Review of literature

CHAPTER II

REVIEW OF LITERATURE

This research project aims to standardise and evaluate ripe jackfruit's thermal and non-thermal processing, specifically its bulb and pulp. To achieve this, a thorough literature review was conducted to gather relevant information that aligns with the project's objectives.

2.1 Jackfruit (*Artocarpus heterophyllus L.)*

Jackfruit (*Artocarpus heterophyllus Lam*.), a member of the Moraceae family and the Rosales order, is believed to have originated in the rainforests of southwestern India, specifically the Western Ghats (Swetha and Ranganna, 2016). Today, it is cultivated extensively in various tropical regions around the world, including Southeast Asia, West Africa's evergreen forests, northern Australia, and southern Florida (Shyamalamma *et al*., 2016). Countries in Southeast Asia and the Caribbean are significant producers of jackfruit, with India being a major contributor. In India, jackfruit cultivation is prominent in both southern and northeastern states such as Kerala, Karnataka, Andhra Pradesh, Tamil Nadu, Assam, Tripura, Bihar, Uttar Pradesh, and the Himalayan foothills. It is commonly referred to as "poor man's food" in eastern and southern India due to its affordability and nutritional value (Srivastava *et al*., 2017). Kerala stands out as one of the primary region for jackfruit cultivation in India, with approximately 156,000 hectares dedicated to this fruit. The annual production in Kerala reaches around 1.826 million metric tons, resulting in an impressive productivity rate of 12 metric tons per hectare (Anon, 2022). This significant yield highlights jackfruit's importance as a staple agricultural product in the state, contributing to local consumption and potential export markets. Jackfruit is renowned for being the world's largest fruit, capable of growing over ten inches long and reaching up to forty inches in size. The ripe fruit features yellow flesh with a sweet flavour that distinguishes it from other tropical fruits. Nutritionally, jackfruit is rich in starch and protein and serves as an excellent source of essential vitamins and minerals such as vitamins A and C, calcium, potassium, sodium, thiamin, iron, and zinc (Dey and Baruah, 2021). Its high carotene content and substantial vitamin C levels play a crucial role in protecting against free radicals, enhancing immune function, and promoting gum health. Compared to other tropical fruits, jackfruit is particularly notable for its elevated levels of protein, calcium, iron, and thiamine (Dey and Baruah, 2021).

India ranks among the top producers of jackfruit, a tropical fruit that thrives in warm and humid conditions, particularly on hilly terrains and in hot plains. This versatile fruit serves multiple roles, with immature jackfruits often prepared as vegetables and ripe ones enjoyed as fresh fruit. Traditionally, jackfruit trees produce fruit once a year, with flowering occurring between November and February, depending on the location and variety (Fathin *et al*., 2021 and Mandave *et al*., 2022). The tender fruits become available in the market from March to August, with ripening taking place in June. However, the fruit's high water content and soft texture make it highly perishable, resulting in significant wastage (around 30-34%) during the peak season (June-July) due to inadequate post-harvest handling practices (Shinde *et al*., 2021). To address this issue, processing and preservation techniques are essential to extend the fruit's shelf life, create diverse and appealing food products, and generate income and employment opportunities.

2.2 Nutritional benefits of jackfruit

Jackfruit (*Artocarpus heterophyllus*) is a tropical fruit renowned for its rich nutritional profile and potential health benefits. The edible pulp of jackfruit is a significant source of carbohydrates, providing approximately 18.9 grams per 100 grams, along with 1.9 grams of protein, 0.1 grams of fat, and 1.1 grams of fiber, making it an energy-dense food (Rahman and Nahar, 1990). Additionally, it is rich in essential minerals such as calcium (20 mg), phosphorus (30 mg), and iron (500 µg) per 100 grams, which play a crucial role in bone health, muscle function, and oxygen transport (Bobbio *et al*., 1978). The nutritional composition of ripe jackfruit in 100 g edible portion-fresh weight basis recorded from previous researches is listed in Table 2.1 below

Table 2.1 Nutritional composition of ripe jackfruit (100 g edible portion-fresh weight basis)

Proximate	Water (g)	72.0–94.0	
composition	Protein (g)	1.2−1.9	
	Fat (g)	0.1−0.4	
	Carbohydrate (g)	16.0–25.4	
	Fiber (g)	1.0–1.5	
	Energy (kJ)	88−410	
Elemental profile	Calcium (mg)	24	source:
	Iron (mg)	0.23	Swami *et al*.,
	Magnesium (mg)	29	2012,
	Manganese (mg)	0.043	Waghmare *et*
	Phosphorous (mg)	21	*al*.,2019 and
	Potassium (mg)	448	Villacís-
	Sodium (mg)	2	Chiriboga *et*
	Zinc (mg)	0.13	*al*., 2020
Vitamin profile	Thiamine (mg)	0.105	
	Riboflavin (mg)	0.055	
	Niacin (mg)	0.92	
	Pantothenic acid	0.235	
	(mg)	0.329	
	Vitamin B6 (mg)	24	
	Folate (µg)	13.8	
	Vitamin C (mg)		
	Phenolics (mg GAE/g)	0.18 to 0.46	
	Carotenoids content (µg/g FW)[2]	1.32	

FW: Fresh Weight

Jackfruit is notably high in vitamins, particularly vitamin C, with 13.7 mg per 100 grams, which plays a role in immune support and antioxidant protection (Swami *et al*., 2012).

It is also a good vitamin A (540 IU) source, contributing to vision health and skin maintenance (Hossain *et al*., 2020). Additionally, it provides B-complex vitamins such as thiamine, riboflavin, and niacin, which are essential for energy metabolism and nervous system function (Nansereko and Muyonga, 2021). Furthermore, jackfruit's low-fat and high-fiber nature makes it a suitable dietary choice for weight management and cardiovascular health (Healthline, 2022). The high antioxidant content in jackfruit, derived from carotenoids, flavonoids, and phenolic compounds, contributes to its anti-inflammatory and disease-preventing properties (Brahma and Ray, 2023).

2.3 The challenges and opportunities of jackfruit processing and preservation

Jackfruit, a tropical fruit renowned for its unique aroma and crunchy, sweet flesh, is a versatile ingredient that can be consumed raw or cooked in a variety of dishes. It is a promising crop for addressing food security and poverty in rural and urban areas, offering a wealth of opportunities for value-added products. The fruit's various parts, including the pulp, peel, and seed, can be utilized to create a range of products. Ripe jackfruit bulbs can be canned in syrup or mixed with dehydrated bulbs to make chutney, preserves, candy, concentrates, and powder. Ripe jackfruit pulp is used to make various products such as juice, biscuits, jam, jelly, leather, RTS products etc. making it a valuable resource for sustainable development. However, its massive size, often exceeding 45 kg, and handling difficulties have hindered its marketing (Jagadeesh *et al*., 2007). Since only one-third of the fruit is edible, jackfruit is a prime candidate for minimal processing, allowing for efficient use of its edible parts.

The demand for fresh cut fruits has experienced rapid growth in recent years. According to Bansal *et al.* (2015) minimal processing is gaining popularity over traditional preservation methods due to its superiority in terms of sensory quality and nutritional value. Furthermore, the food service industry is shifting towards using pre-prepared ingredients to reduce handling and operating costs, thereby increasing efficiency. However, the fruit's high perishability and susceptibility to mechanical injuries result in significant wastage, with an estimated loss of Rs 2,000 crore in India alone (Anaya-Esparza *et al.*, 2018). Given the short shelf life of fresh jackfruit, preserving it as fresh-cut pieces or pulp is crucial to extend its availability and stabilize prices during peak seasons. Modern consumers increasingly favour diets high in natural antioxidants, dietary fibres, natural colourants, minerals, vitamins, low calories, low cholesterol, low sugar, and free from chemicals (Shinde *et al*., 2021). To address the significant postharvest losses of jackfruit, it is essential to research innovative technologies for better preservation quality of safe jackfruit bulbs and pulp, enhancing its value and utilization.

Thermal and non-thermal preservation methods play a major role in preserving ripe jackfruit and extending its shelf life. The choice of preservation method depends on various factors, including the type of jackfruit, its intended use, and the desired shelf life. Thermal preservation methods are often preferred for commercial-scale applications due to their ease of implementation and cost-effectiveness. However, non-thermal preservation methods offer a promising alternative for small-scale producers and consumers who prioritize natural and minimally processed products (Nelluri *et al*.,2022).

2.4 Thermal preservation of fruits

The preservation of ripe jackfruit through thermal methods has gained significant attention due to its potential to prolong shelf life. Thermal processes can be categorized based on the intensity of heat treatment applied (Miller and Silva, 2012). The high temperature long time method, which involves temperatures around 80°C with holding times exceeding 30 seconds, is frequently utilized in processing juices and beverages. This method can be further classified into pasteurisation (below 100°C), canning (approximately 100°C), or sterilisation (above 100°C) (Miller and Silva, 2012). The goal of thermal preservation is to reduce the most resistant microorganisms by 5 logs. This process uses external heat, which is then transferred to the food through conduction and convection. Prolonged exposure to high temperatures can lead to cell death by causing gradual changes in membrane permeability, including lipid phase transitions and protein conformation alterations. The degree of membrane fluidity changes depends on the type of thermal stress applied (Chen *et al*., 2013). Thermal processing has been shown to effectively reduce microbial growth and enzymatic activity, thereby enhancing shelf stability with a significant effect on the physicochemical properties (Saxena *et al*., 2012 and Chen *et al*., 2013).

