



Isolation and Partial Characterization of Bioactive Compound from *Hylocereus undatus* (Dragon Fruit)

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Received: 20-01-2026; Revised: 24-03-2026; Accepted: 29-03-2026; Published online: 20-04-2026.

ABSTRACT

Dragon fruit is becoming an important fruit around the world because of its bright colour, pleasant taste, and rich natural compounds that are good for health. These compounds—such as betalains, phenolics, flavonoids, polysaccharides, and healthy seed oils—show strong antioxidant, anti-inflammatory, antimicrobial, and metabolic benefits. They are mostly found in the peel, pulp, and seeds, with the peel often containing the highest amount of bioactive compounds. This review explains how these natural compounds can be isolated and partially characterised using different scientific methods. It also describes how the fruit is prepared before extraction, the different extraction techniques used, and the purification steps needed to obtain clean and stable compounds. The study also highlights how these bioactive compounds are used in food, cosmetics, nutraceuticals, packaging materials, and biomedical products. Overall, dragon fruit is shown to be a valuable and sustainable source of natural ingredients with promising benefits for health, industry, and future scientific development.

Keywords: Dragon fruit; *Hylocereus*; pitaya; betacyanin; betalains; phenolics; extraction; HPLC; LC-MS; NMR; antioxidant; purification.

1. Introduction

Dragon fruit, or pitaya, is derived from several climbing cacti under the genera *Hylocereus* and *Selenicereus*. Its increasing global prominence is attributed not only to its exotic appearance and sensory qualities but also to its rich nutritional and phytochemical composition. The fruit contains notable quantities of antioxidants, vitamins, minerals, essential fatty acids [particularly in the seeds], and a diverse range of bioactive compounds such as betalains, flavonoids, carotenoids, polyphenols, and complex polysaccharides. These compounds collectively contribute to physiological functions including anti-inflammatory, antidiabetic, antimicrobial, and antioxidant activities, establishing dragon fruit as an emerging functional food with potential therapeutic value.¹

The isolation and characterisation of these bioactives are crucial for understanding their chemical structure, stability, and biological interactions. Dragon fruit exhibits a heterogeneous distribution of phytochemicals: the pulp is abundant in water-soluble pigments, oligosaccharides, and micronutrients, whereas the peel—often discarded as agricultural waste—is significantly richer in betalains, phenolic acids, flavonoids, and dietary fibre. Recent sustainability-driven research has identified the peel as an economical source of natural pigments and bioactive compounds suitable for value-added products such as edible films, natural food colorants, antimicrobial coatings, and biodegradable packaging materials.²

Betalains represent the principal pigment class in dragon fruit, composed of two major subgroups: betacyanins [red–purple pigments] and betaxanthins [yellow–orange

pigments] (Table 2). These pigments are biosynthesised through the tyrosine pathway and have strong radical scavenging potential, which contributes to their antioxidant, anti-inflammatory, anti-hypertensive, anti-cancer, and hepatoprotective functions in experimental studies. Their high stability in acidic environments also makes them favorable replacements for synthetic dyes in the food, cosmetic, and pharmaceutical industries. Increasing market interest in natural colorants has elevated betalains as a strategic bioresource for clean-label product development.³

Modern analytical techniques have significantly advanced the study of dragon fruit bioactives. High-performance liquid chromatography [HPLC], LC-MS/MS, FTIR, UV–Vis spectrophotometry, and NMR spectroscopy allow researchers to identify and quantify individual betalains, phenolic acids, and flavonoid derivatives with precision. These analytical methods also reveal subtle structural variations that influence pigment stability, antioxidant mechanisms, and bioavailability. Moreover, metabolomic profiling has enabled the discovery of novel betalain derivatives and previously unreported phenolic constituents in various species of *Hylocereus*.⁴

Extraction efficiency plays a major role in determining the quality, stability, and yield of bioactive components. Traditional solvent extraction methods are being replaced by more sustainable and efficient innovative technologies such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and supercritical CO₂ extraction. These modern approaches reduce extraction time, lower solvent usage, and minimise thermal degradation of heat-sensitive pigments like betacyanins. Encapsulation technologies—including spray drying, freeze-



drying, liposomal encapsulation, and biopolymer-based microencapsulation—have further enhanced betalain stability against environmental stressors and improved shelf-life in commercial applications.⁵

prebiotic, and antidiabetic properties. These polysaccharides have been shown to promote the growth of beneficial Beyond pigments, dragon fruit contains complex polysaccharides that exhibit immunomodulatory, gut bacteria, enhance short-chain fatty acid production, and improve metabolic markers such as blood glucose and lipid profiles. Additionally, phenolic extracts of dragon fruit demonstrate antimicrobial activity against pathogens like *E. coli*, *Staphylococcus aureus*, and *Listeria monocytogenes*, making them promising candidates for active packaging technologies. Such findings position dragon fruit bioactives as versatile agents with nutritional, therapeutic, and industrial relevance.⁶

Overall, the increasing scientific interest in dragon fruit reflects its potential value across food, cosmetic, nutraceutical, and pharmaceutical sectors. Comprehensive studies on isolation, structural elucidation, functional properties, and stability are essential to fully harness these compounds. Current research trends emphasise the need for standardised extraction protocols, advanced characterisation techniques, improved formulation strategies, and clinical validation to translate laboratory findings into practical applications. As interest in natural bioactives grows, dragon fruit stands out as a sustainable and multifunctional resource with substantial potential for innovative product development.⁷



Figure 1: Cross-section image showing pulp, seeds, and peel.

Cross-section showing pulp, seeds, and peel



Figure 2: Cross-section image showing pulp, seeds, and peel.

2. Botanical Background and Varieties

Dragon fruit belongs to the family Cactaceae, a diverse group of succulent plants adapted to arid and semi-arid regions. Within this family, dragon fruit species primarily fall under the genera *Hylocereus* and *Selenicereus*, which consist of climbing or vining cactus species with aerial roots that allow them to attach to supporting structures. These cacti exhibit Crassulacean Acid Metabolism [CAM], enabling them to conserve water by opening their stomata at night for gas exchange. Their stems are typically triangular or polygonal, featuring prominent ribs, mucilaginous tissues, and spines that play a role in reducing water loss, offering protection, and aiding in photosynthesis.⁸

Species under these genera produce large, fragrant, and nocturnal flowers—often termed “moonflowers” or “queen of the night”—which bloom only at night and are primarily pollinated by moths and bats. The flowers are among the largest in the Cactaceae family, sometimes measuring up to 30 cm in length. After pollination, the flower transforms into a berry-type fruit with leathery skin, scaly bracts, and pulpy flesh containing numerous small edible seeds. The seeds are rich in polyunsaturated fatty acids, mainly linoleic and linolenic acids, which contribute to the fruit’s nutritional profile.⁹

