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# High pressure processing as a Green Technology Approach for the Synthesis of Clean Labels in Dairy Sector: A Comprehensive Review

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**ABSTRACT**

High-pressure-based technologies have emerged as promising alternatives for transforming the dairy industry with cleaner label solutions compared to traditional processing methods. The review explores their efficacy in pathogen inactivation, shelf life extension, and physicochemical quality improvement of dairy products, highlighting their potential for producing safer and longer-lasting items without preservatives. The advantages of High-Pressure Processing (HPP), Ultra High-Pressure Homogenization (UHPH), and High-Pressure Homogenization (HPH) treatments in enhancing milk stability, texture, and nutrition are discussed, offering opportunities for healthier and higher-quality dairy products. The review also addresses their impact on cheese, yogurt, and ice cream, including microbiological safety, proteolysis, and sensory attributes. Challenges and potential solutions for implementing these technologies in industrial dairy operations are considered. Overall, high-pressure-based technologies demonstrate significant potential for revolutionizing the dairy industry and meeting the demands of health-conscious consumers while promoting a more sustainable food industry. This review aims to explore the application of high-pressure technologies with a clean label method in the dairy manufacturing. By leveraging pressure treatments, the dairy production can manufacture natural, very much nutritious foods with minimal requirements, aligning with consumer preferences for clean-labeled foods with zero imitated chemicals.

## INTRODUCTION

Dairy products have played a substantial role in the human diet since the domestication of animals approximately 13,000 years ago and are currently regarded as vital elements of a balanced diet. They offer a wide range of nutritional elements, such as proteins, minerals, vitamins, lipids, and carbohydrates. The World Health Organization/Food and Agriculture Organization of the United Nations (WHO/FAO) suggests that people should consume 1000 mg of calcium each day. Dairy products are excellent dietary sources of calcium due to their high absorption rate, wide availability, and affordability. They offer a higher amount of calcium, protein, magnesium, potassium, zinc, and phosphorus per calorie compared to other common foods consumed by adults (Verruck et al., 2019). Studies on dairy products have primarily concentrated on conventional and innovative components, starter cultures, probiotics, prebiotics, and symbiotics, and their impact on the well-being of consumers. Consuming probiotic microorganisms through dairy products can have both preventive and curative effects. The primary benefits of probiotics are mostly associated with the well-being of the gastrointestinal system. This is achieved through the displacement of harmful microorganisms by competing for resources and attachment sites, as well as the synthesis of antimicrobial substances within the body.

Dairy products are indispensable for a properly balanced diet, since they offer a multitude of nutritional elements and contribute to general well-being (Verruck et al., 2019). Eating behaviors in developed societies are significantly influenced by key trends such as health concerns, sustainability, and convenience. An analysis done in 2015 through a London-based market research organization asked customers about their perception of the "clean label" term, with 36% of respondents associating it with products free from artificial additives. The clean label trend gained prominence in 2019, especially in relation to improvements in packing and processing of food (Roman et al., 2017). A consumer survey conducted in Europe during the same year revealed that 73% of purchasers favor dairy products without artificial flavors or colors (Roman et al., 2017). Today, consumers are increasingly seeking nutritious, environmentally-friendly, reduced-fat, and low-sugar dairy products, posing a challenge for manufacturers to modify ingredient lists and embrace the concept of clean label foods (Aschemann et al., 2019). This term refers to the production of safe food with minimal harm-free ingredients that are acknowledged by consumers. To achieve first-class food produces, a mixture of customary and progressive processing approaches is employed (Kumari et al., 2020). However, the use of novel technologies often leads to the inclusion of unfamiliar ingredients on product labels, prompting educated consumers to scrutinize them for chemical or artificial additives (Aschemann et al., 2019). For milk and milk products, conventional thermal processing is commonly used for shelf-life protection, regardless of its negative impact on nutritional value due to the destruction of beneficial components (Stratakos et al., 2019). Ultra-high temperature (UHT) treatment extends the shelf life of milk but can result in destabilization and spoilage. The dairy industry seeks non-thermal treatments that provide increased storage stability and maintain a "fresh-like" quality, similar to UHT-treated milk (Roobab et al., 2023). High pressure-based technologies, including (HPP), (HPH), (UHPH), and high-pressure jet (HPJ), have been extensively studied for various dairy products such as milk, yogurt, cheese, and ice cream (Patel at al., 2019). However, there is a lack of advanced research on high-pressure technologies specifically for the production of clean label dairy products. Clean label dairy products should have no additives or preservatives while enhancing quality and extending shelf life. Despite the use of various additives in commercial dairy products, a shift towards clean label formulations is desired (Peralta et al., 2023). Hurdle technologies, which combine different preservation methods, are increasingly used to produce fresh, slightly processed, and environmentally-friendly food products. High pressure-based technologies were initially established for fat globule interference but have bring into being the applications in numerous dairy products. These technologies, when combined with natural antimicrobial agents, ensure food safety and contribute to energy sustainability and eco-friendly decontamination (Oliveira et al., 2015). This review aims to explore the application of high-pressure technologies with a clean label method in the dairy manufacturing. By leveraging pressure treatments, the dairy production can manufacture natural, very much nutritious foods with minimal requirements, aligning with consumer preferences for clean-labeled foods with zero imitated chemicals.

## Clean Label Milk Treatment

Clean label milk processing is subject to stringent global regulations that can sometimes restrict the invention capability of industrialists. The FAO's Codex Alimentarius defines "raw milk" as milk, not heated past 40°C or undergone any treatment with a similar effect. In the industrial setting, high pressure-based technologies are commonly used and branded on the basis of their pressure limits, including High Pressure Processing (HPP), High-Pressure Homogenization (HPH), and a novel procedure known as High-Pressure Jet (HPJ). Commercial equipment available can generate pressures of up to 600 MPa (Betoret et al., 2015). These technologies can be useful for both liquid and solid foods, packaged or unpackaged, and with or without the use of preservatives and antimicrobial agents (Horn et al., 2019).

## High-Pressure Processing (HPP)

High-Pressure Processing is a cold pasteurization method applied for various food applications. It serves as a substitute or clean label method for microbial or enzymatic inactivations instead of relying on traditional thermal/heat processing (Komora et al., 2020), shelf life extension (DeInececco et al., 2019), and physiochemical quality (Yang et al., 2020) modifications. The effectiveness of HPP is influenced by variables such as valve geometry (Donsi et al., 2013) and the number of passes or cycles (Ruiz et al., 2013). While multi-cycling HPP has shown benefits for microbial inactivation, l , 2017) Figure 1.