A study by Rathod *et al*. (2014) investigated the effects of thermal processing on the nutritional quality of amla and bael blend juice processed at 80°C to 90°C for a duration of 25 seconds. The findings revealed that treating the blend at 90°C yielded the best results in terms of nutritional quality. This optimal temperature treatment helped in retaining the essential nutrients and bioactive compounds present in both amla and bael juice, which are known for their high vitamin C content, antioxidants, and other beneficial phytochemicals. The treatment also ensured microbial safety and extended shelf life, making the juice blend more suitable for consumption while maintaining its nutritional integrity.

The total sugars content was significantly higher when the carrot and grape blended nectar was subjected to a thermal treatment of 80°C for 5 min. According to Yadav *et al*. (2015), this specific temperature and duration not only helped in retaining the sugars present in the blend but also potentially enhanced their extraction and concentration. This finding underscores the importance of optimizing thermal processing conditions to maximize the retention of desirable nutritional components in fruit and vegetable nectars.

As per the study conducted by Thomas *et al*. (2015), black mulberry juice processed at 107°C for 3 min. exhibited significantly higher total phenolic content, total flavonoid content, monomeric anthocyanin content, and total antioxidant capacities compared to the raw fruit. However, during in vitro simulated gastrointestinal digestion, the monomeric anthocyanins were more bioavailable in the raw fruit matrix than in the juice matrix. The impact of thermal preservation on the physical and chemical properties of fruits and vegetable beverages has also been extensively studied, with thermal treatment found to influence the physico-chemical properties, which are critical quality indicators (Petruzzi *et al*., 2017). The high heat can lead to the degradation of heat-sensitive nutrients, alter the texture and consistency of food, and affect its sensory properties (Allai *et al*.,2023). These changes can significantly impact the overall quality and nutritional value of the food. Although pasteurisation ensured and prolonged microbial safety of watermelon and pineapple juice, it had affected adversely on the colour, ascorbic acid and enzyme activities of pasteurized juices. Treatment time of 10 min significantly reduced the ascorbic acid content of both juices (Mandha *et al*., 2023).

Yıkmış *et al*. (2023) analyzed the thermosonicated and thermal pasteurized black grape juice for its bioactive components, nutritional content, and aroma profile. Thermal pasteurisation resulted in low sensory as well as lower retention of bioactive components, nutritional content, and aroma profile compared to thermosensation process. The study suggests thermosonication as a promising alternative to thermal pasteurisation, potentially improving the juice's taste and bioactive properties. Future research should focus on the amino acid content, phenolic compounds, and health benefits such as anticancer and antimicrobial properties.

Zhang *et al*. (2024) conducted studies on ultra-high pressure, thermal pasteurisation, and ultra-high temperature sterilisation of freshly-squeezed lettuce juice. The study revealed that thermal pasteurisation and treatments significantly affected the physico-chemical characteristics of lettuce juice. The chlorophyll content and total soluble content of juice were reduced significantly with these treatments and it amplified the loss of fat-soluble vitamins.

Despite some disadvantages, thermal processing methods like retort pouch packaging remain commercially viable due to their numerous advantages in preserving food products. Retort pouches offer a lightweight, flexible, and shelf-stable packaging solution, eliminating the need for refrigeration or cold chain logistics, which is particularly beneficial in regions with limited access to these resources. The extended shelf life of thermally processed foods also reduces food waste and allows for broader market distribution, making it attractive for both manufacturers and consumers. Although there are challenges such as potential nutrient loss and higher initial equipment costs, the overall cost savings in transportation, storage, and reduced spoilage make this technology a profitable option for large-scale food production. Moreover, the growing demand for convenient, ready-to-eat meals further supports the adoption of retort pouch packaging in the food industry.

2.4.1 Retort pouch processing

Retort thermal processing, commonly referred to as retort pouch processing, ensures commercially sterile food products by eliminating pathogenic and spoilage-causing organisms while allowing for some heat-resistant bacterial spores that cannot grow under normal storage conditions. These products typically have a shelf life of 2 to 5 years, constrained by quality degradation rather than bacterial spoilage (Clark, 2009). The retorting process involves placing food in sealed containers/flexible pouches and heating them in a large pressure cooker called a retort, where specific temperatures above the boiling point of water are maintained for precise durations depending on the nature of fruit and several other parameters. The processing time and temperature must be sufficient to render the product commercially sterile. After cooking, the container is cooled to room temperature for further study. Key factors such as decimal reduction time (D), thermal resistance constant (z), and thermal death time (F) values are used to determine appropriate processing times and temperatures to achieve commercial sterility while minimizing nutrient loss and sensory degradation.

Establishing an effective thermal processing schedule requires determining the appropriate heating duration at a specific temperature. This process involves assessing the thermal destruction rate of a target microorganism or enzyme under actual processing conditions. Additionally, understanding how microbial destruction or enzyme inactivation varies with temperature is crucial, particularly during the come-up time, when the product reaches the desired processing temperature.

The microbial destruction rate is quantified by the decimal reduction time (D value), which represents the time in min. needed at a given temperature to reduce the microbial population by 90%. Higher temperatures generally result in lower D values, indicating faster microbial reduction. By plotting the logarithm of D values against temperature, a thermal resistance curve is generated, revealing the temperature sensitivity indicator, or Z value. The Z value signifies the temperature range required to alter D values by a factor of ten.

The effectiveness of thermal processing in eliminating microorganisms is measured using the F value or lethality. This metric assesses the overall sterilisation impact of heat treatment. To compare different sterilisation processes, a standard lethality unit corresponds to 1 minute of heating at a reference temperature—commonly 121.1°C for sterilisation and 82.2°C for pasteurisation (Singh and Heldman, 2009).

For thermal processes involving a food product's exposure to a time–temperature profile, the cumulative lethal effects are calculated using the following equation:

$$Fo = \int 10^{(T - T_o)/Z} \, dt \qquad ....(2.1)$$

where, T = Product temperature

To = Reference Processing temperature

Z = Temperature range required for a one-log cycle change in D value

The resulting lethality, denoted as process lethality, represents the overall effectiveness of the heat treatment (F_0). In acidic foods, such as fruits, processing aims primarily at reducing spoilage-causing bacteria and deactivating heat-resistant enzymes rather than achieving complete sterilisation.

The primary concern in canned/retort processed foods is anaerobic bacteria, particularly *Clostridium botulinum*, which can produce a deadly toxin under favorable conditions. The industry employs the 12-D concept to ensure that the thermal process effectively reduces the survival probability of these spores to one in a billion containers. Additional heat treatments are often applied to account for other heat-resistant spoilage bacteria, with *Bacillus stearothermophilus* frequently used as a non-pathogenic surrogate for testing process effectiveness (Clark, 2009).

2.4.2 Retort pouch processing system

Various types of retorts have been developed to meet the diverse needs of packaging and manufacturing in thermal food processing, and they are primarily classified by the method of heating, batch vs. continuous operation, and the mode of agitation. Common heating methods include saturated steam, water immersion, water spray, and steam-air systems (Al-Baali, and Farid, 2007). Saturated steam retorts, typically used for metal cans, are energy-intensive but cost-effective. They require steam saturation to prevent air pockets that could insulate containers and reduce efficiency, with overpressure sometimes applied during cooling to avoid container deformation. Water immersion and water spray retorts enable overpressure processes, making them suitable for more fragile containers like glass or flexible pouches. Steam-air retorts use fans to mix air and steam, ensuring even heating without cold spots, thus accommodating various container types.

Steam air retorts are typically configured in either a vertical or horizontal (Figure 2.1) orientation. These metal pressure vessels are equipped with several key features, including a steam inlet (A), water inlet (B), venting outlets for releasing air during the retort's heat-up phase and for draining (D), outlets for venting at the end of the cycle (C), and a safety pressure relief valve (F). Additionally, the vessel is outfitted with a pocket for instruments such as a thermometer, a temperature-recording probe, and a pressure gauge.

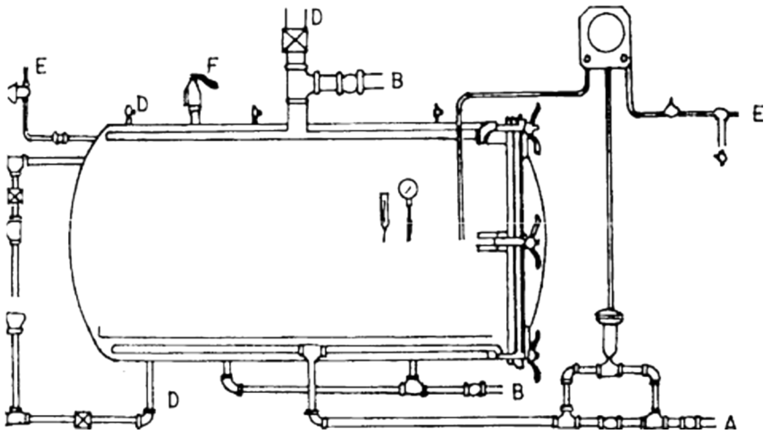


Figure 2.1 Horizontal retort machine

(*Source: Al-Baali, and Farid, 2007*)

The operation of this retort begins by heating it to approximately 121°C. Steam is introduced to remove all air from the retort and the spaces between containers (venting), after which the retort reaches the target pressure and processing temperature (Al-Baali, and Farid, 2007). Once processing is complete, the steam is turned off and a combination of cooling water and air is introduced to cool the containers. The air helps maintain pressure as the remaining steam condenses; without this, containers could deform due to pressure imbalances between the interior and exterior. Current efforts in thermal sterilization aim to enhance heating rates, thereby boosting production efficiency while minimizing quality degradation in the product (Caufield, 2014).

