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CAMEL MILK PROCESSING OPPORTUNITIES: A REVIEW

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ABSTRACT

Camel milk occupies a pivotal and essential position in the dietary customs of individuals residing in semi-arid and arid areas. Historically, the promotion and commercial distribution of camel milk have been negligible, primarily due to the absence of processing facilities in areas where camels are raised. Consequently, the consumption of untreated camel milk has been predominantly limited to nomadic households. However, owing to its health-enhancing effects, a substantial surge in the global demand for camel milk and its derivatives has been observed over the past two decades. This growing demand has prompted the dairy sector to introduce a diverse range of camel milk products, which are distinguished by their enhanced nutritional and functional properties. In contrast to products derived from bovine milk, the current market offers only a limited selection of food items sourced from camel milk. Recent advances in food processing technologies have enabled the production of an array of both dairy and non-dairy products derived from camel milk. This includes a variety of items such as powdered milk, cheese, yogurt, ice cream. Moreover, in certain regions, camel milk is incorporated into customary cuisine, serving as a key ingredient in local culinary practices like fermented milk, camel milk tea, or as a fundamental component in various meals. This review underscores the possibility of transforming camel milk into a range of dairy products by addressing its intrinsic functional constraints. This objective can be realised by adjusting the processing parameters and modifying its chemical composition through enrichment techniques. Furthermore, further research avenues may focus on enhancing product quality and exploring innovative processing techniques.

Key words: Camel milk, dairy products, food powder milk, food processing

Camel milk provides nutrition and food security, especially for populations residing in semi-arid and arid regions of Sub-Saharan Africa and Asian deserts. It possesses unique chemical characteristics and intrinsic functional properties that are distinct from the milk of other livestock. (Muthukumaran *et al,* 2023). Although, chemical composition of key nutrients in camel milk, such as water, protein, lactose and fat, aligns closely with that of cow's milk, there are significant differences in micronutrients. These include variations in immunoglobulin (IgG, IgA), vitamins (A, C), as well as mineral salts (Hammam, 2019; Mullaicharam, 2014). Furthermore, the molecular structure of major components in camel milk differs from that of bovine milk, posing a significant challenge for the dairy industry in transforming camel milk into valuable dairy products (Baig *et al,* 2022). Camel milk exhibits lower concentrations of carotene and short-chain fatty acids but higher quantities of long-chain fatty acids (Al-Nasseri *et al,* 2019). In recent years, there has been a significant increase in global interest and demand for camel milk and its dairy derivatives, attributed to their exceptional potential health benefits and health-enhancing properties (Konuspayeva *et al,* 2023). This trend has prompted the dairy sector to diversify its offerings, providing consumers with camel dairy products characterised by advanced nutritional and functional qualities. Since the 1960s, camel milk production has exhibited a consistent growth rate of 8.9% per year, leading to a significant 6.5-fold increase by 2024 (Faye and Corniaux, 2024) . This growth can be attributed to ensuring food security under challenging environmental conditions, increasing market demand due to perceived "medicinal properties," and the development of the camel dairy industry, which offers potential advantages for camel owners (Bilal *et al,* 2024; FAO, 2022; Faye and Konuspayeva, 2012, 2024).

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In general, milk sourced globally undergoes diverse processing methods employing contemporary technological approaches, aimed at extending its shelf life and producing functional dairy products that possess augmented dietetic value and health benefits. The conversion of milk into both non-fermented and fermented dairy products is a widespread practice, serving the dual purpose of preservation and enhancement of nutritional content to meet increasing demands. The technological and functional qualities of milk, encompassing aspects such as physical and chemical structure, foam generation potential, solubility, emulsifying properties, gelation ability and water holding capacity, are recognised as pivotal factors in milk processing techniques. These attributes play a significant role in the development of innovative food products originating from animal sources (Shokri *et al,* 2022).

The feasibility of utilising camel milk for the development of dairy products depends on its physicochemical and techno-functional properties (Konuspayeva and Faye, 2021). The functional properties of food are subject to the influence of processing technologies, food quality, utilisation practices, formulation and ultimately, their acceptability (Mahajan and Dua, 2002). The conversion of camel milk into processed products possess a significant challenge, requiring the application of appropriate technologies. Although, camel milk shares similar gross composition with bovine milk a range of factors including its distinctive chemical constitution, the presence of a complex colloidal system, inherent functionality, the dimensions of protein micelles and fat globules and the existence of antibacterial agents differs from bovine milk (Arain *et al,* 2023; Bornaz *et al,* 2009). As a result, processing camel milk and manufacturing its dairy products such as butter, yogurt, cheese and ice cream using technologies identical to those used for bovine milk products is reported to be challenging even when such products are produced, they exhibit poor quality (Seifu, 2023).