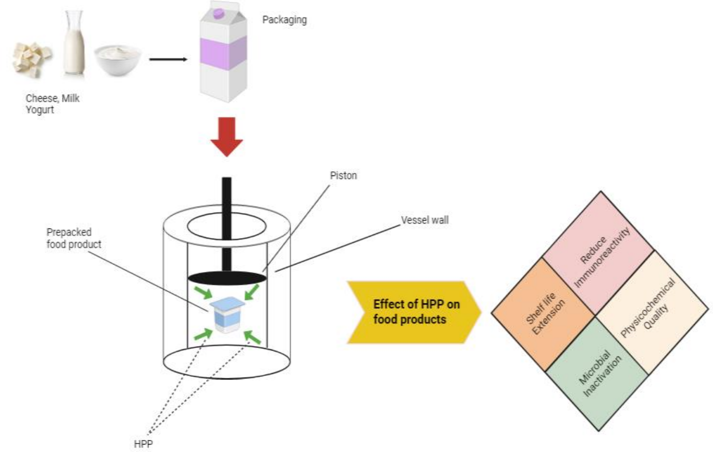


**Figure 1**: Effect of HPP on dairy products

Studies have explored the combination of HPP with other hurdles to enhance milk quality and safety. An illustrative case is the study conducted by Chung and Yousef, which examined the combined bactericidal impact of (HPP) at 350 MPa for durations ranging from 1 to 20 minutes, along with the use of probiotics (specifically, *Lactobacillus casei),* against *Listeria monocytogenes*, achieving a significant reduction in bacterial count. Similarly, Evelyn and Silva combined HPP (600 MPa for 20 minutes) with heat treatment to diminish *Bacillus cereus* spores in skim milk. HPP (400-600 MPa for 1-5 minutes) has also proven effective against various bacteria, including *Escherichia coli*, *Salmonella*, *L. monocytogenes*, *Enterobacteriaceae*, lactic acid bacteria, and *Pseudomonas* spp., resulting in prolonged milk shelf life compared to traditional pasteurization (Stratakos et al., 2019). Table 1 investigates the process of HPP and their key benefits.

**Table 1.** Impact of HPP on Dairy Products Formulation

| Product | Processing | Effects | References |
|---|---|---|---|
| Raw milk | Pressure= 400-600 MPa Time= 1-5 minutes | -Reduction in logarithmic count of *E. coli, Salmonella*, and *L. monocytogenes.* -Extended life of milk by an additional week | Stratakos et al., 2019 |
| Bovine skim milk | Pressure= 400-600 MPa Time=15 minutes | β-lactoglobulin and immunoglobulin G experienced significant denaturation. | Liepa et al., 2018 |
| Skim milk | Pressure= 250 MPa Time=15 minutes | The growth rate of bacteria during storage was suppressed significantly. | Liepa et al., 2016 |
| Yoghurt | Pressure=500 to 700 MPa Time= 10 minutes | Increased viscosity, enhanced color and taste. | Swelam, 2018 |
| Cheese of unpasteurized milk | Pressure=400 to 600 MPa Time= 5 minutes. | It increased the presence of hydrophilic and hydrophobic peptides and enhanced the hydrolysis of α-casein. | Calzada et al., 2015 |
| Cheddar cheese | Pressure= 400 MPa Time= 15 minutes. | Increase in bioactive compounds present in cheese leading to higher antioxidant activity and ACE-inhibitory potential in cheeses | Munir et al., 2020 |
| Camembert type cheese | Pressure= 350 to 550 MPa Time= 10 minutes | Inhibited the development of cheese rind and texture ripening, leading to a firmer body and effectively eradicated surface mold, responsible for discoloration and yellowing of its rind. | Betty et al., 2019 |
| Turkish white goat cheese | Pressure= 300–450 MPa Time= 5 min. | Enhanced proteolytic and lipolytic activities in the cheese, resulting in improved breakdown of proteins and fats | Yaman et al., 2020 |
| Icecream | Pressure= 200 to 500 MPa Time=20 minutes | Augmented viscosity, resulting in a higher resistance to melting and improved texture and mouthfeel without compromising quality. | Huppertz et al., 2011 |

The efficacy of stabilizer activity and different pasteurization methods for acidified milk drinks (AMD) was subjected to thermal and hydrostatic pressure treatments at various pH levels and high methoxyl pectin concentrations. In order to attain the lowest possible steric stability, a concentration of 0.5% HMP was required. The utilization of HMP at a concentration of 0.5%, with a pH of 4.0 and 4.5, resulted in significant improvements in protein solubility, reduced storage sedimentation, and smaller mean particle sizes. The application of heat treatment resulted in reduced variation in particle size and less fluctuations in delta backscattering. Nevertheless, HHP has the potential to substitute heat treatment when using a 0.5% HMP concentration and maintaining a pH level between 4.0 and 4.5 (Tirpanci et al., 2023). Overall, HPP technologies have demonstrated potential for pathogen inactivation and prolonging of the shelf-life in dairy products. These high-pressure techniques offer alternative approaches to traditional thermal processing, contributing to the production of safer and longer-lasting dairy products.

**High-Pressure Homogenization (HPH) treatments**

In high pressure-based milk handling, the application of force breaks down fat globule membranes and casein micelles, increasing the apparent area and acting as a natural emulsifying agent. This results in improved calcium phosphate and casein in the serum phase. The denaturation of proteins under high pressure can be reversible or irreversible, and conformational changes make proteins more susceptible to proteolysis, potentially increasing the availability of free amino acids (Goyal et al.,2013). As shown in table 2, HPH treatments can also reduce the concentration of stabilizers in dairy infusions. However, HPH treatment can disrupt plant matrices, affecting the physicochemical and functional properties of the products. Studies have shown that HPH treatment can improve the nutritional quality of milk by stabilizing ascorbic acid, riboflavin, and antioxidant capacity, while not affecting microbial quality acids (Goyal et al.,2013).

Table 2. The process and effect of HPH treatments on dairy products

| Product | Processing | Effect | References |
|---|---|---|---|
| Milk | Pressure= 100 MPa Temperature=20°C to 60°C. | Reduction in thermal coagulation time and increased milk viscosity | Ambroziak et al., 2019 |
| Powdered skim milk | Pressure= 50 to 150 MPa Temperature=20 to 40°C. | The cohesion and caking properties of the powder were reduced, resulting in improved powder flow properties. | Mercan et al., 2018 |
| Caciotta cheese | Pressure=50 MPa Temperature= 40°C for 65 min. | Increased quality and viability of probiotics, while also reducing the ripening time. | Burns et al., 2015 |
| Brines for cheese | Pressure= 50 MPa Temperature=75°C | Effective in killing microflora, including the reduction of *L. monocytogenes* by 5 log CFU/mL. | Innocente et al., 2019 |
| Ice-cream | Pressure in stage 1= 97 MPa Pressure in stage 2=3 MPa Temperature= 45 to 48°C and an outlet temperature of 65°C | Lowest overrun, indicating a lower volume expansion. Highest hardness, resulting in a firmer texture. Improved resistance to melting, contributing to better heat stability. | Biasutti et al., 2013 |

**Ultra-High Pressure Homogenization (UHPH)**

Researchers have proposed experimental evaluations of new techniques, such as double-stage (UHPH), to prevent fat creaming in UHT milk during long-term storage. UHPH treatment reduces the size of fat globules in the first stage and stabilizes and distributes fat-protein aggregates in the second stage. This approach shows potential for achieving long-term shelf stability without the requisite for synthetic stabilizers. However, dissociation of casein micelles during UHPH can lead to alterations in the look and rheological properties of milk. In the case of UHPH studies have shown its efficacy in reducing the total bacterial count and eliminating Enterobacteriaceae in cream during storage. UHPH treatment, along with traditional homogenized pasteurization, resulted in increased shelf life without the addition of antimicrobial agents. UHPH-treated milk drinks also exhibited better microbiological shelf life and sensorial characteristics compared to conventional pasteurization methods. Table 3 explores the process of UHPH and its impact on dairy products.

