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**Camel milk: A review of its nutritional value, heat stability,
and potential food products**

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Abstract

Camel milk is superior to bovine milk and quite close to human milk in terms of its nutritional value. It contains high concentrations of many bioactive compounds that are essential for human health. Despite its profound nutritional and health benefits, food products produced from camel milk are still very limited compared to bovine milk. Differences in the composition of bovine and camel milk make the production processes for bovine milk products unsuitable for camel milk products. Therefore, a comprehensive understanding regarding the composition, bioactive compounds, and the heat stability of camel milk is essential to preserve the inherent nutritional value of camel milk while achieving desirable attributes in the final products. In this review, the properties and functionalities of macro-nutrients in camel milk, especially heat stability of camel milk and its proteins are described. In addition, technical aspects of the production of various camel milk products, including difficulties in their production and directions for further research to enhance their quality, are comprehensively discussed.

Keywords: Camel milk; Heat treatment; Bioactive compounds; Camel milk products

1. Introduction

A hot climate, scarce water reserves, and lack of pastures are preferred environmental conditions for camels. Therefore, camels are typically raised in countries with large desert areas, and they can be used for many purposes such as milk, meat, wool, transport, race, tourism, agricultural work, and cosmetics (Faye, 2015; Saalfeld & Edwards, 2010). In terms of milk production, according to FAO (2019), African countries (*e.g.* Somalia, Sudan, Nigeria, Kenya, Chad, Mauritania, Ethiopia, and Mali) account for approximately 90% of the fresh whole camel milk (CM) global production, followed by Asian countries (*e.g.* India, Yemen, Saudi Arabia, United Arab Emirates, China, and Afghanistan). Camel milk has nutritional value superior to bovine milk and homologous to human milk, thus CM is considered an excellent alternative to human milk in cases where the acquisition of human milk is limited. Camel milk has a satisfactory balance of essential amino acids for human diets, contains a high percentage of easily hydrolyzed β -caseins, and lacks allergy-inducing β -lactoglobulin (El-Agamy, 2009; Hinz et al., 2012; Kappeler et al., 2003). Camel milk also contains high vitamin and mineral contents, and many protective proteins (*e.g.* immunoglobulins, lactoferrin, lysozyme, and lactoperoxidase) that have anti-cancer, anti-diabetic, and anti-bacterial properties (Barłowska et al., 2011; Konuspayeva et al., 2009; Zou et al., 2021a; Zou et al., 2021b).

Despite profound nutritional value of CM, its global supply and the food products produced from CM are very limited. The current utilisation of CM is much below its potential. The production of CM products is highly challenging, but in the last decade many attempts have been made to optimise the processing conditions to produce high-quality CM products with a long shelf life, which is necessary to enable worldwide distribution of CM. Although many review papers on CM exist in the literature (*e.g.* Farah, 1993; Konuspayeva et al., 2009; Kula & Tegegne, 2016; Shori, 2015; Yadav et al., 2015;

Konuspayeva 2020; Konuspayeva et al. 2021), most are dedicated to describing the composition and nutritional properties of CM, and general production of some kinds of CM products. There is still a lack of comprehensive review focusing on technical aspects of the production of all possibilities of CM products. Therefore, in this review, we focus on the description of the potential production of food products from CM, including pasteurised/sterilised milk, foaming agent, powder, ice cream, cheese, butter, and yoghurt. Along with an update of the current production of CM products, we also point out challenges and limitations in the processing procedures, where applicable. However, understanding the difficulties in producing CM products requires knowledge regarding the properties of CM. Therefore, CM composition, its nutritional value, functionalities, and stability during heat treatment are also presented in this review.

2. Macro-nutrients and bioactive compounds in camel milk

Camel milk composition has been studied throughout the world, and a large number of available references show large variations. A meta-analysis of the literature data of CM composition was published in 2009 (Konuspayeva et al., 2009), and updated in 2020 (Konuspayeva 2020b). The composition of dromedary CM from various geographical origins, taken from this meta-analysis, is summarised along with those of bovine and human milk in Table 1.

