



Review

Morphological, biochemical and molecular diversity of dragon fruits in India and their therapeutic applications: A comprehensive review

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Abstract: Dragon fruit has recently drawn considerable attention among the Indian growers due to its high antioxidant potential, vitamins, dietary fibers, minerals content, and great health benefits (e.g., lowering of cholesterol level, improving digestion, preventing skin infections, and boosting immune function). The aim of this review is to explore the systematic and insightful knowledge about the morphological, biochemical, and molecular diversity of dragon fruits; phytochemistry; and their therapeutic applications against oxidative stress-induced diseases. Dragon fruit extract contains various bioactive compounds, including quercetin, kaempferol, gallic acid, p-coumaric acid, carotenoids, anthocyanins, cyanidin-3-glucoside, and betalains, which are associated with various pharmacological properties (e.g., antioxidant, anti-microbial, anti-inflammatory, anticancer, and anti-diabetic). Dragon fruit demonstrated a high anti-inflammatory property because it consists of betalains that play a significant role in the inhibition of the transcription factor NF- κ B, which reduces the expression of inflammatory genes, such as TNF- α and IL-1 β), while the roots of dragon fruit help in regulation of renal problems and blood glucose level. Certain saponins, such as oleanolic acid, betulinic acid, and lupane, also help in the prevention of chronic kidney diseases. This review discusses various bioactive compounds of dragon fruit that can be used in various herbal health care medicines and as cosmetics ingredients; however, examining the range of natural components in this fruit is crucial for better understanding its possible health advantages and the potential economic boost it could provide.

Keywords: anticancer; antimicrobial; carotenoids; dragon fruit; betalains; health care medicines

1. Introduction

Functional foods are biologically active substances that offer health benefits beyond basic nutrition. They act as a bridge between nutrition and medicine. Functional foods play a significant role in the prevention of lifestyle-related disorders, such as atherosclerosis, hypertension, type 2 diabetes, hormone-dependent and oxidative stress-related cancers, and coronary heart diseases. With advancement in the biotechnological approaches, functional foods are emerging as essential part of modern healthcare. Functional foods act as nutraceuticals and reduce the dependency of pharmaceuticals to support personalized and precision nutrition. Plants contain naturally occurring phytochemicals, dietary fibers, vitamins, minerals, and other bioactive compounds that contribute to functional foods, promote health, and reduce disease risk.

Dragon fruit is a significant tropical fruit crop belonging to the family Cactaceae. Dragon fruit is also known as pitaya, pitahaya, or “noble woman” due to lovely flowers that bloom at night [1]. The fruit's skin is covered with scales or bracts that give it a "dragon-like" appearance [2]. The fruit is also referred to as “the scaly fruit” due to the presence of bracts or scales on the exocarp. In India, three varieties of dragon fruit are commonly found depending on its peel and pulp color (i.e., *Hylocereus undatus* [red peel with white pulp], *Hylocereus polyrhizus* [red peel with red pulp], and *Hylocereus megalanthus* [yellow peel with white pulp]. However, the recent taxonomic revisions based on morphological and molecular evidence have transferred these species to the genus *Selenicereus*. Hence, the word *Selenicereus* is used in the review. Dragon fruit has a staggering color with a mellow and melting pulp.

Dragon fruit is a semi-epiphytic plant that favors the dry tropical or subtropical climate with an average temperature of 21–29 °C, and it shows reduced growth with a temperature of 38–40 °C and freezing temperatures [3]. With its growing demand in both domestic and international markets, dragon fruit production can become a profitable venture for small-scale growers and entrepreneurs with medium to large plantations [4]. The fruit contains several phytochemical constituents that have potential pharmacological properties (Figure 1). It is traditionally used as a coloring agent. The fruit is a fast-return perennial with production beginning in the second year after planting and reaching full yield within five years [5].

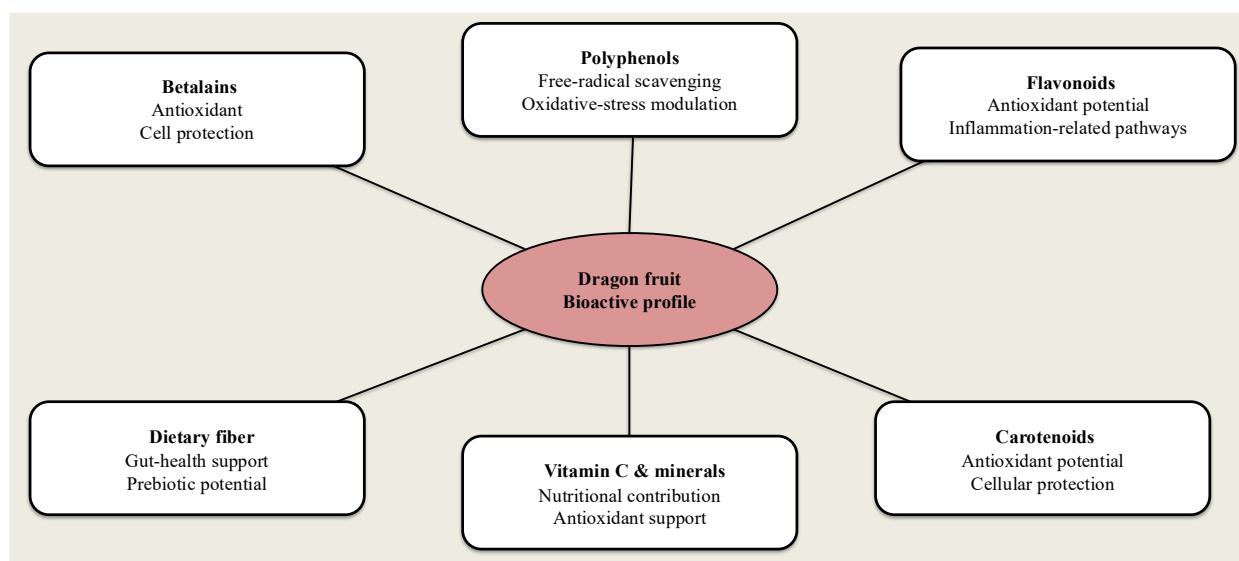


Figure 1. Bioactive compounds present in dragon fruit and their significant contributions to human health.

2. Origin and distribution of dragon fruit

Dragon fruit is well accepted new crop distributed in China, Malaysia, Taiwan, Australia, Vietnam, and Sri Lanka. Dragon fruit is also commercially cultivated in Australia, Brazil, Colombia, Costa Rica, Germany, Indonesia, Israel, Japan, Mauritius, Mexico, Taiwan, Thailand, USA, Vietnam, and Malaysia [6–15]. Vietnam is the largest commercial producer of dragon fruit. Today, dragon fruit is also cultivated in the states of Bihar, West Bengal, Maharashtra, Gujarat, Andhra Pradesh, Karnataka, Tamil Nadu, and Uttar Pradesh. In India, dragon fruit was introduced during the late 1990s [16]. In recent years, the cultivation of dragon fruit has also spread across several states in India, including Rajasthan, Haryana, Punjab, Madhya Pradesh, and the Northeastern states. Currently, India's dragon fruit cultivation is insufficient to meet domestic demand, and the majority of dragon fruits in country are imported from Thailand, Malaysia, Vietnam, and Sri Lanka [17]. The latest data indicates that the nation's production of dragon fruit increased significantly in 2020, reaching over 12,000 tons cultivated on 3,000–4,000 hectares using the concrete pole and ring method [18].