Retorts are also categorized as batch or continuous systems. Batch retorts require manual loading and unloading, with each batch undergoing separate heating and cooling phases, adding time and labour to the process. In contrast, continuous retorts streamline production by allowing containers to enter and exit without temperature and pressure fluctuations, reducing processing time and labour costs. Continuous systems, such as rotary and hydrostatic retorts, rely on conveyors for automated container movement, where the residence time depends on conveyor speed. Retorts can further be divided based on agitation: static retorts hold containers stationary, while rotary and oscillating systems agitate the containers to improve heat distribution. Rotary retorts are widely used for metal cans, while oscillating retorts, a newer innovation, can handle a variety of container types, including flexible pouches and semi-rigid trays (Ramesh, 2020).

2.4.3 Retort pouches

Retort pouches are a type of flexible packaging designed for shelf-stable and sterilized food products, such as soups, stews, and sauces. Made from layers of nylon, polyethylene film, and aluminum foil, these pouches create an oxygen-free environment that prevents spoilage. They are hermetically sealed to withstand high temperatures during thermal processing, resulting in an extended shelf life without the need for refrigeration. This convenience has led to their growing popularity among both manufacturers and consumers, as they are easy to transport and store.

The concept of retort pouches originated in the 1950s, promoted by the US Army and later developed by the United States Army Natick R&D Command in collaboration with Reynolds Metals Company and Continental Flexible Packaging (Primepac., 2020). Their introduction marked a significant innovation in food packaging, leading to a shift away from traditional canning methods. Although there was initial resistance to this new packaging format, its advantages—such as improved nutrient retention and customization options—have been recognized over time. The internal structure of retort pouches consists of four layers: propylene for heat sealing, nylon for abrasion protection, aluminum for light and gas barrier properties, and polyester for strength and printability, all made from FDA-approved materials that enhance durability through thermal processes (plate 2.1) (Caufield, 2014).

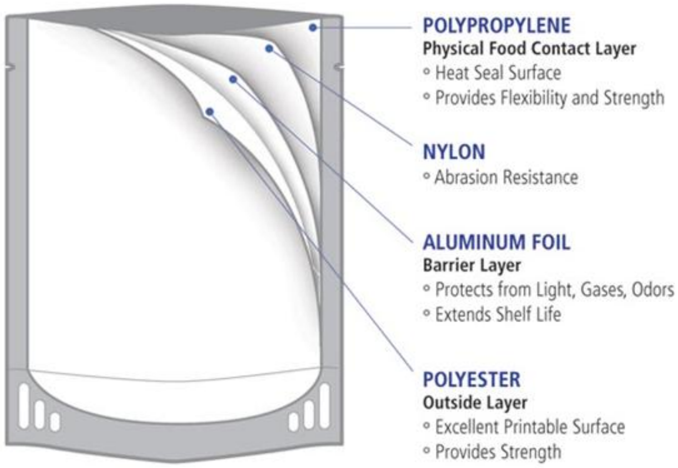


Plate.2.1 Laminate film layers in a retort pouch (Primepac. 2020)

Retort pouch technology is rapidly becoming a popular packaging solution in today's consumer market. In a country like India, where maintaining refrigeration and cold storage can be challenging, retort foods present a significant opportunity to boost the consumption of ready-to-eat (RTE) processed foods. This opens up a promising avenue for entrepreneurs to explore and capitalize on the potential of this innovative technology (Varalakshmi *et al*., 2014).

2.4.4 Effect of retort pouch processing on food products

Retort pouch processing has been widely utilized for various food products to extend shelf life while maintaining safety and sensory attributes. The process involves sealing the food in heat-resistant, flexible pouches and subjecting them to thermal sterilization. This technology is especially advantageous for RTE foods, as it ensures long-term storage at ambient temperatures. In a study by Sreelakshmi *et al*. (2015), retort pouch processing was applied to a ready-to-serve sandwich spread made from mud crab (*Scylla serrata*), processed at different temperatures and F0 values. The optimized process, with conditions of 116°C for 6 min., achieved the best results in terms of texture, colour, and commercial sterility. The total processing time was 42.59

min., with a cook value of 84.29, making it the most favourable combination for maintaining product quality.

Shah *et al.* (2017) explored the retort processing of Rogan josh, a traditional Kashmiri meat dish, and demonstrated that thermal processing at 121°C with F0 values between 7 and 11 min. effectively preserved the product's quality for up to 12 months at ambient temperature. Despite a decline in pH, shear force, and sensory attributes during storage, the product remained microbiologically safe. The study indicated that the samples processed with an F0 value of 9 min. showed the highest overall acceptability in terms of sensory characteristics, suggesting that this method could increase the market demand for such traditional products due to their convenience and long-term storability.

In another study, Pal *et al*. (2019) investigated the effect of retort processing on the Indian dessert, chhenapoda. Using a Response Surface Methodology (RSM), it was found that adding 18.5% sugar and 7.5% semolina to cottage cheese resulted in an optimal formulation. Retort processing at 120°C for 30 min. significantly reduced the total plate count from 110 × 107 to 4 × 104 and eliminated yeast and mold counts. This method produced a microbiologically safe product with acceptable sensory qualities that could be stored for up to 30 days under refrigerated conditions, highlighting the potential for improving the shelf life of dairy-based products through thermal processing.

According to previous research, a study on the development of a RTE thermally processed rice pulav using retort processing revealed that optimal processing parameters of 117.67°C for 22.4 min. resulted in a product with high overall acceptability and desirability (Thakur and Rai, 2018). The study further investigated the product's stability during 180 days of storage at ambient temperature, subjecting it to various chemical, microbial, and sensory analyses. The findings indicated that while the product exhibited an increase in certain chemical parameters, such as free fatty acid, thiobarbituric acid, and peroxide values, over the 180-day storage period, it maintained a satisfactory sensory and microbiological profile.

Research conducted by Krishnaprabha *et al*. (2019) has shown that retort pouch processing is effective in extending the shelf life of traditional Indian foods like Ramasseri idli. For instance, the study indicated that retort-processed idli can be safely stored for up to three weeks without microbial contamination or significant quality degradation, based on physico-chemical assessment. Additionally, the study determined that the ideal thermal processing conditions for retort-pouched idli were 100°C for an F value of 6 min., which maintained physico-chemical, microbiological, and sensory qualities similar to the control sample when refrigerated.

Most recently, Jeyapriya *et al.* (2024) optimized the process schedule for retort pouch processing of chevon patties, finding that the third treatment (retort temperature of 114°C and product core temperature of 90°C) required 15 min. of heating and 7 min. of cooling, achieving a total lethality (F0) of 11.093. The heating lag factor was 1.10, while the cook value was 73.26 min.. This treatment also had the highest heating rate index and sterilization efficiency. Patties processed with an F0 of 11.093 received better sensory scores, reinforcing the efficacy of retort processing in maintaining product quality.

These studies collectively demonstrate that retort pouch processing, despite being a thermal method, can be optimized for different food products to retain sensory attributes, achieve commercial sterility, and significantly extend shelf life. However, optimizing thermal processing parameters to balance microbial safety and quality preservation remains a challenge, requiring further research to refine these techniques for industrial applications. Overall, while thermal preservation offers a viable approach to extending the shelf life of products, ongoing innovations, and rigorous quality assessments are necessary to enhance its effectiveness and consumer acceptance.

Non thermal preservation is an alternative processing technology for quality preservation and shelf-life extension of these products. These technologies are designed to maintain the benefits of conventional heat treatment methods while addressing their inherent drawbacks

2.5 Non thermal preservation of food

The growing consumer preference for fresh and natural foods, devoid of artificial additives, has prompted researchers to explore innovative technologies that minimize the use of chemicals while preserving the natural flavours and quality of food products. In response, novel non-thermal techniques are being developed to ensure food safety without compromising nutritional value, as they have been shown to be less effect on food products compared to traditional methods (Koutchma *et al*., 2016). Non-thermal processing technologies offer a gentler approach to food processing by primarily targeting non-covalent bonds. These bonds include hydrophobic, hydrogen, electrovalent, and ionic bonds, which are crucial in maintaining the structure and functionality of food molecules (Bevilacqua *et al*., 2018). By focusing on these bonds, non-thermal methods allow for the denaturation, inhibition, and gelatinization of proteins, enzymes, and starches. Additionally, these technologies are effective in destroying microorganisms and pathogenic bacteria. The key advantage is that this process preserves the molecular structure of the food, maintaining its nutritional and sensory qualities.

According to researchers, the aroma and exotic flavour of ripe jackfruit are vital quality attributes that significantly impact consumer acceptance. They have noted that thermal preservation methods negatively affect these qualities in fruit juices (An *et al*., 2019, Wang *et al*., 2019). Consequently, there is a demand for preservation techniques to better preserve jackfruit's flavour compounds. Advanced non-thermal preservation methods, such as high-pressure processing and PL technology, are highly effective in maintaining the quality characteristics of fruits and vegetables (Fernandez *et al*., 2019; Mandal *et al*., 2020).

This research work is emphasis on the effect of thermal and non thermal preservation technique to optimize the preservation conditions for ripe jackfruit bulbs and pulp.

2.5.1 High pressure processing

HPP is a cutting-edge technology that has significant attention in the food industry for its ability to preserve fruits and vegetables while maintaining their nutritional and sensory qualities (Chakraborty *et al.,* 2014). In high-pressure processing, the food products are typically subjected to extremely high pressures (typically 100-1000 MPa or 100 MPa or higher) to kill enzymes, microbes, and other components that contribute to spoilage reactions in food products (Elamin *et al*., 2015). This process is effective in extending the shelf life of fruits and vegetables by inactivating enzymes responsible for spoilage and quality degradation

The behaviour of foods under HPP follows three key principles: Le Chatelier's Principle, Isostatic Pressing, and the Microscopic Ordering Principle. Le Chatelier's Principle states that high-pressure shifts equilibrium, reducing volume and altering food components like proteins and enzymes. Isostatic Pressing (Pascal's Principle) ensures uniform pressure distribution, allowing food to retain its shape after decompression. The Microscopic Ordering Principle explains that increasing pressure enhances molecular organization, while heat disrupts it, highlighting their opposing effects. These principles collectively explain how HPP modifies food while preserving its quality (Gopal *et al*., 2017). Gopal *et al*. (2017) reported that pressure severely affects non-covalent bonds, causing low molecular weight food components to remain intact under such conditions. They also noted that since HPP operates independently of the sample's size and geometry, processing time can be minimized.