In recent time, the technological and functional properties of camel milk have attracted significant attention from researchers, owing to the inadequacy of standard technologies used for cow milk in processing camel milk into dairy products. Nevertheless, overcoming these challenges could be feasible through the application of innovative technologies, refinement of processing parameters and modification of its natural functionality by introducing synthetic compounds or fortifying camel milk. The aim of this review is to summarise the processing methods and functional capabilities of camel milk. It provides a thorough and current examination of the literature on camel milk products, highlighting recent advancements, processing limitations and prospects for enhancing camel dairy products.

Global production and technological advancements in camel milk industry

In 2022, global camel milk production was reported at approximately 4.11 million tons. However, estimates suggest actual outputs could be as high as 5.4 million tons annually, due to under reporting in remote areas where traditional herding dominates (FAO, 2022).

During the 1970s, the semi-automated milking process was first introduced in the former Soviet Union (Ermukhan, 1999) and later adopted in other parts of the world. This technology allowed for more efficient milking but required specific adjustments to cater to the unique anatomy and behaviour of camels (Ayadi *et al,* 2013; Ayadi *et al,* 2018). In 2002, a significant milestone was achieved in Dubai with the establishment of a modern camel dairy farm. This farm initially employed a single-camel milking stand, which was tested and optimised in Oman. The development of the herringbone milking system, which enables the simultaneous milking of 5 camels, represented a key advancement in milking efficiency and animal handling (Wernery *et al,* 2006; Wernery *et al,* 2004).

Innovations in milking system design have also included corridor and tandem systems, which provide camels with more space and make it easier for handlers to manage the animals during milking. These designs help prevent camels from sitting down during milking and allow calves easier access to the udder, which is important for the welfare of both dam and calf (Ayadi *et al,* 2015; Hammadi *et al,* 2010). However, these systems typically require larger milking parlours and more time to milk an equivalent number of animals than the more compact herringbone design. The introduction of the herringbone system necessitates specialised engineering solutions and a period of acclimation for the camels, but ultimately yields a more streamlined and efficient milking process (Nagy and Juhasz, 2016).

Camel milk production is not uniformly distributed globally; it is predominantly concentrated in Africa, the Middle East and parts of South Asia. The economic impact of camel milk is particularly significant in arid and semi-arid regions where traditional cattle farming is less viable. The commercialisation of camel milk has provided substantial economic benefits to rural communities, supporting livelihoods and contributing to food security (Orazov *et al,* 2021).

The future of camel milk production faces several challenges, including the need for better breeding practices to enhance milk yield and quality and the adaptation of milking technologies to suit small-scale producers. Moreover, there is a growing need for research into the development of camel milk products, such as cheese and yogurt, which require specialised processing techniques due to the unique properties of camel milk (Ipsen, 2017; Jafarpour, 2017).

Factors influencing the gross composition of camel milk

Similar to other species, the principal determinants influencing milk content in camels include breed, seasonality, diet, parity and lactation. In recent study conducted by Nagy *et al* (2016), 2,332 milk samples from 7 camel breeds or ecotypes—Emirati, crossbreed-Emirati, Majaheem (black), Pakistani, Saudi, Saudi-crossbreed and Sudanese—were analysed. These camels, all from the same intensive dairy farm in the United Arab Emirates, exhibited significant variation in milk composition. The Pakistani breed demonstrated the highest fat content at 2.81%, while the Saudi-crossbreed had the lowest fat content at 2.3%. Protein concentrations were highest in the Emirati-crossbreed at 3.05% and lowest in the Saudi and Saudi-crossbreed at 2.85% and 2.87%, respectively. In contrast, the Saudi-crossbreed had the highest lactose content at 4.27%, whereas the Pakistani breed had the lowest lactose content at 3.7%. Additionally, (Konuspayeva, 2020) in their systematic review demonstrated that camel milk samples from Central Asian Bacterian breeds exhibited significantly higher concentrations of fat (4.87±0.77%) and total protein (3.86±0.57%) compared to those from other regions. Conversely, lower fat concentrations were observed in samples from West and North Africa, while protein concentrations were lower in samples from the West and Middle East Africa. Such variations can be caused, except camel management aspects mentioned earlier in this section, but by reason of physiological stage of all dairy species (Zhang *et al,* 2005). This variability factor was examined in both Bactrian camels and dromedaries (Ahmad *et al,* 2012). In most instances, the available data are reported on a monthly or even quarterly basis. However, the study by (Musaad *et al,* 2013), which collected data on a weekly basis, revealed a lower fat content between weeks 12 and 32, whereas other parameters exhibited a gradual and consistent decline throughout the lactation period.

