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Exploring the potential of dragon fruit (*Hylocereus* spp.): A review of its nutraceutical properties, processing methods and its waste utilization

C. Surya*, K. Shanthi◆, R. Vijayalakshmi***, A. Kalaiselvan**, K.G. Sabarinathan**** and G. Gurumeenakshi***

**Department of Food Science and Nutrition, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

*** Department of Extension Education and Communication Management, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

**** Department of Family Resource Management and Consumer Science, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

***** Department of Agricultural Microbiology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

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Abstract

Dragon fruit (*Hylocereus* spp.), an exotic fruit from the *Cactaceae* family, has attracted considerable attention due to its rich nutraceutical composition, functional properties and diverse health benefits. Native to Central and South America, it is now widely cultivated in tropical and subtropical regions including India, because of its adaptability to arid conditions, early fruiting nature and increasing market demand. Nutritionally, dragon fruit is low in calories and rich in dietary fiber, vitamins, minerals, essential fatty acids and several bioactive compounds such as betalains, polyphenols, flavonoids, tannins, phytosterols and pectin. These constituents contribute to its antioxidant, anti-inflammatory, antimicrobial, anticancer and wound healing activities. However, the fruit is highly perishable, necessitating the development of value added products and preservation techniques. Various processing approaches including the production of beverages, powders, fermented products, dairy based foods, jams, jellies, wines and minimally processed fresh cuts, have been explored to improve shelf life and utilization. In addition, dragon fruit peels and seeds possess significant potential as sources of natural colorants, dietary fiber, pectin, seed oil and other bioactive compounds with applications in food, pharmaceutical and biorefinery industries. This review highlights the nutritional composition, phytochemical constituents, processing technologies, health promoting properties and waste valorization potential of dragon fruit, emphasizing its importance as a functional food and sustainable industrial resource.

1. Introduction

Dragon fruit(*Hylocereus* spp.) is known as pitaya, pearl fruit, night blooming cereus, strawberry pear and cinderella plant, belongs to the *Hylocereus* genus in the *Cactaceae* family and is identified by its peculiar fruit shape (Luu *et al.,* 2021). Native to Central and South America, this fruit now thrives in warm, humid climates around the countries such as Guatemala, Mexico, Costa Rica, Southeast Asian countries like Indonesia, Malaysia, Taiwan, Vietnam, Bangladesh, Sri Lanka and India (Balaji *et al.,* 2025). In India, dragon fruit first appeared in the late 1990s; now it is cultivated around 400 hectares or less in a number of states. This fruit is ideal for Southern, Western and North Eastern India since it grows well in arid, frost free areas (Karunakaran *et al.,* 2019). Successful cultivation has been recorded in states like Andhra Pradesh, Karnataka and Kerala; significant experiments have shown encouraging outcomes (Balaji *et al.,* 2025). Due to strong market demand and growing customer preferences for nutrient dense exotic fruits, dragon fruit production in India has grown significantly with some regions growing at an annual rate of over 30% (Akhil *et al.,* 2024). Farmers in the state have increasingly adopted the crop due to its profitability, early bearing nature and suitability for marginal lands, indicating strong potential for further expansion and diversification of horticultural production in Tamil Nadu.

Corresponding author: Dr. K. Shanthi

Professor (FSN) and Head, Department of Extension Education and Communication Management, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India

E-mail: shanthi.k@tnau.ac.in

Tel.: +91-9443716835

Dragon fruit comes from tropical rainforests and thrives where the air is warm, the light is strong and the humidity clings like morning mist. It climbs on rocks or tree trunks at temperatures between 25 to 35°C. Dragon fruit is a type of cactus that thrives in both fertile and poor soils, loves sunshine and has a strong tolerance to heat, drought and shade. The primary locations for photosynthesis in commercially developed dragon fruits are their triangular, meaty stems. The leaves undergo modification to become small spines that are found in the notches along the stems' wavy edges (Li *et al.,* 2024). Both seeds and stem cuttings can be used to propagate dragon fruit; however, stem cuttings are the best way to encourage vertical development (Chittibomma *et al.,* 2023).

The fruit's exterior has green fins and red skin and it varies in pulp color, shape, skin and genetic diversity (Hossain *et al.,* 2021). Dragon fruit is characterized by its vivid red color, yellow exterior layer, noticeable scales, elliptical and oval shapes and mildly sweet or bland flavor. Its two types of fleshes have a scattered black seeds in it (Balaji *et al.,* 2025). In general, different countries cultivate four types of dragon fruits. They have rather leafy, leathery skin. Dragon fruit is classified based on its colour of the pulp and peel: (i) *Hylocereus polyrhizus*, a red pulp with red peel that grows in Israel and Malaysia, (ii) *Hylocereus undatus*, a white pulp with red peel that comes from Vietnam and Thailand, (iii) *Selenicereus megalanthus*, a white pulp with yellow peel that comes from Colombia and Ecuador (Aiswarya and Rachana, 2025), (iv) *Hylocereus costaricensis*, a red peel with purple pulp that is indigenous to Israel, Ecuador, Nicaragua and Guatemala and the berry like fruit is 5 to 9 cm wide and 7 to 14 cm long and it has tiny black seeds inside (Shah *et al.,* 2023).

Dragon fruit is a low calorie, low fat fruit with glucose as its primary sugar component. It is also abundant in plant albumins and amino acids, vitamins, different minerals and dietary fiber. The dragon fruit has black seeds which contain stearic acid, arachidic acid, palmitoleic acid and unsaturated fatty acids like linolenic acid and linoleic acid (Li *et al.,* 2024). Dragon fruit may provide therapeutic benefits, including better bone, kidney, cognitive and visual function, blood glucose regulation, blood pressure regulation, cholesterol and colon cancer risk reduction and potential application in cosmetic formulations (Cheok *et al.,* 2020).