2.1. Diversity of dragon fruit

As people become more health concerned, the popularity and demand for dragon fruit is increasing rapidly and reflecting its reputation for various health benefits [19]. Dragon fruit is classified into four genera: *Cereus*, *Hylocereus*, *Selenicereus*, and *Stenocereus*. *Selenicereus* species are widely cultivated and popular because of its aesthetic value, attractive fruits, and numerous health benefits [20]. Dragon fruit is also known as a promising future crop for India. Growing demand makes it highly profitable and presents a big opportunity for exploitation. However, large degrees of intra and inter specific hybridization result in significant physical and genetic variety, making it difficult to discriminate between species and varieties. This complicates the process of evaluating performance and setting quality standards for dragon fruit [20,21].

3. Morphological diversity of dragon fruit

Dragon fruit is a long-day plant that has captivated consumers with its attractive color appearance, low calorie content, and sweetened flavor [22]. Dragon fruit stems are prone to rising, spreading, and branching extensively [23]. There may be four to seven fruits, each with a maximum diameter of ten to twelve centimeters and a maximum length of ten centimeters. Adult branches have almost conical to circular spine that range in length from 1 mm to 4 mm, and areoles are placed roughly 2–5 cm apart. The colors vary from bluish green to grayish brown. They produce rectangular to oval-shaped fruits. Its length ranges from 4 cm to 10 cm and 3–8 cm thick. These fruits are made up of a white, red, pink, and violet pulp (depending on variety) that contains a few edible tiny black seeds scattered throughout it [24].

There are many varieties of dragon fruits. *Selenicereus* includes three types of dragon fruits, *S. polyrhizus* (red flesh), *S. undatus* (white flesh), and *S. megalanthus* (yellow skin). *S. polyrhizus* (red dragon fruit) is egg shaped, weighs between 300g and 600g and is 13–15 cm in length [23]. It has green stems, and the flowers that can be measured up to 30 cm long with margins and reddish outer perianth segments, especially at the tips, and rather short and yellowish stigma with seven lobes [25]. It produces a scarlet color with an oblong shape that is covered with scales that vary in size [26]. The fruit contains red flesh, edible black seeds, and a tasty flesh texture. The spherical white pitaya (*S. undatus*) has long, green stems that are slightly thorny at the edges [25].

Dragon fruit are rectangular, rosy- a red, and covered in long, broad scales with red and green tips. They are 15–22 cm long, with white flesh and numerous tiny black seeds. The yellow dragon fruit (*S. megalanthus*) weighs 300–800 g. The flesh is often larger than the red dragon fruit and has a nice texture and flavor [27]. The triangular, fleshy stems of commercially grown dragon fruits are the primary locations for photosynthesis [28]. The leaves have been altered to become short spines that are found in the notches along the stems' wavy edges (Figure 2). The medium-sized yellow dragon fruit contain phytochemicals, such as betaxanthins, vitamin E, and lycopene. Yellow dragon fruits are also commonly used as a yellow coloring agent in gummy candy, drinks, and yogurts [23].

3.1. Vegetative and reproductive biology of red and white dragon fruit

The study was conducted in Sepang place on a five-year-old *S. polyrhizus*. In which 10 separate flowers were measured for floral length during the study, from petal tip to flower root [29]. The observation indicates that the flowers of *S. polyrhizus* are monoecious, nocturnal, and funnel-shaped and the ovary is situated at the base of a long tube that extends 3 cm to the exterior and carries the foliaceous scales. The flower perianth is made up of two different types of tepals: sepaloid and petaloid. Tepals are attached around the rim of the flower cup [30]. The style and stamens in the ventral portion of flowers are zygomorphic, unilocular and ovary contains many tiny, white, unfertilized ovules. Therefore, it is noted that the many stigma lobes that radiate from the tubular style's terminal rim, offering a suitable landing location, are present in the nocturnal bloom of *S. polyrhizus* [31].

Dragon fruit utilizes the Crassulacean acid metabolism (CAM) photosynthetic pathway, which significantly enhances its water-use efficiency [32]. In *Selenicereus* species, the stomata are deeply embedded within the stem tissue [33]. This adaptation allows the plant to thrive in marginal tropical lands. In some species, such as *S. polyrhizus*, the stem surface is coated with a waxy layer that

shields the stomata from direct sunlight [34]. Unlike *S. polyrhizus*, *S. undatus* lacks this waxy coating over its stomata, making *S. polyrhizus* more vulnerable to intense solar radiation. In the southern hemisphere, *S. undatus* and *S. costaricensis* bloom from November to April, and while in the northern hemisphere, flowering occurs from May to October [35]. The plant's reproductive cycle is rapid, with the time from floral bud emergence (Stage 1) to blooming and from flower opening to fruit maturity (Stage 2) each lasting approximately 18–20 days. Anthers dehiscence occurs just a few hours before the flower fully opens (Figure 2).

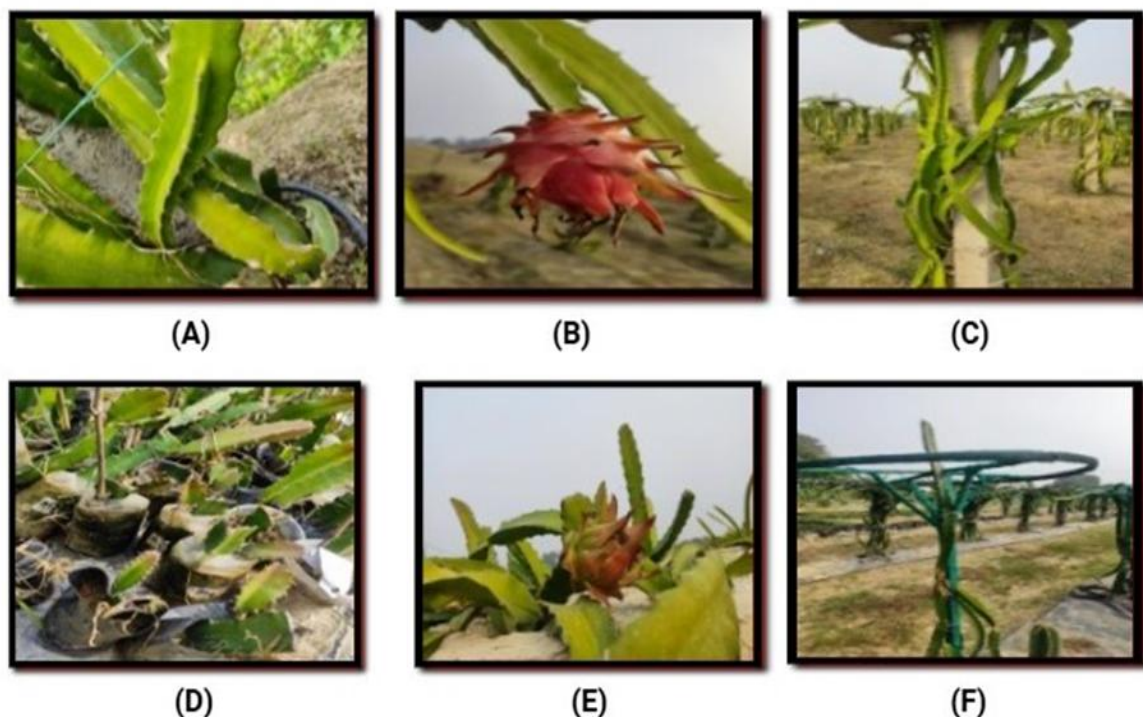


Figure 2. Crop establishment and developmental stages of *Selenicereus* species in Uttar Pradesh (A). Stem: Brown strip at corner of ribs (B). Fruit of *S. polyrhizus* (C). Dragon fruit stem resting on trellis (D). Propagation of dragon fruit through stem cutting (E). Dragon fruit trees blossoming and fruiting in October-November (F). Support system of dragon fruit.

