Journal of Agriculture, Biology and Applied Statistics
Vol. 5, Nos. 1-2, 2026, pp. 53-63
© ARF India. All Right Reserved
URL: www.arfjournals.com
https://doi.org/10.47509/JABAS.2026.v05i01-02.05

High-Pressure Processing as an Alternative to Ultra-High Temperature Processing: A Comparative Assessment of Milk Protein Structure, Functionality, and Digestibility

Vedprakash Sahu[1]* and Aprna Sharma[2]
[1]Department of Dairy Chemistry, College of Dairy Science and Food Technology,
Dau Shri Vasudev Chandrakar Kamdhenu Vishwavidyalaya (DSVCKV), Raipur, Chhattisgarh, India
[2]Department of Dairy Technology, College of Dairy Science and Food Technology,
Dau Shri Vasudev Chandrakar Kamdhenu Vishwavidyalaya (DSVCKV), Raipur, Chhattisgarh, India
**Corresponding Address: kprakash1008@gmail.com*

To Cite this Article

Vedprakash Sahu & Aprna Sharma (2026). High-Pressure Processing as an Alternative to Ultra-High Temperature Processing: A Comparative Assessment of Milk Protein Structure, Functionality, and Digestibility. *Journal of Agriculture, Biology and Applied Statistics,* 5: 1-2, pp. 53-63.

Abstract: Milk processing technologies play a critical role in ensuring microbiological safety while preserving the nutritional and functional quality of dairy products. Ultra-High Temperature (UHT) processing is widely used for commercial milk sterilization because it provides an extended shelf life under ambient storage conditions. Nevertheless, exposure to high temperatures promotes irreversible structural changes in milk proteins, including whey protein denaturation, casein–whey protein interactions, and Maillard reactions, which may influence functional performance and protein digestibility. High-Pressure Processing (HPP) has emerged as an alternative non-thermal preservation technology that inactivates vegetative microorganisms through hydrostatic pressure while minimizing heat-induced chemical modifications.Thispaper presents a comparative assessment of UHT and HPP based on current knowledge of dairy protein chemistry and food processing principles. The discussion focuses on changes in casein micelle organization, β-lactoglobulin stability, protein surface properties, functional characteristics, and gastrointestinal digestibility. Evidence from published studies indicates that pressure treatment primarily alters non-covalent molecular interactions, allowing partial and reversible structural rearrangements without extensive covalent protein damage. In contrast, severe thermal processing promotes irreversible aggregation through disulfide bond formation and protein cross-linking.The preservation of native protein architecture following HPP is associated with improved emulsifying and foaming properties and greater susceptibility to enzymatic hydrolysis

Received : 18 July 2026 • **Revised :** 17 August 2026 • **Accepted :** 28 August 2026 • **Published :** 19 October 2026

during digestion. These characteristics suggest that pressure processing has considerable potential for producing premium dairy products with enhanced nutritional quality and desirable functional performance. Although further industrial validation is required, HPP represents a promising technology for meeting the increasing demand for minimally processed dairy products while maintaining microbiological safety and product quality.

Keywords: High-Pressure Processing; Ultra-High Temperature Processing; Casein Micelles; β-Lactoglobulin; Protein Digestibility; Dairy Processing.

1. INTRODUCTION

Milk is a nutritionally important food that supplies high-quality proteins, essential amino acids, minerals, vitamins, and bioactive compounds required for human health. The protein fraction consists primarily of caseins and whey proteins, each contributing distinct structural and functional characteristics to milk. Caseins are organized into colloidal micelles that provide stability to the milk system, whereas whey proteins remain dissolved in the aqueous phase and contribute to nutritional value and functional properties [10]. Maintaining the native structure of these proteins is essential because structural modifications during processing directly influence product quality, digestibility, and technological performance [16].

Thermal processing has long been the foundation of milk preservation. Among available technologies, Ultra-High Temperature (UHT) processing is extensively employed because it provides commercial sterility and enables long-term storage without refrigeration [11]. During UHT treatment, milk is heated to temperatures exceeding 135 °C for a few seconds before aseptic packaging. While this process effectively destroys pathogenic and spoilage microorganisms, the intense thermal exposure also modifies milk proteins through denaturation, aggregation, and chemical interactions that alter their functional behaviour [6].