Dragon fruit is a highly perishable product that requires careful handling from production to market distribution, making it challenging to establish reliable remote delivery marketing methods. In addition to satisfying the needs of health conscious consumers, regional and exotic fruits promote sustainable agriculture and food security. Increased water shortages, temperature swings that impact fruiting and heightened susceptibility to pests and diseases as a result of rising temperatures are some of the difficulties that climate change presents for the production of dragon fruit. Despite these challenges, dragon fruit's exceptional resistance to extreme heat, drought and poor soil makes it a promising crop for climate resilience. Its shallow root structure allows for efficient water absorption, while trellising methods reduce the damage caused by strong winds and storms (Balaji *et al.,* 2025).

Dragon fruit processing and value addition has recently drawn interest as a major source of income for growers and locals. These communities may diversify their sources of income and satisfy the growing demand for high quality, locally produced goods by turning basic crops into value added products. Because of its bioactive components, dragon fruit can be used in nutritional supplements, functional additives, food products, natural colorants, eco-friendly packaging, edible films and photo protective formulations among other applications. A variety of methods are used to extract the juice from dragon fruit then freeze dried powder, jam, jelly, candy and fermentation is used to produce wine and vinegar, among other products with added value. Fruit by products, such as seeds and peels are used by small enterprises to produce value added goods from fruits, increasing value and reducing waste. This increases productivity by fortifying food with garbage (Jalgaonkar *et al.,* 2022). This review provides a comprehensive and integrated perspective on dragon fruit by combining its nutraceutical properties, processing technologies and waste valorization strategies within a circular economy framework. Unlike previous studies, it emphasizes comparative analysis of fruit varieties, emerging functional and fermented products and advanced extraction and preservation techniques. The inclusion of industrial applications, climate resilience and region-specific insights, along with a focus on bioactive mechanisms and future research directions, distinguishes this review as a multidisciplinary and application oriented contribution.

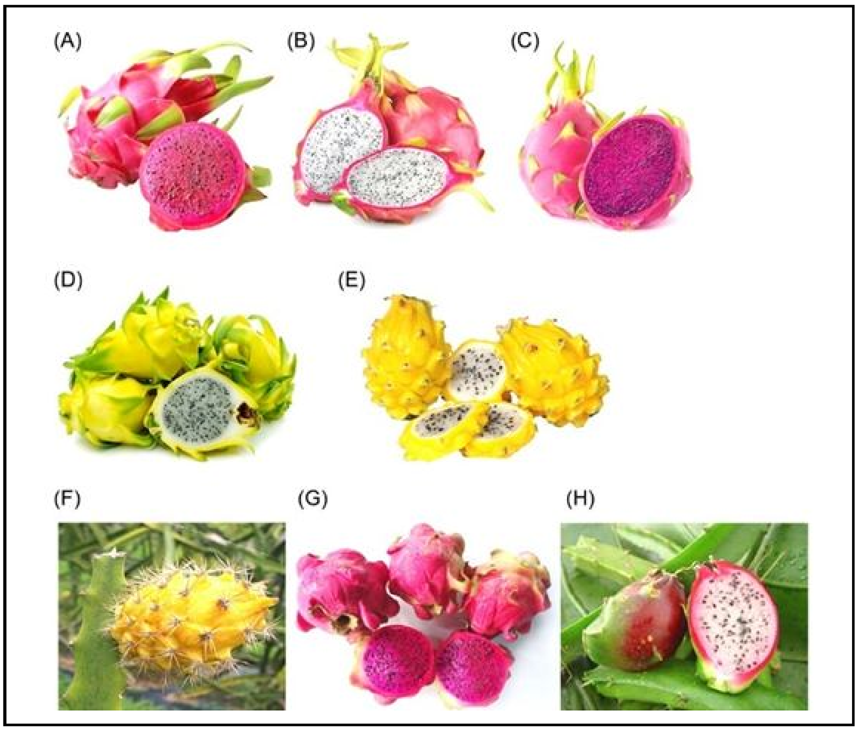

Figure 1: Pictorial display of hylocereus species.

(A) *H. polyrhizus*; (B) *H. undatus*; (C) *H. costaricensis;* (D) *H. megalanthus*; (E) *S. megalanthus* (without spines); (F) *S. megalanthus* (with spines); (G) *H. purpusii* and (H) *H. trigonus* (Tarte *et al.,* 2023).

Table 1: Nutritional composition of dragon fruit

Nutritional composition	Red dragon fruit	White dragon fruit
Moisture (%)	82.5 to 83	85.3
Total carbohydrates (g/100 g)	11.2	11.2
Fructose (g/100 g)	1.8 to 3.2	1.9
Glucose (g/100 g)	4.7 to 5.7	5.5
Fat (g/100 g)	0.21 to 0.61	0.1
Sorbitol (g/100 g)	-	0.33
Protein (g/100 g)	0.159 to 0.229	1.1
Crude fiber (g/100 g)	0.7 to 0.9	1.34
Vitamin C (mg/100 g)	8.9	3
Vitamin A (mg/100 g)	-	0.0111
Niacin (mg/100 g)	-	2.8
Potassium (mg/100 g)	272 to 328.4	272
Magnesium (mg/100 g)	31.3 to 38.9	38.9
Phosphorus (mg/100 g)	27.5 to 36.1	27.5
Calcium (mg/100 g)	2.3 to 10.2	10.2
Iron (mg/100 g)	0.6 to 3.4	3.37
Sodium (mg/100 g)	7.3 to 8.9	8.9
Zinc (mg/100 g)	-	0.35
Energy (KJ)	283	138

Source: Liaotrakoon (2013) and USFDA (2022)

2. Nutritional profile of dragon fruit

Red and white dragon fruit shows notable differences in their nutritional composition despite having similar total carbohydrate content. White dragon fruit has higher moisture content, fiber, protein and a more balanced mineral profile including iron, calcium, zinc, vitamin A and niacin, making it nutritionally diverse and suitable for hydration, digestive health and low energy diets. In contrast, red dragon fruit contains less moisture but higher fat, vitamin C, potassium and overall energy value, indicating a more concentrated nutrients and calories profile. The higher vitamin C and energy content of red dragon fruit suggest greater antioxidant capacity and suitability for increased energy requirements, while the lower fiber and protein content differentiate it from the white variety. Overall, white dragon fruit is more favorable for dietary balance and digestion, whereas red dragon fruit offers enhanced antioxidant and energy benefits.

