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Technological Advancements in Dairy Processing for Cold Arid Regions: Case Study of Yak Milk

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Abstract: Yak husbandry forms the backbone of livelihoods in the cold arid regions of the Himalayas and the Tibetan Plateau, where yak milk and its products constitute an important source of nutrition and income. This review examines traditional and emerging technologies in yak dairy processing, highlighting the unique nutritional composition of yak milk, including its high protein, fat, conjugated linoleic acid (CLA), and omega-3 fatty acid contents. Traditional dairy products such as butter, yogurt, qula, kurut, chugo, and yak cheese are discussed alongside their cultural significance and processing methods. Recent scientific evidence suggests that yak milk contains bioactive compounds and peptides with potential antioxidant, antihypertensive, antidiabetic, and immunomodulatory properties. However, the sector continues to face challenges related to low milk productivity, harsh environmental conditions, pasture degradation, disease risks, and limited market access. The review further explores opportunities for technological advancement through the adoption of autochthonous starter cultures, enzyme-assisted cheese manufacture, high-pressure processing, fermented milk concentrates technologies, and advanced packaging systems. These innovations have the potential to improve product quality, shelf life, safety, and marketability while preserving the unique characteristics of traditional yak dairy products. Strengthening technological interventions and value addition in yak milk processing can contribute significantly to the sustainability and profitability of yak-based production systems in cold arid regions.

Key words: Yak, Yak milk, CLA, HPP, milk peptides.

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In the Asian cold arid regions, the yak (*Bos grunniens*), an indigenous herbivore, is closely associated with over 40 ethnic groupings and is essential to socioeconomic development, livelihood security, ecological stability and ethnic cultural traditions. Yaks are also known as the “gold of Tibetans”, the “bison of Tibet”, “the ship of the plateau”, “the mountain machine” (Wangchuk *et al.*, 2013). Typically, yaks are raised at elevations of about ~ 3000-5400 m above msl. Domestic yaks can be found grazing in the highlands of several regions, including the Hindu Kush and Karakoram mountains in Afghanistan and Pakistan, the Himalayas in India, Nepal, and Bhutan, the Tibetan Plateau and Tian Shan Mountains of Northern China, Western and Northern Mongolia, as well as certain areas of Russia and former USSR countries in Asia (Ura 2002). Largest yak population globally, with around 13 million animals, representing over 90% of the world's total yak population is found in China (Zhang 2000). They supply a variety of vital goods, including meat, milk, fur, and dung, in addition to local transportation in mountains. The Tibetan Plateau, encompassing regions in China, Kyrgyzstan, Nepal, and Bhutan, relies heavily on rancid yak butter in the local diet. This butter is a key ingredient in staples like *Po cha* (tea mixed with rancid yak butter) and *Tsampa* (grilled barley with butter). Furthermore, the sale of yak butter is a significant source of revenue for Tibetan herders (Dong *et al*., 2007). Yaks can withstand a reduced oxygen supply since they are endothermic. These yaks are often semi-domesticated grazers that breed naturally without the use of formulated feed (Ma *et al*., 2020). The cold arid zones of India have a very hostile environment, especially during the cold season, which lasts from October to May (temperature -15 to -05). These months of heavy snowfall and freezing temperatures in the region which result in a lack of grass and a thick layer of snow covering the vegetation, which has an impact on these yaks' ability to survive (Zi 2003). Yaks are the only significant livestock species to coexist in the same ecosystem as their wild ancestors, having been domesticated about 7,300 years ago by early nomadic people (Ren *et al*., 2019). Ever since then many nations, including Pakistan, Nepal, China, India, Kyrgyzstan, Russia, Tajikistan, Afghanistan, Bhutan, and Mongolia have domesticated yaks (Joshi *et al*., 2020). Wang *et al*., (2020) have reported around 16 million domestic yaks and 15,000 to 20,000 wild yaks exist worldwide, with around 30 local dominating groups-21 of which are in China-and two artificially cultivated breeds.