One of the most significant consequences of UHT processing is the denaturation of β-lactoglobulin, the predominant whey protein in bovine milk. Heat-induced unfolding exposes reactive sulfhydryl groups that interact with κ-casein located on the surface of casein micelles, resulting in irreversible whey protein–casein complexes [2]. Simultaneously, prolonged exposure to elevated temperatures accelerates Maillard reactions between lactose and amino groups, contributes to lysine loss, and modifies the mineral equilibrium within casein micelles [11]. Collectively, these changes influence protein solubility, emulsifying capacity, foaming behaviour, and susceptibility to enzymatic digestion.

Growing consumer demand for fresh-tasting, minimally processed foods has stimulated interest in preservation technologies that reduce thermal damage while maintaining microbiological safety. High-Pressure Processing (HPP) has emerged as one of the most promising alternatives [4]. Unlike thermal sterilization, HPP applies uniform hydrostatic pressure, typically between 400 and 600 MPa, at chilled or ambient temperatures. Pressure primarily disrupts weak non-covalent interactions, including hydrophobic interactions and hydrogen bonds, while leaving the primary structure of proteins largely unchanged [14].

As a result, many pressure-induced conformational changes are reversible, allowing proteins to retain much of their native functionality after decompression [15]. Previous investigations have demonstrated that HPP can preserve whey proteins more effectively than conventional thermal processing while inducing controlled modifications in casein micelles that improve functional performance [7].

Pressure-treated milk has been reported to exhibit enhanced emulsifying and foaming properties together with improved accessibility of digestive enzymes during gastrointestinal digestion [4]. These characteristics make HPP particularly attractive for the production of premium dairy products intended to retain fresh flavour and nutritional quality.

Although numerous laboratory-scale studies have investigated pressure-induced modifications of milk proteins, the broader implications for dairy processing continue to be an active area of research [3]. Understanding how pressure and temperature influence protein structure provides valuable insight into the development of future processing strategies that balance microbial safety with nutritional and technological quality.

Accordingly, this paper presents a comparative assessment of UHT and HPP with emphasis on protein structural modifications, functional properties, and gastrointestinal digestibility. By integrating current knowledge from dairy chemistry and food processing research, the review highlights the advantages, limitations, and future potential of High-Pressure Processing as an alternative preservation technology for fluid milk.

2. MATERIALS AND METHODS

2.1. Study Design

This study was conducted as a comparative assessment of the effects of Ultra-High Temperature (UHT) processing and High-Pressure Processing (HPP) on

the structural, functional, and nutritional properties of bovine milk proteins. The assessment was developed through a critical evaluation of published research on dairy protein chemistry, non-thermal food preservation, and gastrointestinal protein digestion. The objective was to compare the underlying mechanisms through which thermal energy and hydrostatic pressure influence milk protein structure and to discuss their implications for dairy product quality.

2.2. Literature Selection

A comprehensive literature search was conducted using scientific databases to identify studies relevant to High-Pressure Processing (HPP) and Ultra-High Temperature (UHT) processing of milk. Search terms included *High-Pressure Processing*, *Ultra-High Temperature Processing*, *milk proteins*, *casein micelles*, *β-lactoglobulin*, *protein denaturation*, *protein digestibility*, *surface hydrophobicity*, *emulsifying properties*, *foaming properties*, and *INFOGEST digestion*. The selected studies were evaluated for scientific relevance, methodological quality, and their contribution to understanding the structural, functional, and digestive effects of HPP and UHT on milk proteins.

2.3. Comparative Evaluation Framework

The comparison between UHT and HPP was performed using four major evaluation criteria:

1. Structural modifications of casein micelles and whey proteins.
2. Changes in protein functionality, including emulsifying and foaming properties.
3. Influence of processing on gastrointestinal protein digestibility.
4. Potential implications for dairy product quality and future industrial application.

These criteria were selected because they collectively represent the major physicochemical and nutritional characteristics affected by milk processing technologies.

2.4. Assessment of Protein Structural Changes

The discussion of structural modifications focused primarily on β-lactoglobulin and casein micelles because these proteins are particularly sensitive to processing conditions and play important roles in determining milk functionality. The

comparative assessment considered reported changes in protein unfolding, aggregation, casein–whey protein interactions, particle size distribution, and alterations in non-covalent molecular interactions following thermal or pressure treatment [7].

2.5. Evaluation of Functional Properties

Functional characteristics reported in the selected literature were compared to assess the influence of processing technology on the technological performance of milk proteins. Particular attention was given to surface hydrophobicity, emulsifying properties, and foaming behaviour because these characteristics influence the manufacture and quality of numerous dairy products.

The discussion emphasizes the molecular mechanisms responsible for differences observed between thermal and pressure-treated milk. Previous studies have demonstrated that pressure-induced modifications can improve protein functionality by altering molecular flexibility while limiting irreversible aggregation [4,7].