3. Phytochemical composition and bioactive compounds

The dragon fruit has a variety of bioactive substances in its various portions. Fatty acids, sterols, tocopherols, tannins and flavonoids are the main classes of bioactive compounds (Nishikito *et al.,* 2023). Dragon fruit has been found to have a significant amount of vitamins, includes thiamine, riboflavin, ascorbic acid and niacin as well as minerals including p-hydroxybenzoic acid, vanillic acid, lycopene, gallic acid, β-carotene and p-coumaric acid (Hossain *et al.,* 2021). Higher quantities of polyphenolic chemicals are observed in species like *H. polyrhizus,* Conversely, *H. megalanthus* species have higher concentrations of reducing sugars like glucose and fructose. The fruit's peel typically contains terpenoids such as lutein, lycopene, retinoid, limonene and carvone. The fruit's peel also contains betacyanin a red pigment (Joshi and Prabhakar, 2020). Kaempferol, quercetin, isoflavones, naringenin and isorhamnetin are among the many flavonoids that are abundant. Fruit contains tannins in two different forms: hydrolyzable and condensed, notwithstanding the fore mentioned bioactive chemicals of different classes. Proanthocyanidins are condensed tannins, whereas ellagitannins and gallotannins are hydrolyzable tannins. However, the entire fruit contains phytosterols like hydroxytyrosol and tyrosol as well as fatty acids like palmitic acid and linolenic acid (Bhadauria *et al.,* 2024). Additionally, the *H. undatus* species is rich in phenols, tannins, anthocyanins, glycosides, steroids, polysaccharides and saponins (Mande *et al.,* 2023).

4. Health benefits and nutraceutical properties

4.1 Antioxidant property

Hylocereus species especially *H. polyrhizus* are rich in betalains and other bioactive compounds like vitamins, flavonoids and phenolics that have strong antioxidant property. The oil extracted from *H. undatus* seeds and peels is a key source of antioxidants and the peels has bright and slightly waxy layer hold more flavonoids than the soft pulp. *H. polyrhizus* fruit holds about 15.92/ mg of gallic acid per gram thus it has a high antioxidant property. Research on dragon fruit's antioxidants showed that pre-diabetic and normocholesterol participants who ate red pitaya ended up with lower overall antioxidant levels. Additionally, a number of studies indicate that the pulp extract may reduce oxidative damage in rats with STZ-induced diabetes. According to this eating red dragon fruit may lower diabetic rat's levels of malondialdehyde (Rebecca *et al.,* 2010).

4.2 Anti-inflammatory property

The phytoconstituents found in dragon fruit, specifically squalene and betalains, that posses anti-inflammatory and antioxidant properties. Betalains break down quickly when exposed to heat, light, pH changes or oxygen its colour is fade but their stability improves when encapsulated or sealed with a tight, protective coating (Tarte *et al.,* 2023). *H. polyrhizus* species has abundance of antioxidants because of its high betalain concentrations and strong anti-inflammatory properties. Anti-inflammatory effect lowers inflammation by lowering free radicals (Mande *et al.,* 2023). Betalains can block the transcription factor NF-κB, making it impossible to separate inflammatory genes like TNF-α and IL-1β. The study on dragon fruit confirmed that it has anti-inflammatory properties by demonstrating a significant inhibitory potential against the acetylcholinesterase enzyme. Dragon fruit also has a strong effect on the enzymes lipoxygenase and cyclooxygenase, which blocks the prostaglandin and leukotriene pathways. According to this finding, dragon fruit contains anti-inflammatory qualities (Safira *et al.,* 2021).

4.3 Antimicrobial activity

The fruit's peel contains a red pigment called betacyanin, which has antibacterial and antioxidant qualities. Microbes die through several mechanisms from breaking down their cell walls to unleashing sharp bursts of reactive oxygen that tear through their membranes (Tarte *et al.,* 2023). The results of the broth micro dilution assay demonstrated that fruits that have been chilled contain more betacyanin than those that have just been harvested. Ten strains of Gram-positive bacteria, including *Listeria monocytogenes, Enterococcus faecalis, Staphylococcus aureus* and *Bacillus cereus* and six strains of Gram-negative bacteria including *Campylobacter jejuni, Salmonella typhimurium, Yersinia enterocolitica* and *Escherichia coli* are effectively inhibited by refrigerated fruits, which also have a higher MIC (Minimum inhibitory concentration). Disc diffusion is another technique for determining the potential of fruit peel microorganisms. Fruit peel extracts made with chloroform had strong antibacterial or antimicrobial properties. *Chloramphenicol* with the extract from *H. polyrhizus* species showed a synergistic inhibitory action against *Pseudomonas aeruginosa*. Dragon fruit peel silver nanoparticles are also effective against gram negative bacteria and gram positive bacteria (Joshi and Prabhakar, 2020). When plant cells come into contact with microbial pollutants, they develop secondary metabolites that are part of the defense mechanism against specific diseases caused by bacteria, fungus and viruses. Fruit extracts from the *H. polyrhizus* and *H. undatus* species have antibacterial action against a variety of bacterial taxa and microorganisms (Cahyati and Putriningtyas, 2021).

