INFORMATICS JOURNALS

Review Article

Journal of Natural Remedies
DOI: 10.18311/jnr/2026/52623

eISSN: 2320-3358 | Vol 26(2), 2026 | pp. 303-316

Dragon Fruit: Review of its Biological Activities, Cultivation Practices, Phytoconstituent Yields, Structural Insights, Nanoformulations, and Semi-synthetic Derivatives

Hemalatha Catna Nagaraj*, Preetham Anton Alphonse, C. S. Saranya Devi, V. M. Abishek Adithya, A. V. Dhilochini, Mohan Chezhian G. Rajendran and Harini Ganesh

Department of Pharmaceutical Chemistry, PSG College of Pharmacy, The Tamilnadu Dr. M. G. R. Medical University, Peelamedu,Coimbatore – 641004, Tamil Nadu, India; hema458@gmail.com

Abstract

Background: Dragon fruit (*Hylocereus* spp.), a tropical cactus fruit valued for its vibrant colours and nutritional profile, has garnered significant scientific interest. Beyond its use as a food source, it possesses potential applications in pharmaceuticals, cosmetics, and nanotechnology. **Aim:** This review aims to provide a comprehensive compilation of existing data regarding the biological activities, cultivation practices, phytoconstituent yields, structural insights, and emerging applications of dragon fruit, including nano-formulations and semi-synthetic derivatives. **Methods:** A comprehensive review of the literature was conducted, synthesising data from over 90 peer-reviewed studies. The analysis covers various *Hylocereus* species (*H. undatus, H. polyrhizus, H. costaricensis*) to compare chemical compositions, extraction technologies, and therapeutic potentials. **Results:** Comparative analysis indicates that red-fleshed varieties exhibit superior antioxidant, antimicrobial, and cytotoxic activities compared to white-fleshed counterparts, attributed to higher betacyanin and phenolic content. While cultivation is expanding in regions like India and Nepal, it faces challenges such as internal rot and specific climatic requirements. Regarding processing, Ultrasound-Assisted Extraction (UAE) is identified as a sustainable method that yields higher preservation of bioactive compounds compared to conventional acid hydrolysis. Furthermore, the fruit serves as a reducing agent in the green synthesis of gold and iron oxide nanoparticles, which demonstrate promising antimicrobial and anticancer properties. **Conclusion:** Dragon fruit represents a multifunctional resource where food science, pharmacology, and nanotechnology intersect. While *in vitro* studies confirm its therapeutic potential, further research is required to bridge the gap toward clinical applicability and to optimise sustainable industrial processing techniques.

Major Findings: Red-fleshed varieties possess superior antioxidant and cytotoxic properties compared to white-fleshed counterparts due to higher betacyanin content. Additionally, ultrasound-assisted extraction proves significantly more effective than acid hydrolysis for bioactive preservation, supporting the fruit's emerging role in green nanotechnology applications.

Keywords: Biological Activities, Cultivation, Dragon Fruit, *Hylocereus* spp., Nano Formulations, Phytoconstituents

(Article Chronicle: Article Received on: 14.10.2025; Revised on: 08.01.2026; Accepted on: 19.01.2026)

1. Introduction

Various studies have investigated the correlation between dragon fruit colour shades and their biological activities. *Pitaya*, specifically *H. undatus*, is characterised by its distinct white pulp and bright red skin, as shown in Figure 1, and has been included in various studies to investigate its biological activities[1]. *In vitro* and

*Author for correspondence

in vivo studies have been conducted to explore the potential benefits of the dragon fruit. The cytotoxic, antioxidant, and antimicrobial properties of dragon fruit have been evaluated based on its chemical composition, particularly the peel. A study conducted using these species, *Hylocereus megalanthus* (Figure 2), *Hylocereus costaricensis* (Figure 3), *Hylocereus undatus,* and *Hylocereus polyrhizus* (Figure 4), reveals the differences in bioactivities and the chemical constituents. Comparative studies have evaluated the chemical composition and bioactivity of different *Hylocereus* species to determine their functional potential. By-products of dragon fruit are known as important sources of bioactive compounds with potential pharmacological benefits. Advanced research has focused on starch-digestible cookies, reducing lipid peroxidation and dietary advanced glycation end products, utilising dragon fruit peel[2]. Similarly, gluten-free cookies formulated with konjac, jack beans, and dragon fruit have been developed to enhance functional properties. A recent study evaluated the nutritional value of the baked meat-fortified products of lyophilised dragon fruit pulp[3]. The neuroprotective properties of the dragon fruit have been studied by investigating the cytotoxicity of the betacyanin dragon fruit and the anti-Aβ aggregation activity, focusing on Alzheimer's disease[4]. From Southern China, a study unveils the biological assessment and *in-silico* analysis of red dragon fruit[5].

