is also rich in bioactive compounds, such as betalains, flavonoids, and polyphenols, which make it have a high antioxidant activity (Wu *et al*., 2006). The compounds have been linked to many health advantages such as antidiabetic, anticancer, antimicrobial, anti-inflammatory, and hepatoprotective properties (Singh & Kumar, 2023). Consequently, dragon fruit is being increasingly considered as an important nutraceutical crop with enormous potential in the functional food and pharmaceutical sectors.

The capacity of dragon fruit to survive in a very harsh environment is one of its most significant qualities. As a cactus plant, it has physiological characteristics like crassulacean acid metabolism (CAM), which enables it to use water efficiently and reduce the rate of water loss to the atmosphere through transpiration (Nobel & De la Barrera, 2002). This helps it to withstand drought conditions and high temperatures, which makes it a perfect crop to be grown in arid and semi-arid regions (Le Bellec *et al*., 2006). Moreover, its comparatively low water and nutrient demand makes it fit resource-constrained farming systems thus contributing to sustainable agriculture and climate-resilient cropping systems (Mondol *et al*., 2025). Considering the issue of climate change, the dragon fruit can be used as a feasible alternative to the conventional water-intensive crops, which will not only save the natural resources but also retain the agricultural productivity (Balaji, 2025).

Besides being environmentally adaptable, the growth of dragon fruit is important in enhancing livelihoods in the rural areas and sustaining the smallholder farmers. The crop has one of the shortest gestation periods and fruits begin to appear in the market after 12-18 months of planting and its market value is very high and this guarantees it good returns with minimal inputs (Ortiz-Hernández and Carrillo-Salazar, 2012). This renders it especially useful to small and marginal farmers wishing to diversify their sources of income and increase the level of economic security. Furthermore, the growth in demand of the dragon fruit both in the domestic and international markets has further enhanced its commercial significance (Kakade *et al*., 2025).

Although these have the benefits, the quality and productivity of dragon fruit is usually limited by a number of factors. Among the challenges that are major is the inability to have standardized agronomic practices, which contributes to the variation in yield and quality of fruits in various areas (Mondol *et al*., 2025). Poor management of nutrients, poor irrigation methods, lack of training and pruning may have a great impact on the growth of plants and the development of fruits. The second important concern is that the quality of planting material is scarce, which prevents the large-scale production and influences the uniformity of crop (Pratap & Tripathi, 2025). Moreover, environmental issues like climate variability, extreme weather, and pollination limitations especially in some species with inability to self-pollinate can also decrease fruit set and yield (Weiss *et al*., 1994).

Traditional farming systems which in many cases are very dependent on chemical fertilizers and pesticides are also a source of concern with regard to environmental sustainability and soil health. Conversely, increased focus is placed on implementing sustainable and environmentally friendly production methods, including organic agriculture, integrated nutrient control, and agroforestry systems, to boost productivity with the least environmental impact (Belbase & Bhaskar, 2025). Increasing agronomic innovations, such as intensive planting, drip fertilization, application of biostimulants, and artificial triggering of flower buds have demonstrated encouraging outcomes in yield, fruit quality, and the efficiency of use of resources (Mondol *et al*., 2025).

Considering the growing significance of the dragon fruit as a climate-sustainable and cost-effective crop, there is a necessity to thoroughly analyze the available information about the agronomic management practices, breeding methods, postharvest management, and latest developments in molecular studies. Thus, the current review will summarize and critically evaluate the recent advances in the field of dragon fruit production with an emphasis on sustainable measures to maximize yield and fruit quality, the current limitations, and the future research avenues to the successful commercialization of this perspective crop.

Botanical Description and Crop Characteristics

Dragon fruit is an edible species of cactus that is a perennial, climbing cactus, belonging to the genus Hylocereus and the family Cactaceae. The genus has a number of commercially significant species, including *Hylocereus undatus* (white-fleshed), *Hylocereus costaricensis* (red-fleshed), and *Hylocereus megalanthus* (yellow-skinned, white flesh), which vary in terms of fruit color, taste, and agronomic behavior

(Ortiz-Hernandez and Carrillo-Salazar, 2012 They are highly adaptable and have economic importance, so they are highly cultivated in the tropical and subtropical areas.

The morphology of the dragon fruit plants is distinguished by the succulent, triangular and fleshy stems (which do photosynthesis) because the plant does not have real leaves. The stems are generally green, waxy and ribbed with spines along the edges which help to save water loss and defend the plant against herbivores (Nobel & De la Barrera, 2002). Aerial roots along the stem enable the plant to cling to structural support like trellis or poles hence is a climbing cactus. The support systems must be used in commercial cultivation to ensure optimization in canopy management and fruit production by this growth habit.

The flowering behaviour of dragon fruit is among the most unique characteristics of this fruit. The plant has huge, white and very fragrant flowers, which open at night and this has made it to be known as queen of the night. The opening of these nocturnal flora are usually in the evening and stay receptive to only a single night which restricts the pollination time but directly impacts fruit set (Weiss *et al*., 1994). Nocturnal pollinators (moths and bats) are the main pollinators, but in commercial agro-ecosystems, manual pollination is commonly used to achieve better fruit set and production.

An important biological trait of most Hylocereus species is self-incompatibility, meaning they cannot self-fertilize and require cross-pollination between compatible genotypes (Mizrahi, 2014). This characteristic may be problematic in monoculture plantations with low genetic diversity resulting in a low fruit set and production. Hence, successful production is dependent on the choice of compatible cultivars and appropriate pollination management.

The growth of fruits in dragon fruit is relatively fast where fruits grow within 30-50 days of successful pollination, under a good environmental condition and species (Le Bellec *et al*., 2006). The fruit is a berry, and has a thick rind, with scale-like projections, which may be of any color, red or yellow. The interior of the fruit, the pulp, may be white, red, or purple, and has many small, black, edible seeds that are full of lipids and proteins.

Dragon fruit has a rapid and sustained growth pattern when provided with good conditions and vegetative growth is all year round in tropical climates. Planting of the crop commonly takes between 12 and 18 months to flower hence it is a relatively short-lived perennial crop with an early payback (Ortiz-Hernández and Carrillo-Salazar, 2012). Training and pruning are necessary to ensure the structure of the plants and enhance the light capture, flowering, and fruit production.

Besides its morphological and reproductive traits, dragon fruit has special physiological adaptations that enable it to survive in the extreme environments. The CAM pathway of photosynthesis enables the plant to open its stomata at night, minimizing the loss of water, and enhancing the efficiency of the use of the water (Nobel and De la Barrera, 2002). This adaptation is especially helpful in the arid and semi-arid areas where the amount of water is small.

Altogether, botanical and physiological peculiarities of dragon fruit precondition it as a very flexible and productive crop. Nevertheless, characteristics like self-incompatibility and nocturnal flowering require special management measures, like proper cultivar choice and pollination management to obtain optimum yield and fruit quality.

Table 1: Comparative characteristics of major cultivated dragon fruit species

Species	Common trait	Flesh colour	Key note for production
Hylocereus undatus	Most widely cultivated	White	Good market acceptance and broad adaptation
Hylocereus costaricensis	Red-fleshed type	Red to purple	High pigment content and strong antioxidant appeal
Hylocereus megalanthus	Yellow-skinned type	White	Distinct fruit appearance and premium niche market

Note. Compiled by the author based on Ortiz-Hernández and Carrillo-Salazar (2012), Mizrahi (2014), and Le Bellec *et al*. (2006).