4.4 Anticancer activity

Several studies have shown that dragon fruit may help fight cancer, its bright pink flesh packed with compounds that protect cells. Researchers have discovered that fruit nanoparticles aid in preventing the growth of human prostate cancer cell lines, human gastric cancer cell lines and MCF-7 breast cancer cell lines. Species of *H. undatus* and *H. polyrhizus* produce acetic acid, propionicandlactic acid that lowers the risk of colon cancer. The compounds like beta-carotene, alpha-amyrin, beta-amyrin, beta-sitosterol, beta-cyanin and flavonoids have the anticancer properties. The fruits bioactive ingredients work well against melanoma, breast and liver cancer cells in humans. Both the peel and the flesh are packed with antioxidants and polyphenols but the peel does more to slow the growth of cancer and melanoma cells (Nishikito *et al.,* 2023). Lycopene, a naturally occurring antioxidant found in *H. polyrhizus* species, is known to prevent the production of free radicals that cause cancer.

4.5 Wound healing properties

The goal of the wound healing process which takes place in multiple stages and involves a variety of cell types as well as the activity of growth factors and cytokines is to repair the injured tissues. Numerous studies demonstrated that extracts from dragon fruit, stem and flower enhance the migration of fibroblasts, which are in charge of wound healing. Antioxidant containing extracts also contain flavonoids and phenolic chemicals, which aid in wound healing and DNA protection (Tarte *et al.,* 2023). Wound healing is one of diabetes's main issues. Gallic acid found in dragon fruit has the potential to heal wounds under both normal and hyperglycemic circumstances. The potent antioxidants in gallic acid trigger growth factors that drive wound healing, speeding the movement of keratinocyte and fibroblast cells (Bhadauria *et al.,* 2024).

5. Value addition of dragon fruit

Dragon fruit processed or incorporated products are rarely available in the market since, in comparison to other local fruits, relatively little effort has been done on dragon fruit in terms of processing, value addition and novel product development. The dragon fruit has 24% to 26% of peel, 6% to 68% of flesh and 7% to 9% of seed. Although, peels and seeds are typically seen as waste, they have strong nutraceutical qualities and can be utilized to create beneficial goods (Tarte *et al.,* 2023).

5.1 Dragon fruit beverages

Dragon fruit based beverages have gained attention as natural functional drinks due to their high levels of antioxidants, vitamins, polyphenols and betalains which contribute to improved health benefits compared with artificially flavored beverages. Enzymatic clarification using pectinases has been widely reported to reduce juice viscosity, enhance extraction yield and improve clarity by degrading pectin and mucilage components. Optimized enzymatic treatments can significantly increase juice recovery and phenolic content, although thermal processing may negatively affect heat sensitive nutrients such as vitamin C. Betacyanin stability in dragon fruit beverages is strongly influenced by processing temperature, pH, light exposure and antioxidant addition with cold storage and ascorbic acid supplementation improving pigment retention. Seed containing juices and purees generally exhibit higher antioxidant activity due to the release of seed derived bioactives during processing. Overall, controlled enzymatic and thermal processing strategies are essential for maintaining nutritional quality and color stability in dragon fruit beverages (Tarte *et al.,* 2023).

5.2 Dragon fruit powder

The dragon fruit powder has been prepared by the methods which includes freeze drying (Shekade *et al.,* 2019), spray drying (Shaaruddin *et al.,* 2017), lyophilization (Molina *et al.,* 2014), *etc.,* In spray drying method, maltodextrin has been added for holding the betacyanin content during processing, storage and light (Shaaruddin *et al.,* 2017). Both red flesh dragon fruit and white flesh dragon fruit powder were made using a spray dryer with a 30% maltodextrin (w/v) concentration (combined with fruit juice prior to spray drying treatment); the air inlet temperature was maintained for 120°C for red flesh dragon fruit and 110°C for white flesh dragon fruit (Lee *et al.,* 2013). Powder production efficiency would be decreased if the air's input temperature has risen over optimal levels. The resulting powder had a smooth texture, a spherical form and a range of particle sizes from 3 to 7 µm. When powder was kept at room temperature (25°C) with a relative humidity of 33% for longer than 25 days, it had no effect on the antioxidant content; however, when it was kept at relative humidity levels of 43%, 54% and 75%, it displayed structural variation or loss, gummy structure and the formation of cakes or lumps during solution. The dried dragon fruit powder was used in candy making, pharmaceuticals industries and also a nutraceutical product.

5.3 Dragon fruit dried chips

Lyu *et al.* (2017) investigated the effect of different pretreatments on the quality of dragon fruit chips and reported that freeze drying followed by explosion puffing drying produced superior chips compared to hot-air drying. This combined treatment improved texture, color, crunchiness and structural integrity while better preserving nutritional quality. Moreover, it significantly reduced browning and betacyanin degradation, resulting in lower color change (ÄE) than hot air dried samples subjected to explosion puffing.

5.4 Dragon fruit yoghurt

Jayasinghe *et al.* (2015) developed white flesh dragon fruit yogurt using Chris Hansen's yoghurt starting culture from Denmark. The fruit content (10%) was maximized with 10% sugar and 0.8% gelatin; Similarly, strawberry (5%) and orange (10%) yoghurt had optimal fruit content (Hossain, 2012). When WFDF yoghurt was stored, its pH dropped from 4.06 to 3.9. 3.2% fat, 9.639% SNF (solid not fat) and 23.58% total solids made up the final product. A shelf-life study indicated that packaged DF yogurt can be kept at 4°C for 15 days.