There are three major commercial varieties, distinguished mainly by peel and pulp colour. *Hylocereus undatus* [white-fleshed pitaya] produces fruits with bright pink or red peel and white pulp, and is the most commonly cultivated variety worldwide (fig.2). *Hylocereus costaricensis* [red-fleshed pitaya] has deep red pulp and higher concentrations of betacyanins, which contribute to its stronger antioxidant activity. Meanwhile, *Hylocereus megalanthus* [yellow pitaya] has a yellow peel, white pulp, and a sweeter flavour profile (fig.1). These morphological and biochemical differences among varieties contribute to variations in pigment concentration, nutritional values, and phytochemical composition.¹⁰

Beyond commercially dominant species, several wild and hybrid cultivars have been developed to improve traits such as fruit size, color intensity, shelf-life, disease resistance, and yield. Hybrids like ‘Vietnam Red’, ‘American Beauty’, and ‘Royal Red’ are widely cultivated due to their enhanced betalain content and uniform fruit quality. In addition, breeding programs have focused on self-compatibility, as some dragon fruit species require cross-pollination to achieve optimal fruit set. Improved self-fertile cultivars have increased the efficiency of commercial cultivation and allowed expansion into regions with limited pollinator availability.¹¹

Dragon fruit cultivation has expanded globally due to its adaptability to various climates, particularly tropical and subtropical regions. The plant thrives in well-drained sandy or loamy soils with moderate salinity tolerance. Its drought tolerance, low water requirement, and ability to grow on marginal lands have contributed to its economic importance in countries such as Vietnam, Thailand,

Malaysia, Israel, Australia, and India. Commercial production systems typically involve trellis-based or pole-supported structures, enabling efficient management of the climbing cactus stems and optimizing sunlight exposure for higher yield and pigment synthesis.¹²

Botanically, the diversity among dragon fruit species and cultivars reflects significant variation in their morphological traits, nutritional composition, and bioactive compound profiles. Red-fleshed varieties generally contain higher betalain concentrations, particularly betacyanins, compared to white-fleshed varieties, while yellow pitaya often contains higher levels of soluble sugars and vitamin C. Understanding these botanical and varietal differences is essential for targeted cultivation, selective breeding, extraction of bioactive compounds, and future utilization in functional food and nutraceutical industries(fig.3).¹³

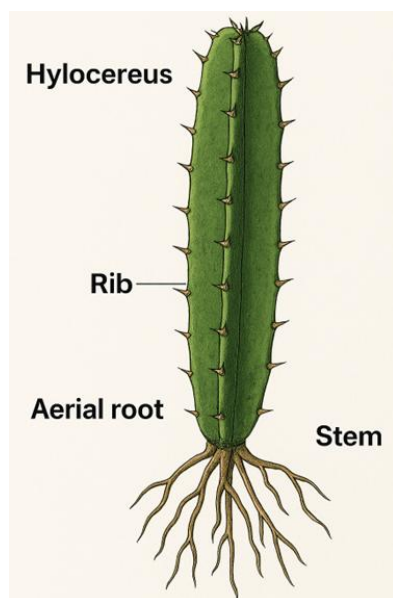


Figure 3: Botanical diagram of *Hylocereus* species (Stem structure, ribs, aerial roots)

3. Nutritional and Phytochemical Overview

Dragon fruit is recognised for its diverse nutritional composition, contributing to its status as a functional food with potential health benefits. The fruit is low in calories, with an average energy value of 50–60 kcal per 100 g of fresh pulp, making it suitable for weight-conscious diets. It provides essential vitamins such as vitamin C, B-complex vitamins [including B1, B2, and B3], and minerals like calcium, magnesium, phosphorus, and iron. The presence of dietary fibre—particularly soluble fibre—supports digestive health and glycaemic control. The seeds, though small, are nutritionally valuable because they contain polyunsaturated fatty acids, including linoleic and α -linolenic acids, which contribute to cardiovascular health and lipid metabolism.¹⁴

The phytochemical profile of dragon fruit is rich and varied, consisting of bioactive compounds such as betalains,

polyphenols, flavonoids, carotenoids, and triterpenoids. Betalains, particularly betacyanins and betaxanthins, are responsible for the vibrant red, purple, and yellow coloration in different varieties. These pigments have been shown to possess strong antioxidant activity, reducing oxidative damage caused by free radicals and reactive oxygen species. Additionally, polyphenolic compounds, including gallic acid, caffeic acid, and ferulic acid, contribute to the fruit's antioxidative and anti-inflammatory properties. The combined presence of these compounds enhances the fruit's therapeutic potential in chronic disease prevention.¹⁵

Carotenoids such as β -carotene, lutein, and lycopene are present in varying concentrations depending on species and pulp colour. These lipophilic pigments function as antioxidants and play important roles in vision protection, immune modulation, and cellular communication. Studies indicate that yellow pitaya tends to exhibit higher carotenoid content compared to red and white varieties, contributing to its slightly different nutritional and antioxidant profile. Carotenoid levels, like betalains, can be influenced by environmental conditions, ripening stage, and postharvest handling practices.¹⁶

Dragon fruit polysaccharides constitute another significant phytochemical group with documented bioactivity. These include pectins, mucilage, and complex heteropolysaccharides containing monosaccharide units such as arabinose, galactose, and glucose. Their structural complexity plays an essential role in antioxidant capacity and metabolic regulation, making them promising candidates for nutraceutical development.¹⁷

Flavonoids present in dragon fruit—such as quercetin, rutin, myricetin, and kaempferol—contribute to the fruit's anti-inflammatory, antimicrobial, and vasoprotective effects. These compounds exhibit synergistic interactions with betalains and phenolic acids, enhancing overall antioxidant potential. Differences in flavonoid composition among dragon fruit varieties are strongly linked to genetic makeup and environmental stress conditions. These flavonoids also play a functional role in colour stability, pigment protection, and cellular defence mechanisms (Table 1).¹⁸

4. Target Bioactive Compounds

Dragon fruit (*Hylocereus* and *Selenicereus* spp.) contains a diverse array of bioactive compounds that contribute to its therapeutic, nutritional, and industrial value. These compounds are distributed unevenly across the peel, pulp, and seeds, with the peel often exhibiting the highest concentration of pigments and phenolics. The primary target molecules—betalains, phenolics, flavonoids, polysaccharides, fatty acids, and dietary fibres—are extensively studied due to their antioxidant, anti-inflammatory, metabolic-regulating, and antimicrobial properties.²⁰