Climate Adaptability and Sustainability

Dragon fruit (*Hylocereus* spp.) is commonly known to be exceptionally adaptable to various climatic conditions especially in tropical and subtropical areas. The crop grows best in warm conditions of 20 ºC to 30 ºC, although it can withstand higher temperatures up to 40o C in case of proper management practices (Le Bellec *et al*., 2006; Mizrahi, 2014). This broad temperature range makes it applicable in the growth in areas with high heat stress and variable climatic conditions.

Exceptional drought resistance is one of the most important qualities of dragon fruit. As a cactus species, the plant has physiological adaptations including crassulacean acid metabolism (CAM) that enables the plant to absorb carbon dioxide at night and reduces water loss to the surroundings through transpiration in the daytime (Nobel & De la Barrera, 2002). Such adaptation makes the plant extremely efficient in terms of water-use and allows surviving in case of limited water supply, which makes it very effective in arid and semi-arid areas (Mondol *et al*., 2025).

Along with the ability to survive drought, dragon fruit is capable of growing in relatively poor and marginal soils where most other fruits do not grow well. Well-drained sandy loam soils of medium fertility are thought to be the best, but the crop can also withstand a broad range of soil conditions, as long as there is no waterlogging (Ortiz-Hernandez and Carrillo-Salazar, 2012). The root rot and fungal diseases may occur due to excess moisture in the soil, and the drainage system of the cultivation system should be considered as an important factor.

Dragon fruit has low water and nutrient needs making it a very sustainable horticultural crop. Dragon fruit needs significantly less irrigation and fertilizer than more conventional fruit crops, which means that it is cheaper to produce and has a smaller environmental footprint (Belbase & Bhaskar, 2025). This attribute is especially useful in areas where there is water depletion and soil erosion where there is an urgent need to have sustainable crop alternatives.

Dragon fruit is also important in climate resilient agriculture. As the issue of climate change is increasingly being raised such as increased temperatures, erratic rainfalls and extended droughts, there is a greater demand to have crops that can be able to cope with the environmental stress and still be productive. Dragon fruit suits the category as it can withstand abiotic stresses and give economic yields even where conditions are unfavourable (Balaji, 2025). Its production would enable the farmers to adapt to the climate changes and minimize the risks of crop failure.

Moreover, incorporation of dragon fruit into sustainable agricultural practices, including agroforestry and mixed planting improves resource-use efficiency and biodiversity. In agro forestry, dragon fruit can be used to enhance soil fertility, mitigate soil erosion, and enhance land use, which can help in long-term environmental sustainability (Belbase & Bhaskar, 2025). Likewise, the implementation of effective irrigation practices like drip irrigation also increases the efficiency of water-use and promotes sustainable production practices.

The other significant area of sustainability in the production of dragon fruit is that it can lessen the reliance on chemical inputs. The crop is sensitive to organic farming practices and integrated nutrient management, which enhances environmental health and lessens environmental pollution. This is in line with the increasing concern in the world on the need to adopt eco-friendly farming methods and sustainable food production systems.

Although it is flexible with favorable benefits of sustainability, there are still some climatic factors that can affect the production of dragon fruits. Drastic temperature changes, heavy rain, and humidity may have negative effects on flowering, fruit set and fruit quality. Moreover, efficiency of pollination could be lower in unfavorable climatic conditions, especially in those areas where natural pollinators are unavailable (Weiss *et al*., 1994). Hence, to alleviate these challenges, proper management practices such as protection structures and artificial pollination are required.

In general, its ability to adapt to a wide range of climatic conditions, the low resource demands, and tolerance to environmental pressures predispose dragon fruit to be a sustainable and climate-resistant crop. Its production provides a bright opportunity to solve the problems of climate change, water shortage and environmental degradation and guarantee the economic gains of farmers.

Nutritional and Medicinal Value

Hylocereus spp., commonly known as dragon fruit, is a well-known functional food that is rich in nutrients and has many health-promoting effects. The fruit has a balanced profile of essential nutrients, such as vitamins, minerals, carbohydrates, dietary fiber, and an extensive variety of bioactive compounds, which are contributing to its growing popularity among health-conscious consumers (Le Bellec *et al*., 2006; Sharma *et al*., 2024).

Nutritionally, dragon fruit is a great source of vitamin C which is very important in boosting the immune system and safeguarding the body against oxidative stress. B-complex vitamins like thiamine, riboflavin, and niacin that are necessary to metabolize energy and support normal functioning of the nervous system are also present in it (Wu *et al*., 2006). Besides vitamins, the fruit contains some necessary minerals, such as calcium, phosphorus and iron, which are essential in the body as far as the bones, cellular activities and transport of oxygen (Singh and Kumar,

2023). The carbohydrates and natural sugars make it energy-rich, and dietary fiber promotes the health of the digestive system and enhances gut microbiota.

One of the characteristics of dragon fruit is that it contains high levels of bioactive compounds, especially, betalains, flavonoids and polyphenols. Water-soluble pigment responsible for the coloration of the fruit (red and purple) is called betalains and is associated with a high antioxidant activity (Zheng *et al*., 2021). These compounds aid in counteracting the effect of the free radicals and decreasing oxidative stress, which decreases the possibility of chronic ailments like cardiovascular disorders and cancer. Another source of antioxidants in the fruit is flavonoids and phenolic compounds, which further add to the overall health benefits of the fruit (Sharma *et al*., 2024).

Pharmacological effects of dragon fruit have been extensively researched and it has been documented to have various pharmacological effects. The antioxidant effect of the fruit has a major role in inhibiting the cell damage and aging diseases. Moreover, dragon fruit has also shown anti-diabetic properties by enhancing insulin sensitivity and controlling blood glucose levels, and therefore can be used by diabetes patients (Wu *et al*., 2006). Its hypolipidemic effects are also caused by the presence of dietary fiber and bioactive compounds, which help to decrease cholesterol levels and enhances cardiovascular health.

Antimicrobial properties are also shown by dragon fruit, which can prevent the proliferation of pathogenic microorganisms, thus improving food safety and human health. Its anti-inflammatory activity is linked to the inhibition of inflammatory mediators, which have the potential to decrease the risk of chronic inflammatory disorders (Singh & Kumar, 2023). In addition, the fruit is reported to have hepatoprotective effects, which help in the liver functioning and detoxification.

The other notable feature of dragon fruit is its prebiotic capabilities. The fruit contains the oligosaccharides that facilitate the growth of healthy gut microorganisms, thus, boosting the digestive system and enhancing immunity. This prebiotic property of dragon fruit renders it a useful ingredient of functional foods that target the enhancement of gut health (Le Bellec *et al*., 2006).

The recent research has also indicated the possible cancer prevention effects of using dragon fruit. Antioxidants and bioactive compounds like betalains and polyphenols have been reported to prevent the growth of cancerous cells and cause apoptosis in some types of cancers (Zheng *et al*., 2021). Though more clinical research is needed to validate these findings, these results indicate that they can find applications in nutraceutical and pharmaceutical sectors.

Besides its direct health value, dragon fruit is also being applied in the production of value added products like juices, jam, wine and dietary supplements. It also uses its natural pigments as food colorants, which is a safer choice compared to synthetic food additives.

In general, the nutritional profile and a high variety of medicinal effects of dragon fruit make it a valuable functional food with a great potential to support human health. Its addition into regular diets and functional food products can help prevent a variety of chronic diseases and enhance well-being.

Agronomic Management Practices

Agronomic management is an important aspect when considering the productivity, quality, and sustainability of the dragon fruit. Being introduced only recently, agronomic management strategies have yet to be established, necessitating the need for adopting proven agronomic methods that will ensure the best performance possible. Appropriate soil, water, fertilizer, canopy and blooming management is necessary for ensuring high yield and high quality fruits (Mondol *et al*., 2025; Mizrahi, 2014).