2.6. Assessment of Protein Digestibility

The influence of processing on protein digestibility was evaluated through studies employing the standardized INFOGEST in vitro gastrointestinal digestion protocol [5]. Comparisons focused on the accessibility of digestive enzymes to milk proteins, the degree of protein hydrolysis, and the release of peptides and amino acids during simulated gastric and intestinal digestion.

These parameters provide insight into the nutritional consequences of structural modifications induced by different processing technologies.

2.7. Data Synthesis

Findings from the selected studies were synthesized using a narrative comparative approach. Rather than performing a quantitative meta-analysis, the available evidence was critically examined to identify consistent trends, similarities, and differences between UHT and HPP.

Mechanistic explanations were interpreted in the context of established principles of dairy chemistry, protein biophysics, and food processing science. This approach enabled the integration of structural, functional, and nutritional perspectives into a comprehensive evaluation of the two processing technologies.

3. RESULTS AND DISCUSSION

3.1. Comparative Effects of UHT and HPP on Whey Protein Stability

The available literature consistently demonstrates that Ultra-High Temperature (UHT) processing and High-Pressure Processing (HPP) influence milk proteins through fundamentally different mechanisms. During UHT treatment, exposure to temperatures above 135 °C causes extensive unfolding of β-lactoglobulin (β-Lg), exposing reactive sulfhydryl groups that readily participate in disulfide bond exchange with κ-casein on the surface of casein micelles. These reactions lead to irreversible whey protein–casein complexes, increased protein aggregation, and changes in the physicochemical properties of milk [6].

In addition, prolonged thermal exposure accelerates Maillard reactions and modifies the distribution of colloidal calcium phosphate, further affecting protein stability and nutritional quality [11].

In contrast, HPP primarily disrupts weak non-covalent interactions, including hydrogen bonding, hydrophobic interactions, and electrostatic forces, while largely preserving covalent peptide bonds [14]. Consequently, pressure-induced conformational changes are often partially reversible after decompression, allowing milk proteins to retain much of their native structural organization [15].

These contrasting mechanisms have important implications for the nutritional and technological quality of dairy products. Greater preservation of native whey proteins following HPP has been associated with improved retention of bioactive protein fractions and a lower extent of heat-induced chemical modification, whereas UHT processing provides superior commercial sterility but at the expense of more extensive structural alterations [4].

3.2. Influence on Casein Micelle Organization

Casein micelles play a central role in determining the stability and processing characteristics of milk. Thermal processing alters the micellar structure through interactions between denatured whey proteins and κ-casein, resulting in increased particle size and the formation of a more compact protein network [2].

These structural modifications contribute to changes in viscosity, heat stability, and rennet coagulation behaviour. Unlike thermal treatment, hydrostatic pressure affects casein micelles by temporarily disrupting hydrophobic interactions and mineral bridges that stabilize the micellar structure [14].

Published studies indicate that pressure-induced dissociation of micelles is largely reversible, with partial reassembly occurring after pressure release [17]. Although the degree of structural modification depends on pressure level, treatment duration, and milk composition, HPP generally preserves micellar integrity more effectively than severe thermal processing.

Maintenance of native casein organization is particularly important because it contributes to protein solubility, physical stability, and desirable functional properties during manufacture of dairy products [10]. Preservation of these structural characteristics may also improve subsequent enzymatic hydrolysis during gastrointestinal digestion.

3.3. Functional Properties of Pressure and Heat-Treated Milk

Structural modifications produced during processing directly influence the technological functionality of milk proteins. Functional properties such as emulsification, foaming, water-holding capacity, and gel formation are closely related to protein flexibility, molecular conformation, and surface hydrophobicity.

Moderate pressure treatment has been reported to expose hydrophobic amino acid residues without promoting extensive irreversible aggregation. This controlled unfolding enhances the ability of proteins to adsorb rapidly at oil–water and air–water interfaces, resulting in improved emulsifying and foaming performance [7].

Greater molecular flexibility also contributes to the formation of stronger interfacial films, which improve emulsion stability and foam persistence.

In comparison, severe thermal treatment often causes irreversible aggregation that restricts protein mobility. Although heating may increase apparent surface hydrophobicity through unfolding, simultaneous cross-linking reduces the ability of proteins to reorganize efficiently at interfaces [6].

Consequently, excessive thermal denaturation may adversely affect several functional properties despite maintaining microbiological safety.

