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REVIEW

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Camel milk products: innovations, limitations and opportunities

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Abstract

Camel milk is the mainstay for millions of people in arid and semi-arid environments. In these areas, it is mainly consumed raw or after it spontaneously turns sour. Although some attempts have been made to produce dairy products from camel milk, processing of camel milk is generally considered to be difficult and the quality of the final products made from camel milk do not correspond to their bovine milk counterparts. This paper reports a comprehensive analysis of the literature on camel milk products and presents synthesis of the latest developments, limitations pertaining processing and opportunities for development of new and improved camel milk products. The protein composition and colloidal structure of camel milk differs from cow milk. It is characterized by absence of β-lactoglobulin, low κ-casein content, high proportion of β-casein, larger casein micelles and smaller fat globules. These differences lead to the difficulty of making dairy products from camel milk using the same technologies as for bovine milk. Some of the challenges of camel milk processing include poor stability of the milk during UHT treatment, impaired rennetability, formation of weak and fragile curd during coagulation, longer fermentation time, and low thermal stability of the milk during drying. Despite these difficulties, it has now become possible to produce a range of commercial and traditional dairy products from camel milk. Some of the strategies that could be applied to improve the quality and characteristics of camel milk products are discussed.

Keywords Camel milk, Medicinal properties, Nutritional value, Processing challenges, Recent developments

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Graphical Abstract

Introduction

Due to their unique physiological characteristics, the one-humped camels have become icons of adaptation to challenging environments in arid and semi-arid regions (Wilson 1998). One-humped camels are multipurpose domestic animal species. They are used for milk and meat production, transport, ecotourism and draft power (Wilson 1998). They also provide hides, wools, hairs, bones and blood, and used as a racing animal. Camels have various social and cultural uses in pastoral communities.

The potential of camels for food production is often overlooked despite their huge potential to provide milk and meat under difficult environmental conditions in arid and semi-arid areas. The one-humped camel is a unique species that can be a better provider of milk and meat in desert areas compared with other farm animals, which are severely affected by heat stress and scarcity of feed and water. Camels can significantly contribute to food and nutrition security, national economic growth and poverty alleviation in developing countries if properly managed and utilized.

Milk production is the most important role and the major reason for keeping camels in arid and semi-arid pastoral regions of the world. Camel milk constitutes the main component of human diets in these regions

(Wilson 1998). In northern Kenya, for example, about half of the nutrient intake of most camel keepers comes from camel milk (Ngeiywa & Njanja 2013). Seifu (2009) reported that milk production is the major contribution rendered by camels in eastern Ethiopia and the main reason for keeping camels in the area. Mbogo et al. (2012) also reported that camels in Kenya are kept mainly for milk production.

Camel milk possesses high nutritional value and therapeutic properties in comparison to milk of other species. Individual components of camel milk vary significantly from milk of goats, sheep and cows. Compared to bovine milk, camel milk contains high concentrations of vitamin C and niacin (Breulmann & Böer 2010), and high water content especially during the dry season when camels are dehydrated. During the dry season, camels produce diluted milk that is high in water content, which is a natural adaptation to provide water to the dehydrated calf (Yagil & Etzion 1980). The fat content of the one-humped camel milk is lower than bovine milk and camel milk creams slowly and less completely as compared to bovine milk (Farah 2011). The carotene content and the proportions of short chain and saturated fatty acids are low in camel milk as compared to bovine milk; however, it contains high percentages of unsaturated fatty acids (Claeys et al. 2014). Camel milk lacks β-Lactoglobulin, which is the major whey protein in bovine milk (Farah 2011; Smits et al. 2011), and as a result it can be consumed by people who are allergic to cow milk. Moreover, people who are lactose-intolerant can consume camel milk with less difficulty (Breulmann et al. 2007; Breulmann & Böer 2010; Cardoso et al. 2010; Konuspayeva & Faye 2021) and it is more easily metabolized as compared to bovine milk (Cardoso et al. 2010).

Camel milk keeps for longer period in comparison to bovine milk (Farah 2011) and this is attributed to the presence of high concentrations of substances with antibacterial property in camel milk (Al-Otaibi & El-Demerdash 2013). Besides, camel milk is claimed to have medicinal properties due to possession of bioactive compounds and protective proteins, which are responsible for its therapeutic role (Al-Otaibi & El-Demerdash 2013). In the Middle East and Africa, camel milk has traditionally been used to treat a range of illnesses such as jaundice, dropsy, tuberculosis, diabetes and anemia (Yagil 1982; Abdelgadir et al. 1998; Hashim et al. 2009; Seifu 2009; Mbogo et al. 2012). Agrawal et al. (2005) reported that camel milk improved long-term glycemic control and reduced insulin dose in patients with type-1 diabetes.

Camel milk plays an important role in contributing to food security and rural economic growth in pastoral and agropastoral areas of north and east Africa, central Asia, and the Indian subcontinent. Nowadays, consumption of camel milk is increasing in these regions especially among the urban population. Reports indicate that it is now common to see camel milk marketing and consumption in big cities and towns in Africa where camels are not found (Mbogo et al. 2012). In addition, owing to its purported medical value, interest on camel milk is growing in recent years among consumers in Europe and North America (Al haj & Al Kanhal 2010; Mullaicharam 2014; Sharma & Singh 2014). Because of this, camel milk is sold for very high price (e.g., USA: ~38 USD/L, Singapore: ~19 USD/L, Australia: ~15 USD/L, India: 7 USD/L) (Ho et al. 2022).

In camel rearing societies in pastoral areas, camel milk is mainly consumed fresh or after it turns sour through natural fermentation (Seifu 2007; Alhadrami & Faye 2016). Camel milk has a similar gross composition like cow milk. However, it differs from bovine milk in terms of the molecular structure, distribution and relative composition of the milk components (Berhe et al. 2017). As a result, processing of camel milk and manufacturing of dairy products such as cheese, yoghurt and butter using the same technology as for dairy products from bovine milk are reported to be difficult and when they are produced, they are often of inferior quality. Nonetheless, scientific evidence indicates the possibility of converting camel milk into products through optimization of the processing parameters (Berhe et al. 2017).

This paper reports a comprehensive and up to date analysis of the literature on camel milk products and presents synthesis of the latest developments, limitations pertaining processing and opportunities for development of new and improved camel dairy products.

Composition of camel milk

The composition of milk is important because it determines its nutritional value and technological properties during processing of the milk into value-added dairy products. A detailed account of the composition of camel milk and its nutritional and health benefits are reported in a recently published article by Seifu (Seifu 2022). The properties of camel milk that have technological implications are discussed below.

There is a considerable variation in composition of camel milk reported in the literature. Konuspayeva et al. (2009) reported an overall gross composition (g/100 mL) of 3.82 ± 1.08, 3.35 ± 0.62, 4.46 ± 1.03, 12.47 ± 1.53, and 0.79 ± 0.09 for fat, protein, lactose, total solids and ash contents, respectively for dromedary and Bactrian camels based on a meta-analysis of literature data. The average composition (g/100 mL) of milk of East African one-humped camels was reported to be 4.14 ± 0.80, 3.33 ± 0.52, 12.69 ± 1.11, 4.18 ± 0.72 and 0.76 ± 0.09 for

Table 1 Composition (g/100 g milk)[a] of camel milk as compared to bovine, caprine and human milk

Milk source	Total protein	Total fat	Lactose	Ash	Total solids	References
Camel	3.1 (2.4–4.2)	3.2 (2.0–6.0)	4.3 (3.5–4.9)	0.8 (0.69–0.9)	11.0 (10.6–11.3)	Medhammar et al. 2011; Roy et al. 2020
Bovine	3.2 (3.1–3.3)	3.8 (3.3–5.4)	5.1 (4.9–5.6)	0.72 (0.7–0.8)	11.9 (10.8–12.3)	Medhammar et al. 2011; Rafiq et al. 2016; Vincenzetti et al. 2022
Caprine	3.3 (3.0–5.2)	4.1 (3.0–7.2)	4.5 (3.2–5.0)	0.8 (0.7–0.9)	12.2 (11.9–16.3)	Park 2017; Roy et al. 2020; Vincenzetti et al. 2022
Human	1.2 (0.9–1.9)	3.5 (2.1–4.0)	6.4 (6.3–7.0)	0.2 (0.2–0.3)	12.2 (10.7–12.9)	Berhe et al. 2017; Roy et al. 2020; Vincenzetti et al. 2022

[a] Values in the Table are averages plus ranges indicated in parenthesis

fat, protein, lactose, total solids and ash contents, respectively (Konuspayeva et al. 2009). The composition of camel milk varies depending on season, feed, watering frequency, method of analysis, interval of milking, breed, lactation stage and climatic condition (Al haj & Al Kanhal 2010; Khatoon & Najam 2017; Roy et al. 2020).