Another interesting feature is that yaks are the only domesticated livestock species that can endure the harsh, frigid climate of the cold deserts and deal with severe food scarcity (Ma *et al*., 2020). Over the decades, yaks have adapted well to the harsh conditions after long periods of natural and artificial selection. Yaks have unique morphological, physiological, biochemical, and genetic adaptations for resistance to high-altitude stress in addition to their economic value. They are able to tolerate hypoxia and cold stress because of their huge hearts and lungs, compact bodies, thick exterior coating of hair, and nonfunctional sweat glands. Yaks survive at high altitudes primarily by physiological and biochemical processes that include slowed metabolism, decreased respiration and sweating, decreased heat output, and effective nitrogen usage (Jing *et al*., 2022). In fact, for these reasons yaks may be considered as model organisms for understanding molecular basis of high-altitude adaptations.

Genomic comparative studies between yak and cattle were established by Qui *et al.,* 2012. Comparing the genomes of yak and cattle reveals that yak has more members of gene families linked to energy metabolism and sensory perception, as well as more protein domains involved in hypoxic stress and extracellular environment sensing. Yak genes that are rapidly evolving and positively chosen are also discovered to be considerably enriched in functional categories and pathways linked to nutrition metabolism and hypoxia. More recently, Ayalew and colleagues reported that genes related to the HIF 1α pathway (ADAM17, ARG2, and MMP3) that are thought to be engaged in hypoxia response pathways (CAMK2B, GENT3, HSD17B12, WHSC1, and GLUL) for nutritional absorption at high elevations are highly expressed in yaks (Ayalew *et al*.,2021). Due to the severe weather, the tribes are unable to engage in intensive cultivation and must instead rely on raising animals, especially yaks. milk, hair, and meat are the chief products of yaks (Gyamtsho 2000). This paper will focus only on yak milk and dairy products and the existing technologies and future prospects in technology upgradation.

Yak Milk Composition: Compared to dairy cow milk, yak milk is much more nutritious, especially in terms of protein and fat content. In contrast to 3.5% in bovine milk, the fat percentage in yak milk ranges from 5.5 to 7.5%, while the protein percentage ranges from 4.9 to 5.9% in contrast to 3.14% in bovine milk (Shi *et al*., 2019. Cui *et al*., 2016). Yak milk is naturally concentrated when milked during the main lactating phase because of the higher quantities of fat (5.7-7.5%), protein (4.0-5.9%), and lactose (4.0-5.9%) (Shikui *et al*., 2007).

Table 1. Gross composition of milk from different mammals

	Yak	Cow	Buffalo	Camel
Dry matter (g kg^{-1})	92-282	105-137	145-184	108-145
Protein (g kg^{-1})	33-64	29-50	7-50	30-50
Fat (g/kg)	42-108	25-60	61-96	26-67
Lactose (g kg^{-1})	33-62	36-55	44-52	31-58
Energy (kcal kg^{-1})	870-910	590-701	710-1180	440-790

Sources: Abd El-Salam & El-Shibing, 2011; Farah et al., 1992; Gaucheron 2011; Li et al., 2011; Medhammar et al., 2012; Nikkhah 2011; Zhao et al., 2015

Table 2. Protein profiles of milk from different mammals

	Yak	Cow	Buffalo	Camel
Total casein (g/kg)	21-40	24-28	27-50	22-48
β-Lactoglobulin (% total WP)	50-86	33-67	43-63	-
α-Lactalbumin (% total WP)	7-20	16-25	16.7-43.3	45-53
Lactoferrin (g/kg)	0.2-0.7	0.02-0.5	0.02-0.3	0.2-0.9

References: Abd El-Salam & El-Shibing, 2011; Farah et al., 1992; Gaucheron 2011; Li et al., 2011; Medhammar et al., 2012; Nikkhah 2011; Zhao et al., 2015

Table 3. fatty acid profiles of milk from different mammals

	Yak	Cow	Buffalo	Camel
SFA	47-86	52-76	62-79	24-70
MUFA	20-79	18-34	23-30	14-44
PUFA	2-6	2-6	2-5	2-6
CLA	0.2-1.2	0.3-1.6	0.4-0.9	0.4-0.6
Cholesterol (mg 100 mL^{-1} milk)	12-22	12-31	6.5-16	27-37
Fat globule size (μm)	4.4	3-4	4-8	3