Table 3. The effect of UHPH treatment on dairy products

| Product | Processing parameters | Effects | References |
|---|---|---|---|
| Commercially sterile milk | Pressure= 300 MPa Temperature= 55 to 85°C. | Bacillus spores demonstrated a 5 log CFU/mL reduction at 85°C. | Amador et al., 2014 |
| Milk | Pressure= 100 to 300 MPa Temperature=20 to 40°C | Decreased fat globule size and enhanced surface of milk fat globules through the adsorption of caseins and whey proteins. | Zamora et al., 2012 |
| Almond milk | Pressure= 350 MPa Temperature=85°C | Altered the mean particle size and shape and reduced antigenicity and sulfhydryl groups. | Briviba et al., 2016 |
| Yoghurt | Pressure=200-300 MPa Temperature=40°C | Improved water-holding ability and firmness, increased constancy, reduced syneresis. | Serra et al., 2009 |

**High-Pressure Jet (HPJ)**

High-pressure jet treatment refers to a process where a substance or material is subjected to a focused and intense stream of pressurized fluid, typically water. This treatment involves directing the high-pressure jet onto the surface of the target material to achieve various effects such as cleaning, cutting, or surface modification. In high-pressure jet treatment, the fluid is typically propelled at extremely high pressures, often ranging from several hundred to several thousand pounds per square inch (psi). The force generated by the high-pressure jet can be used to remove dirt, debris, or contaminants from surfaces, such as in industrial cleaning applications. To overcome the dissociation of casein micelles and related issues, High-Pressure Jet (HPJ) treatment has the potential to reduce the lipid content in the liquid portion, enhance the stability of casein-fat complexes, and minimize foam endurance without the need for artificial stabilizing agents (Roobab et al., 2023) Table 4.

Table 4. High Pressure Jet's impact on dairy products and their stability

| Product | Processing | Impact/effects | References |
|---|---|---|---|
| Milk | Pressure= 125 to 500 MPa Temperature= 55°C or 5°C. | Increased Foaming ability, viscosity and particle size | Tran et al., 2018 |
| Skimmed milk | Pressure=100–500 MPa | Enhanced the expansion index of foam, stability index of foam volume, and activity index of emulsion | Hettiarachchi et al., 2018 |
| Condensed milk | Pressure= 100–500 MPa | Increased apparent particle density (1.25 g cm−3), and a moderate improvement in emulsion stability | Hettiarachchi et al., 2019 |
| Low fat ice-cream mix | Pressure=200–400 MPa | Improved the properties and functionality of foam, consistency and particle size | Voronin et al., 2020 |

**High-Pressure Homogenization (HPH) treatments**

In the case of milk powders, (HPH) treatments have been shown to reduce cohesion and caking properties, improving the flow quality of skim milk powders as described in table 5. Additionally, the combination of an HPJ system with a spray dehydrating step has been used to get condensed skim milk powders that can maintain 85% of their foam capacity over an 8-hour period.

Overall, high pressure-based milk processing techniques can have significant effects on the physicochemical and nutritional properties of milk, influencing fat globule stability, protein denaturation, and flow properties in both liquid milk and milk powders. These techniques offer potential for improving the quality and stability of milk products without the need for synthetic additives or stabilizers table 5.

Table 5. High Pressure Homogenization applied on dairy products and their effects

| Product | Process | Treatment Highlights | References |
|---|---|---|---|
| Milk | Pressure= 100 MPa Temperature= 20°C to 60°C | Thermal coagulation time was reduced by 44% and 30%, decreased size of fat globules, increase in milk viscosity | Ambroziak et al., 2018 |
| Skimmed milk powder | Pressure=50 to 150 MPa, Temperature=20 to 40°C. | Reduced the cohesion and caking properties, resulting in decreased clumping and improved flow-ability of the powder. | Merkan et al., 2018 |
| Peanut milk | Pressure=150 to 300 MPa Temperature=85°C to 121°C | Improved stability, and viscosity of peanut milk. | Zaaboul et al., 2019 |
| Hazelnut milk | Pressure= 150 MPa Temperature=15°C | Improved microstructural characteristics and texture consistency. | Gul et al., 2017 |
| Cream cheese | Pressure= 25-100 MPa Time=2-4 minutes | Achieved smaller fat globules and enhance the texture, making it firmer, the size of curd particles is reduced and spreadability is increased. | Ningytyas et al., 2018 |

**High-Pressure Technologies for Controlling Microorganisms in Cheese Processing**

High-pressure-based technologies have made their way into customary cheese applications, including fresh cheese and mozzarella, which are highly perishable due to their high water activity. By applying high-pressure treatments to packaged products, spoilage microorganisms, especially *Listeria* monocytogenes resulting from manual handling and cross-contamination, can be effectively controlled. HPP can enhance the quality of raw ewes' milk Serra da Estrela cheese while preserving its lipid makeup. The impact of HPP on the qualitative and quantitative lipid compositions of Serra da Estrela cheese after a period of 15 months of refrigerated storage depicted that During storage, all cheeses exhibited comparable levels of saturated, monounsaturated, and polyunsaturated fatty acids. All cheeses had a significant amount of conjugated linoleic acid during the storage period, and they all exhibited comparable atherogenic and thrombogenic indices. HPP can be employed to treat Serra da Estrela cheese in a manner that guarantees the absence of harmful microorganisms while preserving its lipid composition (Inácio et al., 2023). Studies have shown that HPP at 600 MPa can reduce *L. monocytogenes* below the detection limit in fresh cheese, enhancing its safety (Tomasula et al., 2014) Soft Camembert cheese treated with HPP at 500 MPa for 10 minutes also resulted in a "safe" cheese with idled foodborne pathogens, although the taste was comparable to raw milk cheese (Voigt et al., 2011) as shown in figure 2.