Table 1 illustrates the composition of camel milk in comparison to human, caprine and bovine milk. The ash content of camel milk is higher than that of human and bovine milk; however, it has comparable ash content with that of caprine milk (Table 1). Camel, bovine and caprine milk have lower lactose content as compared to human milk (Table 1). Camel milk contains less fat, protein and total solids than bovine and caprine milk. Camel and goat milk are reported to be more easily digestible and less allergenic and closer to human milk than bovine milk (Roy et al. 2020).

Although camel milk contains the same major constituents like milk of other mammals, it shows considerable variations in composition of individual components of the milk as compared to milk of other mammals. For example, the composition of protein fractions of camel milk is quite different from that of bovine milk both in terms of quantity and types of protein fractions (Seifu 2022). Caseins in camel milk account for 52–87% of the total protein whereas they account for about 80% in bovine milk (Khatoon & Najam 2017). Comparison of camel milk with bovine milk proteins shows pronounced differences in the quantitative distribution of casein and whey proteins. The individual casein fractions namely β-casein and κ-casein account for 65 and 3.5%, respectively of the total casein fraction in camel milk while the respective proportions of these casein fractions in bovine milk is 39 and 13% of the total casein fraction (Seifu 2022; Vincenzetti et al. 2022). Goat and cow milk have similar percentages of κ-casein and αs_2-casein; however, goat milk contains lower αs_1-casein content than cow milk (Park 2017; Turkmen 2017). αs_1-casein is the major casein fraction in cow milk (Turkmen 2017). Whereas β-casein is the major casein fraction found in goat and human milk (Park 2017). Goat milk proteins are easily digested than cow milk proteins and this is attributed to the similarity of casein composition between goat and human milk (Moatsou & Park 2017; Turkmen 2017) since β-casein, the major casein fraction both in goat and human milk, is more sensitive to the action of pepsin than αs-casein (El-Agamy 2007).

The casein micelle size distribution of camel milk varies from bovine milk. Camel milk contains higher numbers of large micelles than bovine milk (Muthukumaran et al. 2022; Seifu 2022). The casein micelle size (diameter) of camel milk is 380 nm, goat milk is 260 nm and that of cow milk is 150 nm (Barłowska et al. 2011). The differences in micelle size and casein fractions in camel milk has technological implications. Reports indicate that it is difficult to make fermented dairy products such as cheese and yoghurt from camel milk. This is attributed to the unique structural and functional properties of the milk proteins especially of the low amounts of k-casein (Ramet 2001). The low content of k-casein in camel milk together with its large micelle size are responsible for its poor coagulation compared to cow milk (Hailu et al. 2016). Enzymatic coagulation of milk by rennet/chymosin during cheese making depends on the structure and composition of the casein micelles (Hailu et al. 2016).

Whey proteins of camel milk which account for 20–25% of the total proteins also vary from whey proteins of bovine milk (Seifu 2022; Vincenzetti et al. 2022). The main whey proteins present in camel milk include lactoferrin, immunoglobulins, lactophorin, peptidoglycan recognition proteins, lactoperoxidase, serum albumin, lysozyme, and α-lactalbumin (Ho et al. 2022; Vincenzetti et al 2022). The major difference between camel milk and bovine milk whey proteins is in their β-lactoglobulin content. β-lactoglobulin, which is the major whey protein of bovine milk, is absent in camel milk (Muthukumaran et al. 2022; Seifu 2022; Vincenzetti et al. 2022). Lack of β-lactoglobulin in camel milk affects the rheological properties of yoghurt made from camel milk, which often has weak gel structure and thin consistency (Hailu et al. 2016). During thermal processing of milk at or above 80 °C, β-lactoglobulin denatures and this reaction increases the water binding capacity of the whey proteins and thus responsible for the improved texture and formation of firm yoghurt gels in bovine milk (Hailu et al. 2016).

The presence of a different β-casein than bovine milk and absence of β-lactoglobulin in camel milk are responsible for prevention of food-borne allergies (Ho et al. 2022; Muthukumaran et al. 2022). Camel milk can be used in the formulation of infant foods owing to the absence of β-lactoglobulin, which is one of the major allergenic compounds in bovine milk (Vincenzetti et al. 2022). Camel milk has a different amino acid profile compared to bovine milk and milk of other mammals (Seifu 2022). Like camel milk, goat milk is also reported to have hypoallergenic property and could be used by people who are allergic to cow milk (El-Agamy 2007). The anti-allergic effect of goat milk was reported to be associated to the low αs_1-casein content in goat milk (Barłowska et al. 2011; Turkmen 2017).

Camel milk has a fat content ranging from 2.9 to 5.4% (Farah 2011) and the average fat globules size of camel milk (2.99 μm) is smaller than that of bovine milk (3.95 μm) (Attia et al. 2000; Barłowska et al. 2011; Bakry et al. 2021; Ho et al. 2022; Vincenzetti et al. 2022). The small fat globule size of camel milk has a benefit of high digestibility of the fat (Ho et al. 2022; Muthukumaran et al. 2022; Vincenzetti et al. 2022); however, it leads to difficulty in butter making and results in lower butter fat recovery (Bakry et al. 2021). Goat milk has higher proportions of smaller size fat globules than cow milk (Turkmen 2017). Reports also showed that the goat milk has smaller fat globules (3.19 μm) than buffalo (8.70 μm) and sheep milk (3.78 μm) but bigger than that of camel milk (Barłowska et al. 2011; Turkmen 2017). This difference in goat's milk fat results in better digestibility for humans (Barłowska et al. 2011; Park 2017), a more efficient lipid metabolism (Park 1994, 2017), and also a softer texture to goat milk products (Turkmen 2017).

Camel milk fat is characterized by higher proportion of unsaturated fatty acids compared with milk of other species (Kumar et al. 2016). Higher contents of long-chain fatty acids were also reported for dromedary camel milk fat compared with bovine milk fat (Konuspayeva et al. 2008). Camel milk has a lower carotene content as compared to bovine milk (Stahl et al. 2006; Kumar et al. 2016). This could explain the whiter colour of camel milk fat (Kumar et al. 2016).

Camel milk creams slowly and poorly as compared to cow milk and no skimmable cream can be obtained even after standing for 48 h (Farah & Ruegg 1991; Farah 1996; Barłowska et al. 2011). The slow rate of creaming of camel milk is attributed to deficiency of the protein agglutinin (Farah & Ruegg 1991; Farah 1996; Barłowska et al. 2011; Bakry et al. 2021). Similarly, the creaming ability of goat milk is reported to be poor due to smaller size of the fat globules and also the deficient amount of agglutinin in the milk (Turkmen 2017). The small fat globule size coupled with a thicker fat globular membrane (Farah 1996; Bakry et al. 2021) make it difficult to produce butter from camel milk. The proportion of short-chain fatty acids is less in camel milk fat than cow milk fat. However, the proportions of long-chain monounsaturated fatty acids is higher in camel milk fat than bovine, mare and goat milk fat (Faye et al. 2008; Bakry et al. 2021). On the other hand, goat milk contains higher proportions of short-chain and medium-chain fatty acids compared to cow and camel milk (Barłowska et al. 2011; Turkmen 2017). Short-chain fatty acids represent 15–18% of the total fatty acids of goat milk whereas they are only 5–9% of cow milk fatty acids (Turkmen 2017). The short- and medium-chain fatty acids in goat milk are partly responsible for the strong odour of goat milk (Barłowska et al. 2011; Turkmen 2017).

Camel milk needs to be churned at much high temperature (20–25 °C) than cow milk (8–12 °C) in order to obtain butter (Farah 2011). Camel milk butter has a melting range that varies from 41 to 42 °C (Bakry et al. 2021) and is on average 8 °C higher than the corresponding value for cow milk butter (Farah 2011). The high content of long-chain fatty acids and low proportion of short-chain fatty acids are responsible for the higher melting range of camel milk fat (Ho et al. 2022). This property of camel milk fat makes it difficult to churn the cream at similar temperatures used for churning bovine milk (Bakry et al. 2021). Consequently, higher force is required to separate the fat globule membrane from the camel milk fat and to allow coalescence of the fat globules (Berhe et al. 2013; Bakry et al. 2021).

Camel milk contains comparable lactose concentration like cow milk; however, unlike cow milk, people who are lactose-intolerant can consume camel milk with less difficulty (Cardoso et al. 2010; Muthukumaran et al. 2022) and camel milk is more easily metabolized as compared to cow milk (Cardoso et al. 2010). This is attributed to the less amount of casomorphins produced by camel milk as compared to cow milk, which would cause lactose to become more exposed to the action of lactase by slowing down intestinal motility (Cardoso et al. 2010; Ho et al. 2022).