SFA: Saturated fatty acids; MUFA: mono-unsaturated fatty acids; PUFA: polyunsaturated fatty acids; CLA: conjugated linoleic acid.
References: Abd El-Salam & El-Shibing, 2011; Farah et al., 1992; Gaucheron 2011; Li et al., 2011; Medhammar et al., 2012; Nikkhah 2011; Zhao et al., 2015

Table 4. Minerals (mg 100 g-1) and vitamins (μg 100 g-1) in milk of different mammals

	Yak	Cow	Buffalo	Camel
Calcium	115-154	91-184	70-191	76-197
Phosphorus	77-135	59-235	67-293	49-153
Potassium	83-117	106-170	92-178	60-211
Magnesium	6-15	7-14	2-39	4-21
Sodium	21-48	26-90	16-95	36-90
Iron	0.06-0.98	0.001-0.57	0.04-1.30	0-0.55
Vitamin A	14-90	29-52	29-190	8-97
Thiamine	23-49	20-80	20-50	10-60
Niacin	2-3	80-200	80-170	400-780
Vitamin D	0.15-3.95	0.03-1.0	-	0.03-1.0
Vitamin E	30-92	70-299	24-334	18-150

Sources: Abd El-Salam & El-Shibing, 2011; Farah et al., 1992; Gaucheron 2011; Li et al., 2011; Medhammar et al., 2012; Nikkhah 2011; Zhao et al., 2015

Using reversed-phase high-performance liquid chromatography, the protein content of 24 distinct Maiwa yak milk samples were identified. These samples were gathered in China's Sichuan province. In comparison to cow milk, yak milk had higher levels of total proteins (46.2 58.4 gL^{-1}), total casein (40.2 gL^{-1} on average), and individual caseins. This milk appears to be more suitable for newborn nutrition when consumed by Tibetan nomads due to its high β-casein concentration (over 45%), reduced proportion of αs-casein (about 40%), and slight increase in κ-casein (15%). Serum albumin and β-lactoglobulin, two whey proteins, also exhibited centesimal compositions that were comparable to those of homologous cow whey proteins (Li *et al.*, 2010). The comparative composition of energy, lactose, protein, lipid, Minerals and Vitamins has been summarized in Tables 1-4, respectively. As per the composition, yak milk has higher energy (870-910 kcal kg^{-1}) as compared to cow (590-701 kcal kg^{-1}) and camel milk (440-790 kcal kg^{-1}). The most interesting feature of yak milk is its high content of conjugated linoleic acid (CLA) which has beneficial effects on metabolism. Another salient feature of yak milk is its low cholesterol content (12-22 mg 100 mL^{-1} milk) as compared to camel milk (27-37 mg/100 mL milk) and cow milk (12-31 mg 100 mL^{-1} milk) (Table 3). With exception of niacin, all other vitamins and mineral contents in yak milk are nearly comparable to cow, buffalo and camel milks (Table 4).

However, the yield of yak milk is low, because of harsh climatic conditions, low availability of nutrition. The yak breed, age, body condition, raising areas, milking techniques, milking time also impact the yield of milk. An average yield of 150-500 kg of fresh milk per lactation has been reported by Li and colleagues 2011. This low yield has restricted the industrialization of yak milk production on a wide scale.

Significance in human health: Yak milk makes up 15% of all milk consumed in China, and it, along with yak milk products, makes up the majority of Tibetan pastoralists' daily diet, which is devoid of fruits and vegetables for roughly eight months of the year or even all year long, but does not exhibit any overt symptoms of vitamin or mineral deficiencies (Wang *et al.*, 2023). On a daily basis, adult Tibetan nomads consume 100-200 mL of yak milk, 50-100 g of butter, 30-80 g of *Qula* (a dry curd), and 1-2 kg of yogurt. It has been proposed that the high consumption of PUFA, CLA, antioxidants like vitamin C, and viable lactic acid bacteria (in yogurt) present in yak milk and its products, in addition to energy and protein, give health benefits that help in adaptation of people living in the harsh conditions of the Tibetan plateau (Guo *et al.*, 2014).