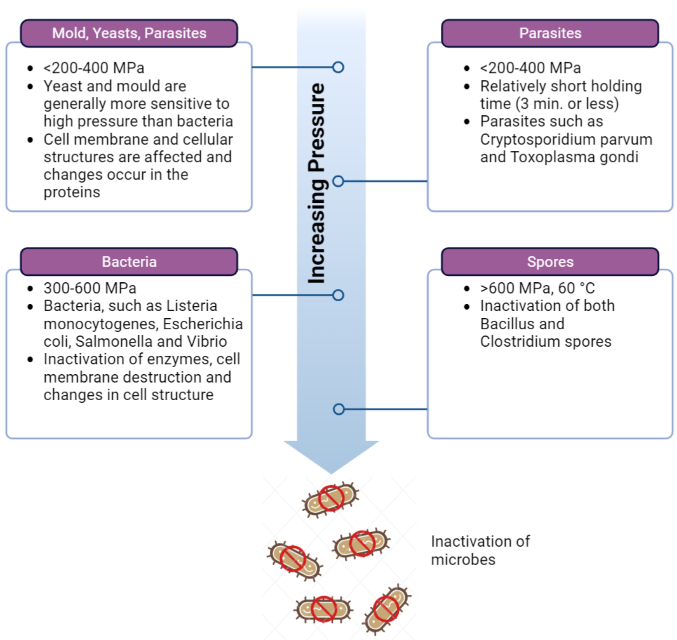


**Figure 2** Effect of HPH on microorganisms

Various types of cheeses have shown reductions in *L. monocytogenes* counts under different HPP treatments. For example, HPP at 400 MPa (20°C for 20 minutes) reduced *L. monocytogenes* by 2 log units in starter-free Queso Fresco cheese, while HPP at 600 MPa reduced it by 4 log units. In comparison, HPP at 500-600 MPa at 6°C for 5 minutes achieved reductions of 7.1 and 7.7 log units in fresh cheese (Evert et al., 2018). Low-pressure (HPH) treatments at 150 MPa also caused the inactivation of native spoilage microorganisms.

The impact of various sterilizing techniques on the microbiological content and qualitative characteristics of processed cream cheese (PCC) was conducted that elucidated the inactivation of bacterial endospores was achieved through the use of ultra-high temperature instantaneous sterilization (UHT, 137 °C/4 s), high temperature sterilization (121 °C/10 min), and pasteurization (65 °C/30 min) in combination with germinant (l-alanine) and high hydrostatic pressure (450, 550 MPa/20 min) (Song et al., 2023). HPP at 200-300 MPa has been identified as an effective constraint to stop late blowing faults caused by Clostridium tyrobutyricum in cheese (Innocente et al., 2019). Specific types of cheeses, such as Bloomy rind, Brie, Camembert, and similar varieties, face an increased susceptibility to contamination as a result of potential contact with environmental pathogens throughout the production and ripening processes. Nonetheless, the implementation of (HPP) after a 45-day manufacturing period can effectively eliminate surface mold and significantly decrease *L. monocytogenes* levels by more than a 5 logarithmic reduction (Batty et al., 2019). The adoption of a dual approach involving the utilization of probiotic cells as co-starters, coupled with High-Pressure Processing (HPP), in the production of probiotic cheese has demonstrated enhancements in sensory attributes and a reduction in the duration of the ripening process. Additional approaches involve combining HPP with antimicrobials like bacteriocins and slight heat treatments. Additionally, the incorporation of fresh lactic curd cheese manufactured at a low pH, which is primarily susceptible to yeasts and molds, can be augmented by incorporating antifungal agents like ascorbic acid or potassium sorbate. In general, the application of HPP within the range of 300-600 MPa presents a compelling clean label method for producing dairy products without the need for preservatives (Daryaei et al., 2008).

**Effects of High-Pressure Technologies on Cheese**

Cheese is a popular fermented milk produce known for its rich content of bioactive peptides, high-quality proteins, calcium, phosphorus, and vitamins. High-pressure technologies have been studied for their effects on proteolysis, volatile compounds, texture, color, and sensory quality of cheese.

Studies have shown that applying diverse pressures (200-500 MPa at 14°C for 10 minutes) can accelerate secondary proteolysis in Castellano cheese and prevent the development of certain volatile composites (Aveila et al., 2017). However, pressures above 500 MPa may negatively impact taste intensity while positively affecting cheese aroma. High-pressure treatments have also been found to delay the development of cheese rind, leading to a firmer body and aiding in textural ripening (Betty et al, 2019). However, applying high pressure after 11 days of cheese manufacturing can cause degradation of cheese appearance. UHPH treatments on milk used for starter-free fresh cheeses have been found to result in lower lipolysis, proteolysis, and moisture loss in contrast to conventionally homogenized milk (Ozturk et al., 2013). HPP applied to starter cultures used for white brined cheese has been shown to increase proteolysis and modify enzymatic activities and substrate reactivity. Pressure treatment during Cheddar cheese manufacture has been found to accelerate secondary proteolysis during ripening (Upadhyay et al., 2007). Additionally, sublethal HPH treatments of probiotic cells have been used to produce short-ripened probiotic caciotta cheese, reducing cheese maturation costs and contributing to sustainable and clean label products. High-pressure treatments have been found to increase milk clotting enzyme activity and stability, improving milk clotting and curd formation in cheese making. HPP has also been shown to stimulate proteolysis and the discharge of bioactive peptides, such as ACE-inhibitory peptides (Mnir et al., 2020). These peptides have potential antihypertensive effects connected to hypertension and coronary diseases. Abundant pressure alters the conformation of proteolytic enzymes, exposing extra active spots to proteins. Cheese treated with HPP has been observed to exhibit elevated release of phenols and enhanced antioxidant capacity when compared to cheese that has not undergone HPP treatment. Nominally processed cheeses treated with HPP have exhibited extended shelf life, stronger texture, and more yellow color paralleled to untreated cheese. HPP has been used to reduce bacterial counts, prevent lipid oxidation, and extend the refrigerated shelf life of local cheeses with subtle sensorial characteristics, such as the traditional "Torta del Casar" cheese. Pressure treatments have provided a clean label solution to overcome quality defects and prevent over-ripening and excessive bitterness in cheeses. By applying HPP treatments during the maturation of raw ewe milk cheese, pH stability and undesirable bitterness can be prevented, improving shelf life. HPP has also been found to reduce the ripening time of hard Reggianito cheese and enhance color stability and texture in ultrafiltered milk cheese. Overall, high-pressure technologies have demonstrated their potential to positively impact the physicochemical and nutritional quality of cheese, enhancing proteolysis, bioactive peptide release, color stability, texture, and shelf life, while providing clean label solutions for the cheese industry.