Land Preparation and Planting

The success of growing dragon fruits depends on how the land is prepared and how the planting site is chosen. Dragon fruits grow best in well-drained soils that have good aeration properties. They thrive in soils with pH values of 5.5 – 7.0. However, the plants cannot tolerate heavy soils as their poor drainage capacity causes roots rot and fungus infection (Le Bellec *et al*., 2006).

Land preparation includes deep plowing followed by land leveling together with the addition of organic matter such as farmyard manure. In commercial farms, the planting beds are dug to form pits of about 45-60 cm. They are then filled with soil, sand, and farmyard manure. Spacing is yet another important aspect that contributes to the growth and yields of these crops. A minimum of 2-3 meters' gap between each plant allows the penetration of enough sunlight and fresh air (Ortiz-Hernández & Carrillo-Salazar, 2012). Dragon fruits require the use of poles because they are climbing cactus types.

High-Density Planting

HDP refers to a modern agricultural practice focused on maximizing the output in terms of biomass produced per unit area through increased planting populations. In dragon fruit agriculture, HDP entails planting fewer gaps between crops while implementing suitable canopy management strategies to prevent overcrowding.

Research evidence indicates that high-density planting methods increase crop yields significantly due to efficient light interception and nutrient utilization capabilities (Mondol *et al*., 2025). Nevertheless, too much density can adversely impact fruit quality due to competition for resources like nutrients, water, and sunlight. Hence, the application of HDP necessitates the adoption of pruning and canopy training techniques to ensure canopy balance.

Commercial systems of HDP include vertical trellising systems or single-post systems.

Irrigation Management

Water management is important for proper growth, flowering, and fruiting of the dragon fruit plant. Although dragon fruits are relatively resistant to droughts, irrigation needs to be performed at certain key stages, particularly during flowering and fruiting periods.

From various research findings, drip irrigation system has been identified as the most ideal irrigation method that assures proper application of water while avoiding any wastage (Belbase & Bhaskar, 2025). The use of the drip irrigation system makes it possible to apply fertilizers along with irrigation (fertigation) to enhance nutrients uptake by plants.

Over-watering should be avoided since it might lead to development of root problems. Thus, when scheduling irrigation, certain key considerations need to be made such as soil moisture levels and weather conditions, among others. Mulching can be done in dry places in order to retain soil moisture.

Nutrient Management

Nutrient management is another important element that determines yield and quality of fruits from dragon fruits. The integrated nutrient management (INM) approach, using both organic and inorganic fertilizers is highly advised for the sake of keeping up the fertility of the soil, and ensuring sustainable production (Pratap & Tripathi, 2025).

Inclusion of the organic elements in the form of farmyard manure, vermicompost, or green manures is helpful in improving the soil structure, microbial composition, as well as its nutritional value. However, the inorganic fertilizers, on their part, help provide important nutrients such as N, P, K needed by plants for vegetative growth, root development, and fruiting.

Vegetative growth requires nitrogen, root system development and blossoming are dependent on phosphorus, while potassium helps develop the fruit size, color, and flavor. Other micronutrients such as zinc, iron, and boron assist in enzyme action, as well as reproduction processes.

There is a process called 'fertigation', which is an incorporation of fertilizers through irrigation, increasing the efficacy of fertilizer application and reducing nutrient loss due to leaching (Mondol *et al*., 2025).

Use of Biostimulants

Biostimulants have become increasingly important as one of the main elements of modern agronomic practices for growing dragon fruits. Biostimulants include various components such as sea weed extracts, humic substances, amino acids, and beneficial microbes. The usage of biostimulants leads to the growth of plants and their resistance to unfavorable conditions.

The utilization of biostimulants promotes the development of the root system, nutrient uptake, flowering, and fruit setting in dragon fruits (Belbase & Bhaskar, 2025). The sea weed extracts are abundant in different growth promoters, namely auxins and cytokinins promoting cell division and elongation.

Microbial biostimulants, such as mycorrhiza or PGPR, enhance nutrient availability and soil quality.

Flower Induction and Management

Flowering in dragon fruit farming is very crucial, since it determines the productivity and quality of the fruits. Dragon fruits bloom several times in a year.

There exist various methods that are adopted in order to stimulate flowering and increase production seasons through artificial flower induction. This method involves the application of plant growth hormones such as gibberellins and cytokinins as well as light treatment to induce out-of-season flowering (Mizrahi, 2014).

Pollination management plays a key role in flower formation. Since some species of dragon fruit are self-incompatible, manual pollination is conducted by farmers in order to improve the setting of fruits and evenness (Weiss *et al*., 1994). Pollination in these plants takes place at night or early in the morning.

Pruning and canopy management are other factors that contribute significantly to flowering. Pruning involves the removal of old and diseased branches as well as those that are overcrowded. This ensures the proper penetration of light and formation of new flowering stems.

Table 2: Core agronomic practices recommended for sustainable dragon fruit production

Practice	Main objective	Expected benefit
Land preparation and support system	Ensure drainage and climbing support	Better establishment and canopy architecture
High-density planting	Optimize plant population per unit area	Higher productivity where canopy is managed properly
Drip irrigation / fertigation	Deliver water and nutrients efficiently	Improved water-use efficiency and nutrient uptake
Integrated nutrient management	Combine organic and inorganic nutrient sources	Improved soil health and sustained productivity
Bio stimulant use	Stimulate growth and stress tolerance	Enhanced flowering, fruit set, and resilience
Flower induction and pollination management	Improve reproductive success	Greater fruit set, uniformity, and yield

Note. Compiled by the author based on Le Bellec *et al*. (2006), Mizrahi (2014), Mondol *et al*. (2025), Belbase and Bhaskar (2025), and Pratap and Tripathi (2025).

Propagation Techniques

Propagation plays an essential role in dragon fruit cultivation because it determines how homogeneous the plants are, their growth rate, productivity, and fruit quality. Dragon fruit can be cultivated using sexual propagation or vegetative propagation, each with its strengths and weaknesses. Vegetative propagation is commonly used for commercial production because it is more dependable and rapid (Ortiz-Hernández & Carrillo-Salazar, 2012; Mizrahi, 2014).

Sexual Propagation (Seed Propagation)

The sexual form of propagation utilizes the seeds obtained from the ripe fruits. Though this technique is rarely employed for producing commercial fruits, it has its utility in the process of genetic enhancement and breeding of fruits. Seed propagation allows for greater genetic variation that aids in the development of varieties with increased resistance to diseases and adaptation to climatic conditions (Le Bellec *et al*., 2006).

In order to propagate from seeds, the latter should be treated through cleaning, drying, and sowing in a suitable growth media consisting of a mixture of soil and other materials providing drainage. The process of germination will last for 1-2 weeks under appropriate conditions of temperature and moisture content. Nevertheless, the plant obtained through this process grows more slowly and takes 3-4 years to begin bearing fruits (Mizrahi, 2014).

The main drawback of seed propagation is associated with inconsistency of individual plants resulting in different qualities of fruits grown by these plants. This explains why this technique is not applied in commercial production of fruits.

Asexual Propagation

Stem Cutting Propagation

Stem cutting vegetative propagation is the widely used technique for dragon fruit cultivation owing to its simple procedure, low cost, and reliability in producing true-to-type plants. Stem cuttings of 20 to 40 cm length that are free from any signs of infection are cut from matured plants and dried for few days to avoid rots (Ortiz-Hernández & Carrillo-Salazar, 2012).

Planting can be done either in the field or in nurseries containing containers filled with well-drained soil or any other growth medium. Rooting usually takes about 2 to 4 weeks under favorable moisture and temperatures and grows quite quickly after rooting. The plants propagated through stem cuttings begin to flower within 12 to 18 months, much faster than those from seeds (Mizrahi, 2014).