Kaur *et al.*, (2017) isolated 17 lactic acid bacteria from yak milk and established their probiotic efficiency, However, these were only in vitro studies and have not been tested in animal models for further verification. Zhang in 2014, had reported that yak milk had a stronger anti-hypoxic effect than ordinary cow's milk. Yak milk powder was observed to increase the life period of hypoxic animals in a hypoxic mouse model, as well as their haemoglobin and red blood cell counts. More recent review papers indicate that yak milk and its derivatives exhibit a wide range of bioactive properties (Kalwar *et al.*, 2023; Saalieva *et al.*, 2025). Enzymatic hydrolysis has been applied to derive bioactive peptides from yak milk casein. Several bioactivities, such as acetyl choline esterase (ACE) inhibitory, antioxidant, anti-inflammatory, antidiabetic, antibacterial, anticancer, and immunomodulatory activities, was demonstrated by yak milk casein degradation peptides, underscoring their therapeutic potential and the need for additional clinical research to confirm these effects (Wang *et al.*, 2024). Earlier, Li *et al* (2023) reported that yak cheese contained the antidiabetic peptide RK7 (IC 50 = 0.45 mg mL^{-1}) by inhibiting DPP IV, which controls insulin production, and lowering α-glucosidase or α-amylase, which controls or delays glucose absorption in the small intestine and lowers postprandial hyperglycemia.

More recently, Using an H_2O_2-induced HEK-293 cell model, the antioxidant potential of yak casein-derived antioxidant peptides (YCAPs: AFK, IEQI, FPFF, LPVPQ, RELEEL) were investigated. Under oxidative stress conditions in vitro, YCAPs downregulated Keap1 expression while upregulating Nrf2, HO-1, and NQO1 (Gao *et al.*, 2026). However, these claims have yet to be confirmed through well designed cohort studies on human subjects. Yak milk's unique composition and high nutritional content imply that it may offer several health benefits and could be a valuable supplement to a healthy diet, but further research is necessary to fully establish its potential health benefits.

Existing Technologies in Yak Milk Processing

Milk contains a variety of bacteria that come from the environment during milk collection and storage or from the animal itself, even when the animal is clinically healthy. Presence of nutrients (Protien, carbohydrate, lipids, vitamins) make it an ideal medium for both good and harmful microbes. Ideally, milk microflora is classified into pathogenic, spoilage-causing and beneficial (that transform milk into dairy products). In yak raw milk, the main pathogenic and spoilage causing organisms are *E. coli*, *S, aureus*, Yeast and molds as reported by Wu *et al*., 2009 and Zhang, 2014. Useful lactic acid bacteria (LAB) have also been detected in raw yak milk (Bao *et al.,* 2012).

The major existing technologies that are currently operative includes yak milk processed as liquid milk or converted into various forms of fermented milk products or cheese products. Recently, Dong *et al*., 2003, documented the methods and procedures of milking and milk processing in yak farming systems.

In Tibet and Mongolia, yak milk is a versatile resource, serving as the foundation for butter and a diverse range of traditional cheeses like öröm, eezgii, byas lag, tarag, and aarul. Following fermentation and distillation, yak milk is also processed into an alcoholic beverage known as arkhii. In China, home to 90% of the global yak population, a modern market for yak milk products is developing. To boost milk production and enable yak farming at lower altitudes, crossbreeding with cows is a common practice, resulting in hybrid offspring known as chauri, dzom, or hainag, depending on the region (Zang, 2000). The unique nutritional makeup of various milk products made from yak milk has developed into a booming dairy sector. Several Chinese brands of fresh, pasteurized, and UHT-treated milk are available in market.

