Journal of Tropical AgriFood 8(Suppl. 1): 35-43 (2026) *p-ISSN 2685-3590, e-ISSN 2685-3604*
3rd International Conference on Food Technology and Nutrition, 2025
September 29-30th, 2025 Samarinda, INDONESIA

CLEAN LABEL APPROACH FOR FRESH GOAT MILK: ENHANCHING MICROBIAL SAFETY AND SHELF-LIFE USING HIGH HYDROSTATIC PRESSURE (HPP)

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Submission: 16.4.2025; Acceptance: 20.2.2026; Published: 28.4.2026

ABSTRACT

The clean-label approach has gained global interest as consumers increasingly prefer minimally processed foods without synthetic additives. Concurrently, the demand for goat milk products is rising because of their nutritional and health benefits. This study investigated the application of high hydrostatic pressure (HHP) for controlling microbial growth and inactivating *Salmonella typhimurium* in fresh Saanen goat milk. Microbiological evaluation of HHP-treated milk samples included an *S. typhimurium* (ATCC 14028) challenge test and monitoring of total plate count, yeast and mold, coliforms, *Escherichia coli*, *Staphylococcus aureus*, lactic acid bacteria, and *Salmonella* during storage. Specifically, HHP was applied at 600 MPa for 6 min using food-grade spout-pouch packaging, based on prior optimization. HHP milk samples achieved complete inactivation of *S. typhimurium*, with reductions of 6 $\log_{10}$ CFU/mL at high spike levels and 3 $\log_{10}$ CFU/mL at low spike levels, demonstrating microbial decontamination kinetics. Shelf-life evaluation showed that HHP-treated milk retained acceptable microbiological, physicochemical, and sensory qualities for up to 75 d under chilled storage (2±7 °C), while fresh untreated milk spoiled by day 6, exceeding permissible microbial limits. Beyond 75 d, viscosity degradation was observed in HHP-treated milk. These findings confirm that optimized HHP treatment enhances microbial safety and extends shelf life, supporting its role in developing clean-label goat milk products.

Keywords: Clean label, fresh goat milk, high hydrostatic pressure, microbial safety, shelf life

INTRODUCTION

Milk is a key source of calcium, protein, and fat, supplying approximately 135 kcal per person daily. In Malaysia, the demand for milk is rising rapidly, and the National Dairy Industry Development Strategic Plan 2021–2025 targets 100% self-sufficiency by 2025 (Ministry of Agriculture and Food Industries, 2021). The National Agrofood Policy 2021–2030 (NAP 2.0) stated that milk (11.69% compound annual growth rate) is the agrifood product with the highest consumption rate, followed by mutton and poultry meat in Malaysia by 2025 (Ministry of Agriculture and Food Industries, 2021). Goat milk, valued for its nutritional content, is particularly susceptible to microbial growth due to its natural chemical composition, posing challenges in ensuring safe, high-quality products for consumers. Conventional thermal pasteurization effectively extends the shelf life of milk but can degrade milk nutrients and alter fat and protein structures, including reduced structural properties (e.g., fat globules and casein micelles) (Barraquio, 2014; Bogahawaththa et al., 2018). Studies have shown that thermal treatments cause 5–15% whey protein denaturation, 10–25% loss of water-soluble vitamins, and increased allergenicity of milk proteins (Bogahawaththa et al., 2018).

Alternatively, high hydrostatic pressure (HHP) offers a non-thermal technique that inactivates pathogens while preserving nutrients and fresh-like qualities (Evelyn and