The advantage of this type of propagation is that it results in genetically similar plants and thus produces fruits of uniform quality. However, repeated use of cuttings from the same source causes the buildup of pests and diseases.

Grafting

The grafting process is yet another technique used in vegetative propagation to enhance the health and adaptability of plants to various factors. Through grafting, the desired scion (cultivar) is attached to a rootstock that has desirable characteristics such as adaptation to unfavorable soil conditions or disease presence.

While grafting is a less used technique in the cultivation of dragon fruits compared to other fruit plants, it has been proved effective in improving the growth of plants especially under adverse environmental conditions (Le Bellec *et al*., 2006).

Nonetheless, this technique is costly in terms of skills and knowledge necessary for effective grafting.

Micropropagation (Tissue Culture)

The technique of micropropagation, or tissue culture, refers to a sophisticated method of propagating plants by allowing for the multiplication of virus-free, clonal planting materials under laboratory conditions. In this procedure, the explant material, such as stem cuttings or meristems, is cultured on nutrient media containing plant growth regulators.

There are many benefits associated with the process of micropropagation, including the ability to produce planting materials at high volumes throughout the year as well as the absence of pathogens (Zheng *et al*., 2021). It is especially suitable for maintaining elite varieties and releasing new varieties.

The high initial cost involved in the establishment of facilities and management, however, poses a disadvantage for farmers practicing small scale agriculture. As demand rises for high-quality planting material, the role of tissue culture becomes increasingly significant in commercial horticulture.

Comparative Analysis of Propagation Methods

Each propagation method has its own advantages and limitations, and the choice depends on the purpose of cultivation, resource availability, and scale of production.

Seed propagation is useful for breeding and research but not suitable for commercial production due to variability and longer juvenile phase.

Stem cuttings are the most preferred method for commercial cultivation due to uniformity, rapid establishment, and early fruiting.

Grafting provides improved tolerance to stress conditions but requires technical expertise.

Micropropagation ensures high-quality planting material but is cost-intensive.

Challenges in Propagation

However, despite the fact that various propagation techniques can be used for the development of the plants, there are still some challenges in dragon fruit farming. Among such challenges, one can mention poor availability of healthy planting material and a lack of standardization in propagating methods, which also increases the risks of transmitting diseases by means of vegetative reproduction (Pratap & Tripathi, 2025).

Moreover, in many cases, due to the lack of certified nurseries, there are difficulties with acquiring healthy planting material.

Future Prospects in Propagation

In future research, efforts should be made to devise economically viable techniques of micro-propagation, increasing efficiency in the process of grafting, and setting up certified nurseries for mass production of good-quality planting material. Involvement of molecular approaches in propagation schemes would add a feather to the cap.

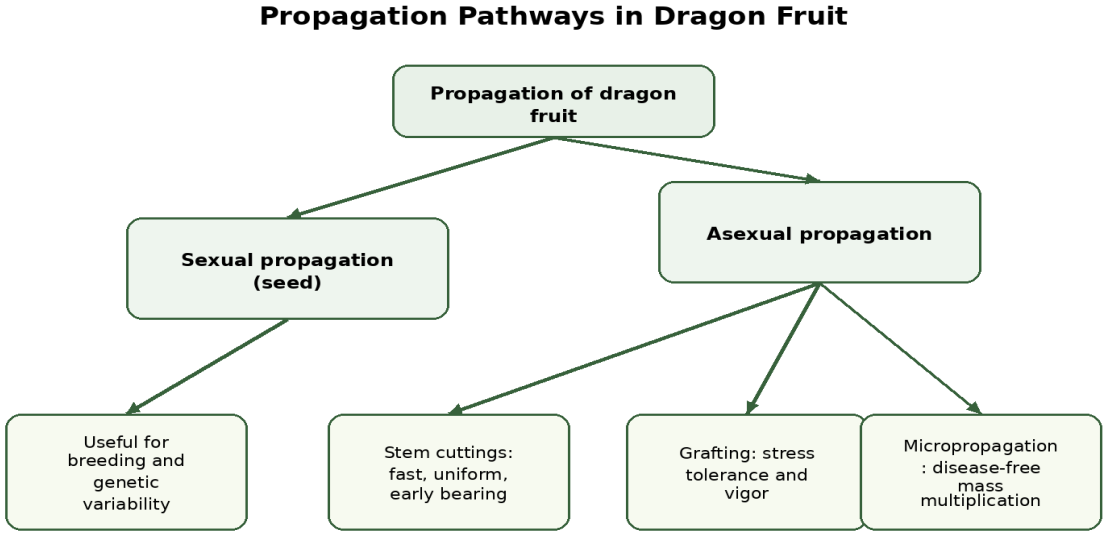

Fig. 1 : Propagation pathways and options in dragon fruit cultivation

Note. Created by the author based on Ortiz-Hernández and Carrillo-Salazar (2012), Mizrahi (2014), Le Bellec *et al*. (2006), and Zheng *et al*. (2021).

Table 3 : Comparison of propagation methods used in dragon fruit

Method	Type	Major advantage	Main limitation
Seed propagation	Sexual	Useful for breeding and genetic variability	Long juvenile phase and non-uniform progeny
Stem cuttings	Asexual	Rapid establishment and true-to-type plants	Risk of pest or disease carryover from mother plants
Grafting	Asexual	Improved vigor and stress tolerance	Requires skill and additional labour
Micropropagation	Asexual / tissue culture	Mass production of disease-free plants	High setup and operating cost

Note. Compiled by the author based on Ortiz-Hernández and Carrillo-Salazar (2012), Mizrahi (2014), Le Bellec *et al*. (2006), and Zheng *et al*. (2021).

Constraints in Dragon Fruit Production

Although dragon fruit (Hylocereus spp.) cultivation has gained more attention and has been associated with considerable economic importance in recent years, it faces various challenges associated with biological and physical constraints, technical difficulties, and socio-economic considerations. The impact of these challenges varies in different geographical settings; however, it poses particular significance especially in the case of recently established dragon fruit cultivation where technology development and refinement processes are ongoing (Mondol *et al*., 2025; Kakade *et al*., 2025).

Inconsistent Agronomic Practices

Another significant limitation associated with dragon fruit production is the lack of scientific guidelines for the agricultural practices involved. As a recently cultivated crop in most countries, farmers tend to use non-scientific methods, which do not necessarily maximize the potential benefits of growing dragon fruits. Factors such as density of planting, timing of watering and fertilization, and pruning all affect the performance of plants, including their productivity and product quality (Mizrahi, 2014).

Overcrowding due to poor canopy management and excessive growth of leaves rather than flowers due to inappropriate fertilization are some examples of the limitations caused by improper farming techniques. The problem is aggravated by the fact that there is no regional advice for the most suitable ways of farming dragon fruits.

Limited Availability of Quality Planting Material

Availability of good quality and healthy planting material is an essential element for achieving success in dragon fruit farming. In most places, however, there are very few accredited nurseries, thus causing farmers to rely on unhealthy or low-quality planting material (Pratap & Tripathi, 2025).

Propagation using cuttings has been common in this farming system, but this method often causes the transfer of pests from the mother plant to the newly planted area. This leads to stunted plant growth, low yields, and increased chances of pest infection.

Climate Variability and Environmental Stress

Variability in climate remains a major threat to dragon fruit farming. Even though this fruit is highly resistant to drought and heat stress, extremely harsh climatic conditions such as hot spells, excess rainfalls, and sudden frost attacks may negatively impact the process of plant growth, flower blooming, and fruit ripening (Balaji, 2025).

Frequent rains and moisture may result in fungal infections and root rotting. Extreme heat may damage fruits by causing sunburns, thus lowering their commercial value. Furthermore, erratic rainfall may alter flowering processes and impair pollination effectiveness.