One of the most well studied yak cheese varieties are qula and kurut. Tibetan yak milk is used to make the hard, gritty, yellow or white cheese known as qula. The Tibetans have been eating it for almost a millennium. Qula is often made in the summer by naturally fermenting yogurt with yak milk. The dominant LAB found in Qula cheese are *Ln. mesenteroides*, *E. hirae*, *Enterococcus mundtii*, *L. lactis*, *L. plantarum*, *L. sakei*, *Lactobacillus buchneri*, *L. diolivorans*, and *L. casei* (Tan *et al*., 2010 and Zhang**,** 2014). Another well-known fermented milk made from yak milk in China is called kurut. The predominant fermentation microbiota in kurut is thought to be yeats like *S. cerevisiae*, *Candida kefyr*, *Candida lambica*, *Candida famata* and *Candida holmii* (Wu *et al*., 2009). Some of the LAB sp isolated from kurut samples were *Lactobacillus bifermentans*, *L. paracasei* subsp. pseudoplantarum, *L. kefiri*, *L. hilgardii*, *Lactobacillus alimentarius*, *L. paracasei* subsp. *paracasei*, *L. plantarum*, *L. lactis*, *L. cremoris*, *E. faecium*, *L. bulgaricus* and *S. thermophilus* (Dewan and Tamang 2007 and Sun *et al*., 2010).

In Nepal and Bhutan, yak milk is traditionally collected in a special cane vessel known as a *Zum* and churned using a wooden churner. The milk is processed into a variety of dairy products, including butter, cheese, and ghee. Two traditional dried cheese products, *Chugo* and *Hapi ruto*, are prepared through further processing of cheese. *Chugo* is produced by cutting hard cheese into pieces measuring approximately 2-3 cm in length, whereas *Hapi ruto* consists of cheese cut into squares about 8 cm in size and 1 cm thick. Among the Brokpa tribes of Merak and Sakteng in Bhutan, cheese is traditionally compressed in leather bags and allowed to ferment for at least one year (Dompnier *et al*., 2007).

Nepal was among the first countries to produce yak milk cheese on a commercial scale (Wiener, ***et al*.,** 2003). Yak cheese is characterized by a high fat content, containing approximately 46.8% butterfat on a dry matter basis. Using capillary gas-liquid chromatography, Or-Rashid *et al*. (2008) examined the esterified fatty acid composition of yak cheese produced in the Nepalese Himalayan highlands and compared it with that of Cheddar cheese derived from dairy cows. The study revealed that yak cheese contained 3.2 times higher total n-3 polyunsaturated fatty acids (PUFA) and 24.8% higher total long-chain saturated fatty acids (C17:0-C26:0) than cow cheese. The n-3 PUFA ratio was 0.87 in yak cheese compared with only 0.20 in cow cheese. Furthermore, the concentration of total trans-18:1 fatty acids was 2.8 times greater in yak cheese (9.18%) than in cow cheese (3.31%).

A particularly notable finding was the substantially higher concentration of conjugated linoleic acid (CLA) in yak cheese. Total CLA constituted 2.3% of the total fatty acids in yak cheese, compared with only

0.57% in cow cheese. Approximately 88.5% of the total CLA in yak cheese consisted of the biologically important cis-9, trans-11 CLA isomer (Or-Rashid *et al*., 2008). This observation is significant because CLA has been reported to possess anticarcinogenic properties. Although the exact dietary requirement of CLA for cancer prevention in humans remains uncertain, Baer *et al*. (2001) suggested, based on extrapolation from animal studies, that a daily intake of approximately 1.33 g of CLA from dairy products containing 90% cis-9, trans-11 CLA could substantially reduce the risk of certain forms of cancer. The proportions of cis-9, trans-11 CLA and trans-11-C18:1 in yak cheese were reported to be 2.0% and 6.23% of total fatty acids, respectively. Based on these values, consumption of 100 g of yak cheese could provide an effective intake of approximately 1.33 g of cis-9, trans-11 CLA, including the amount generated through the endogenous conversion of trans-11-C18:1, assuming a 50% conversion efficiency in the human body (Banni *et al*., 2001; Or-Rashid *et al*., 2008). Comparative fatty acid profiling studies therefore suggest that cheese produced from yaks grazing on Himalayan alpine pastures possesses a more favourable fatty acid composition than cheese derived from dairy cattle raised on grain-based diets, potentially offering enhanced nutritional and health benefits.

Most recently, yak yogurt's flavor profile was established using gas chromatography-mass spectrometry (GC-MS) and an electronic nose. The distinctive taste compounds found in natural yak yogurt produced by herders contained compounds 2, 3-pentanedione, hexanal, 2, 3-butanedione, 3-methyl-1-butanol, and heptanal (Yanting *et al*., 2025). These studies can aid in the screening of possible strains for the production of particular flavored yak yogurt and offer new insight on the connection between flavor and LAB in the yak yogurt.