Silva, 2017). HHP is also called cold pasteurization because the process operates at ambient temperatures and destroys spoilage microorganisms through a pressure range of 300–600 MPa (Stratakos et al., 2019). Many studies have shown that HHP-treated milk can achieve an extended shelf life depending on pressure, duration, and storage temperature: 14–18 d at 200 MPa and 4 °C (Pereda et al., 2007), 18 d at 350 MPa and 4 °C (Mussa and Ramaswamy, 1997), and 28 days at 600 MPa (Alexandros et al., 2019). However, another study reported a shelf life of only 10 d for milk treated at 400 MPa for 15 min or 600 MPa for 3 min when stored at 10 °C, which was 18 days shorter than that at 4 °C (Rademacher and Kessler, 1997). Fresh milk commonly harbors pathogens such as *Salmonella* spp., *Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli* O157:H7, and *Campylobacter* (Zobrist et al., 2005), which pose serious risks to human health. Alexandros et al. (2019) reported that HHP above 550 MPa for 3 min reduced *E. coli*, *Salmonella* spp., and *L. monocytogenes* to undetectable levels. Similarly, Yang et al. (2012) found that 300 MPa for 30 min effectively inactivated *Salmonella* spp., *E. coli*, *Shigella* spp., and *S. aureus*.

Nevertheless, most research on HHP-treated goat milk originates from temperate regions, with limited studies in tropical climates, such as Southeast Asia. Therefore, this study examined the effects of HHP on locally produced goat milk to develop a clean-label, microbiologically safe ready-to-drink (RTD) product with an extended shelf life, supporting organic and sustainable food production.

MATERIALS AND METHODS

Preparation of fresh goat milk upon pressurization study

Fresh Saanen goat milk (*Capra hircus*) was sourced from a local farm in Janda Baik, Pahang, Malaysia, and delivered on the same day of processing to the Food Science and Technology Research Centre, Malaysian Agricultural Research and Development Institute (MARDI), Selangor, Malaysia. The milk was maintained at a chilled temperature (2±7 °C) during transportation to MARDI within 3 to 5 h for packaging into food-grade spout-pouch polyethylene terephthalate / aluminum / polyethylene (PET/AL/PE) with approximately 80 mL of sample per pouch. Packaged goat milk samples were processed using an HHP unit (Hiperbaric 55, Burgos, Spain) at the Faculty of Food Science and Technology, Universiti Putra Malaysia (UPM). High pressure was applied to a cylindrical chamber using a pressure pump and hydraulic system, with water as the pressure medium. The processing conditions were set at 600 MPa for 6 min at 20 °C, as previously optimized using response surface methodology (RSM). In this study, HHP-treated milk was designated as ‘HHP-treated milk,’ while untreated samples (‘fresh milk’) served as controls. All samples were stored at low temperatures for further analysis.

Fresh goat milk samples were analyzed for pathogen challenge test on day 0 post-HHP and for shelf life evaluation in terms of microbiological, physicochemical, and sensory properties based on scheduled intervals. Fresh milk was analyzed up to day 6 at 3-d intervals for microbiological and physicochemical properties, whereas HHP milk was analyzed up to day 90 at 3-d intervals until day 6 and every 15 d thereafter. Sensory analysis was performed only on day 0 for fresh milk and monthly for HHP milk.

Pathogen Challenge Test

Salmonella analysis was performed on HHP milk and fresh milk for a challenge test using a method modified from the Bacteriological Analytical Manual (BAM, 2002). Pathogen challenge test was conducted using *Salmonella typhimurium* (ATCC 14028) at optimized HHP pressure of 600 MPa for 6 min. This specific test involved packaged milk that had been initially sterilized using an autoclave at 121 °C for 15 min. Then, *S. typhimurium* inoculum was inoculated into samples at concentrations of 10^3 CFU/mL as low spike and 10^6 CFU/mL as high spike at a ratio of 1 mL of culture in 80 mL of goat milk. Milk samples in spout packaging containing the inoculated *Salmonella* were filled and packed into nylon plastic as secondary packaging to prevent contamination in case of a leak during HHP treatment. Colonies showing typical reactions on selective media (Xylose Lysine Deoxycholate and Xylose Lysine Tergitol-4: dark red with black centers; Rambach: bright red), as described by the manufacturer, were considered presumptive *Salmonella*. Well-isolated colonies were subjected to biochemical confirmation (Merck, Germany).