The physiological stage has a greater influence on fat content compared to protein content, while lactose and ash content remain relatively stable. However, others (Bakheit *et al,* 2008), have noted a seasonal effect on lactose content. Overall, studies on the seasonal variability of camel milk composition often conflate this with the lactation stage, as the calving season for camels is typically concentrated within a 3-4 months of hot season (Shuiep *et al,* 2008) (Musaad *et al,* 2013; Zhao *et al,* 2015).

Camel milk processing and challenges

It is reported that, on average, camel milk shares similar chemical features with bovine milk (Table 1). Nevertheless, it is noted that molecular composition of proteins, distribution and content of fatty acids are documented to be distinct (Konuspayeva, 2020).

Cheese Production Process- Converting camel milk into cheese is regarded as challenging and has been deemed impractical (Merin *et al,* 2001). The amino acid composition and distribution of caseins in camel milk differ from those in cow milk. Specifically, camel milk casein exhibits a higher proportion of β-casein (65% compared to 39%), a lower percentage of α S1-casein (22% compared to 38%) and reduced κ casein (3.5% compared to 13%) in comparison to bovine milk caseins. This implies that camel milk cannot be coagulated traditionally due to its low concentration of the amino acid composition of κ-casein, which is responsible for the difficulty in coagulating camel milk. Camel milk has been documented to possess a higher whey protein to casein ratio in comparison to cow milk, contributing to the formation of a delicate curd mass easily digestible in the gastrointestinal tract (Shamsia, 2009). The casein in camel milk is characterised by a larger micelle size, with an average diameter of 380nm, in contrast to 150nm, 260nm and 180nm observed in cow, caprine and ovine milk, respectively (Bornaz *et al,* 2009). Small casein micelles in cow milk have been associated with improved gelation properties (Glantz *et al,* 2010). Consequently, the lower concentration of κ-casein (κ-CN), the elevated ratio of whey protein to casein and the greater micelle size found in camel milk have been identified as factors contributing to the difficulties in cheese production. These characteristics contribute to the formation of a softer coagulum and decreased yields in cheese processing, as detailed in research conducted by Bornaz *et al* (2009), Konuspayeva *et al* (2014) and (Konuspayeva, 2020).

Butter Production Process- The fat percentage in camel milk, which varies between 1.2% and 6.4% (Konuspayeva, 2020) is similar to that of cow milk. However, the production of butter from camel milk is not a traditional practice and poses challenges when employing the same production technology as used for cow milk butter. High melting point (Berhe *et al,* 2013; Farah *et al,* 1989) of camel milk fat (41–43°C) complicates the churning process at temperatures optimal for cow milk, which is between 10 and 14°C. The conversion of camel milk into butter is hindered by the milk's limited propensity to form cream is attributed to a deficiency in agglutinin, smaller fat globule dimensions and a more robust membrane in fat globular (Berhe *et al,* 2013).

Camel milk is characterised by a higher concentration of long-chain fatty acids and a diminished quantity of short-chain fatty acids (Konuspayeva *et al,* 2008) This composition accounts for the higher melting gradient of camel milk butter which is attributable to the increased presence of long-chain fatty acids in its fatty acid composition. Nevertheless, the production of butter from camel milk is achievable with the right churning temperature and agitation technique. Berhe *et al* (2017) have shown that the robust agitation of fermented camel milk in a vertical motion, as opposed to the conventional back-and-forth method, at a higher churning temperature, led to the successful extraction of butter. This approach has been found to be efficient and exerts greater force to break the fat globule envelope, promoting the adhesion of the globules to each other. Farah *et al* (1989) also documented the successful production of butter from camel milk at churning temperatures ranging from 15 to 36°C. According to their findings, the optimal fat recovery in butter production, attaining 85%, was achieved when churning run at 25°C. However, the organoleptic property of camel butter has to be improved for encountering the consumers' expectation compared to the butter from other dairy species.