In spite of developments in yak dairy sector there are still several bottlenecks. The challenges of yak animal husbandry are multifactorial.

The main issues faced by the Himalayan tribes are overgrazing and the need for adequate pastureland, as blue sheep, domestic sheep, and horses graze over the same pastureland throughout the year. At wintertime the feed shortages intensify (Tshering, 2004). Other challenges include the effects of climate change, illness prevention, herd management, and locating markets for yak products. Every year, the herders run the risk of losing their yaks due to the lack of pasturelands. The future of yaks and the herding tradition is questionable due to the environment and government policies that are making them more vulnerable. The effectiveness of the government's initiatives will determine how long the traditional tribal culture of yaks can continue. The governments must therefore carefully examine the effects of their activity on the future of the yak herders before putting any developmental projects into place on the semi-nomadics' outskirts. Given the current state of affairs regarding yaks and their herders, there is a real possibility that the tribes of the cold arid zones, particularly the educated young, would give up their custom of leading semi-nomadic lives. Another concern that needs to be addressed is that for the yaks to produce more milk, cross-breeding with superior bulls is also required. Another challenge is prevalence of infectious diseases, such as bovine viral diarrhoea and antimicrobial-resistant and biofilm-forming *Enterococcus* and *E. coli*, that pose risks to herd health and food safety. Yak economic prospects are at risk because of rising ambient temperatures, decreased pasture biomass, and increasing disease prevalence brought on by climate change. Naz and colleagues have comprehensively reviewed the potential climate-based husbandry techniques, disease surveillance, and sustainable breeding to protect the livelihood of the pastoral populations in these settings (Naz *et al*., 2025). Moreover, future government policies should examine a comprehensive strategy for maintaining the traditional culture of yak herding. Additionally, the governments need to improve the market for the tribals and encourage them to sell yak products on a regional and national scale. Analysis of government policies and future recommendations are beyond the scope of this review. However, there is tremendous scope of technological upgradation in yak dairy sector. Some of the potential advancements have been discussed in the subsequent section.

Potential Technological Advancements

Yak dairy species are not only able to live in cold arid mountains but also are able to use low quality and quantity of forage in their pasturelands. Yaks are able to graze on straw which has very low nutrition. Because of these abilities, the yak species are frequently raised in low-resource, low input agricultural systems that are managed by local communities. But it is important to note that yak milk and dairy products are widely self-consumed by small farmers, its contribution to food security is significant in the cold arid areas. Though, compared to cows, yaks generally produce less milk, research suggests that yaks, for example, can produce up to 1000 liters of milk per lactation period (Huang 2000). In fact. there is also a chance to export particular milk products to Western nations, where "exotic products" are in demand for dietary purposes. Certain companies have created cosmetic product lines that utilize milk from donkeys, horses, camels, and goats (Konuspayeva and Faye, 2011). Given the unique composition of yak milk and its products and with proper industrialization, these products could also reach international market creating niche productions with high added value for producers.

The current processing of yak milk is still very primitive except for few provinces in China. For future development, yak milk producers need to focus on the following areas: (i) enhancing milk productivity, which is currently quite low relative to cow milk; (ii) strengthening market integration; and (iii) expanding the range of milk products offered.

It is important to note that the machinery and tools used in the production of yak milk products are largely the same as those used for cow milk products, both at the artisanal and industrial scale. Pasteurization and other heat treatments have comparable effects on yak milk and cow milk and its derivatives in terms of microbial death and enzyme inactivation. Therefore, most of the technologies that have been successfully applied on cow milk processing may also be applied on future to yak milk.

Fermented Milk Concentrates Technologies

Fermented milk products are strained or dried to produce concentrates of fermented milk. Yogurt is made into strained yogurt by filtering it through paper, muslin, or cloth. More recently, mechanical techniques like membrane filtration or centrifugal separation have been used to extract some of the whey. This results in a product with a tougher texture, thicker consistency, and higher dry matter content. Since yak milk contains very high dry matter (92-282 g kg^{-1}) (Table 1), fermented yak milk may be used to create concentrates similar to products like tzatziki from Greece, labneh from Arab countries made from goat and sheep milk.