4. Biochemical diversity of dragon fruit

In dragon fruit pulp is a good source of bioactive phytochemicals that provide health beneficial effects through dietary intake [16]. From last few years, the increasing number of reports confirmed that consumption of fresh fruits and vegetables showed protection against chronic diseases in humans [36]. Recent study focuses attention on the antioxidant activity of dragon fruit that provide protection against oxidative stress-related disorders [37]. *S. polyrhizus* have high total sugar, as well as reducing sugar [38], while *S. undatus* have high non reducing sugar. Peels present in fruit are an inedible waste product that represent up to one third of the fruit's weight. It may be used in economical purification methods to provide extracts and sub-fractions for the formulation of healthcare products

and food applications [39]. Pitaya peel is usually discarded during the processing as food waste and generates a source of pollution. It accounts for approximately 22% of the whole fruit weight [40]. The discarded peel contains high pectin, soluble and insoluble fiber, betalains, phenolic, and others compounds that contain several biological properties [41].

4.1. Biochemical profile of dragon fruit

Dragon fruit have many health imparting biochemical molecules that have strong antioxidant potential [42]. There are various phytochemicals present in different parts of dragon fruit that can be used in life-saving medicine for humans.

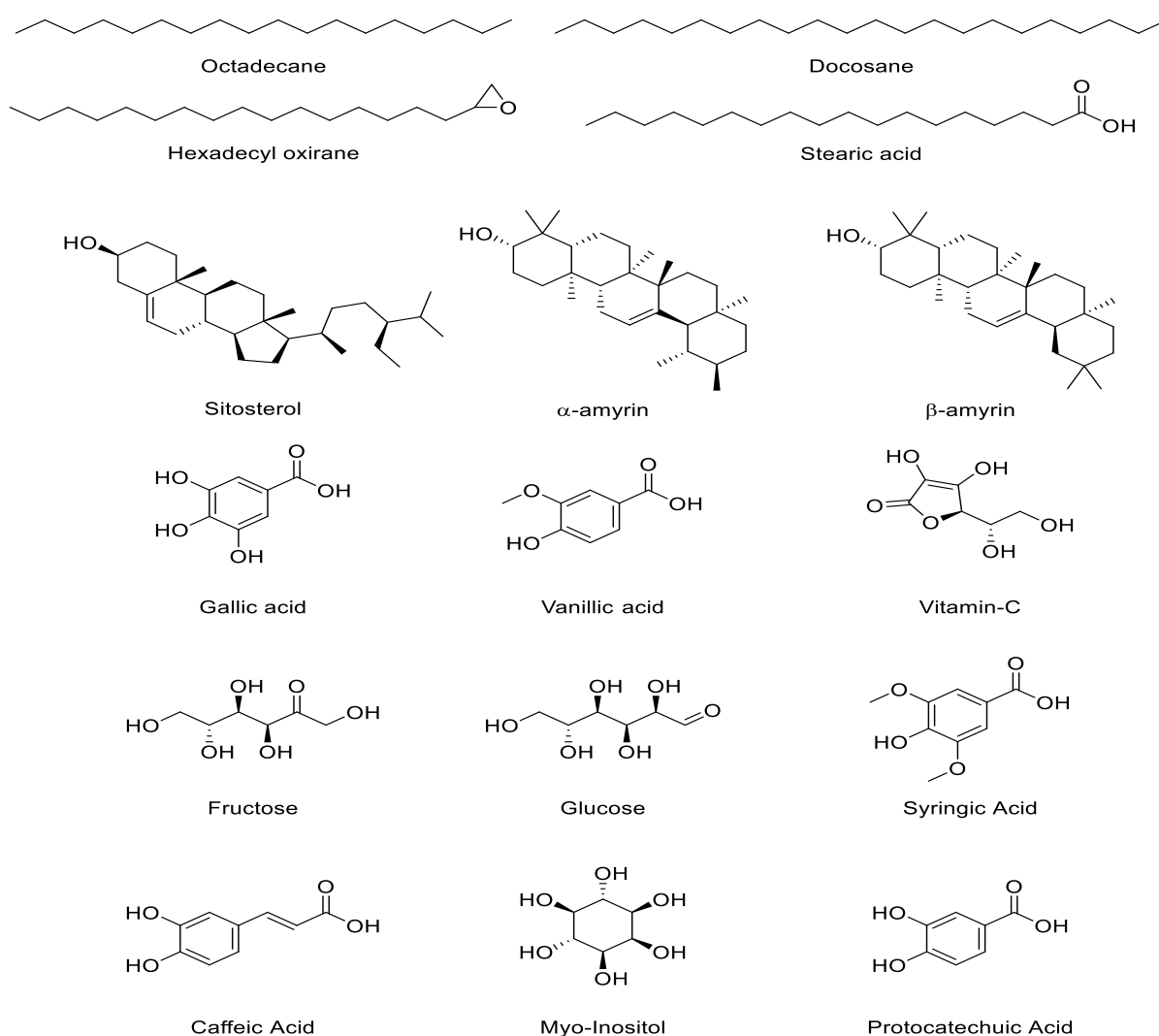


Figure 3. Important phytonutrients present in dragon fruit peel and pulp.

4.1.1. Betalains

Betalains are hydrophilic, nitrogen-containing pigments found in the Caryophyllales order of plants. Dragon fruit also contains significant amount of these pigments [43,44]. These are water-soluble, tyrosine-derived alkaloid pigments chemically known as trimethylamine betaine or

trimethylglycine that have a chemical structure similar to methionine and choline. Recent studies suggest that consumption of dragon fruit helps in improving the blood glucose levels and lipid profiles [45]. Researchers found that dragon fruit has a high betalain concentration and that regular consumption of dragon fruit has a positive effect on the risk of cardiovascular disease. However, the research on its cardioprotective effects in human trials, particularly with amounts typically consumed in the diet, is still lacking. The presence of conjugated diene of 1,7-diazaheptamethin gives betalains their distinct color and gives them absorption maxima in both the visible and ultraviolet light spectrums [46].

4.1.2. Carbohydrates

Dragon fruit contains about 5–7 g of sugars per 100 g of fruit pulp [16]. The sugar composition primarily consists of glucose and fructose (Figure 3). Dragon fruit with white pulp have higher glucose and fructose levels compared to the red-pulp varieties [47]. Other sugars found in the fruit include mannose, inositol, arabinose, ribose, and xylose. Overall, the level of glucose, fructose, sucrose, and ribose shows a remarkable variation across different dragon fruit varieties [48]. Oligosaccharides, mainly fructo-oligosaccharides, are found in dragon fruit [49]. These substances are not broken down in the upper gastrointestinal tract, and they help in providing nourishment to good gut bacteria and thereby improve digestive health [50].