**Reduced-Fat and Low Sodium Cheese through Clean label pressure technologies**

The negative health consequences linked to milk fats, including issues like obesity, atherosclerosis, coronary heart disease, and hypertension, have sparked a growing demand for clean label dairy products with reduced fat content (Grosso et al., 2017). Instead of relying on fat alternatives and chemicals to mask unwanted effects in texture, aroma, and flavor, modifications in processing methods have been explored. The application of HPH technology has been investigated as a processing technique for reducing fat content in creams, and it has demonstrated encouraging outcomes in terms of accelerating lipid hydrolysis, improving yield, and preventing fat loss in whey during the production of low-fat Turkish white cheese (Karaman et al., 2013). In the coagulation process of milk, it has been reported that HPP-treated milk requires less enzyme concentration, resulting in reduced processing costs (Leite et al., 2018). In the case of reduced-fat Cheddar cheese, HPP applied one week after manufacturing (50-400 MPa for 2.5-19.5 minutes) demonstrated microbial and textural properties (Ozturk et al., 2013). The study suggested that HPP at 225 MPa or higher for 5 minutes formed a softer texture throughout cheese ripening, achieving the desired richness of reduced-fat cheese without the need for chemical additives. UHPH treatment of cream (300 MPa) has been shown to increase cheese yield by 13% compared to conventional treatments, resulting in a waterier, elastic, gummy, or chewy texture in fresh reduced-fat cheese (Mayta et al., 2019). Reducing sodium content in processed cheeses poses challenges in terms of texture, reliability, and flavor development. Sodium concentration is closely linked to the protein network, final moisture content, microbial activities, and enzymatic activities in cheese. However, HPP treatment (500 or 600 MPa for 3 minutes) of low-moisture, part-skim Mozzarella cheese has been found to result in reduced starter culture counts, lower water-soluble nitrogen, higher intact αS1-casein content, and a chewier texture with little blister quantity and great strand thickness. The utilization of vacuum packaging in Serra da Estrela cheese, a traditional cheese that holds a Protected Designation of Origin (PDO) status was conducted when the cheese is enveloped in paper without the use of vacuum sealing, however, HPP was employed for cold pasteurization in order to address safety concerns. The study juxtaposes two packaging systems: greaseproof paper wrapping without vacuum sealing and plastic film vacuum packaging. The findings indicate that there were no notable disparities between the two systems. However, the quantity of viable cell numbers of spore microorganisms in HPP-treated cheeses was diminished. The implementation of vacuum packaging enhanced the management of cheese proteolysis, resulting in a tougher texture compared to non-vacuum paper-wrapped cheeses. The study determines that traditional non-vacuum paper wrapping is appropriate for brief storage durations, whereas vacuum packing using plastic film is more advantageous for extended periods (Inácio et al., 2023). In summary, clean label pressure technologies play a significant role in producing safe and long-lasting cheeses by eliminating pathogenic bacteria, inhibiting biogenic amine formation, accelerating ripening, controlling over-ripening, reducing bitterness, and stabilizing sensory value. Notably, HPP applied at the start of cheese maturing allows for commercial auction without the need for further packaging, leading to cost savings and positive environmental outcomes in terms of reduced packaging materials and associated handling and management.

**Pressure-based technologies in yogurt production**

Achieving a clean label approach in yogurt production relies on the quality of milk and starter cultures. To compensate for poor processing and maintain texture and viscosity, additives such as starch, pectin, and gelatin have traditionally been used. Nevertheless, natural exopolysaccharides can function as clean label substitutes to improve the texture, durability, and sensory experience of yogurt. Furthermore, incorporating blends of heat-treated whey protein and buttermilk protein concentrates can reduce the need for starches and hydrocolloids in low-fat yogurts (Matumoto et al., 2011). Pressure-based technologies offer several benefits to the yogurt industry. The viscosity of the resulting yogurt is enhanced, and syneresis is reduced through pre-fermentation milk processing utilizing high pressure. This is achieved by altering the structure of whey proteins and causing disruption to casein micelles. High-pressure treatments applied after fermentation also extend the shelf life of yogurt. It is important to use pressure-resistant starter cultures to guarantee the sustainability of strains after high-pressure treatments, with a minimum requirement of 108 CFU/g.

Gentle or sublethal pressure treatments ranging from 100 to 300 MPa can produce essential peptides and free amino acids that support the growth and viability of probiotics throughout storage. These pressure treatments induce a stress retort in probiotics, aiding in their endurance during fermentation (Mota et al., 2018). Although pressure-induced destabilization and disruption of milk proteins may occur, the functionality of bioactive molecules remains unaffected. This characteristic enables the creation of functional yogurt products. HPH is effective in reducing the size of milk components, enhancing fat globules and protein amalgamation, and reducing the parting of the creamy portion of yogurt. HPH treatments also improve acidification and gel formation, resulting in enhanced aromatic profile and sensorial properties (Serra et al., 2009). Low-pressure HPH technology has been shown to increase gel particle size, gel strength, and viscosity, resulting in a creamy and necessary texture for low-fat yogurt (Ciron et al., 2012). Additionally, HPH treatments can lead to improved yogurt yield, reduced fermentation times, and increased lactic acid production. Buttermilk, which is a by-product of the process of manufacturing butter, is not given enough importance in the dairy industry since it causes issues with the texture of cheese and yogurt. Utilizing technological pretreatments such as membrane filtration and homogenization can enhance the integration of BM (bone meal) into dairy products. The analyzation of the impact of preconcentration using reverse osmosis (RO) and single-pass UHPH on the composition and microstructure of sweet BM in order to alter its techno-functional qualities was demonstrated. The BM and RO BM were subjected to varying pressures and then separated into three fractions using ultracentrifugation: a soluble fraction in the supernatant, a colloidal fraction with a hazy layer, and a high-density pellet. The technique of laser diffraction was employed to observe alterations in the distribution of particle sizes throughout the process of UPH. The monitoring of microstructural alterations was conducted through the utilization of confocal laser scanning microscopy. Particle size analysis revealed that the use of UHPH treatment led to a considerable reduction in the size of milk fat globule membrane fragments in both BM and RO BM. The application of pressure treatment at 300 MPa resulted in an enhanced extraction of total lipids, CN, calcium, and phosphate in the soluble fraction of the BM (Krebs et al., 2023). Overall, pressure-based technologies offer promising opportunities for achieving clean label yogurt production by improving texture, stability, flavor, and functionality without the need for synthetic additives.

**High Pressure Homogenization in the processing of sheep's milk**

Sheep milk yogurt offers distinct advantages over cow milk yogurt, including higher solids content, creamier texture, and enhanced nutritional value (Tribst et al., 2019). However, its widespread production is partial due to seasonal milk availability and lower animal yield. Freezing technology is common to store sheep milk, but it can have detrimental effects on its quality. Freezing damages fat globules, releases lipoproteins from the milk membrane, destabilizes proteins, aggregates casein, alters calcium concentration, disrupts milk saline equilibrium, and separates natural cream.