Autochthonous Starter Cultures

Another area of research, possible technological upgradation and lucrative commercialization would be isolation of autochthonous starter cultures from yak raw milk and traditional yak milk products. Globally, cheese production is done using commercial starter cultures to pasteurized milk. However, pasteurized milk cheese lacks the complex wild microbiota present in raw milk. Moreover, commercial starter cultures may contain a high proportion of diacetyl producing lactic-acid bacteria resulting in altering the sensory characteristics of traditional cheese varieties (Quigley *et al*., 2013). The autochthonous starter cultures could be useful tool for maintaining the flavor and quality of traditional yak milk cheeses when made from pasteurized milk. More recently, Zhang *et al* (2025) examined the metabolic pathways and microbiome of yak milk from Ganzi region of Tibet. The findings showed 207 species, including *Lactobacillus delbrueckii* and *Streptococcus thermophilus* in fermented yak milk, and *Acinetobacter johnsonii* predominated in yak milk.

Another important application of autochthonous starter cultures from yak raw milk could be isolation of bacteriocin-producing lactic acid bacteria and potential probiotic starter cultures. Several recent studies have confirmed the probiotic ability of microbial strains isolated from different yak milk and yak milk products. For instance, Wu *et al* (2025) screened for probiotic strains from yak milk products of Qinghai-Tibet platue and established antioxidant activity through whole-genome sequencing of L plantarum Q-01. Similarly, probiotic properties of *Limosilactibacillus reuteri* was isolated from Tibetan fermented yak milk (Wang *et al*., 2025). The researchers (Wang *et al*., 2025) also established that the strain showed anti-hyperuricemic activity. Most recently. around 850 yeasts were isolated from yak dahi and cchurpi. One of the yeast strain

Saccharomyces cerevisiae DUAY-53, isolated from yak cchurpi demonstrated probiotic efficiency (Lama *et al*., 2026).

Technology Upgradation in Yak Milk Cheese by Application of Enzymes

Proteases, peptidases and lipases have been applied in production of non-bovine (non-cow) dairy products with beneficial outcomes. For example, during production of Manchego cheese, application of proteases from *Bacillus subtilis* to pasteurized sheep milk resulted in more rapid degradation of α- and β-caseins (Nuñez *et al*., 1991). Similarly, an enzyme formulation containing combination of two fungal lipases, from *Mucor miehei* and *Aspergillus niger* and two proteases, from *A. oryzae* and *B. subtilis*, were used in the manufacture of Manchego-type cheese from a mixture of sheep and cow milk. The enzyme combination rendered the manchego-type cheese product with higher flavor intensity and quality, more rapid proteolysis of caseins, higher concentration of phosphotungstic acid-soluble nitrogen, higher levels of hydrophobic and hydrophilic peptides (Fernández-García *et al*., 1994). These enzymes may also be applied to cheese making process with yak milk for more rapid proteolytic activity Furthermore these enzymes can also be applied to introduce volatile compounds to add nuances to the flavor and texture of yak milk cheese.

Application of Novel Non-thermal Techniques

The ease with which milk can be transformed into a variety of well-known dairy products, such as cheese, yogurt, butter, or ice cream, and the simplicity with which its components, such as proteins, lactose, or lipids, can be separated and used in a broad variety of other non-dairy food products, have both contributed to the milk's increased popularity, originating from bovine and non-bovine sources. In order to retain the QA and QC of products from the perspective of food safety, product stability and to attain desired organoleptic properties, traditional techniques like thermal treatment and homogenizations finds wide application through out dairy value chains (Tamime and Robinson, 2007).

