CHAPTER II

REVIEW OF LITERATURE

This chapter provides a detailed review of the existing literature relevant to the present study. It begins by outlining the general composition, bioactive constituents, and documented health benefits of dragon fruit. Recent advancements in the thermal and non-thermal processing of dragon fruit juice are then explored, with emphasis on innovative technologies and their impact on product quality. The review also includes prior research on the development of value-added products from dragon fruit juice. Additionally, this chapter examines ultrasound-assisted and pulsed electric field (PEF)-assisted extraction techniques for fruit juices, highlighting their efficacy and potential benefits. Studies related to PEF-assisted pasteurization are also briefly discussed. The final section focuses on the application of retort pouch processing for fruits, vegetables, and ready-to-eat foods, presenting the challenges encountered and the solutions proposed by previous researchers to enhance product quality and safety.

2.1. DRAGON FRUIT (*Hylocereus spp.*)

2.1.1. Origin and Distribution

Dragon fruit also known by various names such as Pitaya, Pitahaya, strawberry pear, Buah Naga, Kamalam, and wondrous fruit of the 21st century is a perennial climbing cactus that originated in Southern Mexico, Central and South America (Britton and Rose, 1963; Mizrahi and Nerd, 1999; Perween *et al.,* 2018). The name dragon fruit is derived from the unique appearance of the fruit with its leathery skin and scaly spikes on the surface (Torre, 2017; Punitha, 2022).

Red dragon fruit (*Hylocereus polyrhizus*) is gaining global recognition due to its high consumer demand and numerous health benefits. Research has shown that its consumption can help reduce the risk of diabetes, cancer, and atherosclerosis while supporting liver and kidney health. Additionally, the fruit is rich in antioxidants and possesses strong anti-inflammatory properties, making it a valuable addition to a healthy diet (Nishikito *et al.,* 2023a).

2.1.2. Dragon Fruit Varieties

Dragon fruit (*Hylocereus spp*.) is a tropical fruit from the cactus family (*Cactaceae*). Various varieties of dragon fruit are differentiated by fruit colour and size. There are mainly three varieties of dragon fruit. *Hylocereus undatus* (pinkish green peel with white pulp), *Hylocereus polyrhizus* (Pink peel with pink or red pulp) and *celenicereus megalanthus* (yellow peel with white pulp)(Abirami *et al.*, 2021). According to Arivalagan *et al*. (2021), there are five main species, each identified by its skin and pulp color. *H. undatus* has pink skin and white pulp, *H. polyrhizus* has pink skin and red pulp, *H. costaricensis* has pink skin with a deep violet-red interior, *H. guatemalensis* has red pulp and a reddish-orange outer layer, and H. megalanthus has yellow skin with white pulp. However, Li *et al.* (2024) noted that molecular studies in 2017 reclassified Hylocereus species into the Selenicereus genus, which now consists of 33 species. The most commonly grown varieties include S. undatus (red peel, white flesh), *S. costaricensis* (dark magenta peel, violet-red flesh), *S. monacanthus* or *S. polyrhizus* (crimson peel and flesh), and *S. megalanthus* (yellow peel, white flesh). Abirami *et al.* (2021) reported that only four species—*H. undatus, H. monocanthus (H. polyrhizus), H. costaricensis, and H. megalanthus (Selenicereus megalanthus*)—are widely cultivated. In India, H. undatus is the most commonly grown, particularly in Tamil Nadu, Andhra Pradesh, Karnataka, Maharashtra, Punjab, and West Bengal.

2.1.3. Area and Production of Dragon Fruit

Chen & Paull, (2019) noted that precise production data for dragon fruit remains limited due to its relatively recent emergence as a tropical fruit crop. However, Al-Qthanin *et al*.(2024) reported a global production estimate of 2,100,777 metric tons, with India contributing 12,200 metric tons (1% of total production) and ranking ninth. Vietnam leads global production, accounting for 43%, followed by China, Indonesia, Thailand, and Taiwan. Meanwhile, Li *et al*., (2024) identified China as the top producer in terms of both cultivation area and yield. The significance of dragon fruit in tropical fruit production has grown substantially, ranking as the fifth most important subtropical horticultural fruit in South Asia, after lychee, longan, banana, and mango. The fruit originated in Mexico, as well as the central and southern regions of America (Sharma *et al.,* 2021). In India, dragon fruit is actively cultivated in Maharashtra, Karnataka, and Gujarat (Kakade *et al.,* 2020), with cultivation expanding in Kerala, Tamil Nadu, Odisha, West Bengal, and the Andaman and Nicobar Islands.. The majority of dragon fruit available in the Indian market is imported from Thailand, Vietnam, Philippines and Malaysia (Karunakaran *et al.*, 2023). Dragon fruit, a member of the *Cactaceae* family, can be grown at a density of 800 plants per hectare. Once planted, the plant continues to produce fruit for up to 20 years. The fruit is available for harvest over a seven-month period, from May to December (Perween *et al*., 2018). In Kerala, the season slightly varies from March to October.

2.1.4. Red Dragon Fruit Pulp and Juice Composition

Arivalagan *et al.* (2021) studied biochemical and nutritional content of different varieties of dragon fruit. The study reported that dragon fruit is a nutrient-rich, low-calorie superfruit with high mineral and vitamin content. It starts yielding within 12–15 months and stabilizes by the third year. White-pulped varieties have higher yield and sugar content, while red-pulped ones are richer in phenolics and antioxidants. Among the clones, Hirehalli White excelled in yield and quality, while Hiriyur Round Red and Long Red were best among red varieties. This study provided valuable nutritional data, promoting dragon fruit as a healthy dietary choice.

Lande *et al*. (2024) studied two types of dragon fruit: white-fleshed (*H. undatus*) and red-fleshed (*H. polyrhizus*). The red variety was shorter but wider and heavier than the white one. White dragon fruit had a slightly higher juice yield than the red variety. The red dragon fruit contained more sugar, protein, vitamin C, and minerals like calcium, magnesium, and phosphorus. In contrast, the white variety had more fat and carbohydrates and appeared brighter in color. The red dragon fruit was the only one with betacyanin and had higher levels of phenolic compounds in both pulp and juice. These differences show that both types have unique benefits and can be used in various food products like drinks and ice cream.

Chakraborty *et al.* (2024) investigated how different extraction and processing methods affect the antioxidant activity of dragon fruit. Their study highlighted the fruit's rich antioxidant content, including phenolic acids, flavonoids, and betalains, found in the pulp, peel, seeds, and leaves. The peel showed the highest antioxidant activity, with the DPPH assay being the most commonly used measurement method. Storing dragon fruit at 5 °C helps maintain freshness, while advanced extraction techniques like Ultrasound assisted extraction (UAE) and Microwave Assisted Extraction (MAE) improve antioxidant retention, making the fruit valuable for both health benefits and food preservation. Table 2.1. shows the proximate composition, biochemical and physicochemical properties of red dragon fruit pulp and juice.

Table 2.1. Proximate Composition, biochemical and physicochemical properties of red dragon fruit pulp and juice

Properties	Composition of red dragon fruit pulp	Composition of red dragon fruit juice
Moisture (%)	82–85	88
Protein (%)	0.90–1.1	0.66
Fat (%)	0.57	0.13
Total sugars (%)	5.13–7.06	8
Non-reducing sugars (%)	1.8	1.24
Reducing sugars (%)	3.7	4.32- 5.28
Ash (%)	0.7– 0.85	0.5
Dietary fibre (%)	0.8 –1.1	0.41

Total Phenolic content (mg GAE/100g)	25 – 55	41.25
Total flavonoid content (mg CE/100g)	15 – 35	15-30
Betalains (mg BCE/100g)	14 – 23	21.11
DPPH radical scavenging activity (%)	70-80	70-80
pH	4.8-5.4	4.2
TSS (^{0} Brix)	9-11	11
Colour values		
L*	27	30.95
a*	9.2	11
b*	-1.93	-5.2
Vitamin C (mg/100 g)	12.75	9.9
Titratable acidity (%)	0.3-0.48	0.28- 0.45
Mineral composition (mg/100 g)		
Potassium	195	62
Phosphorous	27.85	8.67

Magnesium	20.43	7.45
Calcium	6.75	2.45
Iron	5.59	0.95

References: Islam *et al.* (2012), Abd Manan *et al*.(2019), Arivalagan *et al*. (2021), Kumar, (2021), Lande *et al*.(2024), Liao *et al.* (2020), Liaotrakoon *et al*., (2013), Nur *et al*. (2023), Panchal *et al*.(2018), Tan et al.(2023), (Thakkar, 2019).