These observations highlight the importance of selecting processing conditions that achieve microbial inactivation while minimizing undesirable physicochemical changes in milk proteins. From a product development perspective, preservation of protein functionality is particularly relevant for dairy beverages, nutritional formulations, fermented products, and protein-enriched foods.

3.4. Implications for Protein Digestibility

Protein digestibility is influenced not only by amino acid composition but also by the three-dimensional organization of proteins following processing. Heat-induced aggregation during UHT treatment can reduce enzyme accessibility by producing dense protein networks that limit the penetration of gastric and pancreatic enzymes [6].

Furthermore, formation of whey protein–casein complexes may mask enzymatic cleavage sites and reduce the rate of protein hydrolysis during digestion [12].

Pressure treatment produces a different structural response. Partial unfolding without extensive covalent aggregation increases the accessibility of peptide bonds to digestive enzymes while preserving the nutritional integrity of proteins [15].

Studies employing the standardized INFOGEST in vitro digestion protocol have reported faster early-stage proteolysis and greater peptide release following pressure treatment compared with severe thermal processing [5]. Although the magnitude of these differences varies among studies, the overall trend suggests that preservation of native protein architecture may enhance gastrointestinal digestion.

Improved digestibility may also increase the bioavailability of essential amino acids and bioactive peptides, thereby contributing to the nutritional value of pressure-treated dairy products. Nevertheless, the relationship between processing conditions and protein bio accessibility remains complex and is influenced by factors including milk composition, processing intensity, storage conditions, and individual physiological variability.

3.5. Industrial Relevance and Future Perspectives

The dairy industry continues to seek processing technologies capable of maintaining microbiological safety while preserving nutritional quality and consumer-desired sensory characteristics. High-Pressure Processing has emerged as a promising technology because it minimizes thermal damage while maintaining many of the native physicochemical properties of milk proteins [3,4].

Despite these advantages, widespread industrial implementation requires consideration of equipment cost, processing capacity, refrigerated distribution, packaging compatibility, and product-specific quality requirements.

Future research should integrate pilot-scale validation, process optimization, life-cycle assessment, sensory evaluation, and economic analysis to determine the most appropriate applications of HPP within commercial dairy manufacturing.

Overall, the published evidence indicates that HPP represents a valuable complement to conventional thermal technologies rather than a universal replacement [4]. Selection of the appropriate processing method should be guided by the desired shelf life, nutritional objectives, product characteristics, and manufacturing requirements.

4. CONCLUSION

The comparative assessment presented in this study demonstrates that Ultra-High Temperature (UHT) processing and High-Pressure Processing (HPP) influence milk proteins through fundamentally different mechanisms, resulting in distinct effects on structural integrity, functional performance, and nutritional quality.UHT processing remains an effective technology for achieving commercial sterility and prolonged ambient shelf life; however, exposure to elevated temperatures promotes irreversible whey protein denaturation, casein–whey protein interactions, and heat-induced chemical modifications that may compromise functional characteristics and protein digestibility.In contrast, HPP preserves the native architecture of milk proteins by predominantly affecting non-covalent molecular interactions, thereby minimizing irreversible structural damage while maintaining desirable physicochemical properties. Evidence from published studies indicates that pressure-treated milk generally retains superior emulsifying and foaming properties, exhibits greater structural stability of casein micelles, and provides improved accessibility of digestive enzymes during gastrointestinal proteolysis compared with conventionally UHT-treated milk.

These characteristics highlight the potential of HPP for manufacturing premium dairy products with enhanced nutritional value and fresh sensory attributes.Despite these advantages, HPP should be considered a complementary processing technology rather than a universal replacement for thermal sterilization. Selection of the most appropriate preservation method should be based on product characteristics, intended shelf life, processing objectives, distribution requirements, and economic feasibility. Continued advances in pressure-processing technology, together with further pilot-scale validation, consumer acceptance studies, and sustainability assessments, will support the wider application of HPP in modern dairy processing.

REFERENCES

Anema, S. G. (2008). Heat-induced, pH-dependent dissociation of casein micelles in milk. *Journal of Agricultural and Food Chemistry, 56*(12), 4226–4235.

Anema, S. G., & Li, Y. (2003). Association of denatured whey proteins with casein micelles in heated reconstituted skim milk. *Journal of Agricultural and Food Chemistry, 51*(6), 1640–1646.

Balasubramaniam, V. M., Martínez-Monteagudo, S. I., & Gupta, R. (2015). Principles and application of high-pressure based technologies in food processing. *Annual Review of Food Science and Technology, 6*, 435–462.