Thermal processing techniques are time tested, improve the acid coagulation properties in the manufacture of yogurt, enhance water binding, viscosity, they are versatile for all types of milk, reliable, cost effective and has been adopted for both small- and large-scale dairy industries. However, scientific evaluations (Indyk *et al*., 2008) have indicated that thermal treatment of dairy products not only gives a "cooked flavor" but also results in significant degradation of biologically active proteins like immunoglobulins. This disadvantage has paved way for several novel non-thermal processing techniques which has been tested on bovine and non-bovine (sheep, goat, buffalo, camel, donkey) milk and dairy products. It is fortuitous that these techniques can be extended to yak dairy processing especially in regions where yak milk production has been scaled up. Among these non-thermal processing techniques, high-pressure processing (HPP) is the most prominent alternative processing technologies that has been well researched and applied at commercial scale. A fascinating field for HPP is the structure or texturizing of dairy products, such as concentrated or gelled goods like cheese, yogurt, or ice cream, in addition to extending shelf life and extending nutrient retention.

HP processing entails treating food matrix in batches or semi continuously at high pressures in range of 200-800 MPa (2000-8000 bar). Milk immunoglobulins exhibit a significant level of baro-stability when treated with HP in contrast to low heat stability of immunoglobulins in milk and colostrum, where nearly total denaturation is seen under conventional pasteurization conditions. This property presents intriguing prospects for the use of HP processing to preserve immunoglobulin-rich products such as yak milk where undesirable bacteria can be rendered inactive without causing an undue loss of biological usefulness (Trujillo *et al*., 2007). Another advantage of HP processing is that it does not affect the milk fat globule size even at 600 MPa. Additionally, HP treatment of milk caused β-lactoglobulin (at >100 MPa), α-lactalbumin (at ≥700 MPa), and κ-casein (at >500 MPa) to associate with the membrane of the milk fat globule (Ye *et al*., 2004). Along with these, HP processing has significantly reduced spoilage and pathogenic organisms in milk and dairy products and therefore is considered a potential pasteurization alternative to heat treatment (Smelt ***et al.***, 1998). HPP may also be used in the production of yogurt by treating the gel after fermentation to deactivate starter cultures and prolong the product's shelf life by preventing post-acidification. Thus in future, application of HPP could definitely take yak dairy industry to a new level of profitability.

Advanced Packaging Techniques

The liquid yak milk is being packaged in pouches and tetra packs. The traditional process of maintaining cheese shelf life is smoking the products. Currently other emerging techniques are being explored to the enhance the shelf life of packaged cheese products. One of them is the modified atmosphere packaging. Fresh cameros cheese prepared from pasteurized goat milk was packaged in 60% CO_2 modified atmosphere that not only preserved its sensory qualities throughout refrigeration, it also restrained growth of *Listeria monocytogenes* (Olarte *et al.*, 2002). Similarly, undesirable biogenic amine content was lowered in motal cheese made from raw sheep milk when packed under vacuum (Andiç *et al.*, 2010). Active packaging techniques incorporating antimicrobial films have been developed and tested successfully in sheep and goat cheese. These can also find future applications in yak milk cheese packaging. Recent research on predictive modeling for physicochemical and microbial quality assessment of vacuum-packed yak milk paneer reported that the significant parameters that impacted the shelf life of yak paneer were temperature, pH, titratable acidity, tyrosine content, total free fatty acid content and moisture content by Singh *et al.*, 2022. More such research needs to carried out to establish the best conditions for packaging of yak milk and dairy products.

Conclusions

Emerging evidence from research studies have established the unique composition of yak milk. It is a great source of vitamins, minerals, vital fatty acids, and protein, all of which can support general health and wellness. Yak milk derived peptides have shown antihypertensive properties. Additionally, it has been demonstrated that yak milk possesses antioxidant qualities that can help guard against oxidative stress and associated health issues. The presence of conjugated linoleic acid and omega-3 fatty acids, in yak milk makes it a potential food matrix that deliver several health advantages like lowering inflammation, strengthening the heart, and promoting cognitive function. However, yak herding is a challenging profession in the cold arid regions. In most of these regions, indigenous knowledge and the distinctive, long-standing practice of traditional yak raising have been preserved by the yak herders. However, the farming practices, milking and milk processing still take place at primitive level. In order to utilize the yak milk and its products for its tremendous health benefits, modern technologies are required to improve the profitability of yak farming systems. Adequate training of yak herders is the need of the hour. Research on dairy technology is required to increase the quantity and quality of milk products. For the yak dairy business to flourish, effective marketing strategies are crucial and needs to be addressed in future.

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Competing Interests

The authors declare no competing interests.

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