In a typical HPP procedure, the prepacked product is placed in a flexible container and loaded into a high-pressure chamber filled with a hydraulic fluid, usually water. The fluid is pressurized, transmitting the pressure through the packaging into the food (Plate 2.3), and maintained for a few min. This HPP technique allows for uniform and instantaneous transmission of pressure throughout the product, regardless of its size or shape (Plate 2.2). As a result, HPP can effectively inactivate microorganisms and enzymes, extending the shelf life of food while preserving its nutritional and sensory qualities. After processing, the product is removed and stored or distributed using conventional methods (Daher *et al*., 2017).

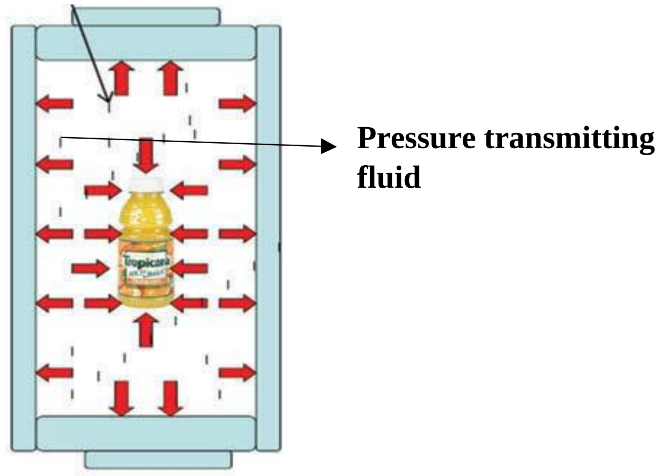


Plate.2.2 Isostatic principle in HPP unit (*Source: Abera, 2019***)**

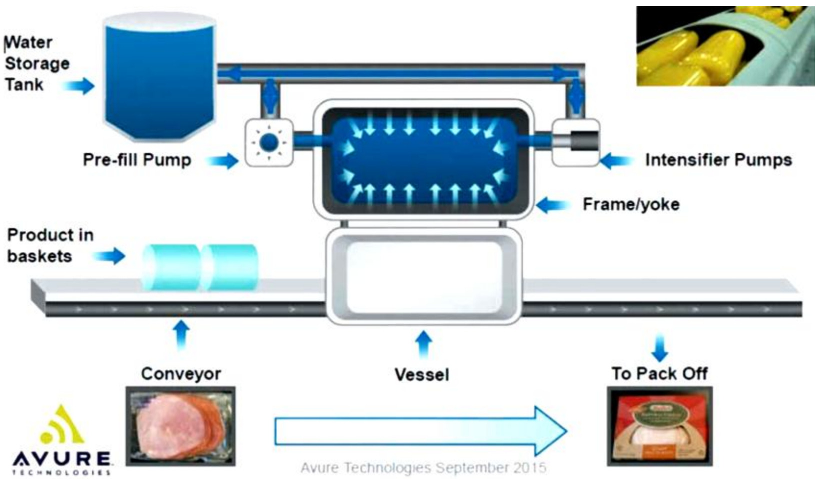


Plate 2.3 Working of HPP unit (*Source: Abera, 2019*)

Industrial HPP systems are classified into batch, continuous, and semi-continuous modes. Both batch and continuous systems are suitable for high-pressure pasteurization. The batch system offers versatility, handling both liquid and solid products, typically pre-packaged before processing. In contrast, continuous and semi-continuous systems are designed exclusively for liquid or pumpable products (Sharma *et al*., 2020).

During HPP, food products undergo volume reduction as pressure increases. In the compression phase (Ts–Tm), both pure water and food products subjected to 600 MPa at ambient temperature experience approximately a 15% volume decrease (Sharma *et al.*, 2020). The product remains at high pressure for a set duration (Tm–T2) before decompression (T2–Tf), where it generally returns to its original volume. However, due to heat dissipation during compression, the final temperature (Tf) is often slightly lower than the initial temperature (Ts). The temperature rise in food products under pressure varies based on factors such as final pressure, product composition, and initial temperature. These principles align with Le Chatelier's Principle, which explains volume reduction under pressure, and Isostatic Pressing, ensuring uniform compression and expansion. Understanding these effects is crucial for optimizing batch, continuous, and semi-continuous HPP systems used for liquid and solid food processing. Figure 2.2 illustrates key variables—pressure, temperature, and time—used to define HPP testing conditions. The ambient pressures before (Ps) and after (Pf) processing are typically 0.1 MPa. Tm represents the maximum temperature reached at process pressure. The temperature difference between the initial (Ts) and final (Tf) ambient states reflects the heat loss during processing, assuming depressurization occurs within a few seconds.

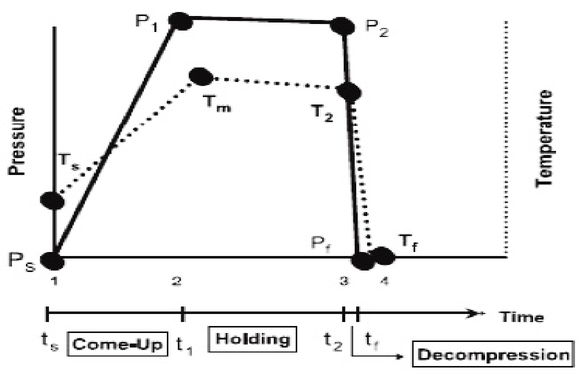


Figure 2.2 Pressure temperature effect in HPP

2.5.1.1 Effects of HPP on fruits and vegetables

The effects of HPP on fruits and vegetables depend on various factors, including pressure level, treatment duration, and temperature. Previous studies revealed that HPP had a positive effect on fruit and vegetable quality. HPP can preserve the colour of fruits and vegetables, including green, yellow, and red colours (Keenaz *et al.*, 2011, González-Cebrino *et al.*, 2012). HPP has been found to have a positive impact on the preservation and extraction of carotenoids in various fruits and vegetables.

HPP is an advanced technology that ensures microbiological safety in food while preserving its nutritional and sensory attributes (Chopde *et al*., 2014). This process works by modifying the functional characteristics of proteins and polysaccharides, as well as influencing biochemical reactions. According to Chopde *et al*. (2014), HPP effectively maintains the colour, texture, and flavour of fruits and vegetables, helping to retain their overall quality. Additionally, HPP has been recognized as an efficient method for microbial inactivation, targeting bacteria, yeast, and mold, thereby extending the shelf life of fruits and vegetables (Chakraborty *et al*., 2014).

The study by Denoya *et al*. (2015) suggested that HPP of fresh cut peaches at 500 MPa for 5 min. under vacuum packaging had a synergistic effect on colour preservation for 21 days. During HPP of minimally processed peach pieces and observed that HPP effectively inactivated the enzymes and retained the colour characteristics of peaches at higher pressures of 600 MPa/5 min. (Denoya *et al*., 2016).

Paciulli *et al*. (2016) observed that beetroot slices subjected to HPP at 650 MPa retained their textural properties, such as hardness and chewiness, better than those that underwent thermal treatment. In terms of inactivating foodborne pathogens, a pressure range of 100-1200 MPa has been shown to be effective, as demonstrated by Dhineshkumar *et al*. (2016).

Yi *et al*. (2017) conducted a study to investigate the effects of HPP on the quality of apple juice. Specifically, they compared the colour retention of apple juice treated with HPP at 600 MPa for 3 min. with thermally treated juice. The results showed that the HPP-treated juice retained its colour better than the thermally treated juice. This is likely due to the fact that HPP is a non-thermal preservation method that helps to inactivate enzymes and microorganisms without affecting the juice's natural colour and flavour compounds.

Aabya *et al*. (2018) reported that their study on the effects of HPP and thermal treatment on strawberry purée and juice suggested that HPP was more effective in preserving quality. They observed that HPP-treated samples retained a higher anthocyanin content, with 67% retention, compared to those subjected to thermal treatment after 35 days of storage at 6˚C.

According to Saikaew *et al*. (2018), the anthocyanin content in purple waxy corn treated with HPP was found to be higher at 700 MPa compared to 550 MPa. They conducted the treatment over a duration of 30 to 45 min. The results indicate that higher pressure levels are more effective in preserving or enhancing anthocyanin content in the corn under these conditions.

Scheidt and Silva (2018) found that for blueberries processed at 200 and 600 MPa, hardness remained unchanged immediately after HPP. Storage tests revealed that processed blueberries maintained their hardness for at least 28 days, whereas fresh, non-processed blueberries lacked resistance to water storage, breaking down within a week due to metabolic activity.

Fernandez *et al*. (2019) conducted a comprehensive study on the effects of HPP on mixed fruit and vegetable smoothies, focusing on enzyme inactivation and quality retention. Their research determined that the optimal HPP treatment conditions were 627.5 MPa at 20°C for 6.4 min., which effectively reduced pectin methylesterase (PME) activity by 85%. By significantly reducing PME activity, HPP helps maintain the viscosity and consistency of the smoothie while preserving its fresh-like sensory characteristics. Additionally, HPP processing at these conditions minimizes thermal damage, allowing for better retention of vitamins, colour, and flavour compared to traditional heat treatments. This study highlights the advantages of HPP in producing high-quality, microbiologically safe smoothies with an extended shelf life while maintaining the natural attributes of fruits and vegetables.