5.5 Dragon fruit jam and jelly

Dragon fruit value addition in the form of jelly like products will result in a commercialized, high quality product that has not yet been offered in the market. Studies on white fleshed dragon fruit (WFDF) jelly have demonstrated its feasibility as a stable value added product. Islam *et al.* (2012) reported that jelly formulated with high methoxy pectin showed good storage stability with the 1.5 per cent pectin achieving superior texture, color, flavor and overall acceptability during six months of room temperature storage (Panchal *et al.,* 2018). further optimized WFDF jelly formulation and observed acceptable physicochemical and sensory stability for up to 90 days under both ambient and refrigerated conditions. Minor increases in acidity, sugars and total soluble solids and slight declines in ascorbic acid and sensory scores were noted during storage, while microbial growth remained within safe limits. Overall, these studies confirmed the potential of dragon fruit jelly as a shelf stable value added product.

5.6 Dragon fruit wine

Choosing the right yeast is the key to shaping the flavor and overall quality of red fleshed dragon fruit wine. Both *Saccharomyces cerevisiae* and non-*Saccharomyces* yeasts such as *Torulaspora delbrueckii* and *Lachanceather motolerans* have been reported to produce comparable fermentation rates, yielding wines with 8 to 9% ethanol and similar total soluble solids. While *S. cerevisiae* generated higher glycerol and ester concentrations contributing to mouth feel and aroma, non-*Saccharomyces* yeasts enhanced organic acid profiles and aroma complexity through increased lactic acid, succinic acid, higher alcohols and terpenes. Notably, *L. thermotolerans* improved acidity balance and wine roundness, whereas greater degradation of betacyanins and antioxidants was observed with *S. cerevisiae*. These results showed how mixed or alternative yeast cultures can boost both the taste and texture of dragon fruit wine adding a fuller aroma and smoother finish to every sip (Jiang *et al.,* 2020).

5.7 Dragon fruit kefir

Narayandas *et al.* (2025) studied the dragon fruit kefir as a fermented product. It was prepared by using water kefir grains, sucrose and salt which involved two stages of fermentations. The work addresses the growing demand for non-fine probiotic solutions by using water fermentation with dragon fruit juice to create kefir, a sustainable and nutrient dense substitute for probiotics that is appropriate for lactose intolerant and herbal customers.

5.8 Fresh cut and minimal processing

Cutting or slicing fruit did not worsen its deterioration, according to Goldman *et al.* (2005) but the cut slices stuck together while being stored and were challenging to remove; this might be avoided by applying appropriate edible coatings. The micro perforated packaging containing peeled and sliced dragon fruit preserved its organoleptic, visual and microbiological qualities for a minimum of 14 days when stored at 4°C or 8°C. Sliced pitayas coated with low molecular weight chitosan (molecular weight = 12.36 ± 0.17 kDa, 95 to 98% deacetylated, viscosity 630 mPa·s; VA and G Bioscience Inc., Taoyuan, Taiwan) at 0.2%, 0.5% and 1.0 per cent reduced water loss (from 86.93% to 70.43%), maintaining SSC (from 12.42° to 12.36°B), TA (from 0.17% to 0.14%) and ascorbic acid (AA) content (from 9.0 to 7.8 mg/100 ml) with improved flavor quality, while also preventing microorganism growth, juice leakage and surface browning. After one week, the fruits covered with chitosan maintained their quality attributes, but the control fruits were deemed undesirable. Values added products like dragon fruit jujubes, squash and RTS, cookies, ice cream also prepared by means of enhance its availability and nutritional value (Archana *et al.,* 2023).

6. Utilization of peel and seed

The peel of a dragon fruit packs plenty of pectin and betacyanins. These substances are beneficial to the food industry when it comes to creating new products. The dragon fruit peel makes up around 20% to 30% of the total weight of the dragon fruit (Tarte *et al.,* 2023). The by product or residue of dragon fruit juice is dragon fruit seeds. Although, seeds are a waste product, they can be used to make other products or processed further to make oil. Because they contain highly bioactive compounds like antioxidants, phenolic acids and phytosterols, as well as essential fatty acids, they can also be used to make other seed oils.

6.1 Dragon fruit peel as substrate for rumen fermentation

Utilizing dragon fruit peel (4%) as a substrate to enhance the *in vitro* rumen fermentation, nutrient degradability and reducing methane production along with non-protein nitrogen (NPN) (1%) due to its phytonutrients includes condensed tannins and saponins. As a result, dragon fruit peel powder may improve ruminant output in a cleaner and more sustainable manner while also reducing greenhouse gas emissions like methane (Matra *et al.,* 2020).

6.2 Dragon fruit peel powder in flour

Chumroenvidhayakul *et al.* (2022) looked into the impact of dragon fruit peel on the physicochemical qualities of flours used in Asian food processing and cooking. From this, the characterized properties were thermal pasting, starch digestibility and physicochemical properties of dragon fruit peel and flours (wheat, glutinous rice, potato and rice). Dragon fruit peel powder is generated from the by-product of dragon fruit has antioxidant activity, phytochemical substances and dietary fibers. With a rise in undigested starch and increased antioxidant activity, Dragon fruit peel powder dramatically reduced the starch digestibility of flour. Additionally, by interfering with the crystalline and amorphous structures in starch, it changed the pasting qualities and gelatinization enthalpy of flours. These discoveries would broaden the range of dragon fruit peel powder applications.

6.3 Dragon fruit peel as a microbial growth media

The increased production and consumption of dragon fruit has contributed to the accumulation of organic waste from discarded fruit peel. In this study, the use of dragon fruit peel as microbial growth substrate was suggested as a method of reducing organic waste (Putri *et al.,* 2017).