Pollination Constraints

Pollination plays a significant role in determining the setting and productivity of fruits in dragon fruit cultivation. Several species of Hylocereus are self-incompatible and require cross-pollination to produce healthy fruits (Weiss *et al*., 1994). Nevertheless, the presence of natural pollinators like moths and bats is not always abundant in commercial cultivation areas.

The occurrence of nocturnal blooms makes the pollination process even more challenging, as the blooms remain open for just a single night. Insufficient pollination leads to low fruit setting, small fruits, and decreased productivity. Manual pollination has been widely employed as a solution to this problem; however, it is time-consuming and expensive.

Pest and Disease Incidence

While dragon fruit has high resistance to various biotic stresses, there are a number of pests and diseases that have been observed in various production areas. These include mealybugs, ants, aphids, and fruit flies that cause damage to the plants' tissues and decrease the quality of fruits. Stem rot, fruit rot, and anthracnose

have also emerged as significant diseases in humid environments (Kakade *et al*., 2025).

The main reason behind the development of various diseases on dragon fruits is the presence of fungal pathogens that are often aggravated by poor drainage and excess moisture in the soil. Viral and bacterial infections are rare but may still impact the plants negatively.

High Initial Investment and Infrastructure Requirements

Dragon fruit farming involves a high level of initial investment, especially in terms of setting up structures like trellises or cemented posts. Such structures are necessary for the climbing nature of the crop, but they increase the cost of growing it (Ortiz-Hernández & Carrillo-Salazar, 2012).

Furthermore, drip irrigation, obtaining good quality planting materials, and labor expenses in pruning the crops constitute other costs associated with dragon fruit farming. This may pose a problem for small-scale farmers.

Lack of Technical Knowledge and Extension Services

Limited access to technical knowledge and information on the cultivation of dragon fruit is yet another key limitation that adversely impacts productivity. Lack of proper information about the use of advanced agricultural technology, pest control measures, and post-harvest handling technologies hampers productivity levels (Mondol *et al*., 2025).

Lack of access to training sessions and demonstrations on scientific methods also constitutes an important impediment to the process of knowledge transfer.

Market and Supply Chain Constraints

Market related problems are also one of the barriers to growing dragon fruits. Some of these problems include price variations, lack of market structures, and limited possibilities for exports. Poor post-harvest handling systems including storage and transportation result in post-harvest loss and lower economic gains.

Other barriers include the lack of grading, packaging, and standardization processes, which can negatively impact marketability and consumer preferences.

Future Directions for Overcoming Constraints

Addressing the constraints in dragon fruit production requires a multi-disciplinary approach involving research, policy support, and farmer participation. Key strategies include:

- Development of region-specific agronomic practices
- Establishment of certified nurseries for quality planting material
- Adoption of climate-resilient cultivation techniques
- Promotion of integrated pest and disease management
- Strengthening extension services and farmer training programs
- Improvement of market infrastructure and value chains

Sustainable Cultivation Practices

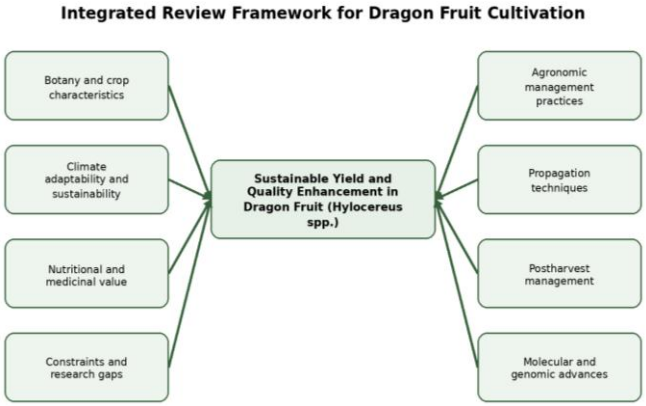

Fig. 2 : Integrated review framework linking major themes in dragon fruit production

Note. Created by the author based on Le Bellec *et al*. (2006), Mizrahi (2014), Mondol *et al*. (2025), Belbase and Bhaskar (2025), and Kakade *et al*. (2025).

Sustainable cultivation practices have become very significant in relation to dragon fruit (Hylocereus spp.) production, given the impacts of climate change, environmental pollution, and other factors necessitating the practice of efficient farming methods. Although dragon fruit cultivation is naturally sustainable and climate resilient, there are various ways in which sustainable cultivation practices may be adopted, which will help to improve productivity, soil fertility, minimize adverse effects on the environment and contribute to profitability (Belbase & Bhaskar, 2025; Mondol *et al*., 2025).

Organic Farming and Eco-friendly Inputs

One of the most sustainable ways to cultivate dragon fruit is through the practice of organic farming. This approach ensures that organic materials are used in farming including farmyard manure, compost, vermicompost, green manure, biofertilizers, etc. Organic inputs play a critical role in improving soil

fertility and the overall nutrient cycle (Pratap & Tripathi, 2025).

These inputs enhance soil structure, increase its moisture holding capacity and aeration. The application of biofertilizers such as nitrogen fixing bacteria and phosphate solubilizing microorganisms plays an integral part in enhancing nutrients and reducing dependence on fertilizers.

Furthermore, the practice of botanical pest management in farming contributes greatly to sustainability by minimizing chemical residues in fruits.

Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) forms an essential part of sustainable agriculture practices involving the use of organic and inorganic sources of nutrients to retain the fertility of the soil and maximize crop production. The INM in dragon fruits includes the use of organic manure, chemical fertilizers, and micronutrients, which depend on the results of soil analysis (Mondol *et al*., 2025).

INM boosts nutrient uptake, minimizes the loss of nutrients, and improves soil quality in the long run. The organic components help in providing a sustained source of nutrients for the crops, while the inorganic nutrients offer an instant supply of nutrients.

Water Management and Efficient Irrigation

It becomes necessary to ensure efficient water management practices for ensuring the sustainability of dragon fruit cultivation, especially when it is being done in areas with limited availability of water resources. The most efficient irrigation technique is that of drip irrigation which ensures maximum application of water directly to the roots and minimizes any wastage of water due to evaporation (Belbase & Bhaskar, 2025).

Use of fertigation along with drip irrigation will increase efficiency in the use of nutrients while using lesser inputs. Mulch can be used for minimizing water loss from the soil through evaporation.

Agroforestry and Integrated Farming Systems

There are several advantages that are obtained by combining agroforestry practices, which incorporate dragon fruits within other crops or trees. Land use is optimized, more biodiversity is created, and additional means to earn revenue can be obtained from the farmers (Belbase & Bhaskar, 2025).

Fruit trees, wood trees, or any other kind of crops can be combined together for the cultivation of dragon fruits based upon environmental considerations. Nutrient recycling is improved, soil erosion is prevented, and microclimate is enhanced through such practices.

Protected Cultivation and High-Tunnel Systems

Protected cultivation methods like high tunnels and greenhouse cultivation are becoming common in dragon fruit farming to counter the negative impacts of harsh weather conditions. In addition, these cultivation methods offer an environment where the plant can be kept safe from harsh weather and pests (Mondol *et al*., 2025).

High tunnels help in promoting flowering, fruits formation, and good quality fruits through the maintenance of favorable temperatures and humidity levels. This method will also minimize cases of diseases that result from excessive moisture. Despite the high costs incurred at the initial stages of setting up, this cultivation method ensures higher yields.

Reduction of Chemical Inputs

Minimizing the use of chemical fertilizers and pesticides is one of the key components of sustainable farming. The excessive use of agricultural chemicals can result in environmental pollution of soils and water and can affect human health negatively.