The SWEET (Sugars Will Eventually be Exported Transporters) family represents a novel group of sugar transporters, with diverse physiological functions, including phloem loading, seed filling, nectar secretion, and fruit development. The HuSWEET (*H. undatus*) family in *Pitaya* has a role in sugar accumulation due to specific genes. The sugar metabolism in the dragon fruit takes place by the genetic mechanism that has been unveiled in the study[6]. Comparative studies demonstrate that *H. polyrhizus* (Red *Pitaya*) possesses significantly higher antibacterial efficacy against pathogens like *Staphylococcus aureus* and *Escherichia coli* compared to *H. undatus*. This superior bioactivity is attributed to the notably higher concentration of phenolic compounds found in the red varieties. Consequently, *H. polyrhizus* represents a more viable candidate for the development of natural antimicrobial preservatives than its white-fleshed counterparts, as it exhibits greater efficiency even at lower concentrations[7-9].

The peel of the red-fleshed variety serves as a source of natural colourants exhibiting significant antioxidant activity, making it suitable for cosmetic and food applications[10]. The aqueous extracts are rich in bioactive compounds such as betacyanins, betanins, and betalains, which contribute to their high antioxidant capacity and potential health benefits such as blood pressure reduction, anti-inflammatory effects and alleviation of gastrointestinal issues, which contribute to the ability of high free radical scavenging and ferrous-ion-chelating agents and reduce oxidative stress[11-14]. The production of the betanin pigments was studied through cell suspension culture and callus using the species *H. costaricensis*. For sustainable

Table 1. Phytoconstituents, biological properties and applications of *Hylocereus* species

Sr. No.	Species	Type of Dragon Fruit	Key Constituents	Biological Properties	Applications
1	*Hylocereus undatus*	White Pulp with Bright Red Skin	Flavonoids, vitamin C, fibre	Antioxidant, anti-inflammatory, gut health, anti-angiogenic	Functional foods, cosmetics
2	*Hylocereus megalanthus*	White Pulp with Yellow Skin	High vitamin C, carotenoids	Antioxidant, laxative, antimicrobial	Gut health, skincare, and cholesterol-lowering agent
3	*Hylocereus costaricensis*	Red Pulp with Red Skin	Betacyanins, betanins, betalains and polyphenols	Strong antioxidant, anticancer, cardioprotective	Health drinks, food colouring, sports nutrition
4	*Hylocereus polyrhizus*	Purple Pulp with Purple-Red Skin	Betacyanin, omega fatty acids, Ferulic, Rutin, Sinapic acids, Hesperidin	Neuroprotective, hepatoprotective, anti-obesity	Superfoods, metabolic health, brain health



Figure 1. Biological name: *Hylocereus undatus.*
Synonyms: *Belle of the Night, Cinderella Plant, Dragon Fruit, Honolulu Queen, Moonlight Cactus, Night-blooming Cereus, Pitaya, Queen of the Night, Red Pitaya, Strawberry Pear, White-fleshed Pitahaya.*



Figure 2. Biological name: *Hylocereus megalanthus.*
Synonyms: *Selenicereus megalanthus*, *yellow dragon fruit, yellow pitahaya, kirin fruit, yellow Pitaya.*



Figure 3. Biological name: *Hylocereus costaricensis.*
Synonyms: *Pitaya roja, red-fleshed Pitaya.*



Figure 4. Biological name: *Hylocereus polyrhizus.*
Synonyms: *Selenicereus/Hylocereus monacanthus, Cereus monacanthus, Hylocereus peruvianus, Hylocereus lamairei.*

production, this culture is an efficient system and has various applications in the pharmaceutical and colouring industries[15].