Shelf Life Evaluation

Microbiological Analysis

Microbial analysis of total plate count (TPC), yeast and mold (Y&M), lactic acid bacteria (LAB), coliform, *E. coli*, *S. aureus*, and *Salmonella* was conducted on HHP and fresh milk following the BAM (2002) and American Public Health Association (APHA, 2000) standard methods. The results were expressed as $\log_{10}$ CFU/mL, with plate counts based on 25–250 CFU/mL, except for 15–150 CFU/mL for Y&M. Microbiological tests were performed 1 h after HHP treatment, with all samples, including fresh milk controls, analyzed in triplicate.

Physicochemical Analysis

Determination of total soluble solids and pH

Total soluble solids (TSS) were measured using a pocket refractometer (Atago, Tokyo, Japan; 0–53 °Bx), and the sample pH was determined using a bench pH meter (FE20, Mettler Toledo, Switzerland) (AOAC, 2000).

Determination of viscosity

Viscosity was measured using a Tuning Fork Vibro Viscometer SV-10 with 45 mL samples placed in the provided containers (AOAC, 2000).

Color analysis (L*, a*, b* values)

The colors of HHP and fresh milk were measured using a Chroma Meter (CR-400/410, Konica Minolta, Japan) based on the CIELAB system (L*, a*, b*). The instrument was calibrated using a standard white plate. In this system, L* represents brightness from 0 (black) to 100 (white), a* indicates red (+) to green (–), and b* indicates yellow (+) to blue (–) (AOAC, 2000).

Sensory Analysis

A total of 40 untrained panelists (aged 21 to 58 years, healthy, and non-smokers) evaluated HHP-treated and fresh milk samples in the Food Sensory Laboratory, MARDI, under ambient temperature and fluorescent lighting. Using a seven-point hedonic scale (1 = strongly disliked to 7 = strongly liked), the panelists assessed the color, aroma, taste, viscosity, and overall acceptability. Samples with mean overall acceptability scores > 5.0 were considered acceptable (Granato et al., 2010).

RESULTS AND DISCUSSION

Pathogen Challenge Test

Table 1 summarizes the microbiological properties of fresh goat milk inoculated with *S. typhimurium* (ATCC 14028) and subsequently treated with HHP. In this study, control samples inoculated with low and high spike levels of *Salmonella* contained 3.50 and 6.74 $\log_{10}$ CFU/mL, respectively, chosen as worst-case scenario levels rather than realistic contamination levels, which are expected to be lower.

Table 1. Microbiological safety effectiveness of HHP-Treated on Goat Milk

Sample	Low spike ($\log_{10}$ CFU/mL)	High spike ($\log_{10}$ CFU/mL)
Fresh milk	3.50 ± 0.03	6.74 ± 0.02
HHP milk	Absent in 25 mL	Absent in 25 mL

Note: Data (mean±SD) were derived from three replicates. Fresh milk = fresh goat milk without HHP treatment followed by *S. typhimurium* inoculation (control). HHP milk = Sterilized fresh goat milk inoculated with *S. typhimurium* (low and high spike) followed by HHP treatment at 600 MPa for 6 min before storage at chilled (2 ±7 °C).

According to Food Standards Australia New Zealand (FSANZ, 2018) and the Centre for Food Safety Hong Kong (CFSHK, 2014), RTD products must be “absent in 25 mL” of RTD products for them to be deemed satisfactory (Table 2). HHP treatment at 600 MPa for 6 min reduced *Salmonella* to undetectable levels at both spike concentrations, with up to a 6 $\log_{10}$ CFU/mL reduction, consistent with Erkmen (2011) on *S. typhimurium* sensitivity to HHP. Similarly, Stratakos et al. (2019) reported that pressures of 400–600 MPa for 1–5 min achieved up to 5 log10 CFU/mL reduction in raw milk. From a microbiological perspective, the effectiveness

DOI: http://dx.doi.org/10.35941/jtaf.26717.8.5.2026.35-43

of HHP in achieving food safety targets is often evaluated by a 5 log10 pathogen reduction, as required by the United States Food and Drug Administration (US-FDA, 2001) for compliance with Hazard Analysis Critical Control Point (HACCP) standards.