Stinco *et al*. (2019) reported that their assessment of HPP on the carotenoid profile of cloudy carrot juice revealed that applying 600 MPa in three cycles led to the lowest degradation of 26% while Al-Ghamdi *et al.*, 2020 reported that pressure assisted thermal sterilisation had no effect on the carotenoid pigments in purees of beetroot and purple potato puree. Additionally, De Ancos *et al*. (2020) found that HPP at 400 MPa/40°C/1 minute as a pretreatment before juicing increased the carotenoid concentration in orange juice.

Sun *et al*. (2019) reported that applying HPP at 400 MPa to carrots resulted in a significant reduction in their textural properties, specifically a decrease in hardness by 71.0% and in chewiness by 73.8%. Notably, they also observed that increasing the pressure beyond 400 MPa did not lead to any further loss in these textural attributes.

Hu *et al*. (2020) studied fresh-cut pumpkins and discovered that their hardness decreased as the pressure increased. HPP caused a significantly smaller reduction in colorimetric and textural properties, such as hardness and chewiness, compared to heat treatment. Immunofluorescence analysis indicated that HPP led to a decrease in the esterification degree of pectin within pumpkin cells. When applied to fresh-cut pumpkin slices, moderate pressure levels (300–400 MPa) proved to be more effective than higher pressures, preserving quality attributes more efficiently. Similarly, Tao *et al*. (2020) investigated the effects of HPP on Laba garlic and identified 200 MPa as the optimal pressure for maintaining its textural quality. This retention of texture in Laba garlic was mainly attributed to the compacted cells and the increased Ca^{2+} cross-linked cell-cell adhesion. These findings suggest that while higher pressures may negatively impact the hardness of some vegetables like pumpkins, there are specific optimal pressures, as demonstrated with Laba garlic, that can effectively preserve textural properties. Furthermore, Fernandez *et al*. (2019) reported a 70.7% PME inactivation in a vegetable smoothie processed at 630 MPa for a holding time of 6 min..

The effects of HPP on fruits and vegetables are influenced by various factors, including pressure level, treatment duration, and temperature. A study by Raghubeer *et al*. (2020) found that HPP of coconut water at 593 MPa for 3 min. was effective in eliminating *E. coli*, *Salmonella, and L.monocytogenes*. Additionally, HPP has been shown to improve the texture of fruits and vegetables, making them firmer and crisper.

A recent study demonstrated that the microbiological safety of pineapple fruit juice can be ensured for a minimum of 21 days through the application of either individual HPP at 500 MPa for 10 min. or thermal processing at 95°C for 3 min.. The findings revealed that both HPP and thermal processing treatments were effective in inactivating Total Aerobic Bacteria, Yeast and Mold, and coliform in pineapple fruit juice. Notably, the HPP treatment did not significantly impact the physicochemical properties of the juice, although a noticeable change in colour was observed, as reported by Wu *et al*. (2021).

The potential of HPP to preserve fruits and vegetables is vast, particularly in countries like India, which is the second-largest producer of fruits and vegetables in the world. According to the National Horticulture Board's 2nd advance estimates for 2023-24, India's annual fruit output totalled 112.62 million metric tonnes, with vegetable production reaching a substantial 204.96 million metric tonnes (Chandrasekhar, 2024). The adoption of HPP technology could significantly reduce post-harvest losses and improve the quality of fruits and vegetables in India.

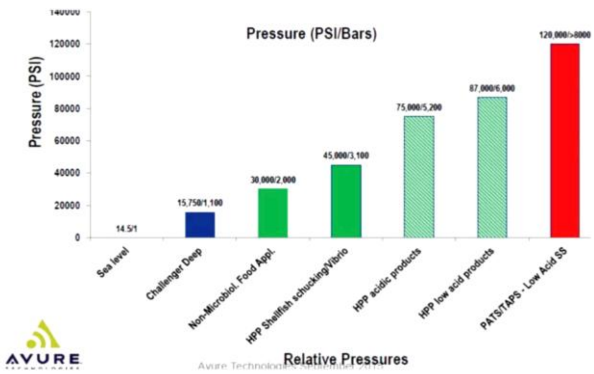


Fig. 2.3 Relative pressure levels in HPP and its applications

(Source: Raghubeer *et al*., 2020)

The figure 2.3 illustrates the range of pressure levels utilized in various HPP applications, highlighting its advancements and benefits in food preservation. As pressure increases, HPP effectively inactivates microorganisms while maintaining the nutritional, sensory, and functional properties of food products. Lower pressures (30,000–45,000 PSI) are used for applications such as shellfish shucking and pathogen reduction, whereas higher pressures (75,000–87,000 PSI) are required for acidic and low-acid food products to ensure extended shelf life and microbial safety. The latest advancements, such as pressure-assisted thermal sterilization/supercritical assisted pressure sterilization (PAT/SAPS) technology, apply ultra-high pressures exceeding

120,000 PSI, enabling the production of low-acid shelf-stable (SS) foods without heat-induced degradation. These innovations demonstrate the growing potential of HPP as a non-thermal, eco-friendly, and effective food processing method, offering an alternative to traditional thermal pasteurization while preserving food quality and extending storage stability.

In conclusion, HPP is a promising technology that has the potential to revolutionize the food industry by providing a safe and effective method for preserving fruits and vegetables. Further research is needed to fully understand the mechanisms of HPP and to develop optimal processing conditions for different fruits and vegetables (Song *et al*., 2023). However, the existing evidence suggests that HPP is a valuable tool for improving the quality and safety of fruits and vegetables, and its adoption could have significant economic and social benefits for the food industry.

2.5.2 PL technology in food industry

In recent years, the food industry has seen significant advancements in non-thermal technologies designed to inactivate microorganisms without the use of heat. PL technology has emerged as a promising non-thermal method for food preservation, leveraging the power of intense, short-duration pulses of broad-spectrum light to achieve microbial decontamination on the surface of foods and packaging materials. The PL spectrum spans a broad wavelength range from 200 to 1100 nm, encompassing the ultraviolet (UV) region (200–400 nm), the visible (VIS) spectrum (400–700 nm), and the near-infrared (NIR) range (700–1100 nm) (Palgan *et al*., 2011).

PL technology, an advanced form of ultraviolet-C (UV-C) treatment discovered in the 1930s, uses xenon lamps to produce high-intensity flashes for food preservation. The ultraviolet spectrum consists of three wavelength ranges: long-wave UV-A (320–400 nm), medium-wave UV-B (280–320 nm), and short-wave UV-C (200–280 nm). PL is highly effective in microbial destruction due to its broad-spectrum UV content, short pulse duration, and high peak power. Research highlights photochemical and photothermal effects as key mechanisms behind its antimicrobial action (Abida *et al*., 2014).

The photochemical effect arises from UV light, which disrupts microbial DNA by altering its double bond alignment, preventing replication. This leads to electronic and photochemical reactions, forming pyrimidine and thymine dimers. The photothermal effect occurs as PL is absorbed and converted into heat, rapidly increasing microbial cell temperatures, sometimes reaching 130°C, causing destruction. While various methods extend fruit juice shelf life, they can alter sensory qualities and consumer acceptability (Ramos-Villarroel *et al.,* 2014).

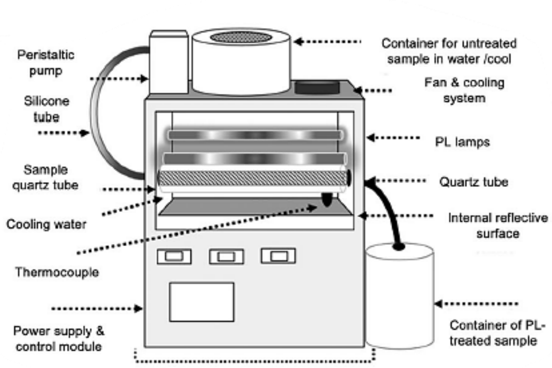
The efficacy of PL inactivation is directly tied to the intensity of the light, measured in J/cm², and the number of pulses delivered (Ortega-Rivas and Salmeron-Ochoa, 2014).

Notably, PL treatments have demonstrated exceptional results in maintaining the quality features of fresh-cut fruits and vegetables, as well as in juice processing. Furthermore, this technology has shown potential as an alternative method for liberating bioactive compounds from vegetable sources, which can be utilized as ingredients in the food industry.

PL technology offers several advantages over traditional thermal processing methods, including significant microbial reduction in a short treatment time, minimal environmental impact, and high flexibility. One of its key benefits is its ability to preserve essential food quality attributes such as colour, texture, and nutritional value (Huang and Chen, 2014). Furthermore, PL technology has been recognized as an energy-efficient and environmentally sustainable approach to food preservation (Abida *et al*., 2014).

PL treatments utilise xenon gas lamps to generate high-intensity pulses ranging from 1 to 20 flashes per second, with pulse durations between 1 µs and 1 s. The fluence (ϕ) varies between 0.01 and 50 J/cm² (Ramos-Villarroel *et al*., 2014). Key parameters include fluence rate (W/m²), pulse width (ms), exposure time (s), and pulse repetition rate (Hz) (Abida *et al*., 2014). The temperature inside the chamber is monitored using thermocouples, and a cooling system prevents overheating. Processing efficiency depends on fluence, lamp distance, light propagation medium, and applied wavelengths (Gomez-Lopez and Bolton, 2016). Additionally, the chemical composition and structure of the food matrix, along with microbial characteristics, influence microbial inactivation (Valdivia-Najar *et al*., 2017). Batch and continuous system of PL equipment are used to process foods. Pumpable liquids or juices can be processed in a continuous system as presented in Plate.2.4.