Prolonged refrigeration storage of yogurt made from frozen sheep milk leads to colloidal calcium solubilization, which upsurges sedimentation and final acidity. It also reduces the acidification rate and affects the constancy of the yogurt. Additionally, freezing and thawing of milk during storage result in undesirable alterations, such as post-acidification, reduced buffering capacity, lower pH value, and decreased firmness and adhesiveness of the yogurt. The investigation of different processing techniques for decreasing the concentrations of 5-hydroxymethylfurfural (5-HMF) and advanced glycation end products (AGEs) in dairy products was conducted utlizing the microbiological safety of milk was evaluated using a combination of high hydrostatic pressure (HHP) and moderate heat pre-incubation at 50 °C (MHHP). The results of the single-factor studies demonstrated a negative correlation between HHP intensity and levels of 5-HMF and AGE. Additionally, there was a positive correlation between HHP intensity with the microbial inactivation of necessary microbiological markers. The most effective processing conditions were found to be pre-incubation at a temperature of 50 °C for a duration of 20 minutes, followed by applying a pressure of 600 MPa for 15 minutes. When comparing MHHP milk to commercially thermal processed milk, it was shown that MHHP milk dramatically decreased levels of 5-HMF and AGEs. The MHHP treatment effectively maintained the protein content of milk in comparison to the ultrahigh-temperature treatment. The findings can aid in developing innovative methods for producing dairy milk of superior quality (Wu et al., 2022). To overcome these challenges (HPH) in conjunction with stirring using a low shear mixer before yogurt production has been found to be beneficial. HPH at a pressure of 3.5 MPa promotes the incorporation of casein micelles and fat globules, preventing plodding and creating naturally stabilized clean sheep milk yogurt (Tribst et al., 2018). The increased incorporation of fat and protein during the initial hour of HPH treatment directly contributes to better firmness and adhesiveness of the yogurt, while reducing creaming. A comparison of the quality of whole milk that underwent pasteurization utilizing high hydrostatic pressure processing (HPP) or a combination of microfiltration and HPP (MF + HPP), in comparison to traditional heat treatments (LTLT and HTST) was conducted. Following 8 days of refrigeration at a temperature of 5°C, both the overall bacterial count and the count of *E. coli* bacteria were decreased to an equivalent level. Milk subjected to high pressure exhibited increased denaturation of β-lactoglobulin, however no notable disparities were observed in stomach in-vitro protein digestion. HTST and HPP-treated milks exhibited comparable fragrance profiles, however LTLT-milks demonstrated elevated levels of ketones. After a duration of 8 days, the sensory study revealed that LTLT milk exhibited the highest intensities for all sensory qualities, although no discernible distinctions were observed between HTST, HPP, and MF + HPP milk. Nevertheless, the MF + HPP combination resulted in a significantly diminished Boiled Taste (Liu et al., 2020).

The effects of non-thermal processing processes on the levels of vitamin B12 in raw milk were conducted as vitamin B12 is an important nutrient. The study entailed the application of HHP, pulsed electric fields (PEF), or ultraviolet-C (UV-C) radiation to pasteurize raw milk. The findings indicated that the application of PEF and HHP techniques successfully maintained the original B12 content, however, the utilization of UV-C resulted in a 10% reduction. The HHP treatment effectively decreased bacteria while maintaining the vitamin B12 concentration. The use of PEF treatment did not have any impact on the levels of vitamin B12, however, it did result in a reduction of 0.9 log10 CFU/mL. The application of UV-C did not result in any decrease in microbial count. However, the greatest dose of UV-C led to a loss of 10% in the content of vitamin B12. The study emphasizes the significance of taking into account the susceptibility of vitamin B12 to pressure, electric field, and UV-C light in order to maintain the integrity of this crucial vitamin in milk (Ceribeli et al., 2023). By utilizing HPH and careful processing techniques, the production of high-quality sheep milk yogurt can be enhanced. This technology helps overcome the challenges associated with freezing and storage, ensuring a stable and desirable texture while preserving the unique characteristics of sheep milk yogurt.

### High Pressure technologies in ice-cream production

Dairy desserts, such as ice cream, are highly popular treats consisting of a complex mixture of fat droplets, air molecules, ice crystals, and a constant water phase. The dispersed phase comprises polysaccharides, lactose, proteins, and minerals. A significant demand in recent years for clean label products, including ice cream, with easily understandable and trustworthy ingredients (Goral et al., 2018). Industrial ice cream production involves pasteurizing milk at high temperatures and homogenizing it to make an emulsion. Stabilizers and emulsifiers play a crucial role in ice cream manufacturing by reducing ice crystal growth, preventing water migration, improving water solubility, controlling fat agglomeration, enhancing protein release during maturation, and enhancing creaminess (Bail et al, 2008). Synthetic emulsifiers and hydrocolloids are commonly used, but there is a growing interest in replacing them with natural alternatives (Goral et al., 2018).

Ice cream is a frozen dessert with rheological properties significantly affecting sensory acceptance. Stabilisers and emulsifiers play crucial roles in ice cream formulation, contributing viscosity, stabilizing protein, ensuring smoothness, providing resistance to melting, and reducing ice and lactose crystal growth. Emulsifiers, such as mono- and diglycerides of fatty acids, phospholipids, and cyclodextrin, are widely used in ice cream production. Lactobionic acid (LBA), a relatively new product obtained from lactose oxidation, has high potential applications in medical, cosmetics, and food processing. LBA can be used as a mineral absorption enhancer, stabiliser, antioxidant, and firming agent in the food industry (Zagorska et al., 2022). A study evaluated the application of LBA in ice cream production, including its effect on the physico-chemical properties of the ice cream mix, overrun, and melting behavior. The study used a traditional Premium ice cream formulation and evaluated its application in the dairy industry.

The study analyzed ice cream samples for fat and nonfat solids, using various methods. The rheological properties of the ice cream mix were determined using a MCR-302 rheometer, while the physico-chemical properties were evaluated using an oscillatory thermo-rheometry test and a texture analyzer. The viscosity exhibited a positive correlation with the concentration of LBA, while it had a negative correlation with the magnitude of the shear rate. Samples with a high starting viscosity shown a substantial reduction. The viscosity of LBA-added samples was substantially greater than that of EXT samples, suggesting a stronger potential to bind water. The viscosity of the product containing LBA exhibited a considerable increase at an equivalent concentration. The investigation revealed that ice cream samples containing 2 or 3 g/kg of LBA exhibited comparable characteristics to those manufactured with EXT. However, an increased concentration of LBA led to a firmer texture and reduced overrun. Among the many concentrations tested, 3 g/kg was identified as the optimal concentration (Zagorska et al., 2022). The study conducted to investigate the effects of recombinant microbial transglutaminase enzyme on the characteristics of ice cream utilizing two different approaches. The initial approach led to a 10% rise in the overrun value, whereas the alternative approach resulted in a 7% increase. The pseudoplastic behavior seen in all ice cream samples suggests that the quantity of transglutaminase has a critical role in enhancing the physicochemical qualities of ice cream (Al et al., 2020). It is possible to produce probiotic ice creams that have the necessary technological and sensory qualities, as well as a high survival rate of probiotics (>6 log cfu/g) throughout storage and simulated gastrointestinal conditions. Factors such as probiotic properties, milk type, process parameters, and additives are crucial to consider (Pimentel et al., 2021). Clean label ice cream focuses on using minimally processed ingredients without chemical additives. Natural emulsifiers, like egg yolk or natural polysaccharides like locust bean gum, can be utilized. However, finding suitable replacements for synthetic stabilizers can be challenging due to the technical difficulties in emulsification while preserving the desired consistency of clean label ice cream. High-pressure-based technologies present promising possibilities for substituting non-dairy emulsifiers and hydrocolloids in ice creams. HPH and HPP have been explored in ice cream production. HPH treatments result in casein masses, denatured whey proteins, and augmented viscosity (Huppertz et al, 2011). HPP-treated ice cream mixes exhibit a shear-thinning behavior and slower melting rates. Ice creams treated with HPH have lesser overrun, higher rigidity, and enhanced resistance to melting compared to conventional homogenization methods. HPJ treatments have also shown promise in low-fat clean label ice cream, forming large casein-fat complexes that act as fences and slow ice crystal development while freezing (Voronin et al., 2019). These high-pressure technologies provide opportunities to enhance the physical and structural abilities of ice cream while maintaining a clean label profile. They offer potential applications in the development of clean label confections, allowing for the production of dairy desserts with improved texture, stability, and sensory characteristics.