Shelf-Life Evaluation

Microbiological Analysis

HHP significantly reduced microbial counts in milk, with TPC, Y&M, and LAB decreasing by 4–5 $\log_{10}$ CFU/mL, coliforms by 3 $\log_{10}$ CFU/mL, and *S. aureus* by 2 $\log_{10}$ CFU/mL (Table 3), all within the international safety limits (Table 2). After 90 d of storage, HHP milk maintained satisfactory microbiological quality, in contrast to fresh milk, which showed rapid microbial growth and became unsafe within six days at 2 ±7 °C. TPC, a standard measure of microbial load in dairy products, is considered safe at ≥ 10^6 CFU/mL (FSANZ) or ≥ 10^7 CFU/mL (CFSHK, 2014). Fresh milk initially contained 10^4 CFU/mL (marginal) but exceeded 10^6 CFU/mL (unsatisfactory) after six days, whereas HHP milk was reduced to <1 CFU/mL and remained <10^2 CFU/mL for 90 d (Table 3).

Table 2. International Food Standards for microbiological safety limit

Analysis	Microbiological Safety Limit						
Bacterial Count (CFU/mL)	FSANZ				CFSHK		
	Satis-factory	Marginal	Unsatisfactory	Potentially Hazardous	Satis-factory	Marginal	Unsatis-factory
TPC	<10^4	10^4 - <10^6	≥10^6	-	<10^4	10^4 - <10^7	≥10^7
Yeast & Mold	-	-	-	-	-	-	-
LAB	-	-	-	-	-	-	-
Coliform	<10^2	10^2 - 10^4	>10^4	-	<10^2	10^2 - ≤10^4	>10^4
E. coli	<3	3 - <10^2	>10^2	-	<20	20 - ≤10^2	>10^2
S. aureus	<10^2	10^2 - <10^3	10^3 - ≤10^4	>10^4	<20	20 - ≤10^4	>10^4
Salmonella in 25 mL	Absent	-	Detected	Detected	Absent	-	Detected

Note: FSANZ, Compendium of Microbiological Criteria for Food (Food Standards Australia and New Zealand); CFSHK, Microbiological Guidelines for Food (Centre for Food Safety, Hong Kong). "-" = Not stated in the Food Standards for Microbiological Safety Limit.

Table 3. Microbiological safety effectiveness on HHP-Treated Goat Milk during storage period at chilled temperature (2-7 °C)

Analysis / Storage	TPC ($\log_{10}$ CFU/mL)	Yeast & Mold ($\log_{10}$ CFU/mL)	LAB ($\log_{10}$ CFU/mL)	Coliform ($\log_{10}$ CFU/mL)	*E. coli* ($\log_{10}$ CFU/mL)	*S. aureus* ($\log_{10}$ CFU/mL)	*Salmonella* in 25 mL
HHP-treated milk							
Day 0	n.d.	n.d.	0.50 ± 0.00	n.d.	n.d.	n.d.	Absent
Day 3	n.d.	n.d.	0.50 ± 0.00	n.d.	n.d.	n.d.	Absent
Day 6	n.d.	n.d.	0.50 ± 0.00	n.d.	n.d.	n.d.	Absent
Day 15	n.d.	n.d.	0.50 ± 0.00	n.d.	n.d.	n.d.	Absent
Day 30	n.d.	n.d.	0.50 ± 0.00	n.d.	n.d.	n.d.	Absent
Day 45	0.50 ± 0.00	n.d.	n.d.	n.d.	n.d.	n.d.	Absent
Day 60	0.50 ± 0.00	n.d.	n.d.	n.d.	n.d.	n.d.	Absent
Day 75	1.05 ± 0.05	n.d.	n.d.	n.d.	n.d.	n.d.	Absent
Day 90	1.22 ± 0.05	n.d.	n.d.	n.d.	n.d.	n.d.	Absent
Fresh milk							
Day 0	4.24 ± 0.06	4.24± 0.06	5.32 ± 0.05	3.43 ± 0.39	n.d.	2.74 ± 0.20	Absent
Day 3	5.77 ± 0.22	4.77 ± 0.37	5.68 ± 0.11	4.93 ± 0.03	0.50 ± 0.00	2.79 ± 0.23	Absent
Day 6	6.32 ± 0.22	4.84 ± 0.13	5.46 ± 0.06	5.12 ± 0.19	0.50 ± 0.00	3.28 ± 0.24	Absent
Day 7	Discontinued due to high microbial counts						