Yoghurt Production Process- The production of yogurt or other processed dairy products from camel milk is acknowledged to be challenging. The coagulum formed from dromedary milk lacks the desired curd formation and firmness; instead, the curd exhibits fragility and heterogeneity, composed of dispersed flakes (Attia *et al,* 2001). The challenge associated with camel milk yogurt stems from its runny consistency and fragile texture. The texture of yogurt is a crucial factor that affects its visual appeal, mouthfeel and general acceptance. Camel milk is recognised for its resistance to easy fermentation, primarily attributed to its antibacterial qualities. Despite this, it has been noted that commercial starter cultures can develop in camel milk. There are several approaches suggested to overcome challenges associated to the production of camel milk yogurt. Hashim *et al* (2009) demonstrated that the texture of camel milk yoghurt can be enhanced by augmenting the milk with alginate, calcium and gelatine. Moreover, Ibrahem and El Zubeir (2016) suggested that the firmnes of camel milk yoghurt texture can be enhanced by mixing camel milk with milk from other dairy livestock species. Additionally, Ifeanyi *et al* (2013) reported that *Lactobacillus bulgaricus* and *Streptococcus thermophilus* can be utilised as the most important starter culture bacteria in the fermentation process to stabilise the development of texture and flavour in yogurt.

Ice cream Production Process

Based on the literature review, commercial production of camel milk ice cream is currently established in the United Arab Emirates, Kazakhstan and Morocco (Konuspayeva and Faye, 2021). The production process includes heating camel milk to 80°C with continuous agitation to create foams, followed by cooling to 20°C and maintaining this temperature for 15 hours (El-Agamy, 2017). The approach of mixing camel milk with bovine milk can be used to make ice cream of high quality and sensory acceptability (Soni and Goyal, 2013). This is feasible mainly because camel milk and cow milk ice cream

Table 1. Comparative analysis of camel milk composition in relation to milk from other livestock species.

Species	Fat (%)	Total solids (%)	Lactose (%)	Ash (%)	Protein (%)	References
Camel	3.5	12.0	4.4	0.8	3.1	(Al Kanhal, 2010)
Cow	3.7	12.7	4.8	0.7	3.4	(Fox *et al,* 2015)
Ovine	7.4	19.3	4.8	1.0	4.5	(Fox *et al,* 2015)
Equine	1.21	13.2	6.4	0.42	2.1	(Jastrzebska *et al,* 2017)

possess similar sensory physicochemical properties (Jafarpour, 2017). Comparable processing parameters can be employed in the production of ice cream using camel milk as with bovine milk. However, this could yield a product with distinct storage stability and quality attributes (Ipsen, 2017). Additionally, it has been noted that incorporating natural ingredient and flavouring agents into the ice cream formulation enhances the nutritional value and sensory attributes of camel milk ice cream (Ahmed and El-Zubeir, 2015 and Ho *et al,* 2022).

Shelf life- The development of fermented milk products likely originated from the necessity to prolong milk's shelf life in the absence of refrigeration, coupled with their nutritional value and potential health advantages. Traditional fermented camel milk, distinct from camel milk cheese, butter and yoghurt, is a commonly available camel dairy product. This fermented milk is known by various names globally, such as *Dhanaan* in Ethiopia (Biratu and Seifu, 2016), *Suusac or susa* in Kenya and Somalia (Mwangi *et al,* 2016), *Gariss* in Sudan (Ahmed *et al,* 2010) and *Shubat* in Kazakhstan (Konuspayeva *et al,* 2023). The antimicrobial properties of the milk contribute to the reported relatively stable nature of fermented camel milk over an extended period at ambient temperatures.

Shubat is documented to exhibit heightened storage stability. Pastoralists in South and West Kazakhstan have noted that Shubat has a prolonged storage stability, remaining viable for several months, particularly when employing continuous back slopping. This method entails inoculating a fresh batch of milk with a sample from a previous batch, thereby extending its viability. Likewise, Sulieman *et al* (2006) reported that withdrawal of batch fermented accumulations and replacing with fresh camel milk can continue for several months. Notably, strains of potential probiotic lactic acid bacteria, isolated from fermented camel milk, exhibit bacteriocin activities capable of inhibiting pathogenic microbes. Additionally, yeasts are crucial in the fermentation process of camel dairy products, owing to their potent lipolytic and proteolytic enzymatic properties (Maurad and Meriem, 2008; Takeda *et al,* 2011).