Chuah *et al.* (2008) analyzed the rheological properties of dragon fruit juice, which are crucial for optimizing equipment design, process control, and consumer acceptance. Juice concentrates of 10° and 12 °Brix were prepared, and their flow behavior was examined at temperatures of 5, 10, 15, and 40 °C. The results indicated that dragon fruit juice exhibits non-Newtonian, pseudoplastic behavior, with both concentrations fitting well within the selected rheological model. Additionally, the effect of temperature on apparent viscosity was best described using the Arrhenius model.

2.1.5. Bioactive Components and Quality Parameters of Red Dragon Fruit and Juice

Bioactive compounds, also known as nutraceuticals, are naturally occurring substances in foods such as vitamins and polyphenols that influence human health. These compounds offer health benefits that go beyond basic nutrition, contributing to overall well-being. The term "nutraceuticals" was introduced in 1979 by Stephan DeFelice to describe these biologically active dietary components (Biesalski *et al*., 2009)

Red dragon fruit contain bioactive phytochemicals which are produced as secondary metabolites. Kim *et al.* (2011) evaluated the phenolic content, antioxidant potential, and anticancer activity of extracts from the peel and flesh of red and white pitaya (dragon fruit) grown in Jeju Island, Korea. Results showed that the peels contained significantly more phenolic compounds than the flesh. Methanol extracts from red and white pitaya peels exhibited 3- to 5-fold higher polyphenol and flavonoid contents than those from the respective flesh samples. Advanced analysis identified the presence of phenolic compounds, hydroxycinnamic acid derivatives, flavonol glycosides, betacyanins, and some unknown compounds. Peel extracts showed stronger free radical scavenging activity and more pronounced antiproliferative effects on AGS and MCF-7 cancer cells compared to the flesh extracts. A positive relationship was found between phenolic levels and antioxidant activity.

Arivalagan *et al.* (2021) conducted a study comparing the composition of red dragon fruit (*Hylocereus polyrhizus*) and white dragon fruit (*Hylocereus undatus*). Their findings revealed that the red variety contains higher levels of betacyanins and has greater antioxidant potential compared to the white variety. Additionally, they reported that vitamin C is the most abundant vitamin in both types of dragon fruit.

Zitha *et al*. (2022) studied variation of bioactive compounds in various developmental stages of red dragon fruit (*Hylocereus polyrhizus*). The study found that the content of betacyanins, flavonoids and DPPH radical scavenging activity increased during developmental stages but vitamin C and phenolic compounds were decreased. They identified six phenolic compounds and catechin was the predominant one. The authors also reported that best harvesting time was 36-38 days after anthesis.

Nishikito *et al*. (2023) have mentioned in their review that dragon fruit contains various phytochemical compounds, primarily including phenols, flavonoids, sterols, fatty acids, and tocopherol. The pulp and peel are rich in numerous bioactive substances such as ascorbic acid, tocopherol, thiamin, niacin, riboflavin, and minerals like calcium, magnesium, potassium, and phosphorus. Additionally, it contains betacyanin, β-carotene, lycopene, p-coumaric acid, protocatechuic acid, vanillic acid, gallic acid, syringic acid, and p-hydroxybenzoic acid.

2.1.5.1. Betacyanins

Choo *et al*. (2019) explored the bioaccessibility of betacyanins in both fermented red dragon fruit drink (RDFD) and pressed dragon fruit juice (RDFJ) through simulated gastric and intestinal digestion. Their study revealed that RDFD possessed a higher antioxidant capacity compared to RDFJ after undergoing intestinal digestion.

Thuy *et al.* (2022) investigated the effectiveness of two extraction methods—conventional and ultrasound-assisted—using water as the solvent to extract betacyanin from the flesh and peel of red dragon fruit (*Hylocereus polyrhizus*). The study revealed that ultrasound-assisted extraction significantly enhanced betacyanin content compared to the conventional method. The highest betacyanin concentrations were recorded at

27.49 mg/100 mL from the flesh after 13.15 minutes of extraction and 22.28 mg/100 mL from the peel, achieved with a peel-to-water ratio of 90.63:9.37 after 12.91 minutes.

The antioxidant effects of betacyanins are higher than anthocyanins and ascorbic acid. Betacyanins also exhibit higher pH stability compared to anthocyanins (Lim *et al*., 2024).

2.1.5.2. Polyphenols

Chen *et al.* (2021) examined the phenolic composition and antioxidant activity of white and red varieties of Australian dragon fruits. The study extracted bioactive compounds separately from the pulp and peel, and quantified total phenolics, flavonoids, and tannins through established assays (including DPPH, FRAP, ABTS, and TAC) to assess antioxidant potential. The results indicated that the pulp exhibited a higher overall concentration of phenolic compounds and greater antioxidant activity. In contrast, the peel was found to be richer in flavonoids and tannins. Advanced characterization using Liquid chromatography electrospray ionization quadrupole time-of-flight mass spectrometry (LC-ESI-QTOF-MS/MS) led to the identification of 80 distinct phenolic compounds, which encompassed phenolic acids, flavonoids, lignans, stilbenes, and other polyphenols. Subsequent HPLC-PDA (photodiode array detector) analysis corroborated that the peel contains a higher concentration of these bioactive compounds. In summary, the findings demonstrated that both the pulp and peel of dragon fruit are valuable sources of phenolic compounds, with the peel—often regarded as waste—showing significant promise for applications in the food and pharmaceutical industries.

2.1.5.3. ***Antioxidant activity***

Zakaria *et al.* (2022) investigated and compared the phytochemical composition, antioxidant capacity, and antibacterial activity of two dragon fruit species: *Hylocereus polyrhizus* (red-fleshed) and *Hylocereus undatus* (white-fleshed). Despite belonging to the same genus and having similar external appearance, the two species exhibited distinct bioactive profiles. Extracts prepared using 50% ethanol were analyzed for total phenolic and flavonoid content, as well as their antioxidant activity using DPPH and ABTS assays. Antibacterial efficacy was assessed against *Escherichia coli* and *Staphylococcus aureus* using the disk diffusion method. *H. polyrhizus* demonstrated significantly higher total phenolic content ($p<0.05$), while *H. undatus* had greater flavonoid content ($p<0.05$). Although both species exhibited comparable antioxidant activity, *H. polyrhizus* showed slightly greater effectiveness in both assays. Furthermore, both extracts displayed antibacterial activity, with *H. polyrhizus* exhibiting inhibition at lower concentrations. These findings suggest that *H. polyrhizus* may possess enhanced bioactivity, potentially attributed to its higher phenolic content

2.1.5.4. *Physico-chemical and rheological properties*

Liaotrakoon *et al*. (2013) explored how heat treatments (50–90 °C for up to 60 minutes) affect white and red flesh dragon fruit purees. Red-flesh puree had superior initial physicochemical and antioxidant properties. Heating led to a significant reduction in betacyanin content (down to 32.35%). Antioxidant activity improved with heating in both types, and viscosity increased, showing shear-thinning behavior. These changes suggested that red-flesh dragon fruit puree may be suitable for use in thermally processed food products due to its enhanced nutritional and functional qualities.

2.1.5.5. *Microbial count and enzymatic activity*

Ismail *et al.* (2024) compared the effects of high-pressure processing (HPP) and traditional thermal pasteurisation (TP) on the quality of the RDF puree over 60 days of refrigerated storage. Key parameters evaluated included betacyanin levels, phenolic and flavonoid content, antioxidant activity, enzyme behavior, microbial stability, and color retention. The puree was divided into three groups: untreated, TP-treated (65°C for 20 minutes), and HPP-treated (350 MPa for 5 minutes), with analyses performed every 15 days at 4 ± 1°C. Results showed that both treatment type and storage time significantly affected the purée's characteristics. HPP was more effective at inhibiting microbial growth and enzyme activity, thus extending shelf life beyond 60 days. The TP maintained phenolic content, antioxidant capacity, and color.