A batch type PL system (Plate 2.5) consists of a chamber with xenon lamps emitting high-intensity light through a quartz window. It includes a cooling blower, shelves for sample placement, and a controller for operation. The power supply ensures energy input, while the chamber door allows secure sample handling, enhancing microbial inactivation efficiency (Bhavya and Hebbar, 2017).



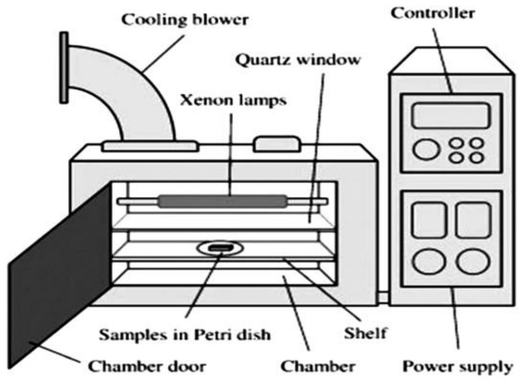


Fig 2.4 Continuous PL processing system (*Source: Salazar-Zuniga et al.,2023*)

Fig 2.5 Batch-type PL unit (*Source: John and Ramaswamy, 2018*).

PL technology effectively decontaminates packaged and unpackaged food and contact surfaces without harmful residues. Using mercury-free xenon flash lamps eliminates the need for chemical disinfectants. Cost-effective and versatile, PL preserves food quality and operates in both continuous and batch modes. Its high-energy pulses enable faster microbial inactivation than continuous UV light (Huang *et al*., 2018).

2.5.2.1 Effect of PL on foods

PL technology has emerged as an innovative, non-thermal decontamination method with significant potential for enhancing food safety and extending shelf life.

Research has demonstrated the effectiveness of PL technology in reducing microbial populations across various food products. Studies have successfully utilized PL systems for non-thermal sterilization of infant foods (Choi *et al*., 2010). Krishnamurthy *et al.* (2010) reported that *Staphylococcus aureus* treated with Pulsed UV (PUV) exhibited severe cellular damage, including cell wall disintegration, membrane shrinkage, and internal structural collapse. Furthermore, xenon lamp-generated intense PL has proven effective in inactivating pathogens like *Listeria monocytogenes* on solid surfaces and seafood (Cheigh *et al*., 2013). Levy *et al*. (2012) demonstrated that PL was more effective than continuous UV treatment in inactivating *Aspergillus niger* spores. Similarly, Orlowska *et al*. (2013) reported a 5-log reduction of *E. coli* in water, achieved at half the energy dose required for continuous mercury lamps, reinforcing the superior efficiency of pulsed lamps in microbial inactivation. These findings highlight PL technology's potential as a reliable method for microbial reduction in food processing.

The study by Teja *et al*., 2017 showed that UV treatment had no significant effect on pH and total soluble solids (TSS) of apple and pineapple juices. The treatment conditions included varying treatment times (5-15 min) and distances from the lamp source (8.6-22.8 cm). Overall, UV treatment had a minimal impact on the quality parameters of both juices, with changes being less pronounced compared to thermal treatments.

In a study conducted by Chakraborty *et al*. (2020), the pasteurisation of gooseberry juice was examined using both thermal processing and PL technology. The research found that the PL pasteurisation method was significantly more effective in preserving the nutritional content of the juice. Specifically, the PL-treated samples retained 45% more phenolics, 54% more antioxidants, and 61% more vitamin C compared to the juice that underwent traditional thermal pasteurisation. This indicates that PL technology not only effectively pasteurizes the juice but also better preserves its beneficial compounds. Vollmer *et al*., 2020 studied the effect of PL technology and thermal pasteurisation on pineapple juices and observed a 5 log reduction of microbes and the bromelanin activity was retained in treatment 2.4Kv/94 or 187 pulses than the thermal pasteurisation.

According to Chakraborty *et al*. (2022), a mixed fruit beverage was formulated from apple ber, carambola, and black table grape juices in a specific ratio. The authors reported that this optimized blend was then subjected to thermal treatment at 90 °C for 5 min. and PL treatment at 30 W cm^2 for 167 seconds, resulting in a total energy dose of 5000 J cm^2. They found that this treatment resulted in complete inactivation of natural microbiota, including aerobic mesophiles, yeasts, and molds, as well as spoilage enzymes such as polyphenol oxidase and peroxidase. Furthermore, Chakraborty *et al*. (2022) noted that the PL pasteurised sample retained significantly higher amounts of vitamin C, antioxidants, and phenolic compounds, with increases of 25%, 27%, and 19%, respectively, compared to the thermally pasteurised beverage.

However, the use of PL technology to decontaminate food still requires more efforts to achieve industrial-scale direct food decontamination. At the current level, few pilot scale studies have been carried out and revealed important considerations. To maximize the effectiveness of the treatment, it is crucial to optimize the conditions and consider the interplay between the time of contamination, PL treatment parameters, and the food matrix. Some authors have addressed the existing limitations by combining PL treatments with complementary techniques, thereby achieving food conservation with minimal compromise on quality. Large-scale studies are now necessary to pave the way for the introduction of this disinfection technique at the industrial level.

From the above discussion, it is evident that food processing methods play a crucial role in improving the safety, shelf life, and quality of food products. Thermal and non-thermal techniques offer distinct advantages, such as microbial inactivation, nutrient retention, and enhanced sensory attributes. Table 2.2 highlights the key benefits of these processing methods, showcasing their positive impact on various food products. The advantages of thermal and non-thermal processing methods demonstrate their significance in food preservation and quality enhancement. While thermal processing effectively ensures food safety, non-thermal techniques help retain nutritional and sensory properties. These benefits contribute to the development of high-quality food products that meet consumer demands for both safety and freshness.

Table 2.2 Effects of thermal and non-thermal processing on food products

Food product	Treatment	Effect
THERMAL PROCESSING		
Mandarin Juice	65°C/15 to 35 min and 75°C/10 to 30 min	• Juice treated at 65°C for 15 min. prese quality over six months of refrigeratio • Maintained TSS, acidity, and ascorbic • Retained sugar content and minimized nonenzymatic browning.
Tomato Juice	100°C/2 to 10 min	• Increased lethality observed against *B. coagulans* (ATCC 8038).
Grape juice	65°C/30 min	• No microbial growth up to 2 yr storag Detection of HMF
Apple, orange Juice blend	70°C/60 and 90 s	• A 60-second thermal treatment had no on *S. cerevisiae* SPA growth. • A 90-second treatment resulted in only log CFU/mL reduction. • After 8 days at room temperature, mic presence remained significant.
Bottle gourd Juice	63°C/30 min and 75°C/10 min	• Ascorbic acid decreased by 35.27% at • Higher pasteurization temperatures inc total phenolic content significant
Ready to eat rice pulav	117.6°C/22.4 min	• Maintained good sensory and microbi quality for up to 180 days.

Mixed formulas of fruits and vegetables pulps (pineapple, beetroot, strawberry and lemon juice)	90°C/5 min and 98°C/2.5 min	• Treatments under 5 min. effectively inactivated POD. • Reduced microbial load by over 2 log cycles. • Preserved optimal sensory attributes.
	HPP	
Apple juice	430 MPa; 7 min	• Complete inactivation of PME and indigenous microbiota. • No significant impact on physicochem properties, nutrition, or sensory quality
Banana Smoothie	350 to 550 MPa; 2 to 10 min; 20 °C	• Significant microbial reduction observ • Total aerobic bacteria inactivation incr with higher pressure and treatment tim • PPO and PME remained active after H 550 MPa/10 min, showing pressure resistance.
Jucara, mango juice blend	600 MPa; 5 min; 25 °C	• HHP preserved anthocyanin content. • Maintained high sensory acceptance.
Mandarin (*Citrus unshiu*) juice	600 MPa, 4 °C and 300 s)	• Total aerobic bacteria content remaine log CFU/mL across all processing met • Sugar and acid composition remained in all treated mandarin juices.
Jackfruit shreds	600 MPa; 8 min	• Increased biochemical compounds

		• 31% maximum extraction of total flav content (TFC)
		PL PROCESSING
Orange juice	Frequency (Hz): 3; Total fluence (J/cm^2): 5.10; Peak power (J/cm2/pulse): 1.213; Pulse width (µs): 360; Exposure time (s): 2.81; Distance from the lamp (cm): 1.9	• *Escherichia coli* reduced by 2.42 log CFU/mL.
Tomato fruit	2.68 J cm−2; 2.5 k/20 °C; 15 day (n=2).	• PL reduced natural and inoculated mic contamination on tomatoes by ~1 log$_{10}$ • Nutritional quality remained unchange while carotenoid levels slightly increas
Green onions	5 and 14.3 J/cm^2 (dry PL) 56.1 J/cm^2 (wet PL) *	• *E. coli* O157:H7 reduced by >4 log.
Spinach	180 to 1100 nm with 17% of UV light. duration− 0.3 μ s and fluence−8 J/cm2	• *L. innocua* reduced by 1.85 log CFU/g • *E. coli* reduced by 1.72 log CFU/g.
Persimmons (*Diospyros kaki* L. cv. Vanilla)	Fluence: 20 kJ m^{-2} Exposure times: 1.2s	• Increased total phenolic content (TPC

	Distance from the sample: 22 cm	
Fresh-cut mangoes	(1.5 and 3.0 × 104 J/m^2	• Minimal effects in their quality param biochemistry and physiology.

2.6 Optimization of technologies

The optimization of thermal processing, high pressure processing, and PL processing technolo enhancing the quality and safety of fruit pulps. Each technology has specific optimized conditions tha nutritional and sensory properties, thereby extending the shelf life of fruit products. As research co may offer even greater benefits for fruit pulp processing in the future.