Thermal processing applied to camel milk

The molecular characteristics of whey proteins can be altered by factors such as heating temperature, pH and salt content (NaCl) (Boye *et al,* 1995). Camel milk's lactoferrin (LF) and immunoglobulin G (IgG) exhibit higher heat resistance compared to their counterparts in bovine milk (El-Agamy, 2000). The thermal denaturation of camel milk whey proteins is contingent upon the physical state of the proteins. While liquid forms of camel and cow milk whey proteins share similar thermal resistance, the process of drying has been reported to diminish the thermal stability of camel milk whey protein due to the absence of β-lactoglobulin (β-LG) in camel milk (Laleye *et al,* 2008; Merin *et al,* 2001). Consequently, in the production of camel milk powder, it is advisable to apply modified thermal treatment and atomisation conditions. In the production of acidified milk products, the application of thermal treatment has been investigated through scanning electron microscopy. Specifically, in the production of *labneh* from camel milk, it was observed that a thermal treatment at 85°C for 30 minutes resulted in acidified milk protein gels with smaller particles. In contrast, a more extensive heat treatment at 90°C for 30 minutes caused casein particles to fuse, forming larger aggregates (Desouky *et al,* 2013). Unheated milk exhibited a protein matrix that was more open, loose and less dense. The higher abundance of α-lactalbumin (α-LA) in camel milk whey led to increased sensitivity in camel whey solubility to pH changes (Laleye *et al,* 2008), a phenomenon known to induce acid denaturation in bovine milk (Paulsson, Hegg and Castberg, 1985). Bovine α-LA forms aggregates in acidic conditions, unlike β-lactoglobulin (β-LG), which aggregates upon heating in both alkaline and acidic environments (Boye *et al,* 1995). Camel serum albumin (SA) has demonstrated lower heat sensitivity compared to SA from bovine or buffalo milk. Notably, denaturation of camel SA at 100 °C for 20 minutes was found to be comparable to the denaturation of bovine and buffalo SA heated at 85 °C for 20 minutes (El-Agamy, 2000). However, the fouling properties, specifically the adherence of milk proteins to heated surfaces, in camel milk have been primarily attributed to α-LA and SA, whereas β-LG is identified as the main foulant in cow milk (Felfoul *et al,* 2015).

Pasteurisation–The pasteurisation process for camel milk requires specific conditions and indicators. Previous research indicates that alkaline phosphatase, commonly utilised for cow milk (Rankin *et al,* 2010), is not a suitable marker for camel milk pasteurisation due to its heat resistance even at 90°C (El-Agamy, 2000). Consequently, it is. proposed using either glutamyltranspeptidase or leucine arylamidase as reliable indicators for camel milk pasteurisation (Loiseau *et al,* 2002).

In a growing body of literature, the indicators for pasteurisation vary considerably (Alhaj *et al,* 2013; Hassan *et al,* 2007; Ibtisam and Marowa, 2009; Rahman *et al,* 2012). It should also be noted that there are no international standards established for the pasteurisation processes of camel milk.

According to Wernery *et al* (2007) should camel milk exposed to pasteurisation at 72°C for 20 minutes, gamma-glutamyl transferase might be the most suitable indicator. On the other hand, Lorenzen *et al* (2011) reported that gamma-glutamyl transferase remained detectable in pasteurised camel milk, suggesting that lactoperoxidase might serve as a more fitting indicator for pasteurisation. Previous study (Tayefi-Nasrabadi *et al,* 2011) verified that camel lactoperoxidase exhibits less heat resistance compared to its bovine counterpart. To date, comprehensive studies in this area remain inadequate, despite the introduction of pasteurised camel milk to the global market. This uncertainty regarding a suitable pasteurisation indicator for camel milk poses a challenge in establishing an international standard (Konuspayeva *et al,* 2023). Therefore, the industrial-scale pasteurisation of camel milk may be conducted improperly, leading to potential inaccuracies in its heat treatment.

Sterilisation- Despite efforts by private companies, the sterilisation of camel milk through extremely high-temperature processing has not yet been successfully implemented. Research focusing on the heat resistance of casein proteins and whey, vitamins, fat globules and other components of camel milk is anticipated to aid in developing a technical resolution for this challenge (Farah, 1986; Farah and Atkins, 1992; Hattem *et al,* 2011; Kherouatou *et al,* 2003; Momen *et al,* 2019).