2.2. HEALTH BENEFITS OF DRAGON FRUIT

Dragon fruit possesses anti-cancer, anti-diabetic, and anti-lipidemic properties. It also exhibits wound healing, hepatoprotective, anti-anaemic, and anti-inflammatory effects, and supports the health of the heart, kidneys, and nervous system. Table 2.2 provides an overview of recent research works on various health benefits of dragon fruit.

2.3. RED DRAGON FRUIT JUICE PROCESSING

Table 2.3 presents a summary of key studies on juice extraction methods for dragon fruit. Table 2.4 outlines various thermal processing approaches applied to dragon fruit, while Table 2.5 highlights research on non-thermal processing techniques for dragon fruit juice. Table 2.6 provides an overview of previous studies focused on the development of value-added products derived from dragon fruit juice.

2.4. ULTRASOUND ASSISTED EXTRACTION

The sound spectrum is divided into three main categories: infrasound (below 16 Hz), acoustic waves (16 Hz to 16 kHz), and ultrasound (above 16 kHz). Ultrasound consists of mechanical waves with very short wavelengths, usually less than 2 cm in the air. Frequencies exceeding 20 kHz are commonly utilized in ultrasonic applications, causing particles to oscillate more than 20,000 times per second—beyond the human hearing range of 16 kHz. The primary properties of ultrasound include power, intensity, and energy density (Zhou *et al*., 2022). Laboratories commonly use two types of ultrasound equipment. The first is the ultrasonic cleaning bath, primarily utilized for dispersing solids in solvents, degassing solutions, and cleaning glassware. Although it is cost-effective and simple to operate, its low and inconsistent ultrasound intensity—diminished by water and glassware—makes it unsuitable for chemical reactions. The second type, the ultrasonic probe (horn system), transmits ultrasound directly into the reaction flask, providing higher intensity and making it more effective for processing small sample volumes. However, it requires careful handling, as it can rapidly increase the sample's temperature (Chemat & Khan, 2011).

2.4.1. Mechanism of Action

Ultrasound induces cavitation within cells by creating gas bubbles in low-pressure areas, which collapse when pressure increases, disrupting cellular functions and causing physical damage to cell structures (Błaszak *et al.,* 2025). In food processing, ultrasound utilizes this cavitation effect, in which high-frequency sound waves generate bubbles that rapidly expand and collapse. This process results in extreme pressure and temperature variations, leading to both mechanical and chemical impacts on the material being treated. These effects can disrupt microbial cell walls for preservation and break open plant cells to release intracellular components (Bora et al., 2017). The process involves phenomena such as the "sponge effect," cavitation, microjetting, and microstreaming, which improve bioactive compound extraction by enhancing mixing, homogenization, and mass transfer (Dadan *et al.,* 2022). Depending on the frequency, ultrasound can cause bubbles to collapse with strong shockwaves (useful for emulsification) or generate higher temperatures for chemical reactions. Higher frequencies, above 1 MHz, have weaker cavitation effects but are used for gentle cleaning and medical imaging (Leong *et al*., 2011).Table 2.7 provides a brief overview of ultrasound assisted extraction of various kind of fruit juices.

2.5. PULSED ELECTRIC FIELD ASSISTED EXTRACTION

Pulsed Electric Field (PEF) treatment is a modern, non-thermal technique used in food processing. Studies have shown that applying PEF to plant materials enhances the movement of substances within the tissues, making it easier to extract valuable compounds. This method uses short bursts of high electric fields (1–10 kV/cm) for microseconds to milliseconds, which temporarily disrupt cell membranes. In addition to boosting juice recovery, PEF selectively disrupts cell membranes while keeping the cell wall intact. This helps improve the purity and overall quality of the extracted juice (Lamanauskas *et al.,* 2016).

A PEF system is composed of three main elements: a treatment chamber, a pulsed power supply, and a control and monitoring system. The power supply is responsible for producing high-voltage pulses that are directed through the treatment chamber, where the food is placed. The pulse power generator consists of various electrical components, including capacitors, inductors, resistors, transformers, and power switches, all of which function together to efficiently store and transmit energy. Keeping energy transfer cost-effective is essential for optimizing the system's overall design. PEF treatment chambers are categorized into batch and continuous systems**.** Batch chambers process a limited volume of liquid or solid food at a time, whereas dynamic chambers allow continuous processing, making them ideal for industrial use. Common electrode arrangements in PEF systems include parallel, coaxial, and colinear configurations (Arshad *et al.,* 2020)**.**

Table 2.2. Health Benefits of Dragon Fruit

Health benefits	Findings
Antioxidant Properties and Anticancer Effects	Synthesized gold nanoparticles (10-20 nm in size) using dragon fruit (DF) extract extract acted as both a reducing agent and a stabilizing agent for the nanoparticle. Dra extract inhibited the growth of MCF-7 breast cancer cells.
	Methanolic extract of *H. undatus* exhibits both anticancer and anti-apoptotic effects liver cancer (HepG-2) cells. The polyphenols present in the extract help combat scavenging nitric oxide (NO) free radicals, which are known to promote tumor gr metastasis.
	Found that Israeli dragon fruits had higher antioxidant activity, polyphenol, and b levels compared to Thai fruits. Both types effectively targeted colon and prostate ca while sparing normal cells, and exhibited strong binding to human serum albumin, s their potential as chemopreventive dietary components.
Anti-Diabetic Effects	Examined the antidiabetic effects of red dragon fruit in 30 type II diabetic patients, fi blood glucose levels decreased from 177.97 mg/dl to 159.50 mg/dl after consump authors suggested that red dragon fruit could be a beneficial non-pharmacological th managing diabetes.

	Red dragon fruit was more effective than soymilk in lowering blood sugar levels
	Examined the antidiabetic effects of methanol extract from dragon fruit peel in alloxa diabetic rats, finding significant reductions in blood glucose levels after 7 and 1 treatment. The extract also helped preserve the structure of pancreatic Langerh particularly at higher doses, indicating its potential to support pancreatic health and lo sugar.
Anti-Lipidemic Effects and Cardiovascular Health	Explored the effects of acute and short-term dragon fruit consumption on vascul Dragon fruit intake improved flow-mediated dilation (FMD), enhanced endothelial and decreased arterial stiffness. Regular consumption of dragon fruit may help reduc of cardiovascular diseases, potentially due to its high betalain content.
	Investigated the effects of red dragon fruit juice on cholesterol levels in women aged finding a significant 6.1% reduction in cholesterol. The juice's high antioxidant, triterpenoid content, along with its ability to inhibit key enzymes like HMG-CoA redu CETP, contributed to the reduction in cholesterol levels.
	Studied the effects of *Hylocereus polyrhizus* fruit extract on hypercholesterolem antioxidant activity in rat serum. Their findings revealed that the extract notably decre cholesterol (TC) and low-density lipoprotein cholesterol (LDL-C) levels in rats

	induced hypercholesterolemia. Additionally, the fruit extract demonstrated strong an properties.
	Explored the health benefits of adding dragon fruit peel powder (DFP) to cookie doug that DFP increased total phenolic content, betacyanin levels, and antioxidant Additionally, DFP reduced the formation of toxic compounds, lowered starch digestil decreased the glycemic index, making the cookies potentially healthier with redu induced toxicity and improved nutritional properties.
Wound Healing Properties	Assessed the cytotoxicity of dragon fruit rind extract on fibroblast cells (BHK-21) and that higher extract concentrations reduced cell survival. The optimal concentration maintaining about 60% cell viability, while concentrations above 60% led to toxic eff
Hepato Protective Effects	Examined the impact of red dragon fruit extract on membrane lipid peroxidation damage caused by hyperlipidemia in a study involving 30 male Wistar rats. Adminis mg of red dragon fruit extract daily showed promising effects in mitigating lipid per damage to liver cell membranes under hyperlipidemic conditions induced by a high-fa
	Investigated the antioxidant mechanisms of betacyanins in Improved-Fermented Re Fruit Drink (FRDFD-dH2O) using HepG2 liver cells. The results demonstrated that be significantly reduced reactive oxygen species (ROS) and enhanced antioxidant e activities, suggesting their dual antioxidant effects and potential hepatoprotective bene