4.1.3. Organic acids

One of the major components present in fruits is organic acid, which plays a key role in physical processes, including growth and maturation [51]. Fruit flavor, color, aroma, fragrance, and other organoleptic qualities are all greatly influenced by the organic acid. Out of the nine organic acids that were tested, red dragon fruit had a much higher level of shikimic acid than white dragon fruit. [16].

4.1.4. Vitamin C

Dragon fruit is a good source of vitamin C (Figure 3) [52], which is an essential nutrient for immune function by supporting the cellular functions of both the innate and adaptive immune system. It also helps in promoting the oxidant scavenging activity of the skin [53]. Vitamin C potentially protects from environmental oxidative stress by enhancing the epithelial barrier function against pathogens [54].

4.1.5. Sterols

The seeds of dragon fruit contain the plant sterols, which have the potential of lowering the cholesterol level [55]. The bioactive compounds present in the dragon fruit vary significantly between different species and varieties. Generally, red-pulp dragon fruit have higher antioxidants and bioactive chemicals compared to white-pulp dragon fruit [56]. Many of these bioactive chemicals are present in higher amounts in the peel of the fruit as compared to the pulp. Although the peel is usually not eaten, studies are being conducted to see whether dragon fruit peels can be used to make nutraceuticals or functional components [57].

5. Genetic diversity of dragon fruit

Detection of genetic differences and elucidation of genetic relationships among genotypes of any plant are of high importance for protection, conservation, utilization, and improvement of its genetic resources [58]. Genetic diversity is a vital resource for the improvement and sustainable cultivation of dragon fruit (*Selenicereus* spp., formerly *Hylocereus* spp.). Early assessments of genetic diversity relied on morphological descriptors, such as stem structure, fruit size, peel color, flesh pigmentation, and flowering behavior. However, these traits are often influenced by environmental conditions, limiting their reliability in determining genetic relationships. In recent years, numerous studies on genetic diversity and relationships among *Selenicereus* species have been carried out on the basis of series of molecular markers, such as RAPD, ISSR, and AFLP.

Genetic diversity of dragon fruits was focused on the specific germplasms. Tel-Zur et al. [59] have used RAPD markers to investigate genetic relationships among *Selenicereus* species and reported considerable genetic variation within cultivated and wild accessions. However, Junghans et al. [60] utilized ISSR markers and observed high levels of polymorphism, indicating a broad genetic base that could be exploited for breeding programs. Among the marker systems, simple sequence repeats (SSRs), also known as microsatellite DNA markers, is considered highly efficient for studying genetic diversity and is also known for improving the characterization of dragon fruit germplasm. SSRs have recently developed in the Cactaceae family. Pan et al. [61] demonstrated that SSR markers effectively differentiated closely related cultivars and revealed significant genetic divergence among white-, red-, and yellow-fleshed dragon fruit species.

These findings highlight the importance of molecular markers for germplasm conservation and cultivar identification. Recent advances in genomics have greatly enhanced the understanding of dragon fruit genetic diversity [61]. A chromosome-scale genome assembly reported by Zheng et al. [62] provides a valuable insight into genome organization and evolution. The study identified approximately 29,000 protein-coding genes and revealed evidence of ancient whole-genome duplication events that contributed to genetic diversification and environmental adaptation. The availability of genome sequences has facilitated the discovery of thousands of single nucleotide polymorphism (SNP) markers, enabling high-resolution genetic analyses. Using genotyping-by-sequencing technology, a high-density SNP-based linkage map was developed and genomic regions associated with fruit weight, peel color, and soluble solid content were identified [63]. These genomic resources have accelerated the identification of quantitative trait loci (QTLs) and candidate genes controlling important agronomic traits. Transcriptomic studies have also provided insights into functional diversity within dragon fruit. Zheng et al. [64] compared the gene expression profiles between red- and white-fleshed cultivars and identified key betalain biosynthesis genes, which regulate flesh coloration. Subsequent studies revealed the involvement of some transcription factors in pigment accumulation, explaining the genetic basis of variation in fruit color and antioxidant content.

The integration of molecular markers, genome sequencing, and transcriptomic approaches has laid the foundation for modern breeding strategies, such as marker-assisted selection (MAS), genome-wide association studies (GWAS), and genomic selection [64]. These tools enable the efficient identification of superior genotypes and accelerate cultivar development. Overall, recent genomic and molecular studies demonstrate that dragon fruit possesses substantial genetic diversity, which can be effectively utilized to develop high-yielding, nutritionally enhanced, and

climate-resilient cultivars. Understanding both interspecific and intraspecific genetic diversity is crucial for the effective conservation, management of plant genetic resources, and successful breeding programs. Genetic differences between different genotypes play a key role for breeders in selecting the high-yielding varieties. The presence of such variability among individuals is essential for development of new varieties that improve the productivity of dragon fruit and enhance the resistance to biotic and abiotic stresses.

Despite significant advances in molecular and genomic studies, research on dragon fruit genetic diversity remains limited compared to major fruit crops. Most studies have involved a relatively small number of accessions and species, restricting the understanding of global genetic variation. In addition, the lack of extensive GWAS, limited availability of high-density molecular markers, and insufficient characterization of wild germplasm hinder the effective utilization of genetic resources in breeding programs [65]. Further large-scale genomic and multi-omics studies are required to fully exploit the genetic potential of dragon fruit.

6. Pharmacological activities of dragon fruit

6.1. Antioxidant effect

Dragon fruit contains various bioactive substances (organic compounds), such as flavonoids, polyphenols, betalains, and vitamin C, that carry a strong antioxidant effect. Vitamin C reduces oxidative damage and lowers the risk of chronic disease. Additionally, the available evidence also indicates that the anticancer potential of dragon fruit is largely supported by preclinical investigations, whereas confirmation through well-designed human clinical trials is still required [66]. In both in vitro and in vivo investigations, dragon fruit consumption has been associated with a decrease in oxidative stress indicators [67]. Its potential value in reducing oxidative stress-related diseases, including cardiovascular diseases, neurological disorders, and some types of cancer, is supported by its antioxidant qualities. Many biochemical processes involve neutralization of reactive oxygen species (ROS) by activating antioxidant defense systems in cells. These mechanisms work synergistically to reduce oxidative stress and protect against cellular damage, supporting the fruit's pharmacological potential in preventing oxidative stress-related diseases [68].

6.2. Anti-cancerous effect

Cancer is a serious public health issue that causes uncounted numbers of death and disability. More than 700,000 people die from liver cancer each year, making it the second most common cause of cancer-related deaths. Phytochemicals analysis suggests that dragon fruit peel and pulp extracts have the highest concentrations of rutin, caffeic acid, chlorogenic acid, syringic acid, and ferulic acid, which help in preventing cancer (Figure 3). Consuming red dragon fruit has been shown to raise the levels of high-density lipoprotein in type 2 diabetes patients while lowering the level of low-density lipoprotein, cholesterol, triglycerides, and total cholesterol [66]. The phytoconstituents of methanol fruit extracts were evaluated by GC-MS chromatogram and experimental findings showed that *S. polyrhizus* methanol fruit extract had the better anti-cancerous efficiency when compared with other extracts of *S. undatus* [69]. The polyphenols reduce the tumor vascularization and metastasis by scavenging free radicals and nitric oxide (Figure 4).