Kaushik *et al*. (2016) conducted a study on optimizing thermal-assisted high-pressure proces pulp using response surface methodology. They investigated the effects of pressure, temperatu physicochemical and nutritional properties. The study provided valuable insights into optimizin processing.

Vargas-Ramella *et al*. (2021) reviewed the impact of PL processing technology on the vegetables. They found that PL can improve the phytochemical content in fresh fruits and vegetables. of PL as a promising non-thermal technology for enhancing the quality of fruit pulps.

Vargas-Ramella *et al*. (2021) also studied the impact of PL processing on the phenolic compounds of fruits and vegetables. They found that PL treatments can stimulate colouration and anthocyanin accumulation in fig fruit (*Ficus carica L*.). The study demonstrated the potential of PL for improving the quality attributes of fresh-cut mango.

Gavahian and Khoshtaghaza (2021) investigated the effect of PL treatments on the texture quality of fresh-cut mangoes. They found that PL can be used to maintain the physical and nutritional quality of fresh-cut mangoes. Guerrero-Sánchez *et al*. (2021) evaluated the effect of PL treatments on the inactivation of Salmonella on blueberries and its impact on shelf-life and quality parameters. The study provided insights into the optimization of PL parameters for ensuring the safety and quality of fruit pulps.

2.7 Physico-chemical properties

Physico-chemical properties are essential indicators of food quality, influencing its stability, safety, and consumer acceptance. These properties, including pH, moisture content, texture, colour, and nutrient composition, help assess the impact of processing, packaging, and storage on food products. Understanding these factors ensures better quality control and product optimization.

2.7.1 Physicochemical properties of thermal processed fruits and beverages

Thermal processing, such as retort processing, has been widely used to preserve food commodities and extend its shelf life. However, this method can have significant impacts on the physicochemical properties of the product. A study by Smith *et al*. (2014) explored the impact of thermal processing on the sensory and nutritional quality of fruit pulp. It emphasized that retort processing effectively inactivates enzymes and microorganisms, but excessive heat can lead to loss of colour and texture, affecting consumer acceptance**.**

A study conducted by Sharma *et al*. (2015) investigated the changes in physicochemical properties of mango pulp after pasteurisation. The researchers found that pasteurisation led to a decrease in moisture content from 88.2% to 85.1% and a reduction in pH from 4.1 to 3.9. Additionally, the acidity increased from 0.6 to 0.8 g citric acid per 100 mL, while the total dietary fiber content decreased by approximately 30%.

Research by Johnson and Lee (2018) investigated the optimal conditions for retort processing of mango pulp. The findings indicated that specific temperature and time combinations could enhance the retention of vitamins and improve the overall quality of the pulp while minimizing undesirable changes in texture and flavour.

A comparative study by Patel and Zhang (2020) analyzed the effects of different retort methods (static vs. agitation) on the heat penetration and quality of canned fruit pulp. Results showed that agitation improved heat distribution, leading to better microbial inactivation and retention of sensory attributes.

In a comparative study conducted by Verma and Singh (2021), the effects of thermal processing, HPP, and PL technology on the physicochemical properties of papaya pulp were evaluated. The researchers found that thermal processing led to a 25% decrease in vitamin C content, while HPP and PL treatment-maintained vitamin C levels at 90% and 95% of the initial value, respectively. Furthermore, the study reported that HPP and PL-treated pulp had higher levels of total carotenoids and better colour retention compared to thermally processed pulp.

Research by Zhu *et al*. (2022) focused on the nutritional retention in retorted fruit pulps, revealing that while retort processing effectively preserves essential nutrients, certain vitamins, particularly vitamin C, were significantly reduced. The study recommended optimizing processing parameters to enhance nutrient retention.

A review by Garcia and Thompson (2023) highlighted recent advancements in retort technology, including the use of flexible pouches that enhance heat transfer. This innovation has been shown to improve the quality of retorted pulp by minimizing the thermal degradation of sensitive compounds. Below is a Table 2.3 summarizing the effects of thermal processing on various products including the methods of analysis, observed outcomes, and references.

Table 2.3 Effects of thermal processing on physicochemical properties

Product	Parameter	Methods of Analysis	Observed Effects of Thermal Processing	References
Fruit-Based Products	Rheological Properties	Rheometer	Thermal processing affects the viscosity and flow behaviour of fruit-based products, influencing texture and mouthfeel.	Vidigal *et al*. (2023)
Tomato Fruits	Colour	Colorimeter, HPLC	Superheated steam treatment at 100°C for 7 min. negatively affected colour but enhanced certain nutraceutical contents.	Narra *et al.* (2024)
Fruit Juices	Sensory Properties	Sensory Evaluation Panels	Thermal treatments can lead to the formation of flavour compounds, altering the sensory profile of fruit juices.	Zia *et al*. (2024)
Tree Nuts	Physical and Chemical Properties	Various Analytical Techniques	Thermal processing methods like drying and roasting significantly impact the quality and nutritional value of nuts.	Ogundipe *et al*. (2024)

2.7.2 Physicochemical properties of HPP processed fruits and beverages

In contrast to thermal processing, non-thermal preservation methods, such as HPP, have gained attention due to their ability to maintain the quality of food products while minimizing the impact on physicochemical properties. Recent studies have investigated the impact of HPP on various physicochemical properties of different fruits and beverages. An early study by Martinez *et al*. (2014) indicated that HPP preserves the nutritional quality of fruit pulp better than traditional thermal methods. The study noted that HPP maintained higher levels of vitamins and antioxidants in the pulp.

Research published by Wang and Zhang (2016) examined the physico-chemical changes in apple pulp subjected to HPP. The results demonstrated that HPP effectively reduced microbial load without significantly altering the pulp's colour or texture, making it a promising alternative to thermal processing. A study conducted by Patel and Rao (2018) evaluated the effects of HPP on the physicochemical properties of pomegranate pulp. The researchers reported that HPP-treated pulp retained higher levels of total phenolic compounds and antioxidant activity compared to thermally processed pulp. Additionally, the colour parameters (L*, a*, and b*) were better preserved in HPP-treated samples, indicating a more natural appearance (Patel and Rao, 2018).

In a study by Agcam *et al*. (2021), the effects of HPP on the physicochemical properties of black carrot pomace were analyzed. The results indicated that HPP preserved the colour and nutritional quality of the pulp better than traditional thermal methods. Specifically, the total phenolic content was found to be higher in HPP-treated samples, which retained more antioxidant properties compared to their thermally processed counterparts. The study reported a significant retention of ascorbic acid levels post-processing, demonstrating the advantages of HPP in maintaining the bioactive compounds of fruit pulp.

Research by Liu *et al*. (2021) focused on the effects of HPP on enzyme activity in fruit pulp. It was found that HPP effectively inactivated enzymes responsible for browning and spoilage, thus maintaining the visual and sensory quality of the pulp over extended storage periods. More recently, a review by Gupta *et al*. 2023 highlighted the advancements in non-thermal preservation technologies and their impact on the physicochemical properties of fruit pulp.

The review emphasized that HPP and PL treatment can effectively preserve the sensory attributes, nutritional value, and microbial safety of fruit pulp while minimizing the negative effects associated with thermal processing. The authors also discussed the potential of combining non-thermal technologies with other preservation methods, such as the use of natural antimicrobials, to further enhance the quality and shelf life of fruit pulp.

The following Table 2.4 summarizes the effects of HPP, along with the methods of analysis, a physicochemical properties of fruits and beverages.

Table 2.4 Effects of HPP on physicochemical properties of specific fruits and beverages

Product	Parameter	Methods of Analysis	Observed Effects of HPI
Mango Pulp	Rheological Properties (Pa.s)	Rheometer	HPP treatment influenced the visc flow behavior of mango pulp, affe texture and mouthfeel.
Cashew apple juice	Vitamin C Content (mg/100g)	Titration method	Maximum reduction is 0.9% Retention at 250 MPa
Strawberry Purée	Microbial Load Reduction (log CFU/mg)	Plate Count Method	Reduced microbial load -extendin shelf life while preserving quality attributes.
Purple Waxy Corn Kernels	Colour Parameters (L*, a*, b*)	Colorimeter	Preserved the colour attributes
Blueberries	Firmness	Texture Analyzer	Better texture retention during sto
Sugarcane Juice	Antioxidant Activity (%)	DPPH Assays	10% increase in the TAC of sugar juice processed at 600 MPa/30 °C
Jackfruit Shreds	TFC (REg/100mg) TSS (°Brix) Firmness (N)	Spectrophotometric Assays Refractometry Texture Analyzer	31% increase in TFC No significant alterations in °Brix after HPP. Higher levels of pressure and time increased the firmness of the shre

2.7.3 Physicochemical properties of PL processed fruits and beverages

PL technology has emerged as a promising non-thermal preservation method for maintaining the quality of fruits and beverages while minimizing nutrient loss and microbial contamination. Over the years, researchers have explored its effectiveness in preserving the physicochemical properties of various fruit pulps. One of the earliest studies in this field was conducted by Nguyen and Patel (2017), who examined the effects of PL on the colour and flavour of strawberry pulp. Their findings indicated that PL treatment effectively retained the vibrant colour and fresh flavour of the pulp, outperforming traditional thermal methods in sensory evaluations. This early success sparked further interest in the potential of PL for preserving fruit-based products.

Building on this foundation, Kaushik *et al*. (2020) investigated the impact of PL on the physicochemical properties of guava pulp. Their study revealed that PL treatment led to a 12% increase in TSS while maintaining a stable pH of around 4.2. Additionally, the microbial load was significantly reduced, highlighting PL technology's potential to extend the shelf life of fruit pulps without compromising their physicochemical attributes. These findings reinforced the idea that PL could serve as an effective alternative to conventional preservation methods, ensuring product quality while improving safety.