Camel milk undergoes separation into two distinct phases following high thermal processing. Thermal processing at 90°C for 5 minutes, 85°C for 5 minutes, 75°C for 5 minutes, 72°C for 30 seconds, 65°C for 30 minutes (Farah, 1986) and at 72°C for 15 seconds and 90, 80 and 63°C for 30 minutes (Hattem *et al,* 2011) have shown that whey proteins in camel milk are highly sensitive and begin to denature. Various methods were experimented with to stabilise camel milk proteins after high thermal processing. These included the addition of bovine k-casein, disodium hydrogen orthophosphate, calcium chloride, sodium hydroxide, sodium dihydrogen phosphate anhydrous, however these attempts yielded unsatisfactory outcomes (Alhaj *et al,* 2011). Further work is required to establish the production of camel milk processed under high thermal conditions.

Therapeutic applications of camel milk

The acknowledgment of camel milk as a suitable alternative to cow milk in human nutrition has been widespread and enduring across various regions worldwide. Various bioactive compounds can be extracted from milk and its derivatives, offering the potential to combat various diseases (Dziuba and Dziuba, 2014). Camel milk exhibits antiviral, antimicrobial properties and has demonstrated potential effects in mitigating tuberculosis and diabetes (Singh *et al,* 2017). The inhibitory effects of camel milk against *Listeria monocytogenes, Staphylococcus aureus* and *Escherichia coli* are attributed to the presence of lactoperoxidase, hydrogen peroxide and lysozyme, respectively. Additionally, the growth of *Salmonella typhimurium* is hindered by camel milk's lactoferrin, which binds iron, rendering it unavailable for bacterial growth (El Sayed *et al,* 1992; Ochoa and Cleary, 2009). Notably, camel lactoferrin has demonstrated greater efficiency in inhibiting Hepatitis C Virus (HCV) entry into human leukocytes compared to human or bovine lactoferrin (Redwan and Tabll, 2007). Fermented camel milk beverage known as *Shubat*, traditionally consumed in Kazakhstan, has been documented to elicit virus-inhibiting properties against both ortho- and paramyxoviruses (Chuvakova *et al,* 2000). These properties endure following storage and the suggested antiviral effectiveness of *Shubat* is believed to be associated with the presence of metabolic byproducts and sialic conjugates derived from yeasts and lactic acid bacteria. In other study, camel milk has been used to treat male patients who suffered from tuberculosis. The outcomes related to clinical, bacteriological and radiological characteristics demonstrated a more pronounced improvement in the group supplemented with camel milk in comparison to the control group (Mal *et al,* 2006). The elevated concentration of insulin-like substances (Su *et al,* 2024), notably half-cystine, in camel milk (Beg *et al,* 1986), the impact of camel milk's small-sized immunoglobulins on b-cells (Agrawal *et al,* 2007) and the absence of coagulation of camel milk in the human stomach collectively, contribute to the hypoglycemic effect observed in individuals with type 1 diabetes (Agrawal *et al,* 2004). This effect has been noted in humans, rats (Dikhanbayeva *et al,* 2021; Sahani *et al,* 2005) and alloxan-induced diabetic dogs (Sboui *et al,* 2010). Furthermore, several studies have demonstrated the potential therapeutic effects of camel milk in treating rheumatoid arthritis and asthma (Arab *et al,* 2017; Bakhtiari *et al,* 2022). These findings suggest that camel milk consumption may elicit anti-inflammatory actions and could be used as an adjunctive therapeutic approach for managing these conditions.

Prospects for the production of camel milk powder

The conversion of liquid camel milk into powder represents the most effective method for preserving camel milk, particularly when it is produced in distant regions with limited transportation and preservation facilities (Konuspayeva *et al,* 2021). Typically, two contemporary processing technologies employed for the production of camel milk powder include spray-drying and freeze-drying (Konuspayeva and Faye, 2021).

Recently, a laboratory-scale study was conducted to determine the optimal freeze-drying conditions, with the objective of assessing the stability of camel milk powder and its components under various temperature settings using a freeze-drying method (Aralbayev, 2022; Zhang *et al,* 2020). Findings revealed that the resulting camel milk powder exhibited enhanced stability at a humidity level of 11.3%. Likewise, another study investigated the impact of drying methods, particularly freeze-drying, on the nutritional value of camel milk compared to fresh camel milk. The study findings suggest that drying technology effectively preserved the comparative nutritional content and enhanced the stability of milk components, such as minerals and vitamins (Ibrahim and Khalifa, 2015). In the context of spray-drying method, Sulieman *et al* (2014) investigated the comparative physical characteristics of camel and cow milk powder produced using this technology. The findings highlighted that spray-drying markedly prolonged the shelf life of camel milk powder, primarily by eliminating the milk's water content.