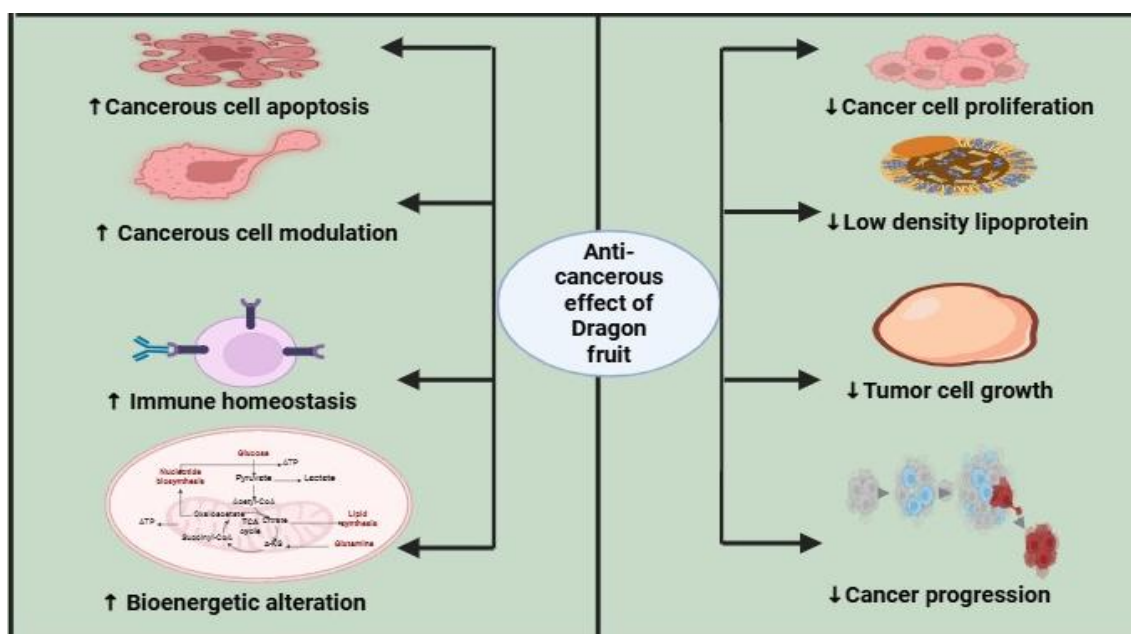


Figure 4. Role of *Selenicereus*-derived compounds in preventing cancer cell proliferation, thereby restricting nutrient supply to tumor cells, and limiting cancer spread (Created by: <https://biorender.com>).

Several researchers reveal that dragon fruit has anti-cancer properties. The fruit's ability to produce nanoparticles was examined by [70], who found that it can significantly decrease the growth of MCF-7 breast cancer cells. Experimental findings suggest that methanolic fruit pulp extract of *S. undatus* has anticancer and anti-apoptotic abilities on human liver cancer (Hep G-2) cells. Phytoconstituents present in fruit pulp act as a natural cytotoxic agent against a variety of cancers. Red dragon fruit shows antiproliferative properties on B16F10 melanoma cells. They reported that the peel extract inhibits the proliferation of melanoma cells more strongly than the pulp [71]. Peel is also rich in polyphenols and a good source of antioxidants. It has been found that cell proliferation was reduced in MCF-7 (ER⁺) cells when treated with pitaya pulp (500–1000 g/mL). The findings from other studies also suggest that eating pitaya reduces the frequency of cancer development. The phytoconstituents found in *S. undatus* pulp and peel extracts show the capacity to induce apoptosis in colorectal and breast cancer cell lines [72].

6.3. Anti-inflammatory activity

Dragon fruit shows anti-inflammatory properties in addition to its antioxidant and anti-cancer properties [73]. Red pitaya's pulp and peel contain anthocyanins (cyanidin-3-glucoside, delphinidin-3-glucoside, and pelargonidin-3-glucoside) [74]. Researchers discovered that the extract from the pulp and peel of dragon fruit, along with the isolated squalene, inhibited pro-inflammatory enzymes, such as cyclooxygenase-2, lipoxygenase, and acetylcholinesterase. It has been concluded that dragon fruit has a good potential for controlling inflammation through a variety of pathways, including prostaglandin, leukotriene, and cholinergic pathways [75]. The primary component of dragon fruit pulp carries a polyunsaturated hydrocarbon (C₃₀H₅₀) with six isoprene units and

betalains having the highest radical scavenging properties. Dragon fruit is abundant in biologically active compounds, such as flavonoids and polyphenols, and these compounds may prevent the production of inflammatory cytokines, such as interleukin-6 (IL-6) and TNF- α , which can reduce inflammation [76] (Figure 5).

Antioxidant content present in dragon fruit can help to combat free radicals and reduce negative effects of oxidative stress and inflammation. Other reports also suggest that antioxidant compounds, such as betalains and vitamin C, increase the body's resistance to oxidative damage and inflammatory processes [77]. Hence, it can be concluded that compounds present in the dragon fruits can act as anti-inflammatory agents.

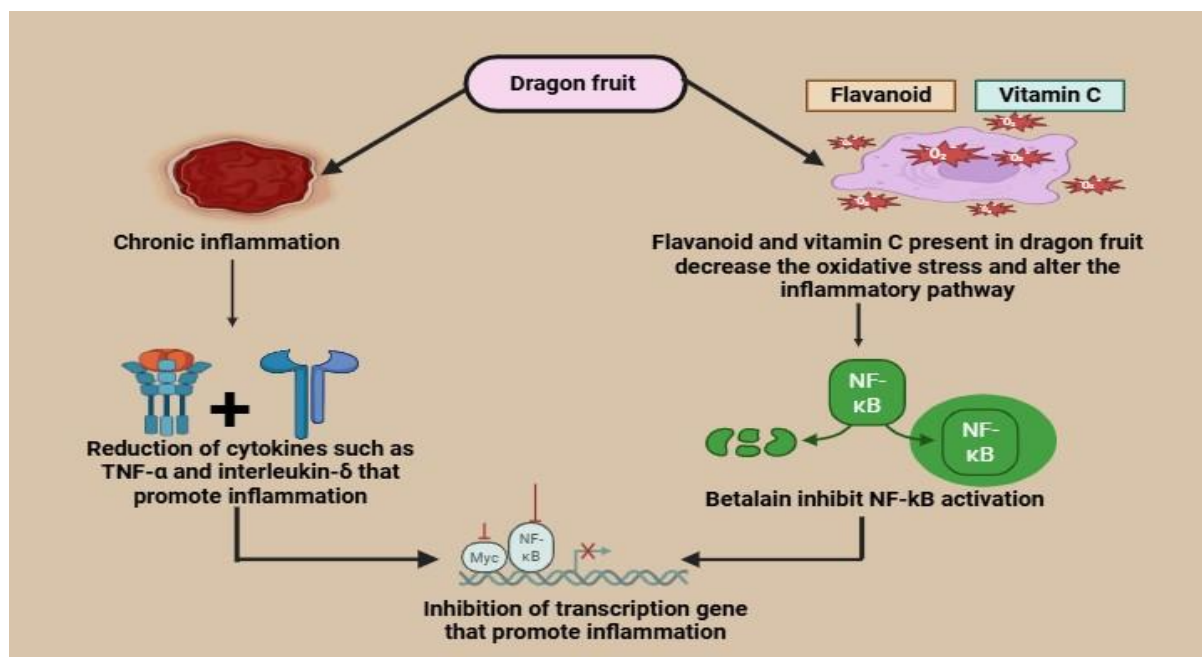


Figure 5. Anti-inflammatory mechanism of dragon fruit phytochemicals. Flavonoids, vitamin C, and betalains may reduce oxidative stress and modulate NF- κ B signaling, potentially leading to decreased expression of pro-inflammatory cytokines and inflammatory genes. The mechanism is based on available evidence from studies on dragon fruit phytochemicals and related bioactive compounds [68]. Created by: <https://biorender.com>.