6.4 Dragon fruit peel as leather

Pectin, a naturally occurring pigment may be present in the dragon fruit skin. It works well as a dietary supplement to make fruit leather. Heating the pulp with water from the fruit's own peel still warm and fragrant makes the dragon fruit leather more stable. RSM's design showed that the leather was crafted with white flesh dragon fruit pulp and sugar mixed in different ratios (10, 20, 30, 40 and 50%), each batch turning slightly pink under the light (10, 20, 30, 40 and 50%). A mechanical drier was used to dry the obtained homogenous mixture at various thicknesses (2, 3, 4, 5 and 6 mm) and temperatures (55, 60, 65, 70 and 75ºC). It can be inferred that the optimal formulation of dragon fruit leather with peel 20%, sugar 40%, drying temperature 60°C and thickness 5 mm . This combination yielded a product with an overall acceptability score of 7.59 and a vitamin C content of 21.1 mg/100 g.

6.5 Dragon fruit peel as coagulant

Dragon fruit peel acts as a natural coagulant, clearing wastewater by reducing turbidity, total dissolved solids (TDS) and total suspended solids (TSS) through the jar test method, leaving the water as clear as glass. At the ideal dosage of 90 mg/l, DFPW eliminated 36% of TSS, 69% of TDS and 67% of turbidity. At the optimal dosage of 50 mg/l, DFPP eliminated 60% of turbidity, 23% of TSS and 65% of TDS. Although, there was no discernible variation across DFPs, the percentage of elimination rose with sedimentation time. DFPs have the potential to be utilized as an environmentally friendly coagulant for wastewater (Ismail *et al.,* 2018).

6.6 Valorization of dragon fruit peel and seed

Waste valorization techniques inspired by the circular economy have been continuously growing, creating new business opportunities and producing valuable bio products from food waste, particularly fruit waste, which may have several uses in the energy, food and pharmaceutical sectors (Tripathi *et al.,* 2023).

6.6.1 Betacyanins extraction from dragon fruit peel

The natural colorants that come mostly from fruits, vegetables and flowers are currently the focus of industry, food scientists and consumers. These colors are in high demand. Thus, research into the creation, durability and sustainability of these hues is equally crucial. One potential alternative to other colorants or artificial colorants is the growing interest in and knowledge of natural hues like betalains.

Betacyanins has the low water activity and can be sustained at low temperature, absence of light with nitrogen containing environment and also has the metal cations (Mg^{2+}, K^{+} and Na^{+}), antioxidants and sugars such as sucrose, glucose, maltose, fructose and lactose (Herbach *et al.,* 2006; Liu *et al.,* 2019). The solvents used for the extraction process were distilled water and methanol, because betacyanins dissolve more readily in water than non-polar dissolving agents. Through steeping and filtration, extraction was carried out for 24 h at a cool temperature. The results showed that methanol had a higher extraction of betacyanins (515.20 µg/100 g) than water (491.16 µg/100 g) and that the sustainability of betacyanins content at ambient temperature declines after 5 h. Sustainability declines more in water (22.58%) than in methanol (10.44%). This study shown that the pH of the extraction solvent (methanol and water) at pH 5 affects the recovery of betacyanins more than lower pH values (pH 1, 2, 3 and 4) (Priatni and Pradita, 2015).

Liu *et al.* (2019) described a method for extracting betacyanin from red fleshed dragon fruit (RFDF) peel that used a 1:20 peel powder distilled water mixture adjusted to pH 5 with a disodium hydrogen phosphate citric acid buffer. The mixture was incubated at 30°C for 50 min, centrifuged (900 g, 15 min, 4°C) and the supernatant was filtered (0.22 µm). Further purification was carried out using macroporous resin columns with 30% ethanol and betacyanin content was measured at 536 nm. Ethanol was removed using a rotary evaporator (45°C) and the extract was freeze dried to obtain powder. The extracted betacyanin yield was 9.22 mg/g and stability studies showed improved betacyanin retention with stabilizers such as 0.08 mol/l potassium chloride and 10% lactose solution.

A spray dryer (inlet temperature 150°C at air pressure 2 kg/cm^3 with a flow rate of 15 ml/min) was used to microencapsulate the betacyanins with 5% maltodextrin in order to preserve and stabilize a greater quantity of betacyanins from RFDF peel (Torres *et al.,* 2020). The produced powder exhibited greater sustainability at lower storage temperatures (4°C) compared to higher temperatures.

6.6.2 Pectin extraction from dragon fruit

Both WFDF and RFDF flesh and peel have a significant amount of mucilaginous polysaccharides such as pectin, which are mostly soluble in water and exhibit less methyl esterification, according to the study (Liaotrakoon and Buggenhout, 2013). This concentration ranges from 38% to 47% (Table 2).

Table 2: Extraction methods

Extraction method	Temperature/time solvent	Pectin yield	Remarks	References
Solvent extraction	75°C 1 h water	14.86% pectin	The efficiency of pectin extraction was determined by the extraction time and pH.	Woo *et al.,* 2010
Distilled water extraction	80° C 20 min 80 min	20.34% pectin 16.20% pectin	The extracted pectin was low -methoxy had strong antioxidant activity and was unaffected by the extraction duration at 40 µg/ml.	Zaidel *et al.,* 2017
Solvent extraction	Isopropyl alcohol 70°C 20 min	20.14% pectin	With low ash level, low methoxy pectin and anhydrouronic acid at 54.44%.	Ismail *et al.,* 2012
Microwave-assisted extraction	Efficacy power (300, 450, 600 W) 5 - 10 min, 70 - 100°C	23.11% pectin	Microwave-assisted pectin extraction produced similar levels of anhydrouronic acid and esterification as conventional techniques.	Tongkham *et al.,* 2017
Ultrasonication technique	45°C 30 min	82.3% to 87.19%	During ultrasonication therapy, with the help of solvent, cell component releases easily through an increase in swelling and hydration of tissues, which is indirectly accountable for increment in pectin production within a shorter time.	Manh *et al.,* 2019; Toma *et al.,* 2002