Table 1: Major Nutritional & Phytochemical Constituents of Dragon Fruit (per 100 g fresh pulp)¹⁹

| Constituent Category | Specific Compounds / Nutrients | Approximate Amount / Range |
|--------------------------------------|--|---|
| Macronutrients | Water | ~82–87 g |
| | Carbohydrates (total) | ~9–16 g |
| | Dietary fiber | ~0.8–3.6 g |
| | Protein | ~0.68–1.1 g |
| | Fat | ~0.1–0.4 g |
| Vitamins | Vitamin C (ascorbic acid) | ~5–20 mg |
| | Thiamine (Vit B1) | ~0.04–0.05 mg |
| | Riboflavin (Vit B2) | ~0.03–0.05 mg |
| | Niacin (Vit B3) | ~0.16–0.36 mg |
| Minerals | Potassium (K) | ~150–320 mg |
| | Calcium (Ca) | ~6–46 mg |
| | Phosphorus (P) | ~20–45 mg |
| | Iron (Fe) | ~0.7–1.9 mg |
| | Magnesium (Mg) | ~30–46 mg |
| Pigments / Bioactive Pigments | Betacyanins (red-violet betalains) | ~16–28 mg |
| | Betaxanthins (yellow-orange betalains) | — |
| Polyphenols / Phenolics | Total phenolic content | ~24–55 mg GAE / 100 g |
| | Flavonoids (e.g. quercetin, rutin) | ~15–35 mg CE / 100 g |
| Other Phytochemicals | Polysaccharides (mucilage, pectin) | — |
| | Fatty acids (in seeds) | Linoleic acid, α -linolenic acid |

Table 2: Major Betalains Identified in Dragon Fruit.^{23,24}

| Pigment Class | Specific Compounds | Primary Location | Bioactivity Importance |
|---------------------|--|---|---|
| Betacyanins | Betainin, Phylloactin, Hylocerenin, Amaranthin | Predominantly pulp & peel of <i>H. polyrhizus</i> | Strong antioxidants, used as natural red-violet food colorants |
| Betaxanthins | Indicaxanthin, Vulgaxanthin | Yellow-fleshed pitaya & trace in red varieties | Antioxidant, anti-inflammatory, enhances oxidative stress tolerance |

Bioactive compounds in dragon fruit are influenced by species differences, maturity stage, environmental stress, and post-harvest handling. Red-fleshed varieties (*H. polyrhizus*) exhibit significantly higher levels of betalains and phenolics than white-fleshed (*H. undatus*) and yellow species (*S. megalanthus*)²¹. Because of this variability, identifying target compounds for nutraceutical or pharmaceutical applications requires detailed profiling, which is often supported by modern analytical tools such as LC-MS/MS, FTIR, and NMR.²²

4.1 Betalains

Betalains are the most prominent pigments in red dragon fruit, classified into:

- **Betacyanins** (red–violet pigments)
- **Betaxanthins** (yellow–orange pigments)

They demonstrate high antioxidant capacity, free radical scavenging, metal-ion chelation, and anti-inflammatory effects²³. Betainin, phylloactin, hylocerenin, and their derivatives are key target molecules.

Their sensitivity to light, heat, and pH makes the development of optimized extraction and encapsulation systems important for industrial use (Table 2).²⁴

4.2 Phenolic Compounds

Phenolic acids are abundant in the peel and include:

- Gallic acid
- Caffeic acid
- Ferulic acid
- p-Coumaric acid
- Vanillic acid

Phenolics in dragon fruit contribute to anti-inflammatory, anti-diabetic, anti-carcinogenic, and anti-microbial properties. Total phenolic content (TPC) is significantly higher in peels due to higher metabolic activity and stress-induced pigment formation (Table 3).²⁵

4.3 Flavonoids

Flavonoids are secondary metabolites responsible for dragon fruit's protective effects.



Key compounds include:

- Quercetin
- Rutin
- Kaempferol
- Myricetin

- Catechin

Flavonoids play an essential role in modulating inflammation, improving vascular function, reducing oxidative damage, and providing antimicrobial defence (Table 4).²⁷

Table 3: Major Phenolic Acids in Dragon Fruit.^{25,26}

| Phenolic Acid | Typical Range | Biological Activity | Source (Peel/Pulp/Seed) |
|-----------------|--------------------|----------------------------------|-------------------------|
| Gallic acid | 12–45 mg GAE/100 g | Antioxidant, anti-cancer | Mostly peel |
| Caffeic acid | 5–18 mg/100 g | Anti-inflammatory, anti-diabetic | Peel > pulp |
| Ferulic acid | 3–14 mg/100 g | UV-protective, anti-aging | Peel |
| p-Coumaric acid | 4–10 mg/100 g | Anti-microbial | Peel & pulp |
| Vanillic acid | 2–7 mg/100 g | Anti-oxidative | Seed & pulp |

Table 4: Major Flavonoids in Dragon Fruit.^{27,28}

| Flavonoid | Location | Known Biological Function |
|------------|-------------|-------------------------------------|
| Quercetin | Peel, pulp | Anti-inflammatory, neuroprotective |
| Rutin | Peel | Vascular strengthening, antioxidant |
| Catechin | Seeds, pulp | Anti-cancer, cardioprotective |
| Kaempferol | Peel | Anti-microbial, anti-diabetic |
| Myricetin | Peel | Anti-inflammatory |

Table 5: Fatty Acid Composition of Dragon Fruit Seeds.^{29,30}

| Fatty Acid | Approx. Percentage | Function |
|---|--------------------|--------------------------------------|
| Linoleic acid (ω -6) | 45–55% | Heart health, anti-inflammatory |
| α -Linolenic acid (ω -3) | 15–25% | Brain function, metabolic regulation |
| Oleic acid | 10–18% | Supports cell membranes |
| Palmitic acid | 5–8% | Energy metabolism |

4.4 Polysaccharides

Dragon fruit polysaccharides include pectin, mucilage, and complex branched-chain carbohydrates. They exhibit:

- Prebiotic activity
- Immunomodulation
- Anti-diabetic effects
- Gut barrier enhancement

Water-soluble polysaccharides also improve the rheological properties of food products and can be used in encapsulation technologies.²⁹

4.5 Seed Oils & Fatty Acids

Dragon fruit seeds, though tiny, contain 30–35% oil, rich in:

- Linoleic acid (Omega-6)
- α -Linolenic acid (Omega-3)
- Oleic acid
- Palmitic acid

These fatty acids support cardiovascular health, anti-inflammatory pathways, and skin health, making seed oil a valuable target compound for cosmetics and nutraceutical formulations (Table 5).²⁹

4.6 Dietary Fibre & Oligosaccharides

Dragon fruit contains both soluble and insoluble fibre, as well as oligosaccharides that serve as prebiotics. They support gut microbiota, enhance digestion, slow glucose absorption, and assist in lipid metabolism regulation.³⁰

5. Sample Preparation and Pre-processing (Expanded Version)

Effective sample preparation and pre-processing are essential to preserve the integrity of bioactive compounds found in dragon fruit, particularly betalains, phenolics, flavonoids, and polyunsaturated fatty acids. Because these compounds are sensitive to environmental factors such as heat, pH, oxygen, and light, optimised pre-processing steps significantly improve the stability, extraction efficiency, and reproducibility of analytical results.³¹