Anti-Anaemic Effects	Explored the impact of red dragon fruit juice on hemoglobin and erythrocyte levels i women, finding significant increases in both by the seventh day of consumption. The in iron, was shown to support healthy blood formation, making it a beneficial dietar for pregnant women to help prevent iron deficiency.
	Tested the effect of pitaya fruit juice, rich in iron and vitamin C, on 32 anemic p mothers. The results showed that those who consumed pitaya juice had significan hemoglobin, hematocrit, and erythrocyte levels compared to those who didn't.This that pitaya juice can help improve blood health in postpartum mothers.
Anti-Inflammatory Effects	Evaluated the bioactive properties of colorants from *Hylocereus polyrhizus* and *I undatus*, revealing that the aqueous extract had the highest phenol and flavonoid co strong antioxidant, anti-inflammatory, and antibacterial effects. Additionally, the aq ethanolic extracts showed low cytotoxicity, supporting their potential use as safe pharmaceutical ingredients.
	Investigated the antioxidant and antifungal properties of red dragon fruit peel extrac that the ethyl acetate extract exhibited the strongest antifungal activity against *Candid* (74.27% inhibition). This extract also contained the highest levels of phenolics (GAE/g) and flavonoids (28.62 mg quercetin/g), suggesting its potent bioactive prope
	Examined the antimicrobial activity of red dragon fruit (Hylocereus polyrhizus) pe against *Streptococcus mutans*, *Enterococcus faecalis*, and *Candida albicans*. T

	showed notable inhibitory and bactericidal/fungicidal effects, indicating its potential a antimicrobial agent.
Protection of Kidney Health	Explored the protective effects of *Hylocereus polyrhizus* extract against sodium nitra oxidative kidney damage in rats. The extract significantly reduced oxidative stress m tissue damage, suggesting its strong potential in preventing kidney injury through a mechanisms.
	Assessed the protective effects of dragon fruit (*Hylocereus polyrhizus*) extract agair media-induced kidney damage in dehydrated rats treated with furosemide. T significantly improved kidney function and antioxidant levels while reducing oxida and tissue damage, indicating its potential as a renal protective agent.
Neuroprotective Effects	Examined the effects of Pitaya (*Hylocereus undatus*) on copper toxicity in zebrafis showed that Pitaya pulp reduces anxiety, aggression, cortisol levels, and improves ar and cholinergic system functions, suggesting potential benefits for aging-related con
	Ealuated the protective effects of red dragon fruit juice (RDFJ) against lead-induced rats, showing that RDFJ significantly improved liver and kidney function, reduced stress, and restored brain neurotransmitter levels. The results suggest that RDFJ antioxidant content helps mitigate lead-induced neurotoxicity and supports neural rec
	Examined the neuroprotective effects of red dragon fruit (RDF) extract on cerebella rats, revealing that aging caused significant structural and biochemical damage in the

Table 2.3. Juice Extraction Studies

Extraction method	Findings
Enzyme Assisted Extraction	This study explored the effects of commercial enzymes on red pitaya juice, finding that e and pasteurization did not significantly alter major nutrients. However, Pectinex CLEA increased protein content and phenolic compounds by 7%, enhancing antioxidant despite a slight reduction in vitamin C due to heat treatment.
	This study evaluated the use of Pectinex Ultra SP-L and Viscozyme L to improve red d juice extraction, showing that enzymatic treatment significantly enhanced juice yield a Optimal results were achieved at 40 °C for 120 minutes with a 70/30 enzyme ratio, higher sugar content, increased phenolics and vitamin C, lower viscosity, and grea compared to non-enzymatic methods
	Examined how different pectinase concentrations (15 to 35 μL/100 mL) and incubation to 90 minutes) at 35 °C affect the turbidity and viscosity of pitaya juice. Treating the ju μL/100 mL of pectinase for 75 minutes at 35 °C significantly improved its clarity and co making it more suitable for subsequent membrane-based clarification processes.
	Explored how pectinase affects the quality of red-fleshed dragon fruit juice. Pectinase (was tested at different concentrations (0–9%) and hydrolysis times (0–45 min). Juice q measured by recovery efficiency, pectin content, betacyanin content, viscosity, and tota

	content. The best results were achieved with 5% pectinase and 25 minutes of hydrolys to 88.16% hydrolysis efficiency, low pectin (0.49 g), low viscosity (1.15 cP), and high b (20.06 mg/100 mL) and phenolic content (88.68 mg/100 mL).
	Examined how cultivation conditions and geographic origin affect the phytochemical c antioxidant properties of red-fleshed dragon fruit from four Vietnamese regions. It also pectinase hydrolysis and thermal sterilization to improve juice quality, resulting in an er formulation with enhanced nutrient retention, microbial safety, and consumer app specific processing parameters.
Ultrasound assisted enzymatic extraction	Using response surface methodology with a Box–Behnken design, the study optimized and enzymatic treatments to enhance antioxidant extraction from red dragon fruit juic showed that ultrasound-assisted enzymatic treatment improved betacyanin and antioxic with different optimal conditions for maximizing betacyanin versus total phenoli confirmed by LC-MS and antioxidant assays.

Table 2.4. Thermal Processing of Dragon Fruit Juice

Processing method	**Findings**
Conventional heating	Investigated how heating white- and red-fleshed dragon fruit purees affected their qu that red-fleshed puree had superior physicochemical and antioxidative properties. H betacyanin content but increased antioxidative activity and viscosity, with color a changes useful for quality control, making heated red-fleshed puree promising for food
	Evaluated the effects of pasteurization, pH, ascorbic acid, and storage on betacyanin fleshed dragon fruit juice and concentrate. Optimal preservation was achieved with acid at pH 4.0 and 65 °C pasteurization, while agitation improved stability and light ex degradation.
	This study evaluated the effects of juice concentration on betacyanin degradatio acceptance in red-fleshed dragon fruit juice, revealing that storage at 4 °C preserved reduced microbial growth. Betacyanin degradation followed first-order kinetics, and rec was preferred for its taste, indicating that concentration improves both stability and ser
Ohmic heating	Investigated the effects of ohmic heating and ascorbic acid on red-fleshed dragon fru during storage, showing that ohmic heating better preserved nutrients than convent Despite declines over eight weeks, the addition of 0.25% ascorbic acid helped maint phenolic content, antioxidant activity, and color, highlighting its effectiveness for juice

Table 2.5. Non-Thermal Processing of Dragon Fruit Juice

Non-thermal technology	Findings
UV –C light	The study explored using UV-C light, citric acid, and dimethyl dicarbonate to reduc red pitaya juice, with UV-C alone reducing microbial counts significantly. The co UV-C with 1.5% citric acid and 15 µL/100 mL dimethyl dicarbonate achieved reductions in microbial levels.
	UV-C treatment of pitaya juice at different flow rates and durations did not affect solids but caused color changes and reduced betalains and phenolic compound antioxidant activity. The treatment effectively reduced microbial counts, achievin log reduction in aerobic mesophilic bacteria and a 1.14 log reduction in yeasts and
	Fresh pitaya juice inoculated with *Zygosaccharomyces bailii* was treated with U different flow rates and treatment times, then stored for 25 days. Longer UV-C exp increased color change and reductions in phenolic compounds, betalains, and antiox with the most intense treatment resulting in a 1.8 log reduction in *Z. bailii* populati
Ozone- HHP	Examined the combined effects of ozone and high hydrostatic pressure (HHP) microbes in pitaya juice. The most effective treatment, ozone followed by HHP, reduced Listeria innocua and Saccharomyces cerevisiae, kept native microbes und

	resulted in the highest sensory preference (79%) after 30 days at 5°C, sugges combination is more effective for juice safety than using either treatment alone.
Thermosonication	The study evaluated thermosonication (TS) for its effects on color stability in rec finding that while longer treatments and higher temperatures caused color chang preserved color compared to thermal processing. TS effectively inactivated polyph retained over 92.97% of polyphenols, and minimized discoloration, making it a pron for maintaining both color and bioactive compounds in fruit juice.
	The study assessed the effects of thermosonication (TS) on microbial safety and pitaya juice during storage. TS (475 W, 56°C for 20 minutes) significantly redu counts and preserved quality attributes like pH and soluble solids, with better c compared to thermal processing, making it a viable alternative for juice preserva slight color deterioration after 10 days.
Ultrasonic pretreatment	The study examined the effects of ultrasonic pretreatment on the physicochemical red dragon fruit juice. Ultrasonic treatment for 60 minutes increased organic acids, p anthocyanins, along with enhancing antioxidant activity, while total soluble so titratable acidity remained unchanged.
Ultrafiltration	The study investigated the clarification of red-fleshed dragon fruit juice using ultraf with polyethersulfone membranes of varying pore sizes. The best results were achie kDa membrane at 3 bar, effectively clarifying the juice while preserving betacyanins