In the case of growing dragon fruit, the implementation of integrated pest management techniques could help decrease the reliance on chemical insecticides. Integrated pest management combines cultural measures, biological control, and the application of resistant varieties for managing pests (Kakade *et al*., 2025).

Also, in order to minimize the impact of nutrient management practices on the environment, organic or biofertilizers are commonly used.

Role of Biostimulants and Biofertilizers

There is a high contribution of biostimulants and biofertilizers in promoting sustainable production practices of dragon fruits through enhancement of plant development, nutrient absorption, and abiotic stress resistance. Seaweed extracts, humic acids, and amino acids act as growth regulators and improve abiotic stress resistance of plants (Belbase & Bhaskar, 2025).

The addition of biological materials like mycorrhizal fungi and PGPR can help promote nutrient availability and improve the quality of soil (Belbase & Bhaskar, 2025).

Climate-Resilient Practices

The dragon fruit plant is naturally resilient to climate change; but by adopting more climate-smart

agricultural practices, farmers can improve their resilience even further. Such practices may involve choosing drought-resistant varieties, employing mulching techniques, installing irrigation facilities, and practicing agroforestry (Balaji, 2025).

Other climate-smart agricultural practices include altering planting times, erecting protective shelters, and implementing soil management practices to mitigate the effects of climate change.

Socio-economic and Policy Support for Sustainability

The use of sustainable agricultural practices is affected by socio-economic considerations like knowledge, resource availability, and government policies. Policies aimed at encouraging organic agriculture, water management, and adaptation to climatic changes could be used to facilitate sustainable farming of the dragon fruit (Mondol *et al*., 2025).

Education and financial incentives would be important in assisting farmers to adopt sustainable agricultural practices. Improved marketing channels would contribute to improved returns on investment.

Yield and Quality Improvement Strategies

Increasing productivity and improving the quality of the fruits produced are some of the main aims in dragon fruit farming. These factors depend on a combination of genetic, environmental, and management factors. Through the implementation of better agronomy practices, optimal management of resources, and technology, farmers can boost their yields while ensuring that their crops produce high-quality fruits characterized by desirable features such as size, appearance, taste, and nutritional value (Mizrahi, 2014; Mondol *et al*., 2025).

Role of Agronomic Practices in Yield Enhancement

Agronomy practices like proper spacing, nutrient management, scheduling of irrigation, and canopy management are extremely important in influencing yield potential. High density plantation along with proper pruning and training results in increasing yield per unit area through efficient use of light (Mondol *et al*., 2025).

Proper fertilization using integrated nutrient management will make sure that the supply of nutrients to the plant is efficient at all crucial stages for its optimum growth and development, thus contributing towards flowering and fruiting process. In addition, proper irrigation techniques such as drip irrigation help increase water efficiency (Belbase & Bhaskar, 2025).

Pruning and training are extremely significant especially in cultivation of dragon fruits because they maintain proper canopy architecture and allow efficient airflow and light penetration. This results in more shoots being produced from the plant.

Flowering and Pollination Management

Both flower formation and pollination play a crucial role in determining fruit production from dragon fruit. The dragon fruit has several flowering stages within a year, and proper management of this stage can help maximize its yield. Flower induction through the use of plant growth regulators and photomanipulation methods can prolong the flowering time and increase fruiting stages (Mizrahi, 2014).

Similarly, proper pollination practices are also required, particularly for self-incompatible varieties. Manual pollination is commonly carried out on commercial farms to increase fruit set and even distribution of fruits (Weiss *et al*., 1994). Proper timing of pollination, especially at night and early mornings when the flowers become receptive, improves the fruit fertilization process.

Nutrient Management for Quality Improvement

Apart from affecting yield, the proper management of nutrients also helps in ensuring improved quality traits in terms of size, color, taste, and post-harvest life of fruits. Potassium is an important element for enhancing the size of fruits, accumulation of sugars, and color development, while phosphorus is known to promote root development and flowering of plants (Pratap & Tripathi, 2025).

The deficiency of micronutrients like boron and zinc affects reproductive growth and enzymatic processes; this ultimately leads to poor fruiting and low-quality fruits. Organic materials have also been proven helpful in improving the quality of fruits by enhancing soil quality and bioactive compound production.

Fertigation, an improved method of applying nutrients in irrigation water, has been found to enhance nutrient-use efficiency along with superior fruit quality as compared to traditional nutrient management practices (Mondol *et al*., 2025).

Use of Biostimulants and Growth Regulators

Use of biostimulants and plant growth regulators (PGR) have attracted a lot of interest in enhancing the fruit production and yield of the dragon fruit. Use of biostimulants like seaweed extract, humic substance, and amino acid has been found to help boost plant growth, nutrient absorption, and stress resistance.

PGR such as gibberellins, auxins, and cytokinins may be used to control flower production and fruit

development. They have been proven to help in increasing fruit production, reducing fruit loss, and boosting the yield level. However, these chemicals need to be controlled to prevent any negative impacts on the plant.

Environmental Factors and Their Influence

The climatic factors like temperature, light, and humidity are very crucial when it comes to production of yields and quality of fruits. Temperature helps in promoting flowering and fruiting of plants, but too much of these factors may cause problems like flowers falling off and low fruit quality (Le Bellec *et al*., 2006).

Sunlight is necessary for fruit sugars to form during the process of photosynthesis, and hence affects the sweetness of the fruits. High humidity levels may favor some plant diseases that might negatively impact fruit quality. Site selection is, therefore, very important when considering fruit yield.

Improved Cultivar Selection

Choosing the right cultivars plays an important role in maximizing the output and producing high-quality fruits. There are differences among various types and species of dragon fruit concerning their potential yields, size, color, flavor, and resistance to insects and diseases (Ortiz-Hernández & Carrillo-Salazar, 2012).

For example, Hylocereus undatus, Hylocereus costaricensis, and Hylocereus megalanthus are some of the popularly grown cultivars that have different features.

Resource-Use Efficiency

Efficient use of water, fertilizers, and even labor resources is necessary to achieve sustainable yields. Methods such as drip irrigation, fertigation, and mulching increase efficiency and decrease costs related to resource input (Belbase & Bhaskar, 2025).

Use of precision farming equipment, such as soil moisture sensors and automatic irrigation systems, would make efficient use of resources easier and result in improved crop yields.

Postharvest Quality Considerations

Post-harvest handling is often considered separately, but it has a lot to do with pre-harvest management. Correct fertilization, proper watering, and harvest at the proper stage of development have a huge impact on post-harvest properties.

Optimally mature fruits have more favorable textural and taste properties and can be stored longer. Factors like appropriate fertilization and pathogen management minimize post-harvest losses and ensure the integrity of the produce during transportation and storage.

Integrated Approach for Yield and Quality Enhancement

Table 4 : Major postharvest interventions for preserving dragon fruit quality

Technology	Primary purpose	Expected outcome
Cold storage	Slow respiration and microbial growth	Extended shelf life and reduced deterioration
Modified atmosphere packaging	Alter gas composition around fruit	Delayed ripening and firmness retention
Edible coatings	Reduce moisture loss and surface contamination	Improved appearance, firmness, and storability
Non-thermal treatments	Control microbial load without heat damage	Safer fruit with better physicochemical quality retention

Note. Compiled by the author based on Le Bellec *et al*. (2006), Mondol *et al*. (2025), and Kakade *et al*. (2025).

In order to maximize yields and produce high-quality products, an integrative approach involving the improvement of agronomy practices, proper resource utilization, modern technologies, and selection of appropriate cultivars must be employed. Sustainable farming techniques are additionally needed for increased long-term productivity and protection of the environment.