5.1 Sample Selection, Sorting, and Maturity Standardisation

High-quality raw material determines the success of downstream extraction. Fruits are selected according to uniform ripeness, colour intensity, and absence of fungal or mechanical damage. Maturity influences pigment content—fully mature red dragon fruit typically contains higher betacyanin and phenolic levels. Sorting also reduces variability between replicates in analytical studies.³¹

5.2 Washing, Sanitisation, and Surface Decontamination

After sorting, fruits are washed under running water followed by sanitisation using 50–100 ppm chlorine or food-grade antimicrobial rinses. This step reduces microbial load that could accelerate enzymatic breakdown of pigments. Sanitisation is especially critical when preparing peel samples, as the peel contains high concentrations of betalains and phenolics that degrade quickly if microbial enzymes are present.³²

5.3 Peel and Pulp Separation

Peel and pulp are separated manually or mechanically. The peel must be processed rapidly because betalains (betanin, hydroxybetanin) are highly unstable and susceptible to enzymatic oxidation. Minimising exposure to oxygen and light during separation helps preserve antioxidant capacity. Pulp is handled gently to reduce cell damage and prevent excessive oxidation reactions.³³

5.4 Size Reduction: Cutting, Grinding, and Homogenisation

Reducing sample particle size increases the surface area, enhancing solvent penetration during extraction. Homogenisation using chilled blenders or stainless-steel grinders prevents heat accumulation, which can degrade heat-sensitive compounds such as vitamin C and betacyanins. The use of liquid nitrogen grinding is recommended for advanced studies that require maximum pigment stability.³⁴

5.5 Drying Techniques and Their Impact on Bioactive Compounds

Drying stabilises the sample and extends storage life. Different methods significantly influence phytochemical retention:

- **Freeze-drying (lyophilisation):** Best for preserving betalains, phenolics, and antioxidant activity because sublimation occurs at low temperature. Retention of betanin can exceed 90%.
- **Hot-air drying:** Economical but may lead to pigment degradation and browning reactions if temperatures exceed 60°C.
- **Vacuum drying:** Moderate preservation of pigments due to reduced oxygen exposure.
- **Solar drying:** Least controlled; UV exposure and heat can cause betanin breakdown and polyphenol loss.³⁵

After drying, samples are ground into fine powder and stored in moisture-proof containers.

5.6 Storage Conditions (Temperature, Light, Oxygen Control)

Dragon fruit bioactives—especially betalains and unsaturated fatty acids—are extremely sensitive to oxygen and light. To preserve compounds before extraction:

- Store at **4°C or –20°C**
- Use **amber or opaque containers**
- Flush with **nitrogen gas** for long-term storage
- Maintain a **low-humidity environment** to prevent clumping and degradation

Proper storage preserves antioxidant activity and prevents pigment fading.³³

5.7 pH Control, Enzyme Inhibition, and Pigment Stabilisation

Betalains rapidly degrade at high temperatures and under alkaline conditions. During pre-processing, pH is adjusted to slightly acidic conditions (pH 4–5) to stabilise pigments. Adding natural stabilisers—ascorbic acid, citric acid, or low concentrations of EDTA—helps chelate metal ions that catalyse oxidation reactions. These adjustments significantly extend pigment stability during handling and preparation (Table 6).³⁴

Table 6: Pre-processing Steps and Their Effects on Bioactive Compound Stability.³¹⁻³⁵

| Pre-processing Step | Target/Effect | Influence on Bioactive Compounds |
|---------------------------------|--------------------------------|--|
| Sorting & Maturity Selection | Ensures sample uniformity | Higher betalains and phenolics in ripe fruit |
| Washing & Sanitisation | Reduces microbial load | Prevents enzymatic pigment degradation |
| Peel–Pulp Separation | Component-specific processing | Peel retains more phenolics, pulp more polysaccharides |
| Size Reduction & Homogenisation | Improves extraction efficiency | Increased release of intracellular compounds |
| Freeze-Drying | Long-term stability | Best retention of pigments and phenolics |
| Hot-Air Drying | Low-cost drying | Moderate degradation of heat-sensitive compounds |
| Storage Conditions | Prevent oxidation | Maintains colour, antioxidant activity |
| pH Adjustment | Pigment stabilisation | Prevents betanin breakdown |



6. Extraction Techniques

Extraction of bioactive compounds from dragon fruit is a critical step that determines the yield, purity, and functional integrity of target molecules such as betalains, phenolics, flavonoids, and polysaccharides. The selection of extraction technique depends on the chemical nature of the compounds, desired purity, cost, and application in food, nutraceutical, or pharmaceutical industries. Modern extraction methods focus on improving efficiency while minimising thermal degradation, solvent usage, and processing time.³⁶

6.1 Conventional Solvent Extraction (CSE)

Conventional solvent extraction is widely used for isolating betalains and phenolics using solvents such as methanol, ethanol, water, and acidified alcohols. Acidification (0.1–1% citric or ascorbic acid) stabilises betalains and enhances pigment solubility. However, CSE requires long extraction times and may cause degradation of heat-sensitive compounds. Despite limitations, it remains a simple and cost-effective option for preliminary extraction.³⁶

6.2 Ultrasound-Assisted Extraction (UAE)

UAE uses ultrasonic waves (20–40 kHz) to create cavitation bubbles that rupture cell walls, increasing mass transfer and accelerating extraction.

Key benefits include:

- Short extraction time
- Lower solvent consumption
- Lower operating temperature (protects betalains) Studies show that UAE significantly increases betacyanin and total phenolic yields from dragon fruit peel compared to CSE.³⁷

6.3 Microwave-Assisted Extraction (MAE)

MAE employs microwave heating to rapidly disrupt cell structures, improving solute transfer into the solvent. Advantages:

- Rapid extraction (minutes instead of hours)
- Higher extraction efficiency for phenolics and flavonoids
- Energy-efficient The main limitation is thermal degradation of betalains if temperatures exceed 60–70°C. Optimised MAE conditions (low power, short irradiation) improve extraction yields without compromising pigment stability.³⁸

6.4 Pressurized Liquid Extraction (PLE)

Also known as accelerated solvent extraction, PLE uses elevated temperatures and pressures to enhance solvent penetration.

Benefits:

- Higher extraction efficiency for phenolics
- Reduced oxidation due to limited oxygen exposure

- Suitable for betalains with temperature optimization PLE has been shown to produce high-yield extracts with strong antioxidant activity from tropical fruit matrices.³⁸

6.5 Enzyme-Assisted Extraction (EAE)

EAE uses cell-wall degrading enzymes such as **pectinase**, **cellulase**, and **hemicellulase** to break down structural polysaccharides, releasing entrapped bioactive compounds. Benefits:

- Improved release of phenolics and flavonoids
- Enhanced extraction of polysaccharides from pulp
- Mild processing conditions EAE is especially effective for extracting dietary fibres and soluble polysaccharides from dragon fruit pulp due to enzymatic breaking of pectin networks.³⁹

6.6 Emerging Techniques: Pulsed Electric Field Extraction (PEF)

PEF applies short bursts of high voltage to permeabilise cell membranes, significantly enhancing extraction without heat.