Further expanding the scope of research, Ali and Smith (2022) assessed the nutritional impact of PL on orange pulp. While some vitamins experienced slight degradation, the study confirmed that the overall nutrient profile remained stable, demonstrating that PL technology is a viable method for preserving the nutritional integrity of fruit pulps. The Table 2.5 illustrate the analysis and effect of physicochemical properties after PL treatment in fruit and beverages.

Table 2.5 Physicochemical properties of PL processed fruits and beverages

Product	Parameter	Methods of Analysis and effect	References
Mango Peel and Pulp	Phytochemical content & Antioxidant potential	HPLC, DPPH & ABTS Assays • Enhanced phytochemical content and antioxidant potential with low fluence PL	Lopes *et al*. (2016)
Blueberries	Microbial Survival & Quality	Microbiological Analysis & Texture analyser • Reduced microbial load while maintaining quality and nutritional characteristics	Jin *et al*. (2017)
Pomegranate Juice	Microbial Safety, Enzyme Inactivation, and Phytochemical Retention	Plate Count Method, Enzyme Assays, HPLC • Effective pasteurization with microbial reduction, enzyme inactivation, and phytochemical retention	Bhagat and Chakraborty, (2022)
Tender coconut water	Enzyme Activity	Enzyme Assays (Polyphenol Oxidase & Peroxidase Activity) • Maintained quality while reducing enzymatic activity	Reddy *et al*. (2024)

The cumulative findings of these studies illustrate the progressive understanding of PL's benefits, from enhancing sensory qualities to maintaining physicochemical stability and nutritional content. As research in this area continues to evolve, PL technology holds significant promise for the food industry, offering a non-thermal, effective approach to fruit and beverage preservation.

2.8 Packaging and Storage Study

The journey of food preservation has always been intertwined with the evolution of packaging and storage techniques. As the demand for high-quality, nutrient-rich, and long-lasting food products grows, researchers have explored various methods to enhance food safety, extend shelf life, and retain essential nutrients. Among these, HPP, PL treatment, and retort processing have gained significant attention for their ability to preserve food quality while minimizing degradation over time.

Patras *et al.* (2014) delved into the effects of HPP and thermal processing on strawberry puree stored in polyethylene terephthalate (PET) bottles at 4°C for six months. Their findings highlighted that HPP-treated samples exhibited superior retention of vitamin C, total phenolic content, and antioxidant activity compared to thermally processed ones. In the same year, Gómez-López *et al*. (2014) investigated the impact of PL treatment on apple juice packaged in PET bottles and stored at 4°C for 28 days. The results demonstrated that PL-treated juice maintained higher levels of vitamin C and total phenolic content compared to untreated samples.

Continuing this exploration, Aguiló-Aguayo *et al.* (2015) examined the effects of PL treatment on tomato juice stored in PET bottles at 4°C for 42 days. Their research revealed that PL-treated juice retained higher lycopene and total phenolic content than untreated controls. Around the same time, Devi *et al.* (2015) investigated retort processing's impact on mango pulp stored in flexible retort pouches at ambient temperature for 12 months. Their study confirmed that the processed pulp maintained its physicochemical properties, colour, and sensory attributes throughout the storage period.

Huang *et al.* (2017) evaluated blueberry puree processed with HPP and stored in PET bottles at 4°C for 60 days. Their findings emphasized HPP's effectiveness in retaining anthocyanins and total phenolic content, boosting antioxidant properties. Similarly, Oms-Oliu *et al*. (2017) studied PL treatment on watermelon juice stored in PET bottles at 4°C for 35 days, concluding that PL-treated samples exhibited higher vitamin C and total carotenoid content compared to untreated samples.

Two years later, Vieira *et al*. (2018) assessed the impact of HPP on orange juice stored in PET bottles at 4°C for 28 days. The study highlighted that HPP-treated juice maintained superior levels of vitamin C and total phenolic content. Around the same time, Kaushik *et al.* (2018) analyzed retort processing on pomegranate arils stored in flexible retort pouches at 37°C for six months. Their research demonstrated that the arils retained acceptable quality in terms of physicochemical properties, colour, and sensory attributes.

The study by Keenan *et al.* (2019) explored the effects of HPP on carrot juice packaged in PET bottles and stored at 4°C for 42 days. Their results confirmed that HPP-treated juice preserved higher carotenoids and total phenolic content compared to untreated samples. Following this, Sharma *et al*. (2020) examined the quality and shelf life of guava pulp processed through retort methods and stored in flexible retort pouches at 37°C for 12 months. Their findings demonstrated that the pulp retained its quality with only minimal changes in physicochemical properties, colour, and sensory characteristics.

The most recent study by Rao *et al*. (2021) focused on pomegranate juice processed with HPP and stored in PET bottles at 4°C for 56 days. Their research concluded that HPP-treated juice maintained higher anthocyanins and total phenolic content, thereby enhancing its antioxidant properties.

The collective findings of these studies illustrate the significant advancements in packaging and storage methods over the years. From HPP to PL treatment and retort processing, each technique plays a vital role in ensuring food safety, extending shelf life, and preserving nutritional integrity. As research continues, these innovations pave the way for a future where food waste is minimized, and consumers can enjoy fresh, high-quality products for extended periods.

2.9 Cost estimation

Beyond ensuring quality and safety, the economics of food processing plays a crucial role in determining the feasibility and adoption of various preservation techniques. As researchers and industries seek to balance costs and benefits, several studies have explored the financial aspects of different processing methods.

Sampedro *et al*. (2014) examined the commercial pasteurization of orange juice using pulsed electric fields (PEF). Their study revealed that while PEF processing cost approximately $0.037 per liter, surpassing the $0.015 per liter cost of thermal pasteurization, its advantages in nutrient retention and reduced processing time made it an attractive alternative in premium market segments.

The following year, Reddy *et al.* (2015) analyzed the economic feasibility of HPP)for fruit pulp, estimating production costs at approximately $0.045 per kg. Despite the substantial capital investment required for HPP equipment, the method's ability to significantly extend shelf life and preserve sensory quality made it a promising option for high-end markets.

Zhang *et al*. (2019) conducted a comparative study of thermal and non-thermal preservation methods, estimating that thermal processing had the lowest cost per kg at $0.020, while non-thermal alternatives such as HPP and PEF ranged from $0.030 to $0.050 per kg. Although more expensive, these advanced techniques offered improved product quality, allowing for premium pricing strategies that could justify the additional costs.

Barcelos *et al*. (2022) investigated the cost implications of continuous pasteurization of açai pulp using plate heat exchangers. Their study found that operational expenses, driven by energy consumption and equipment maintenance, amounted to approximately $0.025 per kg. The authors emphasized that continuous pasteurization provided both an efficient and economically viable approach to pulp processing, ensuring long-term sustainability.

Most recently, Lee *et al*. (2023) assessed the economic viability of PL technology for pasteurizing fruit pulp. They determined that processing costs were around $0.040 per kg, placing it competitively alongside PEF but at a higher cost than traditional thermal methods. Their findings underscored that while PL minimized thermal degradation of sensitive compounds, its cost-effectiveness largely depended on production scale and consumer demand for high-quality products.

As these studies illustrate, the economics of food preservation is as dynamic as the technologies themselves. While some methods demand higher initial investments, their potential to enhance shelf life, maintain nutritional integrity, and appeal to premium markets makes them viable in the long run. The continued exploration of cost-effective and efficient processing techniques paves the way for a future where food remains safe, nutritious, and accessible, while ensuring financial sustainability for producers and industries alike.

2.10 Conclusion and knowledge gap of the study

The study of thermal and non-thermal preservation methods for fruit pulp, particularly through retort processing, HPP, and PL technology, provides a comprehensive understanding of how these techniques can enhance the quality and safety of fruit products. Recent literature highlights the effectiveness of retort processing, which employs high temperatures and pressures to eliminate microorganisms and enzymes responsible for spoilage. This method significantly extends shelf life while preserving sensory and nutritional qualities when heat treatment parameters are optimized to minimize adverse effects (Kuffman and Pacheo, 2020; Kailas Engineering, 2024).

In parallel, HPP has gained recognition as a promising non-thermal preservation method that maintains the integrity of bioactive compounds in fruit pulp. Research indicates that HPP effectively reduces microbial loads while preserving flavor, color, and nutritional content, making it particularly suitable for high-acid fruit products where maintaining organoleptic qualities is crucial (Barbhuiya *et al.*, 2021). Similarly, PL technology has shown potential for enhancing microbial safety without the use of heat. Recent findings suggest that PL can effectively inactivate pathogens while retaining the nutritional and sensory attributes of fruit, though its commercial application remains in developmental stages (Barbhuiya *et al*., 2021).

Despite these advancements, there remains a significant knowledge gap regarding the comparative efficacy of thermal and non-thermal processing techniques specifically for ripe jackfruit. Most existing studies focus on other fruit types, leaving a lack of standardized information on optimal preservation methods for jackfruit. Given the fruit’s short shelf life and susceptibility to microbial spoilage, addressing this gap is essential for ensuring its quality, safety, and commercial viability.

Future research should focus on systematically evaluating and standardizing these processing approaches, particularly in terms of their impact on the physicochemical, microbiological, and sensory attributes of ripe jackfruit. Exploring the synergistic effects of thermal and non-thermal methods, optimizing processing conditions, and assessing consumer acceptance will be critical for advancing fruit pulp preservation. By establishing an optimized approach, this research will contribute to the sustainable utilization of jackfruit, enhance its market potential, and reduce post-harvest losses.