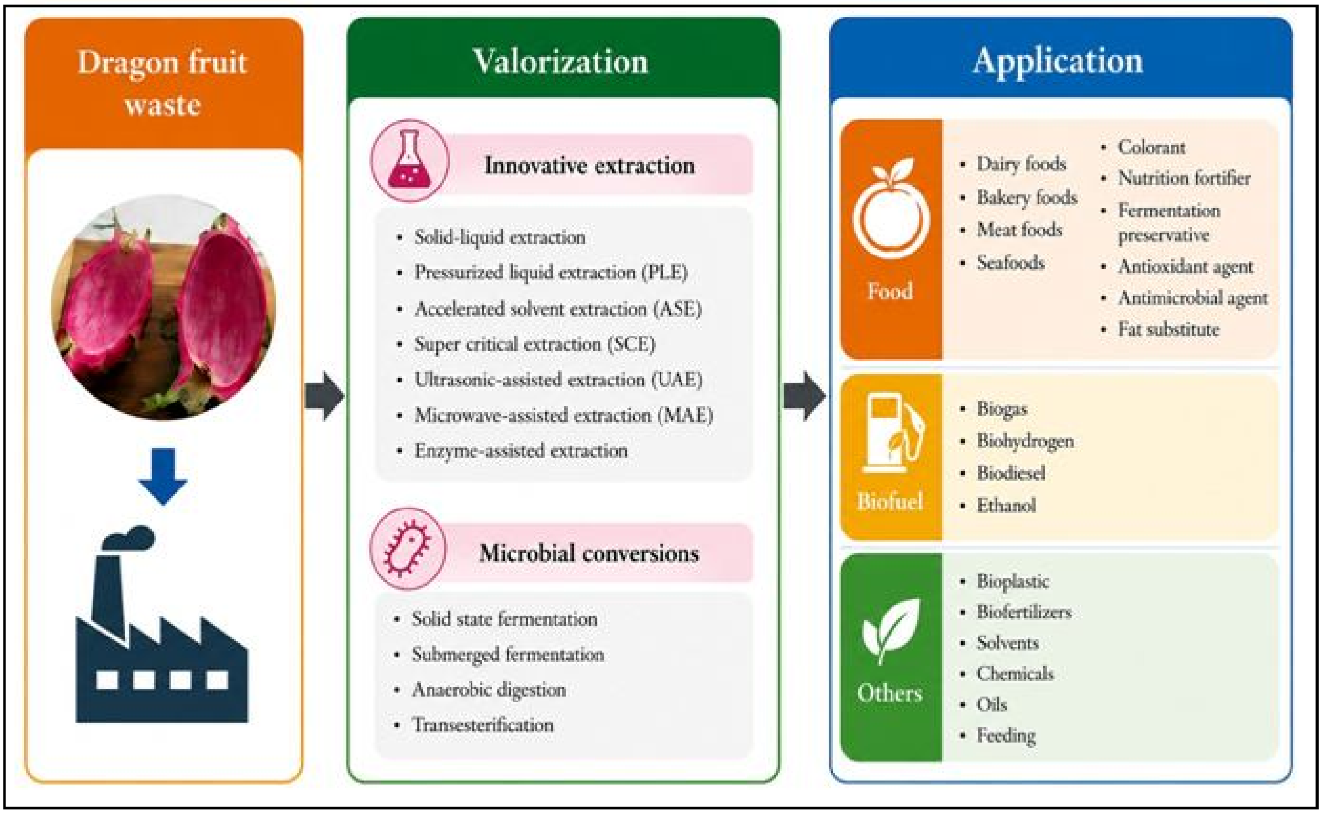

Figure 2: Valorization of dragon fruit waste (Tripathi *et al.,* 2023).

6.6.3 Dragon fruit peel powder

Dragon fruit peel powder can be added to a variety of food products to improve their nutritional value and make them healthier. While corn bran and apple pomace have less dietary fiber than dragon fruit peel powder, it has more than grape peel, lemon peel, orange peel and wheat bran. The white dragon fruit peel powder is extracted by oven drying at 60°C for 12 h. The amount of TDF, IDF and SDF varies depending on the particle size of the DF peel powder. Powder with a particle size of 58 µm contains more TDF (79.37%) than powder with a size of 104 µm (77.57%) or less than 58 µm (69.71%) (Zhuang *et al.,* 2012). To improve the bread's phenolic, betacyanin and antioxidant content, RFDF peel powder was added at 3% flour weight concentration. In contrast to being in the dough, boiling reduced the concentration of these elements. Adding more powder to bread makes it harder, but it also loses cohesiveness, springiness, specific volume and elasticity (Hsu *et al.,* 2019).

Strawberry ice cream was made with Red flesh dragon fruit peel powder (1 %) in place of fat due to its qualities, which include the ability to store water (54.2 g/g) and swell (50.63 ml/g) (Zhuang *et al.,* 2012).It also increases the texture, color, flavor, antioxidants and physical and chemical properties of ice cream. The study concluded that 73.5% less fat was used, which is greater than the quantity of orange fiber used to manufacture lemon ice cream, which is only around 50% (Crizel *et al.,* 2014 and Utpott *et al.,* 2020).

6.6.4 Dragon fruit peel as value added bio-products

Dragon fruit waste is abundant in many valuable chemicals and oils. It can serve as renewable resource to create a variety of valuable compounds with potential uses in various industries. In biorefineries, pretreatment and extraction procedures are crucial tactics for reclaiming biomolecules with added value. Green extractions and biological conversion techniques are two examples of the various methods of valorization (Figure 2). However, one of the most cutting edge methods for recycling or reusing dragon fruit trash is microbe based conversion, which turns it into bioethanol, bioactive chemicals, medications and other valuable goods (Tripathi *et al.,* 2023).