Dragon fruit also exhibits anti-tyrosinase activity, inhibiting the inhibitors such as rutin, which also show strong antioxidant properties. The anti-angiogenic potential is found in the white dragon fruit's suppression of vascularisation in the environmental models[16,17]. Other activities and antioxidants were compared with *H. polyrhizus* (red dragon fruit) and *H. undatus* (white dragon fruit). The peels of both the species *H. undatus* and *H. polyrhizus* had higher radical scavenging activities and phenolic content than pulps[18,19]. A research study takes place comparing two species, such as *H. polyrhizus* and *H. undatus,* under similar conditions and finds that the purple pulp of *H. polyrhizus* has higher bioactive potential and higher antioxidant properties due to higher pH, total betanin content and reducing capacity. Ferulic, Rutin, Sinapic acids, Hesperidin are the main phenolic compounds in *H. polyrhizus*, where species rich in chlorogenic acids were *H. undatus,* illustrated in Table 1, the phytoconstituent profiles vary significantly by species; for instance, *H. costaricensis* is noted for its betacyanins and anticancer properties, whereas *H. undatus* is primarily recognised for its flavonoid content and gut health benefits[20-24]. Figures 1-4 elaborates on phytoconstituents of Dragon fruit, its biological name and synonyms.

2. Materials and Methods

2.1 Literature Search Strategy

To provide a comprehensive overview, a systematic literature search was conducted using electronic databases including PubMed, Scopus, ScienceDirect, and Google Scholar. The search utilised specific keywords and MeSH terms such as "Dragon fruit", "*Hylocereus* spp.", "Phytochemical composition", "Betacyanin extraction", "Green nanotechnology", and "Pharmacological activities". The review synthesises data from over 90 peer-reviewed studies, with a primary focus on articles published between 2000 and 2025. Studies were selected based on their relevance to cultivation practices, extraction technologies (UAE vs. acid hydrolysis), and therapeutic applications, while duplicates and non-English publications were excluded.