Camel milk is also an important source of essential minerals and vitamins. One of the peculiar properties of camel milk is its high vitamin C content as compared to milk of other mammals. Camel milk is reported to contain three- to five-fold more vitamin C than bovine milk (Ho et al. 2022; Muthukumaran et al. 2022). Thus, camel milk could serve as an alternative source of vitamin C in dry and desert areas where it is often difficult to obtain green vegetables and fruits that contain vitamin C. Detailed reports about the mineral and vitamin contents of camel milk can be found in an article written by Seifu (Seifu 2022).

Health benefits of camel milk

Camel milk has traditionally been used to treat some human illnesses in different parts of the world (Mihic et al. 2016). Owing to the high nutritional value and claimed medicinal properties of camel milk, a growing interest has been observed on camel milk and its products in recent years. The therapeutic value of camel milk has been attributed to the presence of various bioactive components in the milk that have potential in disease prevention and treatment (Khatoon & Najam 2017). Some of the claimed therapeutic uses of camel milk include its antihypertensive (Quan et al. 2008; Muthukumaran et al. 2022), antidiabetic (Agrawal et al. 2007; Muthukumaran et al. 2022), anti-microbial (El-Agamy et al. 1992; Muthukumaran et al. 2022), anticarcinogenic (Magjeed 2005; Habib et al. 2013; Muthukumaran et al. 2022), anticholesterolemic (Swelum et al. 2021; Muthukumaran et al. 2022) effects and as an immune booster (Kumar et al. 2016). The purported anti-inflammatory, immunomodulating, antioxidant, insulin-like, and anti-apoptotic attributes are the reasons for using camel milk as a natural health product (Mihic et al. 2016). Unlike raw camel milk, there is a limited information on the medicinal properties of processed camel milk products and thus, this deserves detailed scientific investigation.

The therapeutic values of camel milk reported to date are mainly based on in vitro studies and trials using animal models. Clinical studies involving human beings are limited and are often poorly designed trials (Mihic et al. 2016). The purported therapeutic roles of camel milk and in vivo and clinical studies using human subjects are discussed in the recent publication by Seifu (Seifu 2022).

Heat treated fluid camel milk products

Due to the increased demand of camel milk especially by non-camel rearing societies, currently largescale camel milk production and processing plants have been set up in different countries in the Middle East and Africa. Some of these companies include Tiviski in Mauritania (Gaye 2007), Al-Watania in Saudi Arabia, Tedjane in Algeria, Camelicious in Dubai (Konuspayeva & Faye 2021), Addis Kidan Milk Processing Enterprises in Ethiopia and Vital Camel Milk Ltd. in Kenya. These plants mainly produce and sell pasteurized camel milk (Ipsen 2017). In the UAE and Mauritania, pasteurized camel milk is manufactured using modern processing technologies and available in the supermarkets of these countries (Abeiderrahmane & Abeiderrahmane 2010; El-Agamy 2017). Camel milk can be pasteurized using the same technology (heat treatment at 72 °C/15 seconds) like bovine milk; however, the method used to determine pasteurization efficiency of bovine milk is not suitable for camel milk.

Alkaline phosphatase (ALP) is an indigenous enzyme used to indicate pasteurization efficiency in cow milk. ALP is completely inactivated at the temperature time combination (72 °C/15 seconds) used during pasteurization of cow milk. This property of ALP is used to indicate pasteurization efficiency of cow milk. However, ALP is not suitable as marker for effective pasteurization of camel milk because residual activity of ALP was detected after heating camel milk at 72 °C for 5 min (Wernery et al. 2006). As a result, researchers have been looking for better indicator enzymes for camel milk. The enzyme γ-glutamyl transferase, which is destroyed when heat treated at 72 °C for 10 to 20 min, was proposed as a potential indicator enzyme for assessing proper pasteurization of camel milk (Wernery 2007).

Another enzyme which could be used as an indicator of pasteurization efficiency of camel milk is lactoperoxidase (LPO). In camel milk, LPO activity was found to be below detection limit after pasteurization (HTST) of the milk (Lorenzen et al. 2011). Thus, LPO is suggested as a suitable heat treatment indicator to verify an effective camel milk pasteurization (Lorenzen et al. 2011). Camel milk lactoperoxidase is more sensitive to thermal denaturation and less heat-resistant as compared to bovine milk lactoperoxidase (Tayefi-Nasrabadi et al. 2011). The concentration of the enzyme lactoperoxidase in camel milk was reported to be (2.23 U ml $^{1-}$) (Mal & Pathak 2010).

In the United Arab Emirates (UAE), by regulation, camel milk is pasteurized at 74 °C for 15 seconds and only allowed to be kept for 5 days on supermarket shelves (El-Agamy 2017). However, under refrigerated storage pasteurized camel milk can be kept for at least 15 days (El-Agamy 2017). Mehta et al. (2015) reported a shelf life of more than 10 days for pasteurized camel milk stored at 4 °C. It should be noted that the composition of raw whole camel milk is changed by heat treatment (Farah 1986) and thus camel milk loses the health benefits and medical properties when it is pasteurized (Smits et al. 2011). Thus, it is recommended to use raw camel milk when its medicinal properties are desired (Smits et al. 2011).

Camel milk has very poor heat stability at high temperatures and cannot be sterilized at natural pH due to denaturation and protein sedimentation (Ho et al. 2022; Kamal-Eldin et al. 2022). Producing sterilized and UHT camel milk is therefore very difficult (Ho et al. 2022; Kamal-Eldin et al. 2022). Currently, in most cases camel milk is pasteurized at 72 °C for 15 sec after packaging the milk in retail containers (Ipsen 2017). Ultra-high temperature processing (UHT) of camel milk was not found to be suitable due to sedimentation of proteins (Farah et al. 2004). Mild UHT treatment (150 °C/2 sec) of camel milk in combination with refrigeration was required to achieve only 5 weeks of shelf life (Farah et al. 2004).

UHT treatment and pasteurization at 72 °C do not inactivate the enzyme plasmin in bovine milk; however, it can be inactivated by a more severe heat treatment (e.g., 95 °C for several min) (Rauh et al. 2014). If present in milk, plasmin can cause age gelation and sensory bitterness due to degradation of casein. Baer et al. (1994) reported that the proteolytic activity and activation of plasmin from its zymogen, plasminogen, in camel milk was similar to that of bovine milk although a structural difference is expected between camel and bovine milk plasmin. Thus, the presence of plasmin in camel milk could present an additional challenge for production of shelf stable UHT processed camel milk.

Deficiency of kappa-casein and absence of β-lactoglobulin are responsible for the low stability of camel milk at high temperatures (Ho et al. 2022). Increasing pH and addition of phosphate increases the heat stability of camel milk at high temperatures (Ho et al. 2022). The optimal pH for sterilization of camel milk was suggested to be 7.0–7.2; below which phase separation occurs and above which browning occurs due to Maillard reactions (Mohamed et al. 2022). Increasing the pH to 7.0–7.2 or adding sodium phosphate (1 mmol/L) to camel milk prevented and/or reduced sedimentation when heating camel milk at 121 °C for 15 min (Alhaj et al. 2011). Thus, there is a need for further study to assess the effects of various additives such as phosphates and hydrocolloid stabilizers such as carrageenan to improve heat stability and reduce sedimentation in camel milk (Ipsen 2017). In order to successfully produce UHT milk from camel milk, future research should focus on investigating the potential of various additives, such as kappa-casein from cow milk, disodium phosphate and calcium-chelating agents to stabilize camel milk proteins, and hydrocolloids to reduce the sedimentation and increase the viscosity of UHT processed camel milk (Ho et al. 2022).

In addition to the protein sedimentation problem, UHT treatment (144 °C/5 s) was reported to cause colour change and denaturation of whey proteins in camel milk (Omar et al. 2018). In order to overcome the challenge of sterilization of camel milk and production of UHT milk, high-pressure (< 400 MPa) treatment was suggested as an alternative for camel milk preservation because it has less adverse effect on properties of camel milk than UHT (Ho et al. 2022). Unlike other dairy products, UHT milk from camel milk is not readily available on the market. Currently, UHT camel milk is produced from reconstituted whole camel milk powder by the Emirates Industry for Camel Milk & Products (Camelicious); this product has a shelf life of 12 months when stored in a cool and dry place (Ho et al. 2022).

Pasteurization conditions (temperature-time combinations used) for came milk vary considerably (63 °C for 30 min, 72 °C for 15 s, 80 °C for 20 s) in different countries (Konuspayeva & Faye 2021; Mohamed et al. 2022; Muthukumaran et al. 2022). In camel milk producing countries, there is lack of standards or legislation specifically designed for camel milk (Konuspayeva & Faye 2021; Mohamed et al. 2022). Thus, the current standards used for pasteurisation of bovine milk are applied for camel milk (Konuspayeva & Faye 2021; Mohamed et al. 2022). Pasteurization of camel milk at 80 °C for 20 s is considered the most suitable temperature that can enhance the stability of the milk (Muthukumaran et al. 2022). Temperatures above 80 °C cause separation problem in camel milk (Muthukumaran et al. 2022).