In a recent study, a nutritional content of camel milk, including fatty acid and vitamin C profile has been further investigated under spray-drying and freeze-drying technologies (Habtegebriel *et al,* 2018), (Aralbayev, 2022). The findings indicated that the production output of milk powder is affected by variables like the feed flows, temperature and the airflow of the processing apparatus. It was observed that elevated temperatures and increased airflow correlated with a notable reduction in the vitamin C concentration (Habtegebriel *et al,* 2018). In a recent study, the milk was subjected to fractionation through acid and enzymatic coagulation, followed by either freeze drying or spray drying coupled to gamma irradiation (Harizi *et al,* 2023). This process enabled the production of dried milk fractions that exhibited a higher total phenolic content and greater antioxidant activities compared to corresponding skim milk. Authors concluded that gamma radiation within the range of 5–11 kGy may be employed to improve the preservation of powdered milk. However, it is important to note that implementing this technology in the dairy industry requires a substantial investment to install expensive milk roller driers and spray driers. Furthermore, employing spray-drying method for producing milk powder requires substantial energy consumption. Consequently, the development of a camel dairy industry calls for immediate actions to improve reproductive characteristics of camels and to establish extensive camel farming operations. This should be complemented by an efficient and widespread collection network linking these farms.

The use of ultrafiltration can be also applicalable in the processing of camel milk in terms of fractionation and concentration of milk components (Kashaninejad *et al,* 2021). It is known that the physicochemical properties of camel milk differ from those of bovine milk, particularly regarding protein type and concentration. For instance, camel milk exhibits a higher whey protein to casein ratio compared to bovine milk. Additionally, the distribution of casein micelles in camel milk is broader, with a greater prevalence of larger micelles than is observed in bovine milk (Bornaz *et al,* 2009). Therefore, the production of concentrated milk *via* ultrafiltration in the manufacturing of various dairy products depends on the efficacy of the membrane filtration process and the alterations in milk constituents that occur during the procedure (Grandison *et al,* 2000). The most important limitation of the ultrafiltration process for complex fluids is the decreased membrane efficiency due to fouling phenomena and concentration polarisation. During the initial minutes of the process, concentration polarisation alters the solute rejection pattern, exacerbates fouling and markedly reduces permeate flux (Rao, 2002). Nonetheless, recent study demonstrated that, although, the physicochemical properties of camel milk differ significantly from cow milk, the dynamic behaviour of the fouling resistances and permeate flux during the ultrafiltration process is similar to bovine milk (Kashaninejad *et al,* 2021).

Additionally, in a more recent study the effect of high hydrostatic pressure technique was demonstrated to affect microbial load of camel milk (Aljasass *et al,* 2023). In their study, camel milk treated at 300 MPa for 5 minutes at 40°C reduced the total bacterial count to below 10^3 CFU/mL, maintaining this low count for 15 days when stored at 3°C. In contrast, the microbial load in untreated samples rapidly increased to spoilage levels within approximately one week. This approach could be used as an alternative to heat treatment and preserve nutrient and health values of camel dairy products. However, high pressure treatment up to 400 MPa was found to cause a clotting phenomenon in camel milk but not in cow and goat milk (Aljasass *et al,* 2023). This phenomenon could be explained by the content of proteins and minerals of camel milk. High-pressure treatment of bovine milk is known to destabilise casein micelles, leading to a reduction in their average diameter (Anema, 2008). Moreover, mean casein content and casein fraction of camel milk lower than those in bovine milk. Furthermore, it was identified that each of the 4 primary casein fractions in bovine milk has corresponding fractions in camel milk. However, significant differences were observed between the casein profiles of the two milk types (Laleye *et al,* 2008). Consequently, these variances in milk composition could influence their coagulation response under high-pressure treatment conditions (Aljasass *et al,* 2023).

Conclusion and perspectives

Camel milk and its derived products constitute an essential source of sustenance and economic livelihood for communities residing in exceptionally challenging environmental conditions, where traditional livestock farming is substantially impeded. Unlike conventional dairy sources, camel milk provides vital nutrition in arid and semi-arid regions, demonstrating its critical role in food security and community resilience.