2.2 The Availability, Collection and Cultivation Practices of Dragon Fruit

Cultivating dragon fruit (*Hylocereus* spp.) presents several challenges, including issues like internal rot, which can significantly affect the yield and quality of the fruit. Internal Rot is a common problem in dragon fruit cultivation, often caused by overwatering or poor drainage. Understanding proper cultivation practices is crucial for ensuring a successful harvest and growth of dragon fruits[25]. As illustrated in Figure 5, the crop requires specific climatic conditions, including frost-free dry climates and altitudes up to 1500 meters, to optimise growth. Furthermore, Figure 6 summarises the holistic value chain of the fruit, demonstrating how proper propagation (stem cuttings) and cultural management lead to nutritional benefits such as immune support and cholesterol reduction. Dragon fruit belongs to the genus *Hylocereus*, which is a type of climbing vine cactus indigenous to the Americas. This unique fruit is often referred to by various names, including "*Noble woman*", "*Super Fruit*", "*Pitahaya*", and "*Strawberry Pear*". This fruit can be cultivated in regions with less rainfall at an altitude of 1500 meters above sea level. The marginal and fallow lands of the lower mountain ranges in Nepal, including the Terai, Bhitri, and Madhes valleys, are suitable for cultivation. The Dragon fruit has wide adaptability and can be grown in slightly heavy-textured soils. They are commonly propagated by stem cuttings. Flowering typically occurs 15–18 months after planting, with blooms lasting 28–30 days. Dragon fruit is a good source of vitamins, especially B and C, minerals such as calcium, omega-6 and omega-3 fatty acids in seeds, iron and magnesium, glucose, fructose, dietary fibre and strengthens immune system and it is used in the treatment of heart disease, diabetes, cholesterol reduction, improved digestion and maintaining a healthy body weight, as an antacid, and also in anti-hyperlipidemic. The species growing region, harvesting period, and cultivation methods all affect the nutritional content and productivity of dragon fruit[26,27]. Dragon fruit peel has been used as a natural dye because the number of commercial flowers is gradually increasing in different countries due to the lucrative products and prices in the market. In Nepal, the cultivation of dragon fruit is still in its early stages, having been introduced by Mr Jagannath Rai in 2057 B.S. (2000 A.D.). The Gorkha Millennium Multipurpose Cooperative Ltd. began commercial cultivation in 2070 B.S. (2013 A.D.) The fruit is well-suited for regions with less rainfall and can thrive at altitudes of around 1500 MASL, making it a promising crop for Nepalese farmers[28]. In Malaysia, crop cultivation for the dragon fruit has been increasing due to a high-demand market since 2006. To meet the demand in current and future advanced biotechnology practices is very important in the dragon fruit production[29]. Various efforts have been made to promote and introduce dragon fruit in the coastal areas of Indonesia, Pangandaran, through the establishment of socialisation activities and demonstration plots[30]. Dragon fruit should have a pH of 6.5-8.0 and requires a frost-free and dry climate for optimal growth[26]. Dragon fruit is well-suited to regions with erratic rainfall, making it viable in crop areas with supplementary irrigation. Propagation of plants mainly takes place through stem cuttings under favourable conditions within 14-18 months. Dragon fruit requires specific support systems to facilitate its growth, particularly because it is a climbing vine. Vertical support systems, such as cement poles, are essential for the healthy growth of dragon fruit. Horizontal supports should be positioned at a height of 1.4m to 1.6m, which helps in anchoring the climbing vines effectively[31]. Despite its potential in economics and adaptability, the cultivation of dragon fruit shows high initial investment costs and needs specific cultural management to ensure productivitiy[32]. Regions like China need artificial light supplements to address insufficient sunlight during certain seasons, which enhances the supply cycle and production quality[33]. Light supplementation and cultivation techniques have been taken into further research to improve yield and expand the market for dragon fruit globally. Government programs and research organisations have increased the dragon fruit's cultivation. To fully realise its potential, more study is required on a number of health benefits and cultivation-related topics. The fruit price is available in markets ranging from 160 to 240 rupees per kilogram in Andhra Pradesh[34]. The collection of dragon fruit takes place when it reaches full size and colour, typically 30-35 days after flowering. It has a very short shelf life and should be stored at around 10°C with relative humidity of around 93% to maintain freshness up to 17 days[35]. To increase the yield and income, good agricultural practice has been followed, showing an increase in

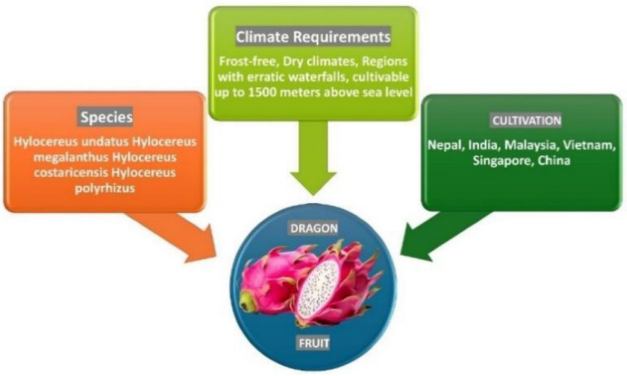


Figure 5. Species, climatic requirements and cultivation of dragon fruit.



Figure 6. Comprehensive overview of dragon fruit: cultivation and benefits.

income and yield with a 140.32% increase reported as an income in some regions[36].