Traditional fermented camel milk

Among camel rearing pastoral communities, camel milk is consumed either fresh or after it ferments naturally. Several fermented products have traditionally been made from camel milk through spontaneous fermentation (Konuspayeva & Faye 2021). The most common and popular fermented camel milk products include *shubat*, *khoormog*, *garris*, *susac*, *laben* (lben), *ititu*, *dhanaan* and *chal* (Konuspayeva & Faye 2021). Descriptions of these products and their country of origin are reported in Table 2. Fermented camel milk products are relatively easy to store, have better taste, have high nutritive value and are reported to have health promoting effects due to their antioxidant and anti-inflammatory properties (Muthukumaran et al. 2022; Kamal-Eldin et al. 2022). Description and processing steps of some of these products are reported in the following sections.

Susac is an indigenous fermented camel milk produced in Kenya and Somalia (Alhadrami 2003; Alhadrami & Faye 2016). It has a long shelf life and pleasant taste and aroma (Alhadrami 2003; Alhadrami & Faye 2016; El-Agamy 2017). *Susac* is made by placing camel milk in smoked wooden buckets and incubating it for up to 3 days (Alhadrami & Faye 2016). Use of selected mesophilic starter cultures instead of spontaneous fermentation was reported to improve the quality of *susac* with a uniform taste and a longer shelf life (Farah et al. 1990; Lore et al. 2005; Alhadrami & Faye 2016). Heat treatment of camel milk at 85 °C for 30 min, addition of mesophilic starter culture at a rate of 2–3%, and incubation of the milk at 27–30 °C for 24 h improved the organoleptic properties and acceptability of *susac* (Farah et al. 1990).

Table 2 Common traditional fermented camel milk products produced around the world

Name	Country of origin	Product description	Reference
Shubat	Kazakhstan	made from raw camel milk by adding small amount of previously fermented milk as a starter culture. It involves mixed lactic acid bacteria (LAB) and yeast fermentation	Akhmetsadykova et al. 2015
Chal	Turkmenistan	made by inoculating raw camel milk with previously fermented milk through a back slopping technique and incubating it at room temperature.	El-Agamy 2017
Khoormog	Mongolia	is a traditional fermented mild alcoholic beverage made from raw camel milk	Oki et al. 2014
Gariss	Sudan	a traditional sour milk made through spontaneous fermentation of raw camel milk by placing it in a skin bag	Abdelgadir et al. 1998
Susac	Kenya/Somalia	made by spontaneous fermentation of camel milk by placing it in smoked wooden buckets for 1–3 days	Farah et al. 1990; Lore et al. 2005
Dhanaan	Ethiopia	a spontaneously fermented sour milk made by placing fresh camel milk in a clean/smoked container and keeping it in a warm place for about 1 day	Seifu 2007
Zrig	Mauritania	a well-known drink in the Saharan region *made* from a mixture of *milk,* water and sugar	Zaroual et al. 2019
Laban	UAE, Gulf countries	the traditional fermented product laban is now made commercially from camel milk in Dubai by the Camelicious company	Ipsen 2017; Rasheed 2017

In Sudan, a similar fermented milk called *gariss* is produced from raw camel milk (Abdelgadir et al. 1998). The raw camel milk is placed in a skin bag and tied to the saddle of a camel. The camel is then allowed to go about its business during which the milk is gently shaken due to the jerky movement as the camel walks (Abdelgadir et al. 1998; Hassan et al. 2008). The container used for fermentation of *gariss* is a large skin bag called "Si'in", which serves as a source of microorganisms responsible for fermentation since it usually contains residuals of previously sour product (Abdelgadir et al. 1998; Hassan et al. 2008). A few seeds of Black Cumin (*Nigella sativa*) and an onion bulb are added to the container to initiate the fermentation process especially when a new Si'in is used (Abdelgadir et al. 1998; Hassan et al. 2008). Camel herders in Sudan designate a special camel called the gariss camel that carries large skin bags with fermented milk (*garris*) while the herders travel long distances. During the journey, the owners consume the *garris* as and when needed. When part of the fermented product has been consumed, the container is filled with fresh camel milk. *Garris* is sometimes fortified with spices or garlic (Alhadrami & Faye 2016) to ensure shelf stability and improve organoleptic quality of the product.

Shubat is a fermented traditional drink made from camel milk in Kazakhstan (Akhmetsadykova et al. 2015). It is also named '*khoormog*' in Mongolia (Alhadrami & Faye 2016). In Kazakhstan, *shubat* is usually made from raw milk obtained from the two-humped (Bactrian) camel (Muthukumaran et al. 2022). *Shubat* is fermented at room temperature (25–30 °C) for 8 h by placing the milk in a leather bag or a ceramic jar (Muthukumaran et al. 2022). Its fermentation involves both lactic acid bacteria and yeasts. *Shubat* is made from unpasteurized milk and its production involves addition of 25% *shubat* culture composed of yeasts and lactic acid bacteria. The final product consists of 500 mg/l vitamin C, 3.8% protein, an acidity of 90–130 °T and 1.0% alcohol (El-Agamy 2017). The fat content of *shubat* is reported to be 8% and it has white colour. Tuberculosis and some gastric and intestinal diseases claimed to have been cured by consuming *shubat* (Alhadrami & Faye 2016).

Chal is a traditional fermented camel milk produced in Turkmenistan, Kazakhstan and Iran (Alhadrami & Faye 2016; El-Agamy 2017; Muthukumaran et al. 2022). It is a sparkling beverage produced through fermentation involving yeasts (Muthukumaran et al. 2022). *Chal* is produced through spontaneous fermentation and its production involves addition of water to raw camel milk, placing the milk in a skin bag or a bottle and allowing it to ferment at room temperature (Muthukumaran et al. 2022). *Chal* is reported to have therapeutic values against diseases such as tuberculosis, jaundice, dropsy, anaemia, asthma and piles (Muthukumaran et al. 2022). According to El-Agamy (2017), *chal* is prepared by the back-sloping technique whereby previously fermented milk is added as a starter to either raw camel milk or camel milk diluted (1:1) with warm water and incubated at 25–30 °C. The coagulation takes 3 to 4 h but is held at the same temperature for 8 h to obtain the typical taste of the product, which results due to the action of the starter cultures used.

Airag is a fermented milk made from Bactrian camel milk in Mongolia (El-Agamy 2017). Its production involves heat treating (35–40 °C) the milk and addition of starter culture which is composed of *Lactobacillus bulgaricus* and *Streptococcus thermophilus* and *Saccharomyces* yeast followed by incubation for 10–16 h

(El-Agamy 2017). *Airag* obtained as such is consumed as is or used for making a low alcohol beverage or a drink known as "*butsalgaa*" by mixing it with boiled camel milk (El-Agamy 2017). *Airag* is also used to make a low-alcohol vodka called "*arkhi*," or a curd known as "tsagaa," (El-Agamy 2017).

Kefir is another fermented milk made from camel milk in Central Asia (Rao et al. 1970). It is made by pasteurization of the milk at 85 °C and inoculating the cooled (26 °C) milk with 3–6% of a kefir culture (El-Agamy 2017). After incubation for 8–12 h at 20–26 °C, a soft curd is formed which has an acidity of 60 to 70 °T (El-Agamy 2017). The product can further be ripened for 24–48 h (El-Agamy 2017). Kefir is believed to have health promoting effects owing to its kefarin content (Kamal-Eldin et al. 2022).

Pastoralists in the Somali Region in eastern Ethiopia produce naturally fermented sour milk called *dhanaan* (also called *Karuur*) from camel milk (Seifu 2007). *Dhanaan* is produced through spontaneous fermentation by incubating the milk at ambient temperature for about 12–24 h after placing fresh camel milk in a clean/smoked container and wrapping the container with a piece of cloth (Seifu 2007). Pastoralists in east Africa make *dhanaan* because of its high nutritional value and long shelf life (5 months) (Seifu 2007). Additional reasons for converting camel milk to *dhanaan* include its pleasant tase and its high demand in the market, the possibility of collecting milk over a few days, ease of delivering milk to the market, and reduction of wastage of milk produced during seasons of surplus production (Seifu 2007).

In the traditional process of *dhanaan* making, starter cultures are not used. Therefore, isolation and identification of microorganisms that are responsible for the fermentation of *dhanaan* would enable development of a commercial starter culture and standardization of the manufacturing procedure for this product. A recent study conducted by Fugl et al. (2017) to characterize the microbial communities in spontaneously fermented camel milk from Ethiopia indicated that the fermented camel milk microbiota was dominated either by Lactobacillales or by Enterobacteriaceae, depending on incubation temperature and the provider of the milk. They isolated strains of species with a potential use as starter cultures which included *Lactococcus lactis*, *Lactobacillus plantarum*, and *Pediococcus acidilactici*. Fast acidifiers of camel milk have been isolated from the species of *Lc. lactis*, *P. acidilactici*, and *Streptococcus infantarius* (Fugl et al. 2017).