It will be necessary in the future to undertake research geared towards development of localized production practices, better genetic materials, and use of modern technologies.

Postharvest Management

Postharvest handling is one of the essential steps involved in dragon fruit cultivation, since it plays an important role in determining the quality of the produce and affects its shelf life. As the dragon fruit has a soft texture and contains high water content, making it prone to damage from pathogens, special care needs to be taken during postharvest handling (Le Bellec *et al*., 2006; Mondol *et al*., 2025).

Harvesting Practices

Proper harvesting at maturity stage is necessary for achieving high-quality fruits. Dragon fruits usually are harvested between 30 to 50 days after flower blossoming based on their variety, cultivars, and climatic conditions (Ortiz-Hernández & Carrillo-Salazar, 2012).

The criteria for mature fruits are changes in color of the skin, which changes from green to red or yellow color; scales develop on fruits along with firm fruits. The process should involve manual harvesting using sharp tools to prevent damages to fruits. This ensures that चोट (injury) due to improper harvest will not spoil the fruits.

Harvesting is normally performed in the morning or evening time to prevent field heat.

Sorting, Grading, and Packaging

Post-harvest classification of the fruits is done according to their size, weight, color, and absence of blemishes like bruises or signs of infections. Grading serves to improve the market value of the products and ensures consistency of the product line (Kakade *et al*., 2025).

Fruits require adequate packaging in order to avoid injury during transport. The dragon fruits should be placed in cardboard cartons padded with cushioning material such as foam or paper. Ventilation holes in the packaging material will reduce chances of fungal infection by preventing accumulation of moisture within the packaging.

Storage Conditions and Cold Storage

Temperature regulation is one of the key components affecting the shelf life of dragon fruits. In an ambient environment, dragon fruits have a limited shelf life period of 5-7 days. Nonetheless, refrigerated storage at temperatures of 7-10 degrees Centigrade with humidity of 85-90 percent results in shelf life periods of up to 2-3 weeks (Le Bellec *et al*., 2006).

Storage of fruits under low temperature reduces the rate of respiration, enzymatic activity, and microbial growth in the fruits. The only disadvantage associated with refrigerated storage is that storing fruits at extremely low temperatures (<5 degrees Centigrade) may result in chilling injury.

Modified Atmosphere Packaging (MAP)

MAP is a highly sophisticated post-harvest technology that entails modifying the composition of gases (oxygen, carbon dioxide, and nitrogen) that surround the fruit, thus reducing respiration rates and delaying ripening.

Studies have proven that MAP can increase the storage period of dragon fruit through the retention of moisture, maintenance of firmness, and retention of bioactive compounds (Mondol *et al*., 2025). In addition, it prevents microbial growth and maintains the fruit's aesthetic quality.

Edible Coatings

Edible coatings refer to environmentally friendly post-harvest processing techniques, which create a thin layer around the fruit to protect it against dehydration and respiration. Edible coatings developed using natural ingredients, such as chitosan, aloe vera, and starch, are common materials used for coating fruits for their preservation properties.

The application of edible coatings in dragon fruit has shown that there is improvement in the shelf-life, firmness of the fruit, and reduced microbial deterioration (Kakade *et al*., 2025). Edible coatings are essential in maintaining the nutritional value of the dragon fruit.

Non-Thermal Technologies

Non-thermal methods are being seen as new techniques that could be useful in preserving fruits like the dragon fruit after harvesting. Some of the non-thermal treatments include cold plasma treatment, ultraviolet (UV) light treatment, and ozone treatment. The use of these techniques ensures that the fruit is free from bacteria without interfering with its nutritional value.

In relation to cold plasma treatment, it has been found to increase the shelf life of the fruit and physicochemical qualities due to the killing of surface microorganisms (Mondol *et al*., 2025).

Control of Postharvest Diseases

Post-harvest diseases, mostly fungal diseases, are among the key reasons for crop losses in dragon fruits. Examples of such diseases are anthracnose and fruit rot, which occur when there is excess moisture and improper handling of the fruits.

Control methods involve good sanitation practices, application of fungicides or biological control agents, and maintenance of ideal storage conditions. Biological control agents provide an effective way of controlling these diseases without exposing the environment to chemicals (Kakade *et al*., 2025).

Preservation of Nutritional and Bioactive Compounds

Dragon fruit is known for its high levels of bioactive ingredients, including betalains, phenolics, and flavonoids, which lend it its anti-oxidative capacity. Practices during post-harvest can impact their preservation.

The use of cold storage, MAP, and edible coatings can help to conserve these bioactive components through minimizing oxidative degradation and metabolic activities (Mondol *et al*., 2025). This is especially vital since dragon fruits have commercial significance in the functional food industry.

Transportation and Supply Chain Management

The transportation and distribution of fruits should be efficient in order to preserve their quality until they reach the market. The application of refrigeration systems (the cold chain) ensures that the optimum levels of temperature and humidity are preserved during transportation.

Efficient supply chains can lead to lower mechanical damage and less post-harvest losses. Efficient supply chains need to be created in order to expand markets for dragon fruit.

Future Prospects in Postharvest Management

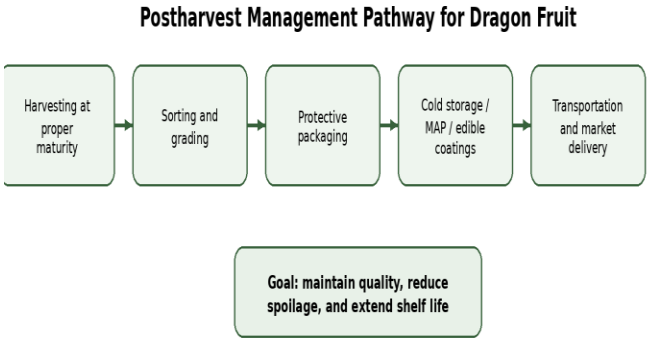

Fig. 3: Postharvest management pathway for maintaining dragon fruit quality

Note. Created by the author based on Le Bellec *et al*. (2006), Mondol *et al*. (2025), and Kakade *et al*. (2025).

Future areas of study in post-harvest management must involve research geared towards devising methods of preserving crops in a cheap and environmentally friendly manner. Application of modern technology such as nanotechnology, smart packaging, and quality control systems may contribute to increasing shelf life.

Standardization of practices in post-harvest handling, together with improved cold chain management, will form a crucial aspect in enhancing market competitiveness.

Molecular and Genomic Advances

Significant strides made in the fields of molecular biology and genomics have greatly improved our knowledge of genetic, physiological, and biochemical mechanisms that underlie vital agronomical traits in dragon fruits (Hylocereus spp.). Given the abundance of genomic information available, the study of genes, metabolic pathways, and heritability of traits, all of which are important for breeding purposes, is now possible (Zheng *et al*., 2021; Mizrahi, 2014).

Genome Sequencing and Genetic Resources

Genome sequencing of dragon fruits is one of the greatest achievements in the scientific study of these plants. Sequencing of the genome will allow a detailed investigation of the genes involved in the formation of such phenotypes as fruit coloring, adaptation to stressful environmental conditions, and disease resistance (Zheng *et al*., 2021).

This will help create molecular markers that will make it possible to implement the approach of marker-assisted selection during breeding. Genetic data also contribute to the analysis of comparative genomics, revealing similarities and differences between Hylocereus species.

Betalain Biosynthesis Pathway

Another significant field that is being explored in the molecular study of dragon fruit is the biosynthesis of betalains. Betalains are the water-soluble pigments that give dragon fruits their distinctive red to purple color and serve as potent antioxidants.