3. Phytochemical Yields and Extraction Technologies

3.1 The Percentage Yield of the Phytoconstituents Extracted from the Dragon Fruit

While dragon fruit peel is a significant source of pectin, reported yields vary considerably depending on the extraction method employed. Conventional acid extraction methods have demonstrated quantitative yields ranging from 10.93% to 26.38% under optimal pH and temperature conditions. However, these thermal methods may compromise heat-sensitive compounds. In contrast, Ultrasound-Assisted Extraction (UAE) has emerged as a superior alternative for preserving bioactive integrity. For instance, while control yields can be as low as 9.5%, the application of UAE with carrier agents like maltodextrin increased the yield to 72.7%, significantly outperforming traditional methods. This suggests that while acid hydrolysis is effective for bulk pectin recovery, ultrasound-assisted techniques are preferable for applications requiring high antioxidant retention[37-41]. This heat, which can harm the chemicals, is not used in this process. The yield achieved was 72.7% with 40% maltodextrin compared to the control yield, which was 9.5%. The whey protein and maltodextrin used as a spray-drying agent significantly increases the yield of the powder from the skin extracts of the dragon fruits. Ethanol produces the greatest extract (26.15%), with an antioxidant value (IC_{50} value of 120.53 ppm) and a total phenolic content of 64.75 ppm[42,43]. The dragon fruit's pectin source has been studied using 0.1M sulfuric acid extraction, which yields a higher degree of amidation (12.90%) and a lower degree of esterification (15.92%) than citric acid extraction[27]. Multi-level extraction was carried out to extract anthocyanins from the dragon fruit peel, showing that with an increase in the extraction time, there is an increase in the yield. The highest yield was 4.1625 mg per 20 grams of peel after five extractions, representing a 36.5% increase from the initial extraction[44-48]. From the inner layer of the dragon fruit, the pectin was extracted with 26.38% on a dry weight basis. Under specific conditions, such as 73°C for a pH of 2.03 for 67 minutes, a sample of the citric acid ratio was 1:4 (w/v). The yield increased proportionately with exposure time. A comparison of extraction efficiencies is presented in Table 3, which demonstrates that Ultrasound-Assisted Extraction (UAE) yields significantly higher antioxidant retention compared to conventional acid extraction methods.

4. Structural Insights and Genetic Diversity

4.1 Structural Similarities among Dragon Fruit Derivatives

The pulp and peel of dragon fruit (*Pitaya*) are rich in nutrients, and bioactive compounds are taken into account in the study for their benefits and structural

Table 2. Extraction methods and percentage yield of phytoconstituents[49-51]

Phytoconstituents	Extraction Method	Yield/Percentage	Conditions/Details
Pectin	Ammonium oxalate/oxalic acid extraction Deionised water extraction Acid extraction	20.1% 15.4% 15%	Highest yield from peel on a dry weight basis - Lowest yield
Pectin	Sulfuric acid extraction	Amidation: 12.90%, Esterification: 15.92%	Higher amidation, lower esterification than citric acid
Pectin	Citric acid extraction	26.38%	pH 2.03, 73°C for 67 minutes, 1:4 sample to citric acid ratio
Phenolic compounds	Ultrasound-assisted extraction	65.16 mg of phenolics, 620 µmol antioxidants	40% maltodextrin, compared to the control yield (9.5%)
Anthocyanin	Multi-level extraction	4.1625 mg per 20 g peel, 36.5% increase from initial extraction[44]	-
Saponins, Alkaloids, Flavonoids, Steroids	Various methods	Saponins (0.5%), Alkaloids (4.21%), Flavonoids (0.74%), Steroids (2.54%)	Fruit flesh, stem, roots
Betalain	Ultrasound-assisted extraction	64.52%	16 minutes, 84% aptitude
Betalain, Pectin	Encapsulation, spray drying	60-93% increase in yield	Using microcrystalline cellulose and dragon fruit peel pectin
Betacyanin	Peel-to-water ratio extraction	22.28 mg/100 ml	High betacyanin content from both peel and flesh
Betacyanin	Ethanol, specific pH and temperature extraction	Varies	pH 5, high temperature (100°C)
Betacyanin	Aqueous two-phase system extraction	85.07%	pH 5.2, 12.57% ammonium sulfate, 30% ethanol
Betacyanin	Aqueous ethanolic extraction	Varies	Ethanol enhances betacyanin stability