Some of the strategies that could be applied in order to improve quality and characteristics of these traditional fermented camel milk products include addition of flavors and appropriate stabilizers (e.g., high methoxylated pectin) and pasteurization of the products to prolong their shelf life (Ipsen 2017). Direct acidification using organic acids such as citric or lactic acid or fruit juices is also a potential strategy (Ipsen 2017). Most of the traditional fermented camel milk products have thin consistency and, in most cases, they are only used for drinking rather than being consumed like commercial products with thick gel. This property of the traditional camel milk products is attributed to lack of β-lactoglobulin in camel milk that is responsible for the thin consistency of fermented products (Ipsen 2017).

Use of exopolysaccharide producing starter cultures would result in a thicker consistency in fermented camel milk products and thereby enhance texture, viscosity and mouthfeel and prevent syneresis (Ibrahim 2015). Addition of maize starch and hydrocolloids could also be used to improve the consistency of fermented camel milk products (Ipsen 2017). Making cereal-based products and milk-based sweets from camel milk as is the case with cow and buffalo milk in south Asian countries such as India (Ipsen 2017) and production of fermented camel milk fortified with cereals as is the case with fermented products made from yoghurt cereal mixture in the Middle East would be worth considering (El-Gendy et al. 2016). Concentration of the milk through ultrafiltration, evaporation or boiling could also be applied in the manufacturing of fermented camel milk (Ipsen 2017).

A comparative study conducted by Berhe et al. (2018) to assess the acidification activities of eight commercial starter cultures (CHN-22, Yoflex mild 1.0, STI-12, R-704, R-707, RST-743, XPL-2 and YF-L904) in camel and bovine milk demonstrated that all the investigated cultures were able to acidify camel milk although the speed of acidification was slower in camel milk than bovine milk. However, a final pH that was similar to bovine milk was achieved in camel milk. The variation in the acidification rate in the two milk types was attribute to difference in proteolysis between camel and bovine milk. R-707 and STI-12 were found to be the best mesophilic and thermophilic cultures, respectively for fermentation of camel milk. These cultures could be used in the production of *dhanaan* and other fermented camel milk products at a commercial scale.

Metagenomic profiling of *dhanaan* samples collected from eastern Ethiopia showed classical and non-classical species of lactic acid bacteria (LAB) under the genera *Lactococcus*, *Streptococcus* and *Weissella* (Berhe et al. 2019). In addition to the LAB, spoilage and/or pathogenic bacteria such as *Enterobacter*, *Klebsiella*, *Clostridium* and *Acinetobacter* were also observed in the *dhanaan* samples (Berhe et al. 2019). OTU-1 (operational taxonomic unit) was found to be the dominant streptococcus unit in four out of six samples (Berhe et al. 2019). This common isolate was closely related to *S. infantarius* and *S. lutetiensis* (Berhe et al. 2019). There is an urgent need for transformation of the traditional practices of *dhanaan* manufacturing to an improved and safer production system since presence of potential pathogens such as those observed in the above-mentioned study could pose health risk to the consumers. The identified *Streptococcus*, *Lactococcus* and *Weissella* microorganisms could potentially be used to develop starter cultures suitable for *Dhanaan* production. However, further evaluation of these species is required to ensure their safety before using them as food-grade bacteria.

Commercial cultures developed for bovine milk acidify poorly in camel milk and cultures optimized for camel milk with inhibitory effects against pathogens are therefore needed. Recently, researchers from Denmark and Ethiopia have developed a freeze-dried lactic starter culture that both acidifies the milk and at the same time kills pathogenic microorganisms present in the milk (Technical University of Denmark 2020). This is a very promising development that will ensure production of wide ranges fermented and safe camel milk products. A study by Bragason et al. (2020) showed that *Lactococcus lactis* MS22333 and *Lactococcus lactis* MS22337 isolated from spontaneous fermented camel milk have antimicrobial abilities and can be applied as a starter culture to promote food safety in African countries. *Salmonella Typhimurium* and *Klebsiella pneumoniae* can be eliminated in pasteurized camel milk by *L. lactis* strains (Bragason et al. 2020). This is a very promising development that will ensure production of a wide range of safe fermented camel milk products.

Camel milk butter

Butter cannot be made from camel milk by applying the same method as for cow milk. Butter making from camel milk is difficult due to the poor creaming ability of the milk. In comparison to cow milk, large quantity of camel milk is required to obtain a small amount of butter. Camel milk cream has to be churned at a higher temperature (22–25 °C) than cow milk (8–14 °C) to obtain a reasonable amount of butter (Alhadrami & Faye 2016; Berhe et al. 2017). This is partly attributed to the high melting range (41–43 °C) of camel milk fat (Farah et al. 1989; Berhe et al. 2017). Camel milk butter has lower (12–13%) moisture content than cow milk butter (15–16%) and this may be the reason for the sticky texture of camel milk butter (Alhadrami & Faye 2016). Camel milk butter has white colour and waxy appearance (Alhadrami & Faye 2016). The difficulty of processing camel milk into butter is also attributed to the little tendency of camel milk to cream up due to deficiency of the protein agglutinin that promotes the clustering of fat globules (Mulder & Walser 1974; Farah 1996), small size of the fat globules (Farah 1996), and a thicker fat globule membrane (Knees et al. 1986; Farah 1996). Camel milk contains a lower proportion of short chain fatty acids, but it has a higher proportion of long chain fatty acids (Berhe et al. 2017). The high melting range of camel milk butter can be associated to the high proportion of long chain fatty acids in the fatty acid profile (Berhe et al. 2017).

Traditionally, camel rearing communities in eastern Ethiopia do not make butter from camel milk because majority of pastoralists in this region believe that it is not possible to make butter from camel milk (Seifu 2007). However, some believe the possibility of making butter from camel milk although it takes long time (2–3 days) to churn the milk and it is difficult to extract the fat (Seifu 2007). Pastoralists in eastern Ethiopia indicated that they make butter from camel milk during a long journey whereby they place camel milk on the back of a camel and the milk gets churned due to the to and fro movement as the camel walks (Seifu 2007). The milk is usually placed in a container made of goatskin and hitched to the saddle of the camel. Eventually the small black butter grains formed are skimmed off and mixed with fresh camel milk and drunk (Seifu 2007). Similar observations were reported by various researchers (Rao et al. 1970; Yagil 1982, 1985; Farah et al. 1989; Wangoh 1993; Yagil et al. 1994; Alhadrami 2003). Production of camel milk butter cannot be easily achieved also because the fat in camel milk is distributed as small micelle-like globules (Yagil 1982) and is firmly bound to the protein (Rao et al. 1970; Khan & Appena 1967). Optimization of cream separation processes from camel milk and improvements on churning methods may solve the problem of butter-making from camel milk.

Butter from camel milk (Shmen) is produced by pastoralists in the Algerian Sahara by using a traditional churning method (Mourad & Nour-Eddine 2006). Similarly, Bedouins in the Sinai Peninsula (Yagil 1982) and pastoralists in northern Kenya (Farah & Streiff 1987) traditionally make butter from camel milk. Moreover, Farah et al. (1989) and Knees et al. (1986) also reported the possibility of making butter from camel milk. Butter made as such is used for its therapeutic properties or as hair pomade.

The possibility of making butter from camel milk by modifying a traditional churning method was reported by Berhe et al. (2013). These researchers showed that a churning temperature of 22–23°C and vigorous agitation of fermented camel milk in a vertical direction as opposed to the traditional to- and fro-churning method resulted in a fat recovery efficiency of 80%. This method allowed the fat globules to coalesce and adhere to one another due to the large force exerted that caused rupturing of the fat globule membrane. Fat recovery efficiency, butter yield and churning time of camel milk were 79.8%, 43 g L^{-1} and 120 min, respectively (Berhe et al. 2013). The average contents of fat, total solids, acid degree value, pH, melting range and refractive index of the camel milk butter were of 55.8 ± 1.6%, 64.1 ± 5.2%, 6.7 ± 2.5 mg KOH g^{-1}, 4.90 ± 0.15, 43.2 ± 0.8 °C and 1.4530 ± 0.0002, respectively (Berhe et al. 2013). It took long time to churn the milk and obtain butter. The resulting butter had a dominant white colour and more viscous consistency compared to cow milk butter.

Nowadays, commercial butter made from camel milk is available in the Middle East (e.g., from Camelicious in Dubai) (Ipsen 2017). Camel milk butter can be used for cooking, for medicinal purposes or as hair pomade, and clarified camel milk butter (ghee) is a highly sought for product that has high consumer demand (Berhe et al. 2013).