	compounds, with cake resistance being the main filtration challenge and no dan sensitive compounds.
High Pressure Processing	The study compared the effects of high-pressure processing (HPP) and thermal (TP) on red dragon fruit purée preservation over 60 days. HPP effectively extende inhibiting microbial growth and enzyme activity, while TP helped preserve phe antioxidant activity, and color stability, with both methods significantly influenci attributes during storage.
Pulsed light	The study compared the effects of thermal and pulsed light (PL) processing on re juice preservation. While both treatments reduced microbial content, PL treatme loss of phenols and antioxidants than thermal processing, offering a promising a preserving juice with minimal nutrient loss, despite thermal processing providing a s shelf life.

Table 2.6. Value Added Products from Red Dragon Fruit Juice

Value added Products	Findings
Wine, jam, soft drinks, flower tea	Optimized protocols for producing various products from *Hylocereus undatus* fruits The best wine formula yielded 12% ethanol, betacyanin extraction reached 14 achieved optimal texture with pectinase and pectin, soft drinks from stems were Pectinex Ultra SP, and dragon fruit flower tea with dried flowers, licorice, and sugar to have superior quality compared to other teas in the Vietnamese market.
Fruit juice drinks, cream cheese spreads, and yogurt drinks	The study explored using red-fleshed dragon fruit in juice drinks, cream cheese s yogurt drinks. The most acceptable juice formulation had a 1:5 juice-to-water ratio 35% puree formulation for cream cheese spread was cost-effective, with the pur higher antioxidant activity than the jam. In yogurt drinks, a 15% puree concentrat most preferred, although 10% and 20% were also acceptable, with higher puree levels antioxidant activity and pH but reducing viscosity
Jelly	The study analyzed the nutritional composition of dragon fruit and developed drago to assess its market potential. The juice had high moisture, total sugar, vitamin C, a 4.20, while jelly made with different pectin concentrations (0.05%, 0.1%, and 1.5 minimal changes in color, flavor, and pH after four months of storage. The 1.5% scored highest in color, flavor, turbidity, and overall acceptability in a taste panel.

Fermented drink	The study found that storing fermented red dragon fruit drink (FRDFD) at 4°C bette betacyanin content and physicochemical properties compared to 25°C. After eight we the drink maintained low microbial counts, high betanin levels, and good sensory ac confirming its potential as a functional beverage
	The study optimized fermentation conditions to enhance betalain concentration in fer dragon fruit drink (FRDFD). The best results were achieved with 7 days of ferme 10% white refined cane sugar, leading to a nine-fold increase in betanin, total ph flavonoid content compared to non-optimized fermentation.
	The study optimized the alcoholic fermentation of Vietnamese dragon fruit j *Saccharomyces cerevisiae*. The optimal conditions—18°Brix sugar, 2% yeast, and 4 fermentation—produced 3.54% alcohol with 14.6°Brix residual sugar.
Wine	The study examined the effects of pectinase pre-treatment on red dragon fruit wine fe using *Torulaspora delbrueckii*, finding a 16% increase in juice and wine yie significantly affecting yeast growth, ethanol, or glycerol levels. While the treatmen ester and terpene aromas and increased phenolic content, it also led to lower betacy reduced color intensity, and less favorable fermentation conditions due to high retention.
	The study optimized fermentation conditions for red dragon fruit wine by evaluating y dilution ratio, and yeast concentration. *Saccharomyces cerevisiae* RV002, a 50% d

	1 g/L yeast provided the best results, enhancing clarity and flavor, maintaining eth and increasing polyphenols and antioxidants despite reductions in sugar and vitamir
Carbonated drink	The study developed a carbonated drink from red-fleshed dragon fruit by optimizir hydrolysis and pasteurization to preserve bioactive compounds and color. Optimal were determined by maximizing polyphenol content, vitamin C levels, and antioxid based on DPPH scavenging.
	The study optimized pectin hydrolysis for red dragon fruit carbonated beverages, ideal conditions of 49.9 °C, 131.3 minutes, and 0.23% pectinase, which enhanced anthocyanin content. Sensory evaluation showed the most preferred formulation con juice, 0.12% citric acid, 13°Bx, and 0.30% mint flavor.
RTS drink	The study developed a ready-to-serve (RTS) drink using dragon fruit, grape juice syrup, optimizing the formulation with response surface methodology. The best con 70% dragon fruit, 5% grape juice, and 3% sugar syrup—resulted in a nutritionall drink with high sensory acceptability.
	The study formulated a dragon fruit RTS beverage using different concentrations of j and citric acid, identifying 14% juice, 12.75% sugar, and 0.38% citric acid as the opt This formulation enhanced sensory qualities and antioxidant activity, achieved 15.70 and improved color without using artificial additives, ensuring nutritional value and

	A lime-flavored dragon fruit RTS beverage was developed using 12% fruit juice, 12 0.1% citric acid, and 3% lime juice, with shelf-life enhanced through thermal, micr chemical treatments. Among the methods tested, 500 ppm ascorbic acid proved mos preserving betacyanin content and sensory quality, especially under refrigeration up
Pigment	The study investigated the stability of ethanol-extracted betalain pigment from red under various conditions over three weeks. Results showed that light exposure caus degradation, while storing the pigment in darkness at refrigerated temperatures bes its quality.
Concentrated juice	The study explored a novel juice evaporation method, JEVA (Juice evapo concentrating red dragon fruit juice while preserving bioactive compounds. JEVA, 35°C, retained over 90% of polyphenols and flavonoids, 74% betacyanin, and 81.5 C, outperforming vacuum evaporation, and showed strong potential for large- processing.
	The study processed dragon fruit juice and concentrate by heating, adding preservati benzoate and ascorbic acid), and then cooling and centrifuging the juice. After 90 da treatments with preservatives and colored PET bottles preserved key biochemical including TSS, ascorbic acid, and betacyanin, improving the shelf life of the concen
Nectar	The study optimized the production and preservation of dragon fruit nectar by evalua like pH, sugar concentration, pasteurization, and storage conditions. The optimal f

	with 8% sugar at pH 4.2, pasteurized at 95°C for 1 minute, and stored in glass bottles maintained sensory quality, stability, and microbial safety.
Syrup	The study aimed to enhance the quality of red dragon fruit syrup by using a double jac evaporator, minimizing nutrient loss from high temperatures. The optimal cor preserving vitamin C were 50°C and -60 cmHg, which maximized vitamin C re reduced moisture content, demonstrating the advantages of low-temperature, lo evaporation
	The study investigated the impact of low-calorie sugar on the chemical, physical, a properties of red dragon fruit syrup. Results showed that while low-calorie sug reducing sugars and total dissolved solids, it did not significantly impact pH, vit betacyanin, with a 15% sugar concentration being preferred for aroma, taste, and co
Candy	The study investigated how varying amounts of red dragon fruit peel and pulp chemical composition and sensory acceptance of jelly candy. The preferred formula on sensory evaluation, included 150g peel, 60g pulp, and 290g sugar flour, with wa of 25.6%, sugar content of 53.7%, and 0.03% vitamin C.
	The study evaluated the impact of varying sugar levels on the quality and storage dragon fruit candy. The 80% sugar formulation produced the best taste, texture, ar properties, while a 55% sugar formulation provided the highest return on investme 90-day storage period at 30°C, despite slight declines in moisture, pH, and sensory c

Juice powder	The study examined the stability and antioxidant properties of spray-dried red and w fruit powders under different humidity conditions. While spray drying reduced content, the powders remained stable after 25 days of storage, with the most stabili at 33% relative humidity, while structural changes occurred at higher humidity level
	The study examined the stability of encapsulated betacyanin from dragon fruit pe using maltodextrin and gum Arabic as coating agents with vacuum drying. The ju showed higher phytochemical concentrations and stability than ethanol-extracted p over 30 days, with both powders maintaining similar color stability, but juice powd a more natural hue, though with lower antioxidant activity. The maltodextrin-g combination (1:1) was most effective in preserving phenolics and betacyanin, su potential for industrial use.