The processing of camel dairy products diverges markedly from traditional dairy methods, presenting unique challenges that stem from the inherent biochemical properties of camel milk. These challenges include the adaptation of pasteurisation and fermentation techniques to accommodate the high mineral content and unique protein configuration of camel milk. Innovations in processing technology have enabled the production of camel milk derivatives such as pasteurised milk, milk powder, yogurt, butter and cheese. However, each product requires specific adjustments to standard dairy processing protocols to preserve the nutritional value and improve the sensory attributes of the final products. In addition to the technological challenges discussed mentioned above, maintaining the hygienic quality of camel milk used during the processing poses a significant hurdle. This is particularly pronounced when using pasteurised camel milk, which can lead to clotting issues, making raw milk a preferred choice. Several surveys have indeed indicated that the hygienic condition of raw camel milk is frequently inadequate. For instance, in Kenya, it has been reported that approximately 75% of camel milk collected across the country exceeds the acceptable limits for total bacterial count (10^6 CFU/ml) and enterobacteria (5 x 10^4 CFU/ml) (Kaindi *et al,* 2011 and Kaindi and Njage, 2020). In Ethiopia, Adugna (2013) reported a coliform count and total bacterial of log 2.9 ± 2.3 and 5.2 ± 1.9 CFU/ml, respectively, indicating inadequate hygiene (Adugna *et al,* 2013). The substandard hygienic conditions of camel milk are attributed not only to improper milking practices but also to transportation and storage conditions (Yam *et al,* 2014).

Enhancement of organoleptic properties- To address the distinct taste and textural characteristics of camel milk products, researchers have explored various biochemical modifications. These include altering the fat and protein content and adjusting the enzymatic activity during processing. Such modifications not only enhance the organoleptic properties of camel milk products but also aim to standardise these characteristics to appeal to a broader consumer base.

Persistent limitations and research directions- Despite significant advancements, considerable processing limitations remain, underscored by the persistent variability in camel milk composition. The study and development of camel milk products thus represent a dynamic and evolving research area with immense potential. Ongoing investigations are required to refine processing techniques and develop protocols that can reliably produce high-quality camel milk products. Furthermore, there is a need for comprehensive research focusing on the scalability of production methods and the integration of novel technologies that can support the industrial processing of camel milk. For example, optimising processing techniques for camel milk through the commercial implementation of high-pressure treatment for preservation, as an alternative to thermal methods and in the development and production of diverse dairy products derived from camel milk.

Further research should be done to investigate the use of veterinary drugs in camels and their residual effect in milk. To date, most discoveries in veterinary drug development have not addressed the specific conditions for administering these drugs to lactating camels.

Future perspectives and global implications- Looking forward, the camel dairy industry must not only address the technical challenges of milk processing but also embrace innovative strategies that cater to specific dietary and medical needs. This includes the development of specialised products such as lactose-free camel milk, high-calcium formulas and hypoallergenic dairy products suitable for consumers with specific health conditions. Moreover, expanding the range of flavoured and specialty camel milk products can enhance market penetration and consumer acceptance both locally and globally. Furthemore, establishing an international standard for camel milk and its products, including guidelines for pasteurisation and microbiological quality, is crucial. This need arises from the absence of national standards for processed camel milk and its derivatives in many camel milk-producing countries. This poses a significant barrier to the trade of camel milk, particularly its export to international markets. Despite, the rising demand for camel milk and its products in Europe and North America, driven primarily by perceived health benefits, consumers in these regions face limited access to camel milk and its associated products due to the absence of quality standards. Consequently, the importation of camel milk to these countries is prohibited (Seifu, 2023).

To compete effectively with products derived from other milk-producing species, camel milk products must meet stringent quality and safety standards. Establishing international guidelines and regulatory frameworks can facilitate the broader acceptance and integration of camel milk into global dairy markets. Additionally, strategic marketing efforts and consumer education are crucial in highlighting the unique benefits of camel milk, thereby fostering a sustainable market demand. As the camel milk industry continues to grow, its contributions to food security, economic stability and dietary diversity will become increasingly significant, particularly in regions most affected by climate change and arid conditions. The future of camel milk and its derivatives lies in leveraging both scientific research and technological innovations to overcome existing challenges and unlock new opportunities in global dairy markets.

Author Contributions

A.R., A.A.: Conceptualisation, funding acquisition, data curation, methodology, formal analysis, investigation. A.K., A.I., B.F.: supervision, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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