Camel milk cheese

Production of cheese from camel milk is difficult due to the poor coagulability of the milk (Breulmann et al. 2007). Ramet (1987) and Farah and Bachmann (1987) reported the poor coagulation of camel milk using a commercial rennet. It takes longer time (two to three fold) (Farah & Bachmann 1987) and much more rennet (four times as much rennet) to coagulate camel milk as compared to bovine milk (Ramet 1987).

Manufacturing of dairy products such as cheese, butter and yoghurt from camel milk is not well developed (Farah 1996) due to the unique functional properties and structure of the milk components (Berhe et al. 2017). The low kappa casein content of camel milk causes loss of dry matter of cheese to the whey due to destruction of casein network during cutting (Ramet 2001). Despite this, several authors reported the possibility of manufacturing of cheese from camel milk (Mehaia 1993a; Khan et al. 2004; Qadeer et al. 2015).

Bovine rennet is not suitable for coagulating camel milk. The low concentration of k-casein in camel milk is responsible for the difficulty of coagulating camel milk (Kappeler et al. 1998; Alhadrami & Faye 2016). The concentration of k-casein is around 3% in camel vs 13% in cow milk (Alhadrami & Faye 2016). Camel milk differs from its bovine counterpart in terms of the relative distribution and amino-acid composition of the caseins. Camel milk has low alpha S_1-casein (α_{s1}-CN) (22% versus 38%) and kappa casein (κ-CN) (3.5% versus 13%) but has high beta casein (β-CN) (65% versus 39%) content as compared to bovine milk (Berhe et al. 2017). Moreover, the camel milk caseins have low similarity (homology) to bovine milk caseins, being 39% for α_{s1}-CN, 64% for β-CN, 56% for α_{s2}-CN, and 56% for κ-CN (Kappeler et al. 1998). Camel milk also differs from bovine milk in terms of chymosin cleavage site of the κ-CN molecule where it is found at the Phe^{97}-Ile^{98} amino-acid sequence site for camel milk and at the Phe^{105}-Met^{106} amino acid sequence site for bovine milk (Kappeler et al. 1998). During hard cheese making, coagulation of milk is mainly achieved by enzymatic hydrolysis of κ-CN at the surface of casein micelles. Thus, the poor coagulation of camel milk by chymosin is associated to the small amount of κ-CN in camel milk.

Like human milk, camel milk lacks the whey protein β-lactoglobulin (β-LG) (Berhe et al. 2017). β- lactoglobulin is the major whey protein in bovine milk whereas alpha-lactalbumin (α-LA) is the major whey protein in camel milk (Berhe et al. 2017). Whey protein to casein ratio is higher in camel milk as compared to cow milk and this is the reason for a soft and easily digestible camel milk curd (Shamsia 2009). The casein micelle size of camel milk is larger (average diameter of 380 nm) than bovine (150 nm), caprine (260 nm) and ovine (180 nm) milk (Bornaz et al. 2009). The gelation properties of bovine milk have been reported to be improved due to smaller micelle size (Glantz et al. 2010). Thus, the difficulty of making cheese from camel milk is associated to the larger micelle size, the high ratio of whey protein to casein, and the lower amount of k-CN in camel milk. Consequently, these lead to formation of a fragile and weak coagulum and lower cheese yield. Bornaz et al. (2009) and Konuspayeva et al. (2014) also reported similar observations of less efficient cheesemaking trails on camel milk.

The possibility of making cheese from camel milk was first reported in the 1980s. The focus of these trials was to improve the coagulation of camel milk using different coagulants such as Camifloc (bovine rennet enriched with minerals), *Zingiber officinale* extract and crude gastric enzymes extracted from camel's abomasum (Alhadrami & Faye 2016). Recently, recombinant specific camel rennet was developed and marketed under the name Chy-Max M1000, from Chr. Hansen A/S, Hørsholm, Denmark (Hailu et al. 2016; Ipsen 2017).

The transgenic camel chymosin (Chy-Max M1000) recently developed by Chr. Hansen A/S significantly improves curd formation in camel milk (Sorensen et al. 2011). Moreover, ultrafiltration and concentration of camel milk (two - or four-fold) was reported to improve gelation of camel milk by rennet (Hassl et al. 2011). As a result, various camel cheese varieties have been developed and are now available on the market (Ahmed & El Zubeir 2011; Konuspayeva et al. 2014; Qadeer et al. 2015). Recently, the Danish company, Chr. Hansen A/S, has developed a camel milk cheesemaking recipe that could be used by pastoralists and small-scale producers (Bruntse 2016). This manual includes suggestions for further processing of camel milk cheese, e.g., dried cheese, cream cheese, cheese sweets and spiced cheeses (Ipsen 2017). Development of the recombinant camel chymosin offers a good opportunity for processing and value addition of camel milk and availability of various camel milk products on the market. This will in turn contribute to the development of camel milk cheese industry (Ipsen 2017) and improve the income and livelihoods of the pastoral communities.

Although it has now become possible to coagulate camel milk, adapting the different cheesemaking technologies to camel milk is still a challenge. Various production protocols have been tested to manufacture mozzarella, white cheese, gruyere, feta and haloumi cheese from camel milk (Konuspayeva et al. 2017). The possibilities of making various types of cheeses from camel milk including soft white cheese (Domiati-type) (Mehaia 1993a), soft unripened cheese (Hailu et al. 2014), soft brined cheese (Hailu et al. 2018), semi-hard cheese (Vkas & Farah 1991), soft cheese, fresh cheese, blue cheese, ricotta cheese, pressed cheese (Ramet 1987, 1991), cottage cheese, dried curd cheese (aarts), and soft French-type cheese (Camelbert) (El-Agamy 2017) have also been reported.

The possibility of making cheese from camel milk by blending it with milk of other mammals has been reported. Pastoralists in eastern Ethiopia believe that cheese can be made from camel milk by blending it with milk of other species (Seifu 2007). Mehaia (1993b) indicated Domiati cheese with acceptable quality (composition and flavor) and a satisfactory yield can be made by mixing camel with cow milk.

It should be noted that most of the studies on camel milk cheese reported so far focused mainly on optimisation of various processing parameters on fresh and/or soft cheese types; however, a standardized protocol for making ripened camel milk cheese has not yet been developed (Baig et al. 2022). Thus, effect of processing parameters on quality of hard cheese should be investigated (Baig et al. 2022). Processing variables such as amount and type of starter culture, heat treatment, amount and type of rennet, standardisation of casein to fat ratio and level of $CaCl_2$ markedly affect the yield and quality of camel milk cheese (Baig et al. 2022). Moreover, effect of salting level, cooking temperature and duration of pressing on the quality of ripened cheese need detailed study. Baig et al. (2022) reported that thermophilic starter cultures are more useful in acidification of camel milk and higher cooking temperature is recommended for camel milk curd to improve the cheese yield.

Camel milk yoghurt

Manufacturing of camel milk yoghurt with a desirable curd firmness and consistency like bovine milk yoghurt is reported to be difficult. Camel milk does not coagulate properly and it results in a less firm, fragile and heterogenous curd that consists of dispersed flakes (Attia et al. 2001). As a result, yoghurt obtained from camel milk has a weak texture and thin consistency. The texture of yoghurt is one of the important quality parameters that determines its mouth feel, appearance, and overall acceptability. Reports indicate that commercial starter cultures can grow in camel milk (Berhe et al. 2018); however, the rate of acidification in camel milk was found to be lower than bovine milk (Abu-Tarboush 1996; Berhe et al. 2018). Despite these difficulties, the possibility of making yoghurt from camel milk has been reported (Ahmed et al. 2010; Eissa et al. 2011).

Manufacturing of yoghurt from camel milk using the same production protocol as for bovine milk (Tamime & Robinson 2000) proved to be difficult due to the structure and functional properties of the milk components. Recently, various researchers have reported the possibility of making camel milk yoghurt (Hashim et al. 2009; Al-Zoreky & Al-Otaibi 2015; Ibrahem & El Zubeir 2016; Galeboe et al. 2018).

Camel milk yoghurt of acceptable quality can be produced using 5% skim milk powder, 1.2% gelatin, 40 ml/l of maple strawberry syrup as a flavouring agent, 1.5 ml/l of calcium chloride, and 6% yogurt culture after incubation of the milk for 18 h at 42 °C (Galeboe et al. 2018). The resulting yoghurt had a fairly thick consistency although it was less viscous and not as firm as cow milk yoghurt. The product resembled more like drinking yoghurt. The weak texture and thin consistency of camel milk yoghurt can be attributed to the compositional properties of the milk such as lack of β-LG and lower amount of κ -CN (Kappeler et al. 1998; Ipsen 2017), high whey protein to casein ratio (Shamsia 2009). Camel milk yoghurt was reported to have 83.4% moisture, 1.13% ash, 4.37 pH, 16.7% total solids and a titratable acidity of 1.255% lactic acid (Galeboe et al. 2018). Cow milk and camel milk yoghurts had comparable microbiological and physicochemical properties; however, camel milk yoghurt was less preferred than cow milk yoghurt. Similar observations were reported by other researchers.