2.5.1. Mechanism of Action

PEF extraction applies low-intensity electric fields (0.5–5 kV/cm) to biological tissues, altering membrane potential and creating pores in the cell structure. This process, known as electroporation, weakens the plasma membrane, increasing permeability and allowing intracellular compounds to be released more efficiently. Depending on the intensity of the electric field, electroporation can be reversible or permanent, potentially leading to structural damage such as cell fusion and protein aggregation. The process occurs in phases, starting with membrane polarization, followed by pore expansion, and ending with an attempt to restore membrane integrity. PEF enhances mass transfer, accelerating nutrient extraction, but under critical conditions, it can cause complete membrane disintegration. The effectiveness of PEF depends on factors like field strength, pulse type, number of pulses, treatment duration, and plant tissue composition, making optimization essential for food processing applications (Bocker & Silva, 2022). Table 2.8 provides an insight in to the previous studies on pulsed electric field (PEF)-assisted extraction of different fruit Juices.

2.6. PULSED ELECTRIC FIELD (PEF) PASTEURIZATION

2.6.1. Mechanism of Microbial and Enzyme Inactivation by PEF

Pulsed Electric Field (PEF) treatment involves applying short, high-voltage pulses (<50 kV/cm) to food placed between electrodes, leading to electroporation, which disrupts microbial cell membranes. This process enhances microbial inactivation, bioactive compound extraction, and juice yield by increasing cell permeability. Larger cells, such as plant and animal cells, require lower field strengths (0.5–2 kV/cm) compared to microbial cells (10–14 kV/cm). Pore formation can be temporary or permanent, depending on the intensity of the treatment. PEF is particularly effective in foods with low electrical conductivity, as differences in conductivity between food and microbial cells enhance ion flow, weakening microbial membranes.

Table 2.7. Ultrasound Assisted Extraction of Fruit Juices

Fruit juice	Findings
Grape juice	Ultrasound-assisted treatment of grape mash significantly increased extraction yiel quality, enhancing sugar, acid, phenolic content, and color density. It also reduced time by more than threefold compared to traditional enzymatic methods, with the b achieved using ultrasound before enzymatic treatment.
	Ultrasound-assisted maceration (UAM) enhanced grape juice quality by acce polyphenol extraction, improving color, and reducing yeast contamination, with results achieved after 100–120 minutes of treatment.
Pineapple	Ultrasound treatment of pineapple mash during juice extraction enhanced yield compared to untreated samples. It also significantly increased the levels of sug phenolics, and vitamin C in the juice, improving both efficiency and nutritional qu
Rose myrtle (*Rhodomyrtus tomentosa*) fruit	Ultrasound treatment of rose myrtle fruit mash significantly increased antioxidant c activity in the juice, particularly total phenolics and ascorbic acid. Optimal cond W/g for 6.5 minutes—boosted antioxidant activity by 86% compared to untreated s
Apple	Ultrasonic treatment of apple mash significantly enhanced the antioxidant conte juice, with notable increases in ascorbic acid and phenolic compounds. Optimal so

	20 W/g for 7.3 minutes led to a 67.5% increase in antioxidant activity compared to juice.
Rumduol *(Sphaerocoryne affinis)* fruit	Ultrasonic treatment of Rumduol fruit mash significantly improved the antioxidant of the extracted juice. Optimal conditions—14.8 W/g for 4.4 minutes—resulted in increase in antioxidant activity compared to untreated juice.
Mulberry	Ultrasound treatment at 45 °C for 60 minutes significantly improved mulberry juice enhanced its nutritional quality, increasing levels of vitamin C, phenolics, anthocy antioxidants.
Red Pitaya	Ultrasonic pretreatment of red pitaya juice, with sonication durations of up to 6 significantly increased concentrations of organic acids, phenolics, and ant enhancing antioxidant activity, while color changes and stable pH, acidity, and to solids were observed.
Strawberry, black currant and raspberry	Ultrasound-assisted juice pressing significantly enhanced juice yield and bioactive extraction in strawberries and raspberries, with similar results to enzymatic macera also preserving total phenolic content and boosting anthocyanin levels, esp raspberries. However, ultrasound was less effective for blackcurrants, and highlighted the potential benefits of ultrasound in improving efficiency by reducing time, energy, and enzyme usage, with a need for further research on long-term effe

In the fruit juice industry, enzyme inactivation is essential to prevent degradation and maintain quality. While thermal treatments have traditionally been used, PEF technology has emerged as an effective non-thermal alternative. According to Roobab et al. (2022), PEF efficiently inactivates enzymes and bacteria while preserving the juice's fresh-like properties. This process alters enzyme structures, leading to energy savings, reduced waste, and new product opportunities. However, some enzymatic activity may recover during storage due to incomplete inactivation or resistant isozymes. To address this, combining PEF with mild heat or other non-thermal methods provides a cleaner alternative to conventional heat treatments. Additionally, integrating PEF with traditional pasteurization improves juice preservation, offering economic benefits such as longer shelf life, better stability, and more efficient production.

2.6.2. Advances in PEF Systems

PEF technology is a developing food processing method, with research focusing on improving chamber designs for even electric field distribution in large-scale systems. Pilot-scale units can handle 400–2,000 L/h, while commercial units process 400–6,000 L/h. The U.S. juice industry adopted PEF, with Genesis Juice Cooperative using it before later switching to high-pressure processing (HPP) for unknown reasons. The cost of PEF processing depends on equipment investment and energy use (Sampedro et al., 2013).

PEF pasteurization helps maintain the freshness and nutritional value of liquid foods compared to traditional thermal methods, but its industrial use remains limited due to system inefficiencies. Arshad et al., (2022) aimed to enhance the electroporator by addressing uneven electric field distribution, which leads to temperature inconsistencies. To improve uniformity and prevent hotspots, a coaxial treatment chamber with sieves and a double-exponential (DE) waveform was introduced. Computational modeling confirmed improved flow properties, and a three-stage Marx generator was developed to generate the DE waveform. Microbial and chemical analyses of PEF-treated, thermally processed, and untreated orange juice stored at 4°C for nine days revealed lower microbial growth in both PEF and thermally treated samples. However, PEF-treated juice retained a brighter color than thermally processed juice, highlighting its potential for effective microbial inactivation while preserving product quality. Table 2.9 gives an overview of advances in PEF assisted pasteurization of fruit juices and fruit based beverages and table 2.10 provides information on combination of PEF with other technologies.

2.7. RETORT POUCH PROCESSING

Retort pouches are heat-resistant pouches made of multiple laminated layers, including an outer polyester or nylon layer for strength and printability, a middle aluminum foil layer serving as a barrier against oxygen and moisture, and an inner polypropylene layer for heat sealing. Once food is packed inside, the pouch undergoes high-temperature and pressure sterilization in an autoclave, ensuring commercial sterility. This method enables RTE foods to be stored at ambient temperatures for up to 18 months without preservatives. Since retort processing is more cost-effective than traditional canning, it presents a viable option for preserving and marketing high-value products (Varalakshmi et al., 2014). This technology offers economic feasibility and potential for widespread adoption (Sudheer et al., 2021). Particularly in countries like India, where refrigeration facilities are limited, this technology presents lucrative business prospects, though further research on investment feasibility is essential for broader implementation (Varalakshmi et al., 2014).

Retorts are categorized as batch or continuous, typically equipped with a pressure gauge, thermometer, and automated controls. Batch retorts handle various container types with minor adjustments but have drawbacks like high energy and labor demands. The sterilization process has three stages: come-up Time, where heating raises the temperature to 115–121 °C at 15–20 psi; holding time, which maintains these conditions to kill microorganisms; and come-down Time, where cooling water reduces the temperature. Gradual cooling is essential to prevent packaging damage, with overpressure air used to maintain structural integrity (Jimenez et al., 2024). Table 2.11 shows the advances in retort processing of fruits and vegetables and tabe 2.12 provides information on retort processing of other ready to eat foods. Table 2.13 discusses the challenges and solutions of retort processing identified by previous researchers.