similarities. A natural pigment found in dragon fruit, such as betacyanin, is unstable, so to establish stability, encapsulation techniques are utilized[52,53]. The peel of the dragon fruit holds significant potential in the nutraceutical industry due to its health benefits, antioxidant properties, and the ability to reduce waste[54]. In ADMET evaluation in drug discovery, the fruit juice has an activity cliff, which has a potential link in structural similarities in the dragon fruit derivatives[55]. The phenolic content of the dragon fruits is a good source of phenol, indicating the presence of similar compounds from the three different dragon fruit derivatives. A study was conducted in the Andaman and Nicobar Islands in 2021 on molecular, morphological, and biochemical traits to give insight into the characteristics of three different dragon fruit derivatives. By using a multi-faceted approach to the difference between species, the work unveils the differences and structural similarities among the dragon fruit derivative[56]. In addition to the research on enhancing the stability of betacyanin, it highlighted the presence of dragon fruit in pulp or peel, highlighting the structural component among the dragon fruit derivatives. The therapeutic potential of dragon fruit has gained significant attention in recent years. A case of *pseudomelanosis* of the terminal ileum, resembling the cut surface of dragon fruit, has been reported, with the condition termed 'dragon fruit ileum'. These findings highlight a structural similarity between the dragon fruit ileum and the actual fruit, highlighting an interesting intersection of human anatomy and natural forms[57]. The structural evolution of the red-fleshed dragon fruit was studied through analysis of its structural and physicochemical properties during development. Dragon fruits exhibit significant compositional and structural changes during fruit growth and

development, offering a colour change and a sigmoid pattern in both pulp and peel on the accumulation of the betacyanin[58]. The understanding of the dragon fruit derivatives in structural vulnerabilities of the fruits to pathogens has been included in the comprehensive review[59]. The structural impact on human health explored the increased levels of erythrocytes and haemoglobin in pregnant women who consumed red dragon fruit juice[60]. The health benefits of the dragon fruit are extensively studied in the peel of the dragon fruit, emphasising the therapeutic properties of the fruit and the structural components. A review highlights the structural aspects of health benefits, nutritional value, and cultivation of the dragon fruit, making it a valuable source of nutrients[61]. The "TwilightZone" of sequence similarities is important for understanding the structural similarities among the dragon fruit derivatives[62]. By working on sequence similarities, there will be valuable insight into the similarities among different traits of the dragon fruit derivatives and genetic relationships. The genomic sequencing studies take place at the Mediterranean basin hotspot collection and offer an understanding of the biology and biodiversity of the olive tree. The genetic diversity of the genotypes of the olive tree, which can be beneficial for the study of structural similarities of the dragon fruit derivative[63]. Development of the dragon fruit plants named 'DF2' and 'DF16' in the horticultural research aimed at enhancing the quality and yield of this exotic fruit. The development of new plant types and the identification of distinctive structural similarities among the derivatives of dragon fruit, which could have an impact on the fruit's characteristics and genetic composition. Different dragon fruit types exhibit unique metabolic characteristics. Metabolomic profiling reveals a distinct divergence between *Hylocereus* species, dictating their potential industrial applications. White and yellow-fleshed varieties (*H. undatus* and *H. megalanthus*) are characterised by higher fructose and glucose levels, making them suitable for direct consumption as energy sources. In contrast, red-fleshed varieties (*H. polyrhizus* and *H. costaricensis*) exhibit superior functional properties due to their high accumulation of betalains and polyphenols. Critical appraisal of these findings indicates a direct positive correlation between flesh colour intensity and Total Antioxidant Capacity (TAC). Therefore, red-fleshed varieties should be prioritised for the development of nutraceutical supplements, whereas white-fleshed varieties remain optimal for fresh market fruit production[64-67]. Various varieties of the *Pitaya* have different monosaccharide composition, surface morphology, and molecular weight, but have similar structural features that lead to antioxidant and anti-inflammatory activity[68]. Dragon fruit varieties exhibit different, distinct morphological traits, including variation in flower colours, fruits, and stems, which are consistent across different regions. Isoenzymic analysis is a valuable tool for understanding genetic relationships among different plant varieties, particularly in the context of fruit crops like the dragon fruit (*buah naga*)[69]. The biology of the reproduction of *H. undatus, S. megalanthus,* and *H. polyrhizus* was studied. Between the clones of *S. megalanthus*, this cross-pollination taking place led to self-fruitfulness. *H. undatus* was self-fruitful, whereas *H. costaricensis* and *H. polyrhizus* were self-unfruitful. In *H. polyrhizus* and *H. undatus, S. megalanathus* meiotic behaviour and chromosome numbers were reported. Research has also characterised the reproductive biology and chromosomal variations contributing to the diversity of these species. Low seed set and pollen viability in *S. megalanthus* are attributed to irregular chromosome junctions[70]. Dragon fruit is recognised for its diverse therapeutic properties, which are largely attributed to its rich phytochemical composition, which is rich in anti-oxidant, anti-diabetic, and anti-cancer properties. Studies indicate that the peel of both white and red *Pitaya*s contains significantly higher levels of flavonoids and polyphenol compounds compared to the flesh. Among the different varieties, red *Pitaya* is noted to have the highest content of flavonoids and phenolic compounds[71-74].