Note: Data (mean±SD)were derived from three replicates. HHP milk = Optimized HHP treatment at 600 MPa for 6 min before storage at chilled (2±7 °C), Fresh milk: Fresh goat milk without HHP treatment (control), Y = Yeast Count.

These findings align with previous studies reporting significant TPC reduction under HHP at 400-600 MPa for 3-10 min (Liepa et al., 2017; Razali et al., 2021; Tan et al., 2020; Lim et al., 2023). The TPC in HHP milk increased to 10^7 CFU/mL only after 28 d, compared with 14 d for pasteurized milk (Lim et al., 2023). Y&M can cause off-flavors in milk, limiting its shelf life and posing potential health risks (Liu et al., 2020). Fresh milk in this study contained 5.4×10^4 CFU/mL yeast, which was reduced to <10 CFU/mL after HHP treatment (Table 3). Similar findings were reported by Tan et al. (2020) and Lim et al. (2023), who found that most vegetative Y&M in cow and goat milk were inactivated within 5–7 min at 450–600 MPa and 10 min at 600 MPa, respectively. In this study, HHP maintained Y&M at undetectable levels for 90 days of storage, exceeding the 22- and 60-day durations reported by Tan et al. (2020) and Lim et al. (2023), respectively. LAB were reduced to <25 CFU/mL immediately after HHP (5 $\log_{10}$ CFU/mL reduction), although low levels persisted until day 30.

This is likely due to the thicker peptidoglycan cell walls of gram-positive bacteria, making LAB more pressure-resistant. The presence of LAB may be beneficial for probiotic properties in milk; however, LAB levels can also indicate sourness or the presence of pathogenic *Streptococci* (Barraquio, 2014).

Within this study, coliform (<1 CFU/mL) and *E. coli* (<1 CFU/mL) remained well below safety limits throughout 90 days of storage after HHP treatment (Table 3), far lower than the FSANZ and CFSHK thresholds of $>10^4$ CFU/mL for coliform and $>10^2$ CFU/mL for *E. coli* (Table 2). In contrast, fresh milk showed coliform counts exceeding marginal safety on day 0, which increased to unsatisfactory levels by day 6. This demonstrates the high efficacy of HHP treatment in ensuring milk safety, despite the potential microbial contamination during milking. Similar reductions have been reported: Stratakos et al. (2019) observed a 5.6–6.8 $\log_{10}$ CFU/mL reduction of *E. coli* at 600 MPa for 3–5 min; Liu et al. (2020) reported a 2.9 $\log_{10}$ CFU/mL reduction at 600 MPa for 5 min; and Tan et al. (2020) documented a 1.6 $\log_{10}$ CFU/mL reduction of coliform at 450–600 MPa for 5–7 min. Pathogenic *S. aureus* and *Salmonella* spp. remained undetected in HHP milk samples throughout 90 days of storage. In fresh milk, a high *S. aureus* count (3.28 $\log_{10}$ CFU/mL) was observed on day 6, exceeding the FSANZ limits and indicating spoilage. For safe consumption, *S. aureus* in RTD milk should be $<10^3$–10^4 CFU/mL, and *Salmonella* should be absent in 25 mL; both criteria were met in this study. The absence of *Salmonella* in fresh milk in this study may be attributed to good milking hygiene, local breeds, and the cool climate of Janda Baik, Malaysia. Notably, Chye et al. (2004) reported *Salmonella* contamination of 1.4% in raw cow milk samples in Malaysia. These results are consistent with those of Tan et al. (2020), who found that HHP (600 MPa for 3 min) reduced *S. aureus* and *Salmonella* more effectively than pasteurization.