Hashim et al. (2009) reported the possibility of making good quality yoghurt from camel milk using stabilizers, skim milk powder, food-grade calcium chloride and commercial yogurt culture. However, Al-Zoreky and Al-Otaibi (2015) reported that gel firmness and consistency of camel milk yoghurt did not improve when stabilizers were added in comparison to cow milk yoghurt. It takes longer duration (17–18 h) for camel milk to ferment than cow (Galeboe et al. 2018) and sheep (Ibrahem & El Zubeir 2016) milk.

Although research conducted so far indicate the possibility of making yoghurt from camel milk, there is lack of consistency on the results reported and they are often conflicting. This suggests that yoghurt production protocols for camel milk are not well established and detailed research needs to be conducted in order to optimize the operating parameters, standardize the production procedures and improve acceptability of camel milk yoghurt.

Camel milk powder

Currently, spray drying technology has been used to produce camel milk powder in countries such as Saudi Arabia, UAE, India and Pakistan (El-Agamy 2017; Kamal-Eldin et al. 2022). Research on spray drying of camel milk is scarce and focused mainly on the investigation of the effect of spray dryer operating conditions on the physical properties of the powders. Sulieman et al. (2014) studied the effect of direction of feed on the water activity, degree of lightness, solubility, flowability and yield of camel and cow milk powders. Similarly, Al-Alawi and Laleye (2008) investigated the effect of inlet temperature, direction of feed and level of total solids on the physical properties of cow and camel milk. Recently, Habtegebriel (2021) investigated the effect of spray drying operating conditions and the composition of the milk on the final nutritional and techno-functional properties of camel milk powders.

The performance of the spray drying of milk could be affected by operating parameters such as outlet temperature, inlet temperature, feed flow rate, velocity of drying air and the concentration level of milk solids. The inherent properties to the milk such as protein, fat and lactose levels can also affect the efficiency of spray drying of milk. Final quality of the milk powder and retention of heat sensitive nutrients could be modulated by choosing appropriate drying conditions.

A study conducted to assess the effect of spray drying operating parameters viz., atomization pressure (800, 600 and 400 bar), inlet temperature (160 °C, 140 °C and 120 °C) and feed flow rate (5, 4 and 3 rev/s) on cyclone (yield) and vitamin C recoveries of whole camel milk powder revealed that the cyclone recovery of milk powder was influenced by atomization pressure, inlet temperature and feed flow rate (Habtegebriel et al. 2018). Yield was also affected by the interaction between the treatments. Atomization pressure increased cyclone recovery in a certain range. The interaction between inlet temperature and atomization pressure significantly influenced the effect of feed flow rate on cyclone (Habtegebriel et al. 2018). An inverse relationship was observed between cyclone recovery and feed flow rate. Increasing inlet temperature increased cyclone recovery due its effect on increasing the outlet temperature (Habtegebriel et al. 2018). The results showed that controlling the inlet temperature, feed flow rate and atomization could help in modulating the cyclone recovery (Habtegebriel et al. 2018).

The lowest vitamin C recovery (31.47%) was recoded in samples operated at inlet temperature of 160 °C, atomization pressure of 800 bar and feed rate of 3 rev/s, with a corresponding outlet temperature of 107 °C (Habtegebriel et al. 2018). On the other hand, the highest vitamin C recovery (68.14%) was recorded in samples operated at inlet temperature of 160 °C, atomization pressure of 400 bar and feed rate of 5 rev/s, with a corresponding outlet temperature of 92 °C (Habtegebriel et al. 2018). The lowest vitamin C was recovered when the outlet temperature was at maximum and the atomization pressure was at its highest level. The highest vitamin C was recovered when the atomization pressure was at its lowest level and the outlet temperature was relatively lower (Habtegebriel et al. 2018). Increasing temperature and atomization pressure significantly decreased the total vitamin C recovery (Habtegebriel et al. 2018).

In general, the results showed that total vitamin C, cyclone recovery and recovery of fatty acids could be affected by controlling the atomization pressure and outlet temperature during spray drying of camel milk. Cyclone recovery is inversely related to feed flow rate and it increased with increasing inlet temperature. The outlet temperature can be controlled by controlling the atomization pressure, feed flow rate and inlet temperature (Habtegebriel et al. 2018).

Unsaturated fatty acids (C18:1, C18:2 and C18:3) are more susceptible to oxidation than saturated fatty acid (C18:0) due to high atomization pressure (Habtegebriel et al. 2018). Moreover, high heat treatments caused increased denaturation of camel milk proteins in whole camel milk powders (Habtegebriel et al. 2018). This suggest that loss of solubility of camel milk proteins can be minimized by operating at lower spray drying temperature ranges (140 °C) (Habtegebriel et al. 2018).

Whole camel milk powder had a total solids content ranging from 94 to 97% (w/w), protein 22–29% (w/w) and lactose 27–31% (w/w) whereas the corresponding values for skimmed camel milk powder were 94–98% (w/w), protein 32–36% (w/w) and lactose 44–52% (w/w) (Habtegebriel et al. 2018).

Another spray drying experiment was conducted by varying drying temperature from 140 to 200 °C while maintaining the drying air flow rate (7.5 m^3/min), emulsion feed rate (0.0003 kg/s) and atomization pressure (0.52 MPa) constant (Habtegebriel et al. 2019). Camel milk powder had a moisture content of 7.04% [w/w] at lower temperature (140 °C) and 2.7% [w/w] at higher temperature (200 °C). Moisture removal from camel milk and yield of powder could be increased with inlet temperature only up to 160 °C (Habtegebriel et al. 2019).

In a study conducted to investigate the effect of spray and freeze drying on physicochemical, functional and morphological characteristics of camel milk powder, Deshwal et al. (2020) found that freeze dried camel milk powder (FDW) showed higher retention of calcium (15.33 g/kg) and iron (0.012 g/kg) as compared to spray dried camel milk powder. Freeze dried whole camel milk powder (FDW) had highest dispersibility and solubility (Deshwal et al. 2020). FDW, spray dried whole (SDW) and skimmed (SDS) camel milk powders had porous, agglomerated and brain type structure, respectively (Deshwal et al. 2020). A recent report by Kamal-Eldin et al. (2022) also showed that freeze-drying or lyophilization of camel milk has the benefit of retention of vitamins and minerals, and a very good storability and enables distance transport of the powder.

Recent reports by Zouari, Briard-Bion, et al. (2020) and Zouari et al. (2021) indicated the possibility of making an acceptable quality camel milk powder with high solubility and low denaturation extent using a spray drying technique. Chemical composition and physical properties of skim camel milk powder in comparison with skim bovine milk powder are indicated in Table 3 (Zouari, Briard-Bion, et al. 2020). Results of this study showed that camel milk powder exhibited higher tapped bulk and bulk densities as compared to bovine milk powder (Table 3). Also, higher whey proteins and ash contents were observed in camel milk powders as compared to bovine milk powder (Zouari et al. 2021).

A similar finding was reported by Zouari, Schuck, et al. (2020) for camel milk powder that contained a protein, lactose, ash and fat contents of 33.3 ± 0.2 g 100 g − 1, 52.7 ± 0.2 g 100 g − 1, 8.8 ± 0.1 g 100 g − 1 and 1.0 ± 0.1 g 100 g − 1, respectively. Analysis of whey protein nitrogen index (WPNI) showed that spray-drying causes limited denaturation on camel milk proteins in comparison to bovine milk (Zouari, Schuck, et al. 2020; Zouari et al. 2021). The heat sensitivity of camel milk whey proteins (up to 90 °C for 30 min) is lower than that of bovine milk whey proteins (Farah & Atkins 1992; Zouari, Schuck, et al. 2020). A report by Smits et al. (2011) indicated that the solubility of camel milk powder was higher than bovine milk powder and no damage to protein fraction of raw whole camel milk was observed due to spray-drying.

In conclusion, camel milk powder of desirable quality with increased retention of heat sensitive nutrients could be produced by optimizing operating parameters of the spray drying process. Production of camel milk powder would promote commercialization of camel milk in regions of surplus production. It would facilitate export of camel milk in the form of powder, provide a shelf stable product and enable distribution of camel milk to areas where camels are not found. The availability of camel milk powders will also encourage the development of other food ingredients (such as yoghurt, cheese, confectionaries, etc.) from camel milk. In the long run, this would contribute to the betterment of the livelihoods of camel rearing societies living in different parts of Africa.