4.2 Nano Formulations Derived from Dragon Fruit

Recent advancements have shifted focus from traditional synthesis to green nanotechnology, utilising dragon fruit extracts as eco-friendly reducing agents for metal nanoparticles. The literature consistently highlights the efficacy of these plant-derived nanoparticles, particularly gold and iron oxide forms, in exhibiting strong antimicrobial and anticancer potential. However, a critical limitation in the current body of research is the reliance on *in vitro* models.

While the encapsulation of dragon fruit extracts has shown promise in improving drug delivery and stability, there is insufficient data regarding the long-term biocompatibility and *in vivo* pharmacokinetics of these formulations. Future research must bridge this translational gap to validate the therapeutic viability of dragon fruit-based nanomaterials in clinical settings[75]. Dragon fruit has been used to study the glycaemic control in pre-diabetes and type 2 diabetes. A systematic review and meta-analysis showed dragon fruit may have a positive impact on glycaemic control. The nano formulation derived from dragon fruit may have potentially been used in the development of novel therapeutic strategies for managing diabetes[76].

4.3 Methodologies Employed for the Semi-synthetic Derivative Production from Dragon Fruit

The production of semi-synthetic derivatives from dragon fruit involves the utilisation of the specific chemical precursor and appropriate manufacturing methods. These derivatives are important in various applications, notably in the cosmetic and pharmaceutical industries. This literature search method is employed in studying the environmental impacts of the production of food and highlights the importance of considering natural sources, such as dragon fruit, in comparison to synthetic alternatives as well. In addition to recycling waste into graphene, derivatives bring attention to the use of techniques like XPS for studying synthetic material, which can be applied for the production of semi-synthetic derivatives of the dragon fruit[77,78]. Natural sources could be included in innovative manufacturing processes through the green manufacture of metal nanoparticles. Antioxidants are classified as natural derivatives and quantified using techniques like spectrophotometry[79-81]. Plant extracts are utilised in the green synthesis of metal-based nanoparticles, enhancing their biocompatibility and functional properties for diverse applications[82]. The various extraction techniques for dragon fruit to explore the bioactive properties of the peel of dragon fruit are discussed here[83-85]. The bioactive properties of the dragon fruit peel highlight the importance of utilising the extraction techniques to maximise the benefits of natural ingredients[86]. In the context of the colourants, the utilisation of toxic synthetic substances has shifted towards natural dyes, including those derived from dragon fruits[87,89]. The systematic review of the natural pigments highlights the need for a technique that can be applied to the processing and extraction of dragon fruits[90,91]. In addition, the analysis of the pharmaceutical and cosmetic products reinforces the noteworthiness of incorporating synthetic and natural substances for various treatments, such as those derived from dragon fruit[92]. A study investigated the effects of dragon fruit consumption on vascular function in healthy individuals. The result of the randomised, placebo-controlled crossover study unveils the potential cardiovascular benefits of dragon fruit. Similarly, the effects of dragon fruit consumption on blood pressure and glycemic response for type-2 diabetes individuals are explored. The work aims to impact blood pressure and blood glucose levels by utilising edible dragon fruit highlights in managing metabolic health. The benefits of the dragon fruit are being studied; other research focuses on promoting the overall vegetable and fruit intake for improved health outcomes, specifically cardiovascular health. Another ongoing research project focuses on investigating the effects of dietary changes by incorporating dragon fruit. Investigation of the effect of the duration and amplitude on betacyanin extraction utilising the Ultrasonic-Assisted Extraction (UAE) method, which focuses on assessing the influence of the extraction parameters on yield, betacyanin extraction, and redness value in the dragon fruit peel[86]. Another work focuses on the extraction of the phytocompounds from the dragon fruit peel utilising ultrasound-assisted methods, the effect of intermittent microwave convective drying on the properties of the dragon fruit, encapsulation of the anthocyanins, and the formulation of the dragon fruit peel extract microcapsules for the functional pasta. This type of study highlights the innovative techniques for utilising dragon fruit by-products and enhancing their nutritional value. Using ultrasound-assisted enzymatic treatment, the antioxidant capacity of the dragon fruit juice and the ultrafiltration of red-fleshed dragon fruit are explored. These types of studies provide valuable information on the preservation of bioactive compounds of the dragon fruit and processing techniques[86]. This type of research involves encapsulating extracts of red