6.4. Cardiovascular activity

Currently, cardiovascular diseases (CVDs) represent the leading cause of death [78]. In 2019, the British Heart Foundation reported that CVDs accounted for 27% of all deaths in the United Kingdom and 34% of deaths worldwide, with coronary artery disease being the most prevalent. Dragon fruit consumption can enhance the endothelial function by reducing arterial stiffness in healthy humans. Cardioprotective benefits of *Selenicereus polyrhizus* are due to the high content of polyphenol and antioxidant compounds [79]. It has been observed that dragon fruit juice consumption reduces the diastolic stiffness in rats with diet-induced metabolic syndrome [45]. These findings suggest that dragon fruit, particularly due to its betalain content, may contribute to

cardiovascular health. However, the available evidence is primarily derived from in vitro and animal studies. Therefore, well-designed human clinical trials are needed to confirm these potential benefits (Table 1).

Table 1. Functions and health benefits of some bioactive compounds present in dragon fruit pulp and peel.

Bioactive compounds	Health effects	Function	Ref
Betacyanin, betanin, iso-phoracanthin, 3-O-beta-glucopyranoside	Antioxidant activity	These compounds help to neutralize free radicals protecting cells from oxidative stress and damage.	[90]
Betacyanins and related phytochemicals	Anticancer activity	The fruit compounds have properties that may help in converting certain cancer treatment to their active form promoting cancer cell death and inhibiting their proliferation.	[71]
Chlorogenic acid, syringic acid, ascorbic acid	Anti-inflammatory effects	These compounds help to reduce inflammation potentially, reduces the symptoms of inflammatory diseases; mucosal protection and inhibition of stomach acid secretion	[76]
Flavonoid, alkaloid, saponin, and triterpenoid	Cardiovascular protective activity	Pulp extracted from red pitaya reduces the arterial stiffness, as rated by pulse wave velocity	[91,92]
Linoleic acid, arachidonic acid, vitamins (A, B ₃ , B ₆ , B ₁₂ and C)	Wound healing	These compounds contribute to the wound healing process by promoting cell regeneration and tissue repair.	[86]
Glucopyranoside 3-O-beta-glucopyranoside, vitamin C, betacyanin, gallic acid	Antidiabetic activity	These compounds help in managing the blood sugar levels that may help to regulate blood glucose level in patients with diabetes.	[74]
Syringic acid, betacyanin, betanin	Antimicrobial activity	The dragon fruit has properties that help to prevent microbial infection. Bioactive compounds interconnect with the lipid bilayer of microorganism and increase the permeability.	[93]
Betalains, flavonoids, polyphenols, vitamin C	Neuroprotective potential	Bioactive compounds support neuroprotection by preventing the development of oxidative Stress. Compounds search the radicals that are free and protect the neurons from oxidative damage.	[94]

6.5. Wound healing activity

The functional role of skin is to shield the body's water-rich interior organs from the dry outside world [80]. Two essential requirements for healthy survival are having a strong ability to repair wounds and maintaining the integrity of the skin. In order to repair the damaged tissues, a variety of cell types and mediators work together in a multiphase process known as wound healing [81]. Vitamin C plays a crucial role in generating collagen, a protein that promotes the wound healing process and maintains the integrity of the skin. The antioxidant qualities of vitamin C protect the injured area from oxidative stress and help in the healing process. In both normal and hyperglycemic situations, fruit contains gallic acid showed wound-healing properties [82]. It has been found that dragon fruit extract (stem, flower and fruit) accelerates wound healing by boosting the fibroblast migration. Another study also suggests that quercetin and a number of other phytochemicals help in wound healing by encouraging the angiogenesis and growth of fibroblasts and epithelial cells [83]. To fully investigate dragon fruit's ability to cure wounds, more research is needed.

6.6. Anti-ulcer activity

Helicobacter pylori infections are the main cause of ulcers, especially gastric ulcers, which damage the gastrointestinal tract's lining. Various trials have been demonstrated that dragon fruit has anti-ulcers effects. Dragon fruit extracts enhance the mucosal protection by reducing the ulcer size and speeding up the healing process of ulcer. Report suggests that quercetin, isolated from peel of red pitaya, showed potential anti-ulcer activities [84]. Clinical studies also reveal that regular consumption of dragon fruit can improve the ulcer healing rate by reducing ulcer symptoms. It has also been found that dragon fruit extract has the potential to enhance the gastric mucus barrier and protects the stomach lining from acidic digestive juices. The fruit's extract has many antioxidant compounds that help in the protection of gastric tissues from oxidative damage, which is a major factor for ulcer formation.

Experimental studies suggest that dragon fruit may possess gastroprotective and antiulcer properties, although human clinical evidence is currently lacking. Additionally, dragon fruit has anti-inflammatory properties that reduce inflammation in the gastric mucosa and may heal ulcers [85]. Studies suggest that dragon fruit components may also have antimicrobial effects against *Helicobacter pylori* that may be the cause of gastric ulcers [86]. Although these results are encouraging, more research is needed in order to fully understand dragon fruit's anti-ulcer properties and possible applications in human gastrointestinal health.

6.7. Prebiotic effect

Dietary fiber and oligosaccharides present in dragon fruit resist digestion in the upper gastrointestinal tract and reach the colon, where they are selectively fermented by gut microbiota, such as *Lactobacillus* and *Bifidobacterium*, mentioned in Figure 6. This fermentation leads to production of short chain fatty acids (SCFAs), which lower colonic pH, inhibit pathogenic bacteria [87]. Some studies appear to show that dragon fruit enhances the growth of healthy gut bacteria. It may have a positive effect on the gut microbiome, strengthen the mineral absorption, and modulate immune responses, ultimately promoting gut health and overall physiological well-being.

Recent studies have expanded the potential applications of dragon fruit in functional foods and gut health. Red pitaya pulp has been shown to serve as an effective plant-based matrix for probiotic delivery while maintaining betacyanin content and desirable sensory characteristics, supporting its use in the development of functional food products [88]. Furthermore, probiotic-fermented red pitaya was found to modulate gene expression and metabolic pathways associated with vitamin D receptor signaling and inflammation, indicating potential benefits for gut health, immune regulation, and anti-inflammatory activity [89]. These findings highlight the growing importance of dragon fruit as a bioactive ingredient with applications beyond its nutritional value.