Molecular genomic and transcriptomic studies have helped in identifying various genes responsible for betalain biosynthesis. Some of these include tyrosinase and DOPA dioxygenase (Zheng *et al*., 2021). Knowing how this process works has made it possible for researchers to manipulate pigment biosynthesis and optimize its color and nutritional quality.

Betalains have great potential uses in the food and drug industry as natural colorants and therapeutic molecules.

Self-Incompatibility Mechanisms

The phenomenon of self-incompatibility is a major reproductive constraint in Hylocereus plants, as it impacts the process of pollination and production of fruits. Scientific investigations regarding self-incompatibility have been helpful in unraveling the genetic basis of this process, such as identifying genes related to pollen-stigma interaction (Mizrahi, 2014).

Such scientific understanding of self-incompatibility will be helpful in increasing efficiency in the process of pollination and developing varieties of self-compatible plants.

Gene Expression and Stress Tolerance

Studying gene expressions has greatly contributed to our knowledge about how the dragon fruit reacts to stress conditions like drought, heat, and salt. Gene expressions can identify genes that react to stress conditions and control biological and physiologic functions during such conditions (Zheng *et al*., 2021).

Such research can be used to create more stress-resistant strains using genetic modifications or selective breeding techniques. Stress resistance is especially critical for increasing production in dry and semi-dry areas.

Molecular Breeding and Marker-Assisted Selection

The molecular breeding techniques such as marker-assisted selection (MAS) could be instrumental in achieving this goal. Markers associated with positive characteristics such as fruit weight, color, sweetness, and pathogen tolerance could be used to identify the best genotypes even before the flowering stage (Zheng *et al*., 2021). Such a technique saves costs and time associated with traditional breeding techniques.

MAS is especially important for perennial crops since they have long cycles of breeding.

Biotechnological Approaches

Biotechnological methods, such as genetic transformation and tissue culture, have played an important part in the development of dragon fruit. Genetically engineered plants with desired characteristics, like increased nutritional value and resistance to stresses, diseases, and pests, can be produced using genetic transformation technologies.

Micropropagation and other methods of tissue culture allow for the rapid propagation of high-quality genotypes and the preservation of genetic material.

Functional Genomics and Metabolomics

Functional genomics and metabolomics are new fields of study that can give more understanding about the gene activity and metabolism occurring in dragon fruit. This field of study helps to uncover the different biochemical pathways responsible for fruit development, ripening, and bioactive components biosynthesis.

Using metabolomics analysis, different phytochemicals, such as phenolic compounds, flavonoids, and betalains, have been identified, which are responsible for its nutritional value and potential health benefits (Zheng *et al*., 2021).

Challenges in Molecular Research

Although there have been notable advancements in this area, there are still certain hurdles to be addressed when using molecular and genomic approaches for dragon fruit studies. For one, the amount of genome information available is still limited for various species. Moreover, there are no established protocols to use and the expense involved in doing so can be quite prohibitive.

One of the major obstacles to be considered when improving traits like yield and quality is that their development involves several genes and is affected by environmental conditions.

Future Prospects

The integration of molecular biology, genomics, and biotechnology is promising in the cultivation of dragon fruits in the future. Gene editing techniques, like the CRISPR/Cas technique, can help make genetic modifications precisely to ensure that only desirable traits are produced in the plant.

Future work can include molecular breeding techniques that will result in the production of cultivars that are stress tolerant and yield high quantities.

Research Gaps and Future Prospects

Notwithstanding all the progress made in dragon fruit research, there are still a number of limitations which affect the crop's full agricultural potential and market value. It is important to close these gaps in order to maximize the production level, enhance fruit qualities, and increase competitiveness in the international market.

Firstly, it is important to emphasize the necessity to develop location-specific agronomic recommendations since most studies related to dragon fruit cultivation are not regionalized, leaving space for inconsistencies and inefficient use of resources (Mondol *et al*., 2025). In particular, future investigations should be focused on establishing site-specific growing packages which take into account specific soil types, climatic factors, and available resources.

Secondly, it is necessary to note that there are currently not enough high-quality planting materials since vegetative propagation methods are common but no large-scale certified programs have been developed yet (Pratap & Tripathi, 2025). Therefore, it will be important to consider advanced micropropagation approaches.

Additionally, pollination biology and reproduction also demand additional research. In some plants, the presence of self-incompatibility hampers fruit formation and necessitates manual pollination that is expensive and time-consuming (Mizrahi, 2014). Research needs to be conducted to produce self-compatible cultivars and improve pollination biology and natural pollination methods through various ecological and genetic means.

The issue of climate change needs to be explored in further detail. Dragon fruit is known to be climate resilient, but even under extreme conditions like drought, heat waves, and irregular rainfall, the productivity of the plant might be hampered (Balaji, 2025). Developing resilient and productive varieties is essential to ensure the stability of the crop yield.

Integrated pest and disease management (IPM) techniques need more research. Information about pests and diseases is lacking, along with sustainable means of managing the above-mentioned challenges (Kakade *et al*., 2025).

As far as postharvest technologies are concerned, there is an urgent need to find innovative, low-cost technologies that will help reduce losses and increase shelf life. Even though modern technologies, including modified atmosphere packaging and non-thermal treatments, have proven to be efficient, their commercialization is hindered by high prices and poor technological infrastructure (Mondol *et al*., 2025).

There is ample room for molecular and genomic studies. Even though sequencing of the dragon fruit genome helped researchers make some advances, more effort is required to study the functions of genes responsible for yield potential, product quality, and stress resistance (Zheng *et al*., 2021). Genomic analysis should be linked to plant breeding and new hybrid varieties.

Finally, there is room for exploring innovations in digital agriculture. Such technologies as remote sensing, Internet of Things irrigation systems, and data analytics can help improve resource use efficiency and optimize agricultural practices.

With regards to socio-economic aspects, it would be necessary to conduct further market studies to investigate the economic benefits of dragon fruit production and explore ways of increasing profitability for producers and farmers.

Overall, bridging these research gaps requires a multidisciplinary approach involving agronomy, biotechnology, engineering, and socio-economic studies. Collaborative efforts between researchers, policymakers, and farmers will be key to unlocking the full potential of dragon fruit as a sustainable and high-value crop.

Conclusion

One of the crops that have taken the centre stage as a sustainable agricultural crop is the dragon fruit (*Hylocereus* spp.), owing to the following qualities; it has the capacity to grow in arid and semi-arid climates, less input needs, and it has high demand in the market.

Based on this review it is quite clear that the agronomic management strategies are instrumental in attaining high yields and quality of fruits in the production of dragon fruits. High density planting, effective irrigation through drip system, balanced nutrition and application of biostimulants are some of the agronomic measures that improve plant growth and production. Appropriate canopy management and fruit development with appropriate flower development and fertilization methods improve fruit setting and quality.

Some of the strategies of cultivation such as organic farming, nutrient management and agro forestry are used to enhance the soil fertility as well as foster sustainability of agricultural production. Concurrently, viable ways of multiplication such as vegetative reproduction are critical in maintaining uniformity in productivity.

Despite the potential positive outcomes of dragon fruit production, there are several constraints to the success of this practice, including variability in agronomic management, inaccessibility to good quality planting resources, climatic variations, and pollination issues. There is therefore a need to introduce new initiatives that will see to it that enhanced productivity is achieved.

In addition, the advancement in the use of post-harvest management practices and molecular research presents alternative options on how the quality of the fruits and their shelf life can be improved. To be embraced successfully however, the farmers must make these technologies readily available to them.

To summarize, it is possible to say that the complex of scientifically supported agronomic activities and sustainable technology is necessary in the growth of the yield and the quality of the fruit, thereby, making the dragon fruit growing sustainable in the long run. The opportunities of this fruit as a valuable asset to farmers, which can be used to promote food and nutritional security, are enormous.

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