Table 2.8. Pulsed Electric Field (PEF)-Assisted Extraction of Fruit Juices

Fruit	Findings
Sugar beet cossettes	The application of PEF technology in cold juice extraction from sugar beet cosse significantly improved juice yield and quality, increasing yield from 29% to 8 enhancing purity, and reducing impurities. PEF treatment also led to larger sugar crys minimized sugar loss, and retained beneficial nutrients in the pulp, resulting in hig quality juice compared to conventional methods.
Apples	PEF treatment (450 V/cm, 10 ms, <3 kJ/kg) significantly increased juice yield, larger apple mash samples achieving 71.4% compared to 45.6% in untreated sm mash, while having no effect on the acid-sweet balance. However, it resulted in lo light absorbance and reduced native polyphenol content, likely due to oxidation indu by electroporation of cell membranes and subsequent adsorption of oxidized prod onto the mash.
	PEF treatment at 400 V/cm significantly improved juice yield, clarity, turbi reduction, and polyphenolic content, with higher antioxidant activity, especially in w apples. However, while PEF enhanced extraction efficiency and juice quality, it accelerated browning, particularly in whole apples, making it an energy-effic alternative to conventional juice processing methods.

	PEF treatment at 650 V/cm, 23.2 ms, and 32 kJ/kg increased apple juice yield f 71.1% to 76.3%, enhanced polyphenol concentration by 8.8%, and improved juice c and sensory properties, including aroma and flavor. While chemical composi remained unchanged, fructose and glucose content in the pomace decreased compare the control
Prickly pear	HPEF treatment at 8 kV/cm for 10 minutes significantly increased juice yield in pri pear varieties, with the Sandía variety showing the largest improvement, from 4.48 52.28%. Additionally, HPEF enhanced betalains, phenolic compounds, and antioxi activity, while the Orejón and Tapón Aguanoso varieties exhibited the highest c stability under pH and temperature variations.
Blueberries	PEF treatment at 1 kV/cm and 10 kJ/kg increased juice yield by 28% and enhan phenolic, anthocyanin, and antioxidant content, with no added benefits at higher fiel strengths, while also boosting bioactive compound retention in the press cake.
	PEF treatment of frozen and thawed European blueberries at electric field strengths to 5 kV/cm significantly increased cell permeability and disintegration, with the Zp in rising from 0.2 to 0.6. This resulted in greater polyphenol and anthocyanin rele enhancing antioxidant activity compared to untreated samples.

	PEF treatment at 3 kV/cm and 1–10 kJ/kg significantly boosted blueberry juice yield antioxidant levels, while enhancing anthocyanin recovery from press cake by up to 7 demonstrating its effectiveness for juice extraction and by-product valorization.
Raspberry	PEF pretreatment of raspberries at 1 kV/cm and 6 kJ/kg increased juice yield by 9– and enhanced the recovery of phenolics, anthocyanins, and antioxidant activity in press cake. This gentle PEF treatment proved effective for improving juice extrac and the recovery of beneficial compounds.
Sweet cherries	PEF treatment at 1 kV/cm and 10 kJ/kg enhanced juice yield, anthocyanin content, antioxidant capacity in "Duroni Nero" cherries, while press-cake treated at 0.5 kV showed the highest increases in bioactive compounds without anthocyanin degradat
Citrus fruits	PEF treatment at 3 and 10 kV/cm significantly enhanced juice yield and polyph extraction in oranges, pomelos, and lemons. Disintegration indicators confir effective tissue breakdown in both whole fruits and peel stacks, demonstrating P potential for improving citrus juice processing.
Sohiong juice	PEF treatment under optimal conditions (10 kV/cm, 60 seconds, 1:1 solid-to-liquid r significantly enhanced Sohiong juice yield and quality, boosting ascorbic acid, pheno anthocyanins, and antioxidant activity by up to 89%. Compared to thermal treatm PEF preserved desirable properties while SEM and FTIR analyses confirmed improved pomace porosity and efficient bioactive compound extraction.

Table 2.9. Advances in PEF Assisted Pasteurization of Fruit Juices and Fruit Based Beverages

Fruit juice	Findings
Apple juice	PEF treatment combined with 50 ppm LAE significantly enhanced microbial inactivatio juice, achieving over 5 Log_{10} reductions in pathogens at reduced treatment time, tempe energy input, offering an efficient, non-thermal alternative to conventional pasteurizatio
	This study demonstrated that combining PEF with mild heat (30 kV/cm, 1000 µs, 60 °C) inactivated Polyphenol Oxidase (PPO) and Peroxidase (POD) in red apple juice, with PC greater resistance. The treatment achieved enzyme inactivation comparable to conventio pasteurization while better preserving the juice's natural color, highlighting its potentia thermal preservation alternative.
	This study compared thermosonication (TS), pulsed electric field (PEF), and heat treatme Gala apple juice stored at 3°C and 20°C for 30 days, finding that TS and PEF-treated distinct flavors and better preserved antioxidant activity compared to heat-treated juic samples remained stable, with no fermentation or polyphenoloxidase reactivation, TS an identified as promising alternatives to thermal treatment, though refrigeration is recomi PEF-treated juice to maintain quality.
	This study examined the effects of PEF treatment on apple juice shelf life and nutritional finding that PEF preserved vitamin C and polyphenol content while effectively eliminati microorganisms. The juice remained stable for 72 hours with 400 pulses, maintaining

	activity and microbial safety, suggesting PEF as an effective method for enhancin preservation without compromising bioactive compounds.
Mango juice	This study evaluated the impact of High-Intensity Pulsed Electric Fields (HIPEF) on m finding that HIPEF treatment effectively reduced microbial contamination and enzyr while preserving color, sensory properties, and bioactive compounds better than thermal over 75 days of storage. HIPEF treatment maintained microbial stability and improve content, demonstrating its effectiveness in enhancing the shelf life and nutritional qualit juice.
Opuntia dillenii cactus juice	This study compared PEF, high hydrostatic pressure (HHP), and thermal pasteurizatic microbial inactivation and quality retention in *Opuntia dillenii* cactus juice, finding th HHP were more effective at preserving ascorbic acid, antioxidant activity, and bioactive c while achieving similar microbial inactivation as TP over 15 days.
Tomato and watermelon juice	This study assessed energy consumption and environmental impact for preserving t watermelon juice at a production capacity of 120 L/h, finding that high-pressure proces required the most energy, followed by PEF and thermal processing. Despite higher energ PEF and HPP preserved product quality better than thermal methods, and strategies energy efficiency and reduce environmental impact, such as optimizing raw materi packaging, were suggested.

Orange juice	This study compared the effects of thermal, high-pressure (HP), and PEF processing o pasteurization of orange juice, ensuring equivalent microbial inactivation. While a preserved most chemical and biochemical quality parameters, thermal and HP treatments effective in inactivating enzymes, particularly peroxidase and pectin methylesteras significant differences in other quality factors such as sugar content, bitterness, and vitar
	This study evaluated the cost of PEF pasteurization for orange juice, meeting US I standards and extending shelf-life to two months at 4 °C. The total cost was 3.7¢ per lite being 2.2¢ more expensive than thermal pasteurization, and while it effectively reduce load, its adoption has been slow due to limited cost analysis and industry resistance benefits.
	Moderate-intensity PEF processing at electric field strengths of 0.9 and 2.7 kV/cm, com heating between 65-90°C, effectively preserved the freshness and quality of orange juice, retention of flavor compounds and greater microbial inactivation compared pasteurization. PEF treatment at 78°C or higher reduced pectinmethylesterase (PMI ensuring cloud stability while maintaining juice quality.
	A cost-effective, portable electroporator for liquid food pasteurization using PEF techno developed, achieving a 5.4 log reduction in microbes and extending orange juice shelf days at 4°C without affecting quality. Compared to traditional thermal pasteurization,

	nearly half the energy while maintaining similar microbial inactivation, offering a susta efficient method for fruit juice preservation with potential for industrial applications.
	PEF treatment at 30 kV/cm for 10 pulses effectively achieved a 5-log microbial reduct orange juice while better preserving quality attributes such as pH, color, viscosity, vitami and minerals compared to conventional thermal pasteurization. It also consumed less generated less heat, making it a recommended method for maintaining both microbial nutritional value in juice processing.
	PEF pasteurization of Siam cultivar orange juice for 10 minutes (2 cycles) effective microbial safety without significantly affecting nutritional, physical, or chemical proper vitamin C, pH, and total soluble solids, making it the optimal treatment duration.
	This study evaluated the effectiveness of PEF, ultrasound, and thermosonication i *Paecilomyces variotii* spores in orange juice, finding PEF to be the most effective, espe followed by heat treatment. The combination of PEF and heat significantly damaged improved juice safety, offering a promising alternative to traditional pasteurization meth
	This study assessed PEF technology with heat recovery as a sustainable alternative to co high-temperature pasteurization for orange juice. Despite higher initial costs, PEF with and 20% thermal recovery proved more energy-efficient, cost-effective, and envir friendly, supporting sustainable food processing.