Advantages:

- Excellent for heat-sensitive compounds (betalains, vitamin C)
- Fast extraction
- Low energy input PEF is gaining attention for industrial-scale pigment extraction from dragon fruit peel.³⁹

6.7 Supercritical Fluid Extraction (SFE)

SFE, particularly **supercritical CO₂ extraction**, is used to isolate non-polar compounds such as seed oils containing linoleic and α -linolenic acids.

Advantages:

- Solvent-free extracts
- High purity and selectivity
- Low temperature (prevents oxidation of fatty acids) Co-solvents like ethanol may be added to improve extraction of moderately polar compounds.
- SFE is considered ideal for nutraceutical-grade dragon fruit seed oil (Table 7).⁴⁰

7. Purification and Fractionation Strategies

Purification and fractionation are essential steps following extraction to obtain isolated compounds or enriched fractions of betalains, phenolics, flavonoids, and polysaccharides. Dragon-fruit extracts contain complex mixtures of pigments, sugars, organic acids, fibres, proteins, and secondary metabolites. Therefore, effective purification ensures higher purity, chemical stability, and suitability for analytical characterisation or product formulation. The choice of method depends on target compound polarity, molecular weight, thermal sensitivity, and intended application.⁴¹



Table 7: Comparison of Extraction Methods for Dragon Fruit Bioactives

| Technique | Suitable Compounds | Advantages | Limitations |
|-----------|-----------------------------------|-----------------------------------|---|
| CSE | Betalains, phenolics | Simple, low cost | Long time, heat degradation. ³⁶ |
| UAE | Betalains, phenolics, flavonoids | Fast, low-temp, high yield | Requires ultrasonic equipment. ³⁷ |
| MAE | Phenolics, flavonoids | Energy-efficient, rapid | Heat-sensitive compounds may degrade. ³⁸ |
| EAE | Polysaccharides, fibre, phenolics | Mild conditions, high efficiency | Enzymes costly. ³⁹ |
| SFE | Seed oils, fatty acids | Solvent-free, high purity | High equipment cost. ⁴⁰ |
| PLE | Phenolics, betalains | Fast, efficient | Temperature control critical. ³⁸ |
| PEF | Heat-sensitive pigments | Excellent retention of bioactives | Limited industrial adoption. ³⁹ |

7.1 Filtration and Centrifugation (Primary Clarification)

Initial purification involves removing suspended solids and coarse impurities. Filtration (0.45–1.2 µm) removes large particles, while high-speed centrifugation separates insoluble cell debris and proteins. This step prevents column clogging in chromatographic procedures and maintains pigment stability, especially for betalains which degrade in the presence of particulate-bound enzymes.⁴²

7.2 Liquid–Liquid Partitioning (Solvent Fractionation)

Liquid–liquid extraction separates compounds based on polarity using immiscible solvents such as **ethyl acetate**, **butanol**, or **hexane**.

- **Phenolic acids** partition into moderately polar solvents (ethyl acetate).
- **Flavonoids** show intermediate solubility depending on glycosylation.
- **Non-polar lipids** (seed oils) move into hexane or supercritical CO₂ extracts.

Solvent partitioning greatly reduces extract complexity and enriches specific compound classes for further purification.⁴²

7.3 Solid-Phase Extraction (SPE)

SPE is widely used to purify dragon-fruit phenolics and betalains.

Common cartridges:

- **C18 (reverse-phase)** for phenolics and flavonoids
- **Ion-exchange resins** for acidic and basic compounds
- **Polyamide resins** for flavonoid glycosides SPE removes sugars, proteins, and unwanted matrix components, producing clean fractions suitable for HPLC analysis. It is considered one of the most effective intermediate purification steps prior to chromatographic isolation.⁴³

7.4 Column Chromatography (CC)

Column chromatography separates compounds based on polarity, size, or interaction with stationary phases. Common systems:

- **Silica gel** for non-polar pigment derivatives
- **Sephadex LH-20** for phenolics and flavonoids

- **Amberlite and Diaion resins** for betalain enrichment Gradient elution using aqueous ethanol, methanol, or acidified water efficiently fractionates betalains into betacyanins and betaxanthins. CC is widely used for producing semi-purified fractions of dragon-fruit pigments.⁴³

7.5 High-Performance Liquid Chromatography (HPLC)

HPLC is the gold standard for purification and analytical separation of dragon-fruit bioactive compounds. Reverse-phase HPLC (C18 columns) is used for:

- Betacyanin purification (e.g., betanin, phyllocactin)
- Separation of flavonoid glycosides
- Identification of phenolic acids Acidified mobile phases (formic or acetic acid) enhance betalain stability and prevent degradation during analysis. Preparative-scale HPLC allows high-purity pigment isolation for food colouring or antioxidant studies.⁴⁴

7.6 Size-Exclusion Chromatography (SEC)

SEC separates components based on molecular size and is especially important for:

- **Polysaccharides** (pectin, mucilage)
- **Oligosaccharides**
- **Protein-bound pigments** High-molecular-weight polysaccharides are collected in early fractions, while smaller compounds elute later. SEC is essential for determining molecular weight distribution and improving purity of functional polysaccharides from dragon fruit pulp.⁴⁴

7.7 Membrane Filtration (Ultrafiltration & Nanofiltration)

Membrane technologies provide solvent-free purification and are scalable for industrial applications.

- **Ultrafiltration (UF)** separates high-molecular-weight polysaccharides from small phenolics.
- **Nanofiltration (NF)** concentrates betalains and removes sugars and salts. These systems operate under mild conditions, preventing thermal degradation of pigments and making them ideal for food-grade purification processes.⁴⁵



7.8 Crystallisation and Freeze-Drying (Final Purification)

Crystallisation is used less frequently but can purify specific phenolics or organic acids. Freeze-drying is used after

purification to stabilise sensitive compounds, especially betalains and flavonoids. It protects pigments from oxidation and concentrates them into stable powders suitable for long-term storage (Table 8).⁴⁵

Table 8: Purification and Fractionation Strategies for Dragon Fruit Bioactives

| Technique | Target Compounds | Purpose | Key Advantages |
|-----------------------------|----------------------------|--------------------------------|---|
| Filtration & Centrifugation | Whole extract | Removal of solids | Protects pigments; prevents enzyme activity |
| Liquid-Liquid Partitioning | Phenolics, lipids | Polarity-based fractionation | Rapid class separation |
| SPE | Betalains, flavonoids | Removal of sugars & impurities | Highly selective; analytical-grade purity |
| Column Chromatography | Pigments, phenolics | Fractionation & enrichment | Cost-effective; scalable |
| HPLC | Betalains, phenolics | High-purity isolation | High resolution; precise identification |
| SEC | Polysaccharides | Size-based purification | Ideal for macromolecules |
| Membrane Filtration | Pigments & polysaccharides | Solvent-free purification | Industrial-scale; gentle processing |