### Dulce de leche

Dulce de leche is a Latin American confection produced by heating a blend of milk and sugar under specific conditions to form a paste with a caramel hue and sugary flavor. It is frequently available for purchase in Argentina, Uruguay, and Brazil, with varying names and manufacturing methods based on the country (Silva et al., 2015). Various varieties of dulce de leche are categorized as paste, ice cream, confectionary, and cream. Variations in production process factors lead to the creation of distinct types of dulce de leche. There are three primary production processes: batch, semicontinuous, and continuous (Chaves et al., 2018). The statute permits the use of additives such as peanuts, cocoa, chocolate, and dried fruit to enhance the variety of the dulce de leche product. The substitute should range from 5% to 30% (w/w) to prevent misrepresenting the product. Coloring, stabilizers, thickeners, and wetting agents are allowed to be used in the making of ice cream. Dulce de leche containing additional dairy fat is a high-calorie version that has decreased in popularity because of market shifts and rising costs. Dulce de leche for sweets is mass-produced and supplied in bulk packaging, making it cost-effective and flavorful. The diet dulce de leche needs special care because reducing sugar directly impacts the product's sensory characteristics. Pingo de leite is a unique variation of dulce de leche with a solid exterior and a smooth, creamy interior. Dulce de leche is available as bars or tablets, with larger levels of sucrose and lactose, and requiring a lengthier manufacture procedure. Varying forms of dulce de leche lead to many goods and applications, such as breakfast items, confections, sweets, and chocolates (Stephani et al., 2019). Dulce de leche can be made using three methods: classic open system, semicontinuous, and continuous. The conventional open system procedure includes combining ingredients in stages, heating them to 30°C, and concentrating them to get a final concentration of around 70%. The final concentration is established by examining the behavior of a drop of dulce de leche when placed in water. After cooling to prevent crystallization, the product is packaged in jars. Semicontinuous and continuous manufacturing methods utilize multiple-effect evaporators to pre-concentrate milk and sugar mixes, with the goal of decreasing steam consumption and processing time. The continuous technique is designed to efficiently create dulce de leche on a large scale while minimizing steam usage, however it is exclusively utilized in large industrial facilities. The final homogenization and packaging procedures occur after the continuous and semicontinuous operations. Ingredients are typically added to vary the types of dulce de leche throughout the concentration process (Penci & Martin, 2016; Stephani et al., 2019). Chaves et al. (2018) created a dulce de leche using goats' milk, chia flour, and a portion of defatted chia flour as a replacement for starch. The lipid profile was changed to include higher levels of monounsaturated and polyunsaturated fatty acids. The product displayed elevated levels of moisture, color, and sensory attributes in comparison with a dairy product containing starch. Researchers have investigated the use of alternative components including milk from different species or the addition of fruits to create a variety of products comparable to dulce de leche. Goat's milk has less water and more fatty acids than cow's milk, which may explain the need for less processing time. Researchers have investigated the utilization of sheep's milk in dulce de leche, emphasizing its potential as a feasible alternative from both a technical and nutritional standpoint. The researchers discovered that adding cream to sheep's milk did not alter its physicochemical and microbiological characteristics, and the product maintained stability for 150 days during storage. The blend of sheep's and cows' milk was discovered to be a feasible option both technically and nutritionally. Utilizing inexpensive components such as whey in the manufacturing of dulce de leche enhanced the finished product's value (Vargas et al., 2021). Recent research has investigated novel methods to enhance dulce de leche manufacturing, with the goal of preserving the quality and ultimate attributes of the product. Milk is a complex structure with abundant components, allowing for easy alteration by bacteria and enzymes. Nevertheless, certain methods can change the sensory and nutritional characteristics of the product. Emerging technologies encompass ultrasound, high pressure therapies, irradiation/ultraviolet light, pulsed electric field, and thermosonication. These procedures are designed to mitigate the adverse impacts of conventional processing methods and enhance the production process. Ohmic heat therapy can maintain food quality while deactivating pathogens and spore-forming bacteria. It can also enhance sensory attributes, luminosity, viscosity, and taste (Vargas et al., 2021). Producing fermented beverages from whey is appealing due to whey's abundance of water and nutrients, which are advantageous for promoting microbial development. The production process is problematic because too quick microbiological deterioration, scaling of processing equipment, flavor flaws, and instability of the finished product (Bandara et al., 2023).

**Industrial Challenges and Future Directions in High Pressure-Based Technologies for dairy products**

Research on high pressure-based technologies has made significant progress, but there were initial technological limitations that hindered their industrial applications until the 1990s when reliable and productive HPP equipment became available. Currently, around 2% of global HPP apparatus is utilized for dairy applications. By effectively inactivating spoilage microorganisms, these technologies, particularly HPP, have demonstrated remarkable success in significantly extending the shelf life of dairy products, achieving a reduction of over 5 logarithmic colony-forming units per milliliter (log CFU/mL). However, the neutral pH and great nutritional significance of dairy products can lead to the potential retrieval of injured bacteria, necessitating additional investigation to establish the safety of pressurized milk and address regulatory concerns connected to labeling and claims. Guiding principle such as Regulation (EC) No 852/2004 state that HPP, when used for decontamination, should be considered a processing step. This complicates the label of claiming HPP milk as "fresh" or "raw" in the European market. In United States, the commercialization of milk treated with HPP is only permitted when it is equal to heat pasteurization and provides a reduction of at least 5 log CFU/mL for *Coxiella burnetii*, although there is currently no evidence regarding the effectiveness of high pressure-based technologies against *C. burnetii* in milk. From an environmental perspective, high pressure-based processing has shown a lesser load paralleled to conventional thermal processing, mainly owing to lower electricity consumption. HPP) offers a more cost-effective alternative to modified atmosphere packaging, while also reducing the environmental footprint. Further improvements in the efficiency of UHPH processes at an industrial scale can contribute to reducing the carbon footprint by up to 88% (Valasina et al., 2017). Optimization of experimental setups is crucial to achieve desired sensorial characteristics, as higher pressures or "over-processing" can have undesirable effects on physicochemical and functional qualities, such as increased fat globule size and coalescence. To improve shearing and mechanical impact, facilitate liquid jet impact, and achieve spore inactivation at lower temperatures, there is potential for investigating novel materials and exploring innovative designs and geometries for specialized valves (Cocace et al., 2020). Capital expenditure and operating costs are significant considerations for implementing pressure-based technologies, as they are typically higher than traditional technologies. However, the added value and distinct benefits provided by these nonthermal technologies can justify the higher costs (Huang et al., 2017). In recent years, the inclusive demand for high pressure-based technologies has increased, leading to more effectual production processes and decreased equipment charges. The removal of chemical additives through the use of high pressure-based technologies aligns with the objective of clean labeling in the food manufacturing and can contribute to meeting consumer demands for natural and additive-free products.