Effects of HHP on Physicochemical Properties

The physicochemical properties of HHP and fresh milk are shown in Table 4. The pH of HHP milk remained stable (6.44–6.69) over 90 d, whereas of that fresh milk ranged from 6.06 to 6.46 over 6 d. These results indicate minimal pH changes, consistent with previous studies reporting no significant pH differences in HHP-treated goat (Mustapa Kamal et al., 2021; Park et al., 2007) and cow milk (Tan et al., 2020). However, some studies observed pH increases after HHP treatment; Tan et al. (2020) (450–600 MPa for 7 min) in goat milk, Liepa et al. (2017) (500–600 MPa for 15 min) in cow milk, and Zobristal et al. (2005) (100–600 MPa for 30 min) in cow milk. Such variations may result from HHP-induced changes in the mineral distribution, including calcium, phosphate, and other ions (Zobristal et al., 2005). Goat milk naturally has a lower pH than cow milk because of its higher acidity (Mahmood and Usman, 2010).

Overall, our study showed that HHP treatment had minimal effect on pH, °Bx, and color of milk over 90 d of storage compared to controls (Table 4). However, the viscosity increased on day 75 (4.94 ± 0.03 mPas) and day 90 (6.57 ± 0.02 mPas). This gradual increase likely reflects pressure-induced modifications of milk proteins, leading to their aggregation during storage. HHP disrupts casein micelles and alters whey protein conformations, promoting protein–protein interactions and the formation of larger aggregates or gel-like networks, which increase viscosity and alter rheological behavior. Similar trends have been observed in bovine and small ruminant milks, which are attributed to casein micelle fragmentation, whey protein denaturation, and calcium redistribution, followed by slow reassociation and disruption over time (Serna-Hernandez et al., 2021).

Table 4. The physicochemical profile of HHP-treated goat milk during storage period at chilled temperature

Length of storage (d)	pH	Total soluble solids (°Bx)	Viscosity (mPas)	Color		
				L*	a*	b*
HHP milk						
0	6.61 ± 0.02	11.00 ± 0.00	2.04 ± 0.07	61.07 ± 0.03	1.02 ± 0.01	0.35 ± 0.05
3	6.53 ± 0.04	10.00 ± 0.00	2.18 ± 0.08	67.59 ± 0.01	2.70 ± 0.01	1.15 ± 0.01
6	6.55 ± 0.05	10.67 ± 0.12	2.69 ± 0.02	68.24 ± 0.00	2.60 ± 0.01	4.69 ± 0.01
15	6.44 ± 0.10	10.73 ± 0.12	4.18 ± 0.08	68.63 ± 0.06	2.61 ± 0.01	4.51 ± 0.01
30	6.69 ± 0.00	10.77 ± 0.06	4.25 ± 0.06	66.55 ± 0.02	2.08 ± 0.02	2.98 ± 0.01
45	6.58 ± 0.01	10.00 ± 0.00	4.44 ± 0.13	68.50 ± 0.36	2.56 ± 0.02	3.89 ± 0.02
60	6.69 ± 0.00	10.73 ± 0.12	4.21 ± 0.04	66.94 ± 0.03	2.16 ± 0.02	2.98 ± 0.01
75	6.52 ± 0.01	10.60 ± 0.00	4.94 ± 0.03	68.80 ± 0.10	2.49 ± 0.09	3.88 ± 0.06
90	6.52 ± 0.02	10.67 ± 0.06	6.57 ± 0.02	68.03 ± 0.25	2.49 ± 0.09	3.82 ± 0.01
Fresh milk						
0	6.46 ± 0.02	11.00 ± 0.00	1.84 ± 0.01	87.99 ± 0.01	-4.51 ± 0.11	11.57 ± 0.02
3	6.06 ± 0.01	9.50 ± 0.20	1.83 ± 0.06	79.94 ± 0.01	-3.05 ± 0.01	5.48 ± 0.01
6	6.45 ± 0.01	9.97 ± 0.15	3.81 ± 0.07	74.43 ± 0.01	-2.66 ± 0.01	4.14 ± 0.00
7	Discontinued due to high microbial counts					

Note: Data (mean±SD) were derived from three replicates. HHP milk = Optimized HHP treatment at 600 MPa for 6 min before storage at chilled (2±7 °C), Fresh milk = Fresh goat milk without HHP treatment (control).