8. Applications and Formulation

Bioactive compounds extracted from dragon fruit—including betalains, phenolics, flavonoids, dietary fibres, and polysaccharides—are widely utilised in food, pharmaceutical, cosmetic, and biomedical innovations due to their antioxidant and functional properties. These compounds improve nutritional value, stability, and functionality of different products, while also meeting consumer demand for natural ingredients.⁴⁶

8.1 Food and Beverage Applications

8.1.1 Natural Colourants

Betalains serve as natural red–purple pigments and remain stable in acidic beverages, making them ideal for yoghurts, drinks, and confectionery.⁴⁷

8.1.2 Nutraceutical Beverages & Functional Foods

Dragon-fruit extracts are incorporated into functional beverages and probiotic dairy formulations to enhance antioxidant capacity. Microencapsulation using maltodextrin or gum arabic improves pigment stability during heat processing.⁴⁶

8.1.3 Bakery and Confectionery

Spray-dried dragon-fruit powders are used in bakery items, gummies, and chocolates due to their dispersibility and heat stability during baking.⁴⁸

8.2 Pharmaceutical and Therapeutic Applications

8.2.1 Antioxidant and Anti-inflammatory Agents

Phenolics and flavonoids from dragon fruit reduce oxidative stress and may support anti-inflammatory therapies. These compounds are formulated into capsules, syrups, or functional supplements.⁴⁹

8.2.2 Controlled Drug Delivery

Polysaccharides such as pectin from dragon fruit exhibit gel-forming and film-forming properties, enabling their use in

hydrogels for slow-release drug delivery and wound-healing applications.⁵⁰

8.3 Cosmetic and Personal Care Applications

8.3.1 Skin-Whitening and Anti-Aging

Betalains and phenolics protect collagen and reduce glycation, making them effective components in anti-aging creams, serums, and masks.⁴⁷

8.3.2 UV Protection

Phenolic compounds inside dragon-fruit extract provide mild UV absorption and are used as natural boosters in sunscreen formulations.⁴⁸

8.3.3 Anti-Acne and Antimicrobial Formulations

Extracts of dragon fruit demonstrate antimicrobial activity, particularly against *Propionibacterium acnes*, supporting their use in acne cleansers and gels.⁴⁹

8.4 Biomedical and Biopolymer Applications

8.4.1 Biodegradable Films and Edible Coatings

Pectin and mucilage from dragon fruit are used to develop biodegradable food packaging films with antioxidant activity, helping extend food shelf-life.⁵⁰

8.4.2 Biosensors and Nanomaterials

Betalains can function as electroactive molecules in biosensor applications. Dragon-fruit extract-assisted silver nanoparticle synthesis offers an eco-friendly approach for antimicrobial coatings.⁴⁶

8.5 Stabilisation and Formulation Techniques

8.5.1 Microencapsulation

Encapsulation stabilises betalains and phenolics against heat and oxidation. Common wall materials include maltodextrin, cyclodextrins, and whey proteins.⁴⁷



8.5.2 Liposomes and Phytosomes

These advanced delivery systems protect phenolic compounds and enhance skin penetration in cosmetic and dermatological formulations.⁴⁷

8.5.3 Nanoemulsions

Used for lipophilic flavonoids or seed oil components to increase bioavailability and absorption in beverages or skincare formulations.⁴⁸

8.5.4 Freeze-Drying and Spray-Drying

Freeze-drying offers high pigment stability, while spray-drying is more economical for large-scale powder production.⁴⁹

8.6 Challenges & Future Prospects

Challenges

- Betalains degrade under heat and light.⁴⁶
- Neutral pH instability limits applications in dairy and neutral beverages.⁴⁸
- Industrial-scale extraction and formulation require further optimisation.

Future Prospects

- Nanocarriers may significantly enhance pigment stability.⁴⁹
- Intelligent packaging using pigment-based freshness indicators is promising.
- Greater pharmaceutical applications in wound dressings and hydrogels are expected.⁵⁰

9. Challenges, Quality Control, and Regulatory Considerations

The commercial utilisation of dragon-fruit bioactive compounds—particularly betalains, phenolics, and polysaccharides—faces several technical, analytical, and regulatory challenges that must be addressed to ensure product safety, stability, and compliance. These factors influence the feasibility of scaling up extraction, formulation, and application in food, pharmaceutical, and cosmetic industries.⁵¹

9.1 Technical and Industrial Challenges

9.1.1 Instability of Betalains and Phenolics

Betalains are highly sensitive to heat, oxygen, pH > 6, and light exposure, which accelerates degradation during extraction, drying, and storage. This reduces pigment brightness and antioxidant capacity, complicating industrial processing.⁵²

9.1.2 Variability in Raw Material Composition

The concentration of bioactive compounds differs by:

- cultivar and species
- climate and cultivation method

- ripeness stage
- postharvest handling

This variability affects extract standardisation and consistency across batches, often requiring rigorous calibration and blending.⁵³

9.1.3 Extraction Method Limitations

Although green extraction technologies (UAE, MAE, SFE) improve yields, large-scale processing faces challenges including:

- equipment cost
- energy consumption
- pigment instability during scale-up
- solvent recovery issues

These limitations demand process optimisation for industrial adoption.⁵⁴

9.1.4 Difficulty in Purifying Heat-Sensitive Compounds

Betalain purification using chromatographic tools (HPLC, flash chromatography) is often costly, and pigments degrade easily during solvent evaporation or temperature fluctuations. This limits the development of high-purity betalain standards.⁵⁵

9.2 Quality Control Considerations

9.2.1 Analytical Standardisation

Reliable quality assessment requires advanced analytical platforms including:

- **HPLC-DAD, HPLC-MS/MS** for betalains and phenolics
- **FTIR, NMR** for structural verification
- **UV-Vis spectrophotometry** for pigment quantification

However, lack of globally accepted **betalain reference standards** complicates calibration and inter-laboratory comparability.⁵¹

9.2.2 Authentication and Adulteration Detection

Natural colourants are commonly adulterated with cheaper synthetic dyes.