dragon fruit into nano-emulsions for drug delivery systems. This type of study exemplifies innovative methodologies in amplifying the functionality and bioavailability of bioactive compounds from natural sources, conducting research focused on the ultrafiltration of red-fleshed dragon fruit juice and the antioxidant capacities of dragon fruit juice extract. A study provides insights into transmembrane pressure, pore size of the membrane, and extraction methods on the quality and antioxidant properties of the red-fleshed dragon fruit juice. The impactful benefits of the dragon fruit are unveiled in the study. Different methods, such as hot water, cold water, ultrasound, and enzymes, are used to extract pectin from the dragon fruit peel. These types of methods affect the physicochemical properties of the pectin and yield, which can be used as a food-grade ingredient. Using genetic algorithms and artificial neural networks to extract phytocompounds such as betacyanin and polyphenols from dragon fruit peel. To improve yield, it is essential to optimise process parameters, including solvent concentration, treatment duration, and others. To maximise efficiency and yield, betalains and pectin are extracted using micro wave-assisted extraction procedures, which optimise temperature, power, and time. The approach of synthesis methodologies, such as the green chemistry approach and water extract catalysis are used for the synthesis of bis-coumarin, dragon fruit juices are unutilized, highlighting an efficient product yield in an environmentally friendly method. The synthesis of dihydropyridines via Hantzsch condensation was achieved using a solvent-free and sustainable method, utilizing the water extract of dragon fruit peel as an acid catalyst[92]. For extracting valuable compounds from dragon fruit peel, various methods have been explored. Applied techniques are green extraction methods, such as supercritical fluid extractions and ultrasound-assisted extraction methods. These kinds of techniques can extract bioactive substances with a range of characteristics. Pectin, polyphenols, flavonoids, vitamin C, lycopene, and betacyanin, for instance, have anti-inflammatory, anti-cancer, anti-oxidant, and anti-diabetic qualities[93,94]. To maximise betacyanin and phenolic content in dragon fruit, certain surface methodologies have been utilised. These types of sustainable approaches offer promising applications in the chemical, food, and pharmaceutical industries, promoting circular economy practices.

5. Conclusion

Dragon fruit (*Hylocereus* spp.) represents a multifunctional resource with significant potential in food science, pharmaceuticals, and nanotechnology. This review highlights that red-fleshed varieties generally exhibit superior antioxidant and cytotoxic activities compared to white-fleshed counterparts, attributed to higher betacyanin and phenolic content. While cultivation practices are expanding in regions like India and Nepal, challenges such as internal rot and specific climatic requirements remain. Furthermore, advanced extraction techniques, particularly ultrasound-assisted methods, have proven more effective than conventional acid hydrolysis in preserving bioactive yield. Future research should focus on bridging the gap between *in vitro* success and *in vivo* clinical applicability, particularly regarding the long-term biocompatibility of dragon fruit-derived nanomaterials and semi-synthetic derivatives.

6. Acknowledgement

The authors thank the management of PSG College of Pharmacy for providing the facilities to carry out the review work.

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Author Contribution

Hemalatha CN, Preetham Anton A collaborated closely with the team and contributed to the overall writing and organisation of the manuscript; Abishek Aadithya VM and Dhilochini AV verified the content of the manuscript with the article and cited references throughout the review; Saranya Devi CS worked on reviewing grammar and content flow, tabulated the data, and contributed to the graphical abstract; Mohan Chezhian GR and Harini GB collected all relevant articles and assisted us in every process. All authors have read and agreed to the published version of the manuscript.