6.6.4 Extraction of dragon fruit seed oil

Dragon fruit seeds are the second most significant by-product after pulp removal. However, separating the seeds is difficult because they are tightly embedded within the pulp. To extract them, the pulp is typically mashed, fermented and then filtered through muslin cloth. Despite being treated as waste, dragon fruit seeds are highly nutritious. They are rich in vitamins such as vitamin C, vitamin A and niacin, which support skin health, vision, bone development, immunity and cell growth. Additionally, the seeds contain prebiotics that aid digestion, enhance immune function, and reduce the risk of intestinal diseases. Dragon fruit itself is also known for its anti-inflammatory and antibacterial properties (Figure 3).

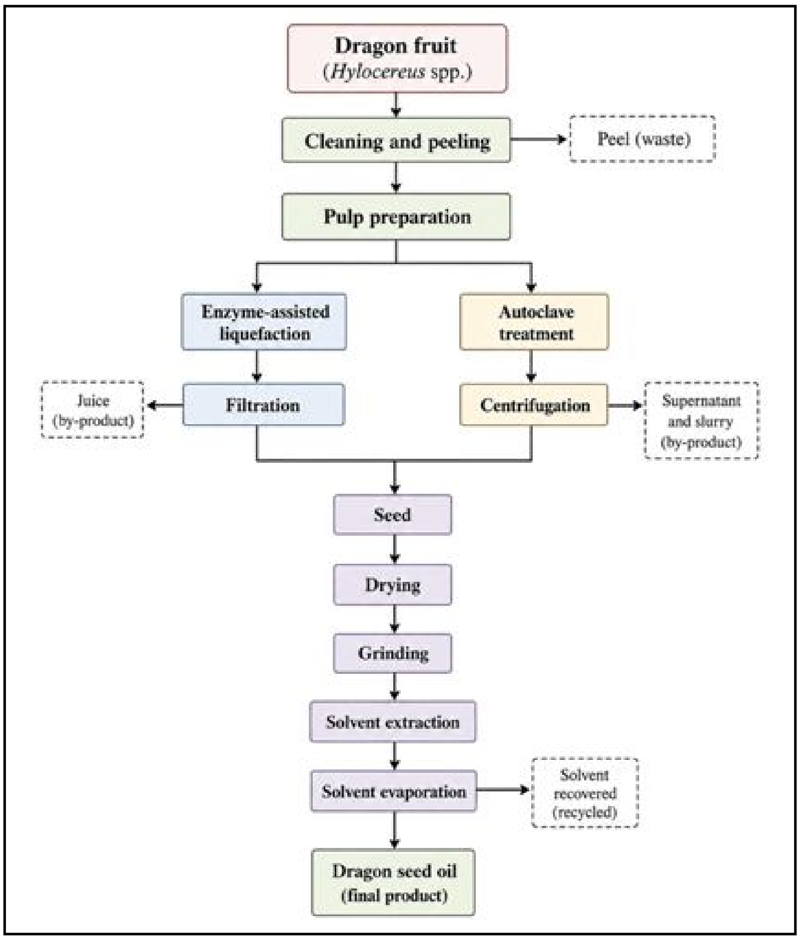

Figure 3: Dragon fruit seed oil extraction (Jalgaonkar *et al.,* 2020).

In addition to the traditional soxhlet extraction method, microwave assistant extraction, aqueous enzymatic extraction (using pectinase, amylase, cellulase and protease enzyme), supercritical fluid extraction and a combination of microwave and aqueous enzymatic extraction were used to extract WFDF seed oil. The microwave assistance approach is the quickest extraction process; however, the microwave plus aqueous enzymatic extraction method is best suited to higher yield concerns. Supercritical fluid extraction results in a higher concentration of vital fatty acids.

A three month storage study of dragon fruit seed oil was conducted under both room and refrigerated conditions. The results showed a decline in tocopherol content over time with a more pronounced reduction observed at room temperature compared to cold storage. This decrease is attributed to an increased rate of oxidation during storage, which accelerates the degradation of tocopherols (Liaotrakoon and Clercq *et al.,* 2013).

7. Future aspects

Future research on dragon fruit should prioritize strong clinical validation of its nutraceutical and therapeutic benefits along with the standardization of its bioactive compounds to ensure consistent efficacy. There is also a need to develop advanced, scalable processing technologies that can preserve functional properties and extend shelf life. Improving post harvest handling and minimizing losses through efficient supply chain management will be equally important. In addition, greater emphasis should be placed on the sustainable utilization of by-products such as peel and seeds to support circular economy approaches. Breeding programs aimed at developing climate resilient and high yielding cultivars are essential for stable production. Expanding its applications in functional foods, pharmaceuticals and other industrial sectors will further strengthen the future potential of dragon fruit as a high value crop.

8. Conclusion

Dragon fruit is a promising functional fruit owing to its rich nutritional composition, bioactive compounds and numerous health promoting effects including antioxidant, anti-inflammatory, antimicrobial, anticancer and wound healing activities. Although, highly perishable the development of value added products such as beverages, powders, fermented foods and dried products has improved its shelf-life and commercial potential. Furthermore, the valorization of peels and seeds for the production of natural colorants, dietary fiber, seed oil and other bioactive ingredients contributes to sustainability and waste reduction. The integration of advanced processing technologies with efficient by product utilization can support food security, enhance farmer income and promote environmentally sustainable practices, establishing dragon fruit as an important resource for future functional food and industrial applications.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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