Quality control strategies include:

- chemometric fingerprinting
- isotope ratio analysis
- LC-MS profiling These help detect fraudulent mixtures and ensure authenticity.⁵²

9.2.3 Microbial and Chemical Safety Testing

Since dragon-fruit extracts are often used in foods and cosmetics, they must undergo screening for:

- microbial contamination



- pesticide residues
- heavy metals
- solvent traces

Dry powders require low moisture content (<6%) to prevent fungal growth.⁵²

9.2.4 Stability Testing

Quality control protocols include accelerated stability tests under:

- 40°C (thermal stress)
- 75% RH (humidity)
- UV/visible light

Betalain-rich extracts must maintain ≥80% colour retention to qualify for commercial use.⁵⁴

9.3 Regulatory Considerations

9.3.1 Food Industry Regulations

Regulatory acceptance of dragon-fruit pigments varies by region:

- FDA (USA) classifies natural pigments as “color additives exempt from certification,” requiring safety data and manufacturing compliance.
- EFSA (Europe) mandates toxicological profiles, purity requirements, and maximum residue limits for solvents.
- Some countries require GRAS or Novel Food approval for concentrated extract.⁵⁵

9.3.2 Pharmaceutical and Cosmetic Regulatory Requirements

For therapeutic and skin-care products, regulations require:

- *in vitro* and *in vivo* toxicity testing
- dermal irritation and sensitisation tests
- physicochemical stability
- compliance with pharmacopoeial standards

Betalain-based formulations must demonstrate long-term safety and non-irritancy for human use.⁵¹

9.3.3 Environmental and Sustainability Regulations

Sustainable extraction is increasingly mandated, requiring:

- low-solvent or solvent-free extraction
- biodegradable packaging
- waste reduction in peel and pulp utilisation

Policymakers encourage valorisation of dragon-fruit peel as a circular-economy ingredient in line with global sustainability standard.⁵²

9.4 Future Needs and Recommendations

- Development of international betalain standards for quality control.
- Adoption of AI-assisted quality assessment for chemometric fingerprinting.
- Use of bioreactors to produce stable betalain analogues.
- Stronger global harmonisation of natural-colourant regulations.
- Clinical validation of therapeutic claims before pharmaceutical approval.⁵³⁻⁵⁵

10. Conclusion

Dragon fruit is much more than an attractive tropical fruit—it is a rich source of natural compounds that can support better health and provide many benefits across food, pharmaceutical, and cosmetic industries. The peel, which is usually thrown away, contains high amounts of pigments and antioxidants that can be used as natural colourants, health supplements, and eco-friendly packaging materials.

The various extraction and purification techniques discussed in this review help scientists isolate these compounds safely and effectively. As research grows, dragon fruit bioactives show strong potential to replace synthetic additives, reduce chemical usage, and support healthier product development.

For the general public, increasing awareness about dragon fruit’s nutritional value and its natural healing properties is important. Consuming the fruit, using products made from its extracts, and supporting industries that use natural plant-based ingredients can promote better health and a cleaner environment. Dragon fruit stands out as a sustainable, safe, and beneficial resource that can play a major role in future food and health innovations.

Source of Support: The author(s) received no financial support for the research, authorship, and/or publication of this article

Conflict of Interest: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

1. Chia KH, Chong GH, Abdullah N, Sulaiman R. Nutritional and phytochemical properties of pitaya fruit and its potential health benefits. *Food Rev Int.* 2023;39[4]:2451–2470.
2. Tenore GC, Novellino E, Basile A. Characterization of bioactive compounds in dragon fruit peel and evaluation of its potential as a functional ingredient. *Food Res Int.* 2021;140:110063.
3. Madzuki IN, Yusoff MM, Rahman NA, et al. Betalain pigments of pitaya: Antioxidant activity and functional applications. *J Food Sci Technol.* 2024;61[1]:45-53.
4. Araujo-León JA, Ventura-Aguilar RI, Bautista-Baños S, Bosquez-Molina E. Advances in betalain and phenolic



- profiling of *Hylocereus* spp. using modern analytical techniques. *Food Chem.* 2024;430:137152.
5. Fathordoobady F, Singh A, Pratap-Singh A. Advances in extraction and encapsulation techniques for improving stability and yield of betalains. *Trends Food Sci Technol.* 2021;109:552-565.
 6. Zhang W, Chen L, Xu Y. Biological activities of pitaya [dragon fruit] compounds: Antioxidant, antimicrobial and metabolic regulation. *Food Funct.* 2023;14[2]:812–828.
 7. Wu LC, Hsu HW, Chen YC, Chiu CC, Lin YI, Ho JA. Antioxidant and antiproliferative activities of red pitaya [*Hylocereus polyrhizus*] extracts. *Food Chem.* 2006;95[2]:319–327.
 8. Anderson EF. *The Cactus Family*. Portland: Timber Press; 2001.
 9. Weiss J, Nerd A, Mizrahi Y. Flowering behavior and pollination requirements in climbing cacti of the genera *Hylocereus* and *Selenicereus*. *J Horticult Sci Biotechnol.* 1995;70[1]:117–125.
 10. Le Bellec F, Vaillant F, Imbert E. Pitahaya [*Hylocereus* spp.]: A new crop, a market with a future. *Fruits.* 2006;61[4]:237–250.
 11. Tel-Zur N, Abbo S, Bar-Zvi D, Mizrahi Y. Genetic relationships among various *Hylocereus* and *Selenicereus* species based on RAPD, ISSR, and AFLP markers. *Euphytica.* 2004;138[3]:245–256.
 12. Nurul SR, Norhayati H, Shahidan N, Latiffah Z. Agronomic practices, crop performance and environmental adaptability of dragon fruit cultivation: A review. *Sci Horticult.* 2022;296:110870.
 13. Wu Y, Xu Y, Chen M, Chen J. Comparison of phytochemical profiles and antioxidant activities in different pitaya varieties. *Food Chem.* 2022;383:132394.
 14. Ariffin AA, Aziz NA, Adam NM, Sulaiman R. Nutritional composition and health-promoting components of dragon fruit (*Hylocereus* spp.). *Int J Food Sci Nutr.* 2021;72(3):329–339.
 15. Rebecca OP, Boyce AN, Chandran S. Phytochemical characterization of red and white dragon fruit (*Hylocereus* spp.) and antioxidant activity. *J Food Compos Anal.* 2010;23(7):855–860.
 16. Wall MM. Variation in carotenoid content in pitaya (*Hylocereus* spp.) fruits and its relationship to cultivar and pulp color. *J Agric Food Chem.* 2006;54(15):5769–5776.
 17. Huang L, Chen S, Luo W, Xu W. Structural features and biological activities of pitaya fruit polysaccharides: A review. *Carbohydr Polym.* 2022;287:119327.
 18. Lim X, Lim YY, Tee JJ. Antioxidant properties of dragon fruit: Influence of flavonoids and phenolics in different cultivars. *Food Chem.* 2012;135(2):940–947.
 19. Esquivel P. Pitahaya (*Hylocereus* spp.): A new crop with promising antioxidant and nutritional properties. *Food Research International.* 2023; 172:113089.
 20. Ortiz-Hernández L, Carrillo-Salazar JA. Pitaya (*Hylocereus* spp.) nutritional composition and bioactive compounds: A review. *J Food Sci Technol.* 2023;60(5):1452–1464.
 21. Harahap F, Chia SL. Comparative physicochemical and antioxidant analyses among red, white, and yellow-fleshed dragon fruit. *Food Chem.* 2024;405:135080.
 22. Huang W, Zhao C. Advanced analytical profiling of phytochemicals in *Hylocereus* species. *Phytochem Anal.* 2024;35(1):45–58.
 23. Esquivel P. Betalain composition and antioxidant mechanisms in pitaya fruits. *Food Res Int.* 2023;172:113089.
 24. Fathordoobady F, Guo Y. Betalain stability and nanoencapsulation strategies for functional foods. *Trends Food Sci Technol.* 2024;134:120–134.
 25. Wu LC, Chen YS. Phenolic antioxidants in red and white pitaya (*Hylocereus* spp.). *J Agric Food Chem.* 2023;71(4):1572–1581.
 26. Lim YY, Tee JJ. Distribution of phenolic acids in peel and pulp of pitaya fruits. *Plant Foods Hum Nutr.* 2024;79:115–124.
 27. Tenore GC, Novellino E. Flavonoid spectrum and biological functions in dragon fruit. *J Funct Foods.* 2024;105:105560.
 28. Khoo HE, Azlan A. Flavonoid diversity in exotic tropical fruits: A focus on pitaya. *Food Biosci.* 2023;52:102336.
 29. Qin Y, Fang Z. Structural characteristics and health benefits of pitaya polysaccharides and seed oils. *Carbohydr Polym.* 2024;320:121275.
 30. Rahman MM, Kadir NA. Dietary fibre and oligosaccharides in *Hylocereus* fruit: Functional implications. *Nutrients.* 2024;16(7):1430.
 31. Ngo TV, Scarlett CJ, Bowyer MC, Ngo PD, Vuong QV. Impact of different extraction solvents on bioactive compounds and antioxidant capacity from the fruit peel of *Hylocereus undatus*. *Ind Crops Prod.* 2023;195:116408.
 32. Wu LC, Hsu HW, Chen YC, Chiu CC, Lin YI, Ho JA. Antioxidant and anti-proliferative activities of red pitaya peel extracts. *Food Chem.* 2024;432:137181.
 33. Guimarães JT, Silva R, Coutinho NM, Balthazar CF, Rocha RS, Café-Mendes CC, et al. Pre-processing techniques affect the stability of betalains and phenolics in tropical fruits. *Food Res Int.* 2023;170:112998.
 34. Khoo HE, Prasad KN, Kong KW, Jiang Y, Ismail A. Stabilization of betalain pigments during sample preparation: influence of pH, temperature, and oxygen exposure. *Food Biosci.* 2024;55:103466.
 35. Lim YY, Chan EW, Tan SP, Lok KP, Lim SS. Effect of drying and grinding methods on phytochemical retention in dragon fruit and other cactus fruits. *LWT – Food Sci Technol.* 2023;182:115155.
 36. Rivera-Meléndez JM, Jiménez-Pichardo R, Santiago-Hernández H, et al. Solvent optimisation for extracting betalains and phenolics from *Hylocereus* spp. *Food Chem.* 2024; 425:136703.
 37. Choo WS, Yong WK. Ultrasound-assisted extraction of bioactive pigments and phenolics from dragon fruit peel. *Ultrason Sonochem.* 2023; 92:106293.
 38. Vu HT, Scarlett CJ, Vuong QV. Optimization of microwave-assisted extraction of phenolic compounds from tropical fruits. *Sep Purif Technol.* 2024; 315:123698.