**Clean Label High-Pressure-Based Technologies: Opportunities for Dairy Producers**

Clean label high-pressure-based technologies offer a viable alternative to artificial or synthetic additives, which are a source of concern for consumers. However, a substitution of them could present practical challenges in food manufacturing processes. Dairy products labeled as "free from artificial additives" have experienced significant development in the health and wellness sector. High-pressure-based technologies leverage simple phenomena, making them a suitable option for clean label processing. Although the higher cost of products processed using high-pressure techniques may impact production, food companies are increasingly inclined to minimize the usage of unnecessary and possibly dangerous chemicals in their formulations. The combination of high pressure-based technologies with clean label approaches presents dairy producers with a range of opportunities, taking into account factors such as organoleptic characteristics, nutritional value, raw material quality, and consumer preferences for organic food consumption. Table 6 lists the types and uses of artificial additives that are frequently employed in the dairy industry.

Table 6. Artificial additives utilized in the dairy sector with their types and utilities.

| Artificial Additives | Types | Utility | References |
|---|---|---|---|
| Emulsion stabilizers | Calcium lactate stearate, spans, and sucrose fatty acid ester, also Monoglyceride, diglycerol, tripolyglycerol monostearate, propylene glycol alginate, succinylated monoglycerides, sodium stearoyl lactylate. | Enhance the firmness and uniformity of the emulsion, maintain the appearance stability, and enhance the taste of liquid milk. Inhibit the growth of ice crystals and increase the foam ability and arrangement of ice cream. | Euston et al., 2019 |
| Thickening agent | Natural gums | Enhancing the structural integrity of dairy products and enhancing their sensory attributes. | Suieman et al., 2018; Torres et al., 2019 |
| Antioxidation agents | Palmitoyl ascorbic acid | Utilized to inhibit or delay oxidative degradation and enhance stability and shelf life. | Carocho et al., 2018; Lin et al., 2010 |
| Coloring agent | Synthetic dyes | Enhancing visual appeal and gloss to enhance consumer preference and stimulate appetite. | McWilliams, 2023 |
| Sweetening substitutes | Lactitol, trichlorosucrose, erythritol and acesulfame. | Imparts a pleasant, sugary taste to the food or animal feed. | Rao & Pagote, 2018 |
| Food preservers | Sodium carbonate/bicarbonate, formaldehyde/formalin, bronopol, potassium dichromate, mercuric chloride, azidiol, hydrogen peroxide, salicylic acid, benzoic acid, sorbic acid, and boric acid. | Inhibits the growth of microorganisms and the spoilage of milk, prolonging its shelf life. Regulate the presence of different harmful bacteria, yeasts, and fungi associated with foodborne illnesses and spoilage, including *E. coli*, *L. monocytogenes*, *Aspergillus spp.*, and *Penicillium spp.* | Singh & Gandhi, 2015 |
| Viscosity modifiers, or gel-forming substances. | Guar gum, gelatin, pectin, alginates, carrageenan, locust bean gum, cellulose gum, gellan gum, and xanthan gum | Contribute crucial structural characteristics, improve processing functionalities, deliver the desired texture or mouthfeel, and assist in maintaining structural integrity. | Yousefi & Jafri, 2019 |

**Customer Perception**

Emerging technologies, like ohmic heating, are being considered as substitutes for pasteurization in dairy products, with ohmic heating being the most often discussed thermal technology. Nonthermal methods such as high-pressure processing, ultrasound, and cold plasma are increasingly being used in the preparation of meat and fruit products. These technologies can enhance color, aroma, flavor, and texture, and boost acceptance in comparison to pasteurization. Yet, insufficient knowledge regarding these technologies and elevated prices of treated products are the primary obstacles to customer approval.

Traditional thermal processes including pasteurization, sterilization, and ultrahigh temperature can alter the nutritional, physicochemical, and sensory characteristics of food items. Emerging technologies can be categorized as nonthermal or thermal technologies, providing benefits such preserving larger levels of bioactive chemicals, enhancing functional qualities, and introducing a variety of volatile molecules. Barriers to entry include high investment costs, limited access to quality equipment, scientific information, and funding, as well as higher product prices.

Consumer acceptability, preference, and choice are essential factors that industries rely on to make judgments regarding food goods. Consumers may reject processed items owing to alterations in sensory attributes, lack of familiarity, health and safety issues, ethical and environmental concerns, and higher product costs. This study seeks to outline the effects of thermal and nonthermal developing technologies on the sensory attributes, acceptance, and consumer perception of food products (dos Santos Rocha et al., 2022). Research in sensory and consumer science has focused on studying how developing processing technologies affect sensory features. Free comment (FC) is a study method that enables participants to assess a product by expressing their thoughts using their own words, without the use of predefined scales or lists. This work utilized Fourier transform infrared spectroscopy in conjunction with the statistical analysis method developed to analyze the properties of high-protein vanilla flavored milk beverages produced using ohmic heating or pasteurization. The goal was to confirm the use of FC and the proposed statistical method for characterizing samples analyzed by developing technologies. The preparation of the flavored milk drink included refrigerated raw milk, 10% industrial whey protein isolate (WPI), 3% sucrose, and 0.5% vanilla flavor. The data analysis approach used was to identify the main product characteristics to study consumer perception and connections between products /and characteristics. The statistical analysis revealed that pasteurization and OH treatment produce distinct impacts on the sensory characteristics of products, whereas the electrical field strength significantly influences the sensory profile of flavored milk drinks. It was the first to utilize free comments to characterize the sensory profile of flavored milk drink treated with ohmic heating and determine the factors influencing preferences and aversions. Consumers identified the characteristics typically found in studies employing other sensory methods through the FC approach (Rocha et al., 2023).

**CONCLUSION**

HPP effectively inactivates pathogens and extends shelf life, making dairy products safer and longer-lasting without the need for preservatives. UHPH and HPH treatments improve the physicochemical and nutritional properties of dairy products, enhancing texture, stability, and sensory characteristics. These technologies enable the reduction of fat and sodium content in dairy items while maintaining quality and functionality. High-pressure treatments control spoilage microorganisms in cheese, ensuring safety and stability. Advantages include eliminating synthetic additives and stabilizers, and meeting consumer demand for minimally processed and additive-free foods. Challenges include cost, regulatory considerations, and process optimization. Ongoing research and equipment advancements address challenges, making high-pressure technologies more accessible. Embracing these technologies allows dairy producers to offer safer, cleaner, and higher-quality products, meeting consumer demands and promoting sustainability.

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The datasets generated used and/ or analyzed during the current study are available from the corresponding author on reasonable request.

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All the co-authors are willing to participate in this manuscript.
**Consent for publication**
All authors are willing to publish this manuscript.
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This article does not contain any studies with human participants or animals performed by any of the authors.
**Authors Contribution**
Nosheen Amjad and Ali Imran-original draft equal; Muhammad Sadiq Naseer, Fatima Tariq, and Fakhar Islam-formal analysis; Ahmed Elawady, Aashna Sinha, and Abdela Befa Kinki-Reviewing editing equal and supervision equal.

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