Strawberry juice	A pilot-scale study used PEF technology to pasteurize strawberry purée, achieving o reduction of *E. coli* and preserving color and flavor for three months. A cost-eff acquisition system monitored over 1.4 million pulses per hour, offering reliable validatior FDA approval of the method.
	This study compared HPP, US, and PEF to thermal pasteurization for preserving straw finding all nonthermal methods effectively reduced microbial counts while better r enhancing antioxidant properties. HPP and PEF notably improved total phenolic cont scavenging activity, and anthocyanin levels, indicating their strong potential as quality- nonthermal alternatives for juice processing.
Sour cherry juice	The study investigated how PEF treatment affects sour cherry juice and found that i antioxidant capacity without degrading key nutrients or forming harmful compounds l and HMF. Optimal results were achieved at 350.9 µs, 6.78 kV/cm, and 98 Hz, with freque a greater effect than electric field strength on juice properties.
Pomegranate fermented beverage	The study optimized PEF treatment for milk-date beverages and found that conditions of off time, 80 pulses, and storage at 5 °C effectively minimized microbial growth and product stability for six days. PEF significantly affected microbial load, pH, color, and t solids, supporting its use as a reliable method to preserve quality and extend shelf temperatures.

Table 2.10. Combination of PEF with Other Non-Thermal Technologies

Combination	Findings
Thermosonication and PEF	The study compared thermosonication followed by PEF treatment to HTST pasteuriza juice, showing similar sensory acceptance and stable physical properties over 168 d However, TS/PEF-treated juice had slightly higher microbial counts and noticea differences, suggesting a need for further optimization to enhance overall quality
Sonication and PEF	The study investigated the combined effects of sonication and PEF on grapefruit juic significant changes in pH, acidity, °Brix, or conductivity, but a decrease in viscosity ar in cloud value. The treatment also reduced enzymatic browning, indicating its potenti juice quality for commercial processing.
High power ultrasound and PEF	The study found that combining high-power ultrasound (HPU) with PEF treatmen preserved bioactive compounds in strawberry juice, especially when HPU was applie and with shorter treatment times. Despite a decline in antioxidant activity over storag showed strong potential for maintaining juice quality and could be suitable for industr
Membrane-assisted pulsed electric field (M-PEF) technology	The study employed membrane-assisted PEF (M-PEF) to enhance juice preservation, u membrane followed by PEF at varying field strengths and pulse widths. Optimal c kV/cm, 150 μs) significantly reduced enzyme activity and microbial load while preser acid, boosting antioxidant capacity, and removing proteins and polysaccharides, highlighting M-PEF's effectiveness for fresh juice processing.

Table 2.11. Advances in Retort Processing of Fruits and Vegetables

Fruit product	Findings
Pureed pumpkin, peas in brine, and pineapple in juice	The study compared metal cans and retort pouches for three food types, fin significantly reduced processing times and better preserved quality in homoge heated foods like pureed pumpkin. However, for particulate foods in liquid, a more efficient, suggesting that the benefits of pouches depend on the product ty
Canned apricot juice, papaya puree, apricot nectar, papaya nectar, and two apricot-papaya nectar blends.	The study investigated thermal processing of various apricot and papaya juice p penetration data and predictive modeling to optimize processing conditions for safety, and nutrient retention. Sensory evaluation identified 50:50 and 60:40 pap blends as the most preferred options.
Carrot pieces	The study noted that while thermal processing extends shelf life, it can neg quality of fruit- and vegetable-based foods by reducing vitamins and altering te may also improve nutrient bioaccessibility, and understanding these changes processing to preserve overall food quality.
Tender jackfruit	The study optimized blanching and thermal processing methods for retort po jackfruit, identifying 0.3% citric acid blanching for three minutes as ideal. samples showed the best texture, color, and microbial stability, remaining safe the method proved cost-effective at Rs. 11.51 per 140g pouch for year-round a

Jackfruit varatty	The study developed a shelf-stable jackfruit varatty using retort pouch thermal p that pasteurization at 100 °C with refrigerated storage preserved the best qualit While ambient storage for 90 days was also microbiologically safe and cost-ef 100g pouch), refrigeration provided superior sensory and physicochemical resu
Tomato salsa	The study developed heat-processed tomato salsa (HPTS) using retort pouches significantly extending shelf life compared to fresh salsa. Both packaging n quality and minimized microbial activity, with HDPE packs maintaining acceptability for 90 days and retort pouches for 60 days.
Tender jackfruit.	The study optimized thermal processing of tender jackfruit, achieving seve preservative-free storage with pasteurization at 90 °C for 19 minutes and steri for 8 minutes. It also demonstrated that near-infrared reflectance spectrosc effective, non-destructive method for assessing jackfruit quality, especially us and dry spectra.
Canned mango and pineapple	The study examined how thermal processing impacts phytochemicals in ca pineapple, finding that higher temperatures led to nutrient degradation and le with mango retaining more bioactive compounds overall. Strategies like lo reduced liquid, steam blanching, or microwave pretreatment were recommende nutritional quality during commercial canning.

Table 2.12. Retort Pouch Processing of other Ready to Eat (RTE) Foods

Food	Findings
Cassava	The study optimized thermal processing protocols for two cassava varieties, ide ideal blanching and processing conditions that ensured microbiological safety for u months under refrigeration. Sensory evaluations showed the processed cassava resembled fresh, offering a cost-effective (Rs. 19.20 per 100g pouch), ready-to-eat suitable for year-round industrial use.
Coconut skim milk	The study developed and optimized a retort pouch processing protocol for ready-t flavored coconut milk, identifying 85 °C for 30 minutes as the ideal condition sensory quality. This process also enhanced microbial safety during storage, with n impact on product quality.
Coconut neera	The study compared pulsed light (PL) and retort processing, finding that PL caused n changes to the drink's properties but led to a 28% loss of ascorbic acid, whil processing resulted in more significant color changes and up to 64% ascorbic acid lo optimal conditions for PL were 150 pulses at 5 mm depth and 7 cm distance, whil processing at 82 °C for 19 minutes achieved the best microbial reduction, with sh lasting 25 days for retort-treated samples and 20 days for PL-treated ones un refrigeration.

Table 2.13. Retort Processing of Foods- Challenges and Solutions

Challenges	Findings
Browning	The study identified that oxygen trapped in pouches and ascorbic acid degradation w causes of browning and texture deterioration in MRE pears, particularly when using c By optimizing vacuum packaging, increasing vacuum time, incorporating agitated r switching to fresh D'Anjou pears, the quality and shelf life of MRE pear rations were improved.
Furan formation	The study identified furan as a common contaminant in thermally processed baby recommended VRTP and retortable pouches to reduce its formation, preserve quality, texture for vulnerable consumers.
Discoloration	The study found that while A2P and Pycnogenol were ineffective, α-glucosyl rutin reduced browning and preserved ascorbic acid in diced peaches, making it a promisi for improving shelf life in MRE rations.
Fungal contamination	The study examined fungal contamination in pasteurized fruit and vegetable-base finding that heat-sensitive fungi (HSF) were the most common, followed by heat-ser (HSM) and heat-resistant fungi (HRF). It emphasized the need for improved sanitat practices, and preventive measures like HEPA-filtered air and UV technology to e sterilization and prevent post-processing contamination.