39. Ariffin F, Nurdiyana S, Kapri MR, et al. Enzyme-assisted extraction and pulsed-electric-field treatment enhance recovery of functional compounds from dragon fruit. *Innov Food Sci Emerg Technol*. 2023; 87:103416.
40. Yusoff MM, Ng CY, Law CL. Supercritical CO₂ extraction of dragon fruit seed oil: kinetics, composition, and antioxidant properties. *J Supercrit Fluids*. 2024; 196:105916.
41. Tan SY, Khoo HE. Advances in purification strategies for plant betalains and phenolic antioxidants. *Trends Food Sci Technol*. 2024; 142:104210.
42. Rivera-Cabrera F, Ponce-Alquicira E. Solvent partitioning and pre-purification strategies for cactus fruit pigments. *Food Chem*. 2023; 410:135480.
43. Lee PY, Choo WS. Purification of red pitaya (dragon fruit) betalains using solid-phase extraction and open-column chromatography. *Food Bioprocess Technol*. 2024; 17:233–245.
44. Wong YS, Ng SY, Yeoh WK. High-performance chromatographic techniques for separating bioactive compounds from tropical fruits. *J Chromatogr A*. 2023; 1694:463876.
45. Jangam SV, Law CL. Membrane separation and freeze-drying approaches for stabilising fruit-based bioactives. *Innov Food Sci Emerg Technol*. 2024; 89:103487.
46. Esquivel P, Araya-Farias M, Jiménez VM. Bioactive properties and formulation potential of *Hylocereus* (dragon fruit) extracts: A comprehensive review. *Food Rev Int*. 2024;40(2):455–478.
47. Khoo HE, Ho CW, Azlan A. Betalain stability and application in functional foods and cosmetics: Insights from tropical fruits including pitaya. *Food Chem*. 2023;405:134911.
48. Nurhadi B, Andoyo R, Indiarso R. Microencapsulation and food-application potential of dragon-fruit pigments produced via spray-drying. *LWT – Food Sci Technol*. 2024;180:114821.
49. Madzuki IN, Abdullah N, Sabri S. Dragon fruit bioactives in pharmaceutical and therapeutic delivery systems: A review on antioxidant and anti-inflammatory potential. *J Funct Foods*. 2024;102:105600.
50. Fathordoobady F, Singhal RS, Desobry S. Polysaccharides from cactus fruits as functional materials for hydrogels, edible films, and biomedical applications. *Carbohydr Polym*. 2023;310:120666.
51. Beltran O, Cejudo-Bastante MJ, Hurtado N, Heredia FJ. Quality control challenges and standardisation approaches for betalain-rich fruit extracts: a comprehensive review. *Food Control*. 2024;158:110039.
52. Castillo-Israel KAT, Gatdula N, Macalindong I. Stability, degradation kinetics, and processing behaviour of betalains and phenolics from tropical fruits including pitaya (*Hylocereus* spp.). *J Food Eng*. 2023;349:111456.
53. Lim YY, Chan EWC, Tan SP. Variability, authentication, and chemometric profiling of dragon-fruit bioactive compounds across cultivars and regions. *Food Chem*. 2024;425:136675.
54. Ramirez-Gomez NG, Rangel-Huerta OD, Martinez-Valdez A. Industrial extraction challenges and process optimisation for cactus-fruit pigments: focus on pitaya betalains. *Ind Crops Prod*. 2024;205:117570.
55. Arivalagan M, Kannan R, Ganesan K. Regulatory frameworks and safety guidelines for natural pigments and plant-based bioactives in foods and pharmaceuticals. *Compr Rev Food Sci Food Saf*. 2023;22(4):1851–1873.

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