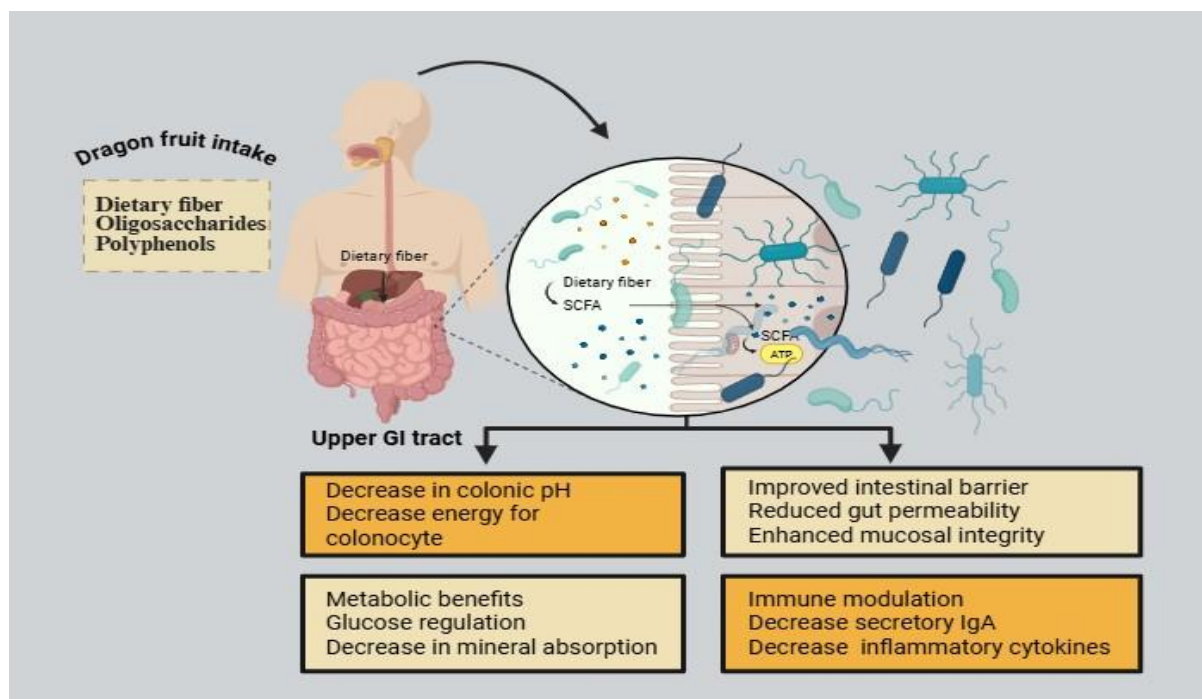


Figure 6. Dietary fiber and oligosaccharides from dragon fruit escape enzymatic digestion and reach the colon, where they selectively stimulate *Lactobacillus* and *Bifidobacterium spp.* resulting in short-chain fatty acid production, immune modulation, and enhanced gut barrier function. Created by: <https://biorender.com>.

7. Diverse applications of dragon fruit

Currently, the fruit market is becoming more competitive and open to originality, such as native and exotic fruits, mainly due to numerous health benefits and their diverse applications in day-to-day life [92]. Dragon fruit are exotic fruits that have arisen consumer interest due to their tolerance of abiotic stress [95]. Every part of dragon fruit (pulp, peel, seeds, flowers, buds, and dried flowers) has numerous nutritious contents, including their therapeutic properties, which motivate humans to convert the fruit into various edible and processed forms, such as beverages, skin care products, jams/jellies, seed oils, food colorants, and many pharmaceutical products (Table 2) [96]. Dragon fruits have antalgic activity because of the presence of a compound Gallic acid (3,4,5-trihydroxybenzoic acid) [46].

Table 2. Nutraceutical benefits of dragon fruit with its wide range of applications in various food and the pharmaceutical industry.

Specific parts of Dragon fruit	Category	Uses	Ref
Young stem and fresh flower buds	Used as vegetables	Young stems and flower buds are consumed as vegetables in some regions.	[97]
Dried flowers	Industrial use	Used to make tea rich in antioxidants	[98]
Fruit pulp	Culinary use	Pulp can be used to produce juice, jam, jellies, and other products.	[92]
	Pharmaceutical and cosmetic Industry	Betacyanin's are natural red-violet pigments used as colorants and bioactive ingredients in food, cosmetic, and pharmaceutical formulations.	[96]
	Beverage industry	Dragon fruit pulp has been incorporated into fermented beverages (e.g., beer) to enhance antioxidant capacity, color, flavor, and aroma.	[97]
Fruit peel	Industrial use	Fruit peel is used as a source of natural betalain pigments for food colorants and cosmetic formulations (e.g., eye palettes, hair serums, and anti-ageing creams).	[98]
	Meat Industry	Improve color and sensory acceptance of meat products.	[99]
	Packaging industry	In development of ecofriendly, active packaging and bioplastic films to expand shelf life of food products.	[100]
Seeds	Food industry	Seeds are ingredient in many food products, such as syrups, ice-cream, candies, and yogurt.	[95]
Dragon fruit (Whole part)	Cultural use	Used in traditional practices in some cultures and also used in festivals and ceremonies for its fascinating appearance.	[22]
Dragon fruit powder	Bakery use	Dragon fruit powder, rich in dietary fiber and phenolic compounds, is incorporated into fiber-rich bakery products, such as biscuits.	[101]

8. Dragon fruit associated diseases and casual pathogens

There are 17 genera, including 25 species, of plant pathogens that infect dragon fruits [102]. Fruit and stem rot (*B. cactivora*), canker (*Neoscytalidium dimidiatum*), anthracnose (*Colletotrichum* species), and viral disease (*Cactus virus X*) are the most commonly reported diseases in India [103] (Table 3). Report reveals that some fungal and bacterial disease, such as anthracnose, brown spots, stem rots, and canker, severely affect the yields and quality of the dragon fruit (Figure 7) [104]. Rats and birds cause serious damage to flowers and fruits [104]. The first demonstrated impact of a disease in dragon fruit was reported in the 1990's in Colombia when the fungus *Drechslera cactivora* reduced the planted area from 4000 to 250 ha with *S. megalanthus*. So, plants need proper netting to

prevent rat and bird damage to fruit. Excess light damages the plant parts, such as in bacterial rot, sun burn, and calcium deficiency. Hence, timely detection and important precautions are needed from farmers to protect the fruit [105].