Camel milk ice cream

Ice cream and frozen desserts are popular and widely consumed dairy products especially in countries with hot climate such as the Middle East (Muthukumaran et al. 2022). Currently, camel milk ice cream is made commercially in the UAE, Kazakhstan and Morocco (Konuspayeva & Faye 2021). In the UAE, camel milk ice cream as well as camel milk chocolate are produced in addition to fluid milk (El-Agamy 2017). In Mongolia, a soured cream called *Orom* is produced from Bactrian camel milk (El-Agamy 2017). Its production involves heating camel milk at 75–85 °C with continuous mixing to make foams, cooling to 18–20 °C, and keeping it at this temperature for 10–15 h (El-Agamy 2017). The soured cream obtained, *Orom*, is usually consumed fresh (El-Agamy 2017).

Ice cream with good quality and sensory acceptability can also be made by mixing camel milk with bovine milk (Soni & Goyal 2013). Similar processing parameters can be used in the manufacture of ice cream from camel milk as is the case with bovine milk although this may result in a product with different storage stability and quality characteristics (Ipsen 2017). When ice cream is made from camel milk using the same formulation as for cow milk, it usually has lower viscosity, lower dry matter content and lower melting point than cow milk ice cream (Jafarpour 2017). This is attributed to difference in total solids content between cow milk (12.30%) and camel milk (10.02%) (Jafarpour 2017). However, camel milk and cow milk ice cream have similar physicochemical and sensory properties (Jafarpour 2017). It was also reported that use of additives and flavouring agents in the ice cream formulation improves the nutritional value, health benefits and sensory properties of camel milk ice cream (Ho et al. 2022). An increase in viscosity, consistency and melting resistance, and a decrease in hardness and overrun as well as improvement in the sensory properties were observed when camel milk ice cream was fortified with 2% camel milk casein and its hydrolysates (Hajian et al. 2020).

Dried fermented camel milk products

A dried fermented camel milk called *Oggtt* is produced in Saudi Arabia (Farah 1996; El-Agamy 2017). Its production involves leaving camel milk at an ambient temperature to ferment for 2 days after which the fermented milk is churned. The resulting buttermilk is boiled while stirring until it becomes thick. The paste is allowed to

Table 3 Chemical and physical characteristics of skim camel milk powder in comparison with skim bovine milk powder (Zouari, Briard-Bion, et al. 2020)

Variables	Skim camel milk powder	Skim bovine milk powder
Total solids (%)	96.1 ± 0.5	96.5 ± 0.1
Total protein (%)	33.3 ± 0.2	33.1 ± 0.3
Caseins (%)	26.1 ± 0.1	27.5 ± 0.1
Whey proteins (%)	7.2 ± 0.1	5.6 ± 0.5
Fats (%)	1.1 ± 0.1	1.0 ± 0.1
Lactose (%)	53.3 ± 0.7	54.5 ± 0.5
Ash (%)	8.4 ± 0.2%	7.9 ± 0.1%
Water activity (a_w)	0.251 ± 0.01	0.252 ± 0.01
Whey Protein Nitrogen Index (WPNI in g of N_2 kg^{-1})	11.5 ± 0.2	8.9 ± 0.2
Bulk density ($kg.m^{-3}$)	287.2 ± 1.2	233.4 ± 0.7
Tapped bulk density ($kg.m^{-3}$)	638.2 ± 0.8	378.1 ± 0.5

cool to about 30–35 °C and is then shaped by hand into small cakes, which are then pressed and sun dried (El-Agamy 2017). The product is consumed either dry or after reconstitution with water.

Another dried camel milk product produced in Kazakhstan and Uzbekistan is called *Kurt* (El-Agamy 2017; Pak et al. 2019; WHO 2019). It is also termed as Kurut or *Qurt*. It has a longer shelf life, salty taste and solid texture. *Chaka* or *Suzma*, a kind of strained yoghurt, is traditionally used to make *Qurt*/*Kurt* (Pak et al. 2019). It is also produced by drying a local yoghurt variety called *Qatiq*. Spices are added to impart good flavour and the final product has a solid texture. The duration of production of *Qurt* is temperature dependent and it takes 3 to 5 days in summer or 15–20 days in winter. It is used to be the main protein source for people residing in the arid desert parts of Uzbekistan (Pak et al. 2019).

Camel milk chocolate

Chocolate can be made from camel milk in the same way as bovine milk chocolate. The first report of camel milk chocolate came from Dubai where a confectionery company called Al Nasamma Chocolate Inc., started producing chocolates from camel milk and made it available in the market since 2008 (Muthukumaran et al. 2022). The product is reported to contain important vitamins and minerals such as Zn, Fe, K, Mg and vitamin C (Muthukumaran et al. 2022). The chocolate bar made from camel is reported to be delicious and liked by consumers. It is claimed to have several health benefits including antidiabetic effect owing to its possession of camel milk (Muthukumaran et al. 2022). However, it should be noted that its alleged health benefit has not yet been scientifically proven. Thus, further research is needed in order to verify the claimed health benefits of camel milk chocolate.

Conclusions and scope for future intervention

Camel milk presents various processing challenges as compared to bovine milk. Some of the challenges of camel milk processing include poor stability of the milk during UHT treatment, impaired rennetability of the milk as compared to bovine milk, formation of weak and fragile curd during coagulation of the milk, longer fermentation time until the pH reaches 4.6., low thermal stability of camel milk during drying, and effect of pH change on the solubility of camel milk whey proteins.

The composition, structure and functional properties of individual proteins of camel milk differ considerably from that of bovine milk and this is the reason for the difficulty of making products from camel milk. Camel milk contains small amounts of κ-casein and a high proportion of β-casein and it lacks β-lactoglobulin. Moreover, the casein micelle size of camel milk is larger and its fat globule size is smaller than bovine milk. The difficulties of processing camel milk and manufacturing of value-added dairy products are associated to the above-mentioned properties of camel milk. There is often limited information about functional properties and processing technologies of camel milk. Thus, detailed studies are needed to fully understand its properties and utilize its functional and technological potentials.

Based on the gaps identified through the review of literature, the following intervention strategies are suggested to overcome the challenges associated with camel milk and camel milk products:

- In many countries where camel milk is produced, there is no national standard for processed camel milk and camel milk products. This causes a major hindrance to the trading of camel milk especially its export to the international market. Although the demand for camel milk and milk products is increasing in recent years in Europe and North America mainly due to its alleged health benefits, consumers in these regions do not have easy access to camel milk and its products because of absence of quality standards for camel milk and consequent ban of importation of camel milk to these countries. Thus, there is an urgent need to develop quality standards for camel milk and milk products in order to facilitate global trading of camel milk and ensure easy access of the international community to camel milk and camel milk products. Setting an international standard for camel milk and camel milk products (e.g., standards for pasteurization of camel milk, microbiological quality standards for camel milk and its products) recognized by all stakeholders is very important in order to develop the camel dairy sector and to provide sustainable supply of camel milk products to the global consumers.

- Although some camel milk products (pasteurized milk, cheese, yoghurt, butter, powder) are commercially available at present, the quality of these products as compared with their bovine counterparts are generally low and have less consumer acceptability. Thus, more research is needed in order to improve the nutritional quality, functional properties and consumer acceptability of dairy products made from camel milk and make them competitive in the global market. Such efforts will enable production of camel milk products that meet consumer demands for tasty and healthy food products.
- Camel milk is different from bovine milk and milk from other species in composition, colloidal structure and functional properties. It is difficult to process it into products such as cheese and yoghurt using the same protocols used for bovine milk processing. Thus, there is a need to develop specialized processing technologies for camel milk in order to obtain consumer acceptable and value-added products.
- Fermented camel milk products have been claimed to have therapeutic potential against a number of human illnesses including diabetes and autism. However, these claims have largely been based on in vitro studies or trials using animal models. Clinical studies and trials on human beings are limited. Thus, detailed clinical studies involving human subjects are needed in order to prove the claimed therapeutic potential of fermented camel milk products.
- Although there are some attempts on isolation and characterization of lactic acid bacteria from fermented camel milk and selection of strains for use in the production of fermented camel milk products, there is limited information on the subject and more work needs to be conducted to develop starter cultures suitable for production of fermented camel milk products with typical flavour and aroma that meets the demands of the consumers.

Abbreviations

USA	United States of America
USD	United Sates Dollar
ALP	Alkaline phosphatase
GGT	γ-glutamyl transferase
LPO	Lactoperoxidase
HTST	High temperature short time pasteurization
UAE	United Arab Emirates
UHT	Ultra-high temperature processing
LAB	Lactic acid bacteria
β-CN	Beta casein
α_{s1}-CN	Alpha S_1-casein
α_{s2}-CN	Alpha S_2-casein
κ-CN	Kappa casein
α-LA	Alpha-lactalbumin
β-LG	β- lactoglobulin
Chy-Max M1000	Camel chymosin
WPNI	Whey protein nitrogen index
Fe	Iron
Zn	Zinc
Mg	Magnesium
K	Potassium

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