Barba, F. J., Terefe, N. S., Buckow, R., Knorr, D., & Orlien, V. (2021). High-pressure processing of milk and dairy products: A review. *Foods, 10*(8), 1867.

Brodkorb, A., Egger, L., Alminger, M., Alvito, P., Assunção, R., Ballance, S., Bohn, T., Bourlieu-Lacanal, C., Boutrou, R., Carrière, F., Clemente, A., Corredig, M., Dupont, D., Dufour, C., Edwards, C., Golding, M., Karakaya, S., Kirkhus, B., Le Feunteun, S., Lesmes, U., Recio, I., & Others. (2019). INFOGEST static in vitro simulation of gastrointestinal food digestion. *Nature Protocols, 14*(4), 991–1014. https://doi.org/10.1038/s41596-018-0119-1

Broersen, K., van Teeffelen, A. M. M., Visschers, R. W., & de Jongh, H. H. J. (2006). Heat-induced aggregation of β-lactoglobulin: Molecular mechanisms. *Biomacromolecules, 7*(6), 1891–1898.

Cadesky, L., Walkling-Ribeiro, M., Kriner, K. T., Karwe, M. V., & Moraru, C. I. (2017). Structural changes induced by high-pressure processing in micellar casein and milk protein concentrates. *Journal of Dairy Science, 100*(12), 8655–8671.

Considine, T., Patel, H. A., Anema, S. G., Singh, H., & Creamer, L. K. (2007). Interactions of milk proteins during heat and high hydrostatic pressure treatments—A review. *Innovative Food Science & Emerging Technologies, 8*(1), 1–23. https://doi.org/10.1016/j.ifset.2006.08.006

Corredig, M., & Dalgleish, D. G. (1999). The mechanisms of the heat-induced interaction of whey proteins with casein micelles in milk. *International Dairy Journal, 9*(3–6), 233–236.

Dalgleish, D. G., &Corredig, M. (2012). The structure of the casein micelle of milk and its changes during processing. *Annual Review of Food Science and Technology, 3*, 449–467.

Datta, N., & Deeth, H. C. (2001). Age gelation of UHT milk—A review. *Food and Bioproducts Processing, 79*(4), 197–210.

Donato, L., &Guyomarc'h, F. (2009). Formation and properties of whey protein/κ-casein complexes in heated milk. *Dairy Science & Technology, 89*, 3–20.

Fox, P. F., & Brodkorb, A. (2008). The casein micelle: Historical aspects, current concepts and significance. *International Dairy Journal, 18*(7), 677–684.

Huppertz, T., Fox, P. F., & Kelly, A. L. (2004). High pressure treatment of bovine milk: Effects on casein micelles and whey proteins. *Journal of Dairy Research, 71*(4), 489–497.

Huppertz, T., Kelly, A. L., & Fox, P. F. (2006). Effects of high pressure on constituents and properties of milk. *International Dairy Journal, 16*(10), 1114–1126.

McMahon, D. J., & Oommen, B. S. (2013). Casein micelle structure, functions and interactions. *International Dairy Journal, 29*(1), 1–11.

Needs, E. C., Stenning, R. A., Gill, A. L., Ferragut, V., & Rich, G. V. (2000). High-pressure treatment of milk: Effects on casein micelle structure and on enzymic coagulation. *Journal of Dairy Research, 67*(1), 31–42. https://doi.org/10.1017/S0022029999004021

O'Reilly, C. E., O'Connor, P. M., Kelly, A. L., Beresford, T. P., & Murphy, P. M. (2001). Use of hydrostatic pressure for the inactivation of microorganisms in milk. *International Dairy Journal, 11*(10), 729–737.

Oldfield, D. J., Singh, H., Taylor, M. W., & Pearce, K. N. (2000). Kinetics of denaturation and aggregation of whey proteins in heated milk. *International Dairy Journal, 10*(8), 509–516.

Rastogi, N. K., Raghavarao, K. S. M. S., Balasubramaniam, V. M., Niranjan, K., & Knorr, D. (2007). Opportunities and challenges in high pressure processing of foods. *Critical Reviews in Food Science and Nutrition, 47*(1), 69–112.

Trujillo, A. J., Capellas, M., Saldo, J., Gervilla, R., &Guamis, B. (2002). Applications of high-hydrostatic pressure on milk and dairy products: A review. *Innovative Food Science & Emerging Technologies, 3*(4), 295–307.

Walstra, P. (1990). On the stability of casein micelles. *Journal of Dairy Science, 73*(8), 1965–1979.