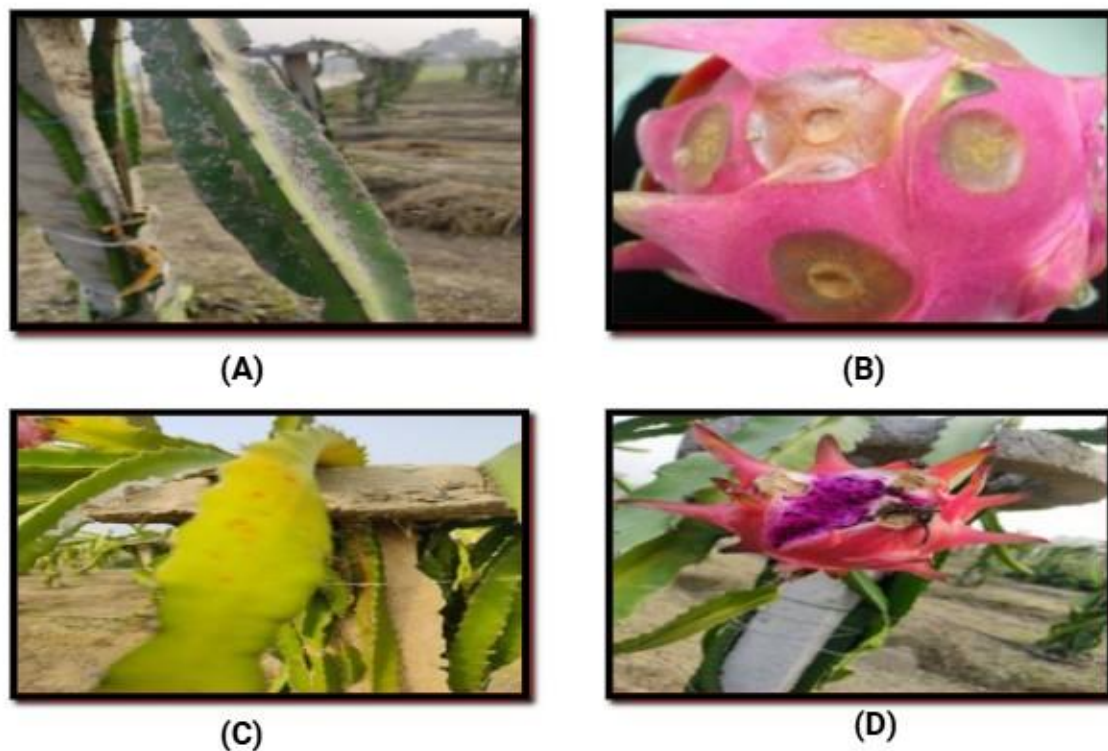


Figure 7. Various diseases associated with dragon fruit (A). Stem canker symptoms (B). Fruit Anthracnose disease (C). Yellow rot disease on infected cladode (D). Bird infection in dragon fruit.

In recent years, disease management in dragon fruit cultivation has shifted from conventional control methods toward integrated and sustainable approaches. Integrated disease management (IDM) combines the use of healthy planting materials, field sanitation, pruning of infected tissues, proper irrigation and nutrient management, regular field monitoring, and the judicious application of chemical fungicides to effectively reduce disease incidence and severity. In addition, biological control agents, such as *Trichoderma* spp., *Bacillus* spp., and *Pseudomonas* spp. have shown potential in suppressing plant pathogens and reducing dependence on chemical fungicides [106]. Furthermore, significant advances in disease diagnosis have enabled rapid and accurate pathogen identification through molecular techniques, such as polymerase chain reaction (PCR), quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP), DNA barcoding, and next-generation sequencing (NGS). These technologies facilitate early disease detection and support the timely implementation of effective management strategies. Therefore, the integration of biological control, modern molecular diagnostics, and IDM practices represents a promising approach for sustainable management of dragon fruit diseases and improved crop productivity [107].

Table 3. Major fungal, bacterial, and viral diseases of dragon fruit, their causal agents, affected plant parts, symptoms, and management strategies.

Disease	Causal agent	Affected plant parts and symptoms	Control	Ref
Fungal diseases				
Anthracnose	<i>Colletotrichum gloeosporioides</i>	Fruit	Synthetic fungicide spray, Sodium nitroprusside	[108]
Stem canker disease	<i>Neoscytalidium dimidiatum</i>	Stem	Spray of Sodium salt and calcium chloride	[109]
Stem grey blight disease	<i>Diaporthe eugeniae</i> ; <i>Diaporthe hongkongensis</i> ; <i>Diaporthe tecton endophytica</i>	Stem: color changes from green to grey	Good ventilation, sanitation, and removal of infected stems.	[105]
Yellow rot disease	<i>Colletotrichum gloeosporioides</i>	Black lesions develop on the stem, gradually turning yellow to black, followed by tissue softening and rot.	Field sanitation, removal of infected tissues, and appropriate fungicide application.	[108]
Bacterial disease				
Soft rot disease	<i>Enterobacter cloacae</i> , <i>Enterobacter aerogenes</i> , <i>Klebsiella oxytoca</i> , <i>Pantoea adispora</i>	Stems and fruits develop yellowish-brown, water-soaked soft rot lesions.	Avoid over-irrigation, improve drainage, sanitation, and use disease-free planting material.	[110]
Viral disease				
Cactus virus X disease	<i>Cactus virus X</i>	Young cladodes exhibit chlorosis, necrosis, and morphological abnormalities.	Use virus-free planting material and remove infected plants.	[111]

9. Challenges and future outlook

Currently, the world fruit market is becoming more and more competitive due to their numerous applications in day-to-day life. However, dragon fruit can be damaged by various environmental conditions. Indian farmers face many challenges in dragon fruit cultivation [112]. Inconsistent and irregular supply of dragon fruit leads to large fluctuation in the market price. Lack of knowledge about packaging and material uses leads to fruit damage during transportation. While for profitable dragon fruit cultivation and commercial development across different agro-climatic zones, efforts are needed to establish standardized cultivation protocols and management practices. The variable size of fruit is a serious issue that arises in all varieties of dragon fruit from the start to the end of ripening season [113]. Effective management of fruit density and soil moisture-nutrient levels is necessary at the beginning of the fruiting season. The high price of cultivation has been identified as the second most significant barrier to widespread adoption. To achieve better outcomes, it is important for the

government to offer subsidies, training programs, and extension services through various organizations, such as international non-governmental organizations (INGOs) [114]. The demand for dragon fruit arises due to its various bioactive and nutraceutical properties that open new research opportunities. Therefore, there is an urgent need to transform dragon fruit into a profitable crop, especially on degraded lands. Future studies for *Selenicereus undatus* should mainly focus on discovering its bioactive components, initiating its advantageous effects on human health through clinical studies, and evaluating its effect on persistent illnesses (e.g., heart disease and diabetes) [115]. Its health importance could also be maximized by research on the effects of environmental conditions on its nutritional, biochemical, and material composition.

10. Conclusions

Dragon fruit has emerged as a valuable horticultural crop because of its remarkable morphological, biochemical, and molecular diversity, as well as its rich nutritional and phytochemicals composition. The presence of bioactive constituents, such as betalains, phenolic compounds, flavonoids, dietary fiber, and vitamins, has generated considerable interest in its potential role as a functional food. Experimental studies indicate that these compounds exhibit antioxidant, anti-inflammatory, antimicrobial, and other biological activities that may contribute to improved metabolic and cardiovascular health. However, most of the available evidence is derived from in vitro studies and animal models, while well-controlled human studies remain limited. The nutritional quality and phytochemicals composition of dragon fruit vary among species and are influenced by genotype, environmental conditions, cultivation practices, and stage of harvest. These variations highlight the importance of continued research on the morphological, biochemical, and molecular diversity of dragon fruit, particularly under Indian growing conditions, to support crop improvement and the development of nutritionally superior cultivars. Future investigations should also focus on strengthening the production system and value chain, improving post-harvest management, and ensuring the sustainable utilization of bioactive compounds. In addition, well-designed clinical trials and mechanistic studies are needed to validate the health benefits suggested by preclinical research and to establish evidence-based recommendations for human consumption. With increasing consumer awareness and expanding market demand, dragon fruit has strong potential to contribute to sustainable horticulture, nutritional security, and the growing functional food and nutraceutical sectors.

Author contributions

Tripti Shukla: Writing-original draft, reviewing and editing; Neelam Pathak, Pankaj Singh and Manikant Tripathi: Conceptualization, writing, reviewing, editing, and supervision.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflicts of interest

All authors have no conflicts of interest in this paper.

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