Effects of HHP on Sensory Properties

Table 5 shows the sensory scores of HHP milk and fresh milk, indicating only slight differences in color, aroma, taste, viscosity, and overall acceptability, demonstrating the effectiveness of the HHP treatment. During the 90-d storage of HHP milk, viscosity decreased from 5.8±1.2 at month 2 to 4.5±0.8 at month 3, with only minor declines in overall acceptability (4.8), indicating gradual quality changes, likely due to protein aggregation and mild fat oxidation. In contrast, fresh milk initially scored high (overall acceptability 6.1 on day 0) but was rejected after one month due to microbial spoilage, consistent with its physicochemical instability.

Table 5. Sensory Analysis of HHP-Treated Goat Milk Throughout Storage Period at Chilled Temperature

Sensory characteristics	HHP-treated milk storage (month)				Fresh milk storage (month)	
	0	1	2	3	0	1
Color	6.2 ± 0.8	6.4 ± 0.7	6.4 ± 0.8	6.0 ± 0.6	6.2 ± 0.9	Discontinued to high microbial counts
Aroma	5.7 ± 1.0	5.9 ± 0.9	5.8 ± 1.0	5.2 ± 0.7	5.8 ± 0.9	
Taste	5.8 ± 0.7	5.9 ± 1.1	5.7 ± 1.0	5.1 ± 0.5	5.7 ± 0.9	
Viscosity	5.7 ± 0.9	6.1 ± 0.9	5.8 ± 1.2	4.5 ± 0.8	5.8 ± 0.8	
Overall acceptability	6.0 ± 0.6	6.1 ± 0.9	6.0 ± 0.8	4.8 ± 0.9	6.1 ± 0.6	

Note: HHP milk = Optimized HHP treatment at 600 MPa for 6 min prior to storage at chilled (2 °C ± 7 °C), Fresh milk = Control (Fresh goat milk without HHP treatment). All results were averaged over three replicates.

Previous studies have shown that goat milk experiences significant protein oxidation and aggregation during cold storage, as reflected by increased malondialdehyde levels, turbidity, and particle size, which correlate with sensory decline. HHP treatment slows but does not entirely prevent lipid oxidation and free fatty acid accumulation, especially at higher pressures or longer durations (Zhu et al., 2025). Sensory analysis at day 60 still indicated acceptable overall acceptability (>6.0) with satisfactory microbial results; however, viscosity quality gradually declined on day 90. Considering the overall sensory, physicochemical, and microbiological properties, HHP milk remained satisfactory for up to 75 d under chilled conditions. Therefore, the optimized HHP parameters within this study effectively extended the shelf life of milk up to 75 d, compared to fresh milk, which exceeded microbial limits and spoiled by day 6. These findings are supported by other studies that demonstrated quality preservation in clean-label products, such as fresh milk (Roobab et al., 2023; Lim et al., 2023).

CONCLUSION

HHP treatment at 600 MPa for 6 min effectively inhibited *S. typhimurium*, achieving a maximum reduction of 6 $\log_{10}$ CFU/mL in fresh goat milk and ensuring a robust food safety margin. The optimized process also extended the shelf life of HHP-treated milk to 75 d at chilled (2±7 °C) while maintaining satisfactory microbiological, physicochemical, and sensory quality. In contrast, untreated milk spoiled by day 6, with microbial counts exceeding permissible limits. Overall, HHP is a promising technique for producing clean-label, minimally processed RTD fresh goat milk that complies with international standards for food safety.

ACKNOWLEDGEMENTS

Authors acknowledge the research support from the Food and Agro-Based Industry Division under Ministry of Agriculture and Food Security of Malaysia (Project No.: K-RF288) through the project entitled “Shelf Life Extension, Safety and Quality Validation for Fresh Goat Milk Through HHP Technology”.

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