2.1. Proteins

Caseins in CM account for 61.8–88.5% of the total protein (Ereifej et al., 2011). The components of camel caseins, including α_{s1} -casein, α_{s2} -casein, β -casein, and kappa-casein constitute 21, 10, 65, and 3.5% of the total caseins, respectively (Kappeler et al., 2003; Mati et al., 2017). Similar to human milk, CM contains a high percentage of β -casein (65% of total caseins) (Kappeler et al., 2003). As β -casein is less resistant to peptide hydrolysis than α s-casein, its abundance in CM is considered to be one of the

major reasons for easy digestibility of CM to human infants (El-Agamy et al., 2009). The amino acid composition of camel and bovine milk casein fractions is quite similar, except for camel caseins which contain less cysteine and more proline (Kappeler, 1998).

Camel milk whey proteins mainly comprise α -lactalbumin, serum albumin, immunoglobulins, lactophorin (also called glycosylation-dependent cell adhesion molecule-1 or GlyCAM-1), and lactoferrin. The concentrations of α -lactalbumin, serum albumin, and lactoferrin in CM were determined to be 2.01, 0.40, and 1.74 mg/mL, respectively, by capillary electrophoresis (Omar et al., 2016). The high content of α -lactalbumin and lactoferrin, and the absence of β -lactoglobulin in CM are very similar to human milk (Hinz et al., 2012). As β -lactoglobulin is one of the major allergens in bovine milk, its absence in CM makes it a promising alternative protein source in infant formula. Studies show that CM can be considered as an alternative to human milk due to hypoallergenic properties of its proteins (El-Agamy, 2007).

A range of bioactive proteins with potential antimicrobial activity has been identified in CM, including lactoferrin, GlyCAM-1, immunoglobulins, lactoperoxidase, peptidoglycan recognition protein (PGRP), lysozyme, and whey acidic protein (Mati et al., 2017). The physiochemical properties and bioactivities of these proteins are summarised in Table 2. Mati et al. (2017) presented a comprehensive review on the potential biological activities of the CM proteins and their peptides released during fermentation/digestion.

2.2. Lipids

Camel milk fat content was found to closely relate to the geographical origin according to the meta-analysis results of CM composition (Table 1). The fatty acid composition of CM was well described and compared with cow and human milk in a study reported by Dreiucker and Vetter (2011). Camel milk fat only contains small amounts of short-chain

fatty acids (C4–C12) but a higher concentration of long-chain saturated fatty acids compared with bovine and human milk fats. The highest concentration of branched-chain fatty acids was observed in CM fat (3.03%), compared with 1.82 and 0.36% in bovine and human milk fats, respectively (Dreiucker & Vetter, 2011). Regarding cis-monoenoic fatty acids, CM fat also contained a high concentration of palmitoleic acid, 16:1 cis-9 (10.1%) in addition to oleic acid, 18:1 cis-9 (17.2%) (Dreiucker & Vetter, 2011).

Camel milk fat showed melting point and solidification temperatures at 41.9 and 30.5°C, respectively, while those of bovine milk fat were 32.6 and 22.8°C, respectively. The increased melting point of CM fat may result from its high content of long-chain fatty acids, low content of short-chain fatty acids, and *trans*18:1 isomers (Abu-Lehia, 1989). The milk fat melting profile is dominated by the higher molecular weight triacylglycerols (TAGs, $\geq$ C40). The low levels (<1%) of TAG C24–C40 and very high levels of TAG C48–C52 in CM fat were regarded as the main reasons for its relatively higher melting temperature compared with those observed for bovine, goat, sheep, horse, donkey, and water buffalo milk in the same study (Smiddy et al., 2012).

The average diameter of the milk fat globules follows an ascending order for camel (2.99 μ m), goat (3.2 μ m), sheep (3.78 μ m), bovine (3.95 μ m), and buffalo (8.7 μ m) milk. Relatively smaller fat globules size (from 0.1 to 4.0 μ m) comprise 80.6, 68.4, 55.3, 73.3, and 23%, of the total fat distribution in camel, bovine, sheep, goat, and buffalo milk, respectively (El-Zeini, 2006). As small fat globules are more vulnerable to lipolytic enzymes, camel and goat milk are believed to be more easily digested by humans (Tomotake et al., 2006).

2.3. Lactose

The lactose content of dromedary CM is similar to that of bovine milk (Table 1). The CM lactose content was found to be low at birth of the calf (2.8%, w/v) and increased to 3.8%

within first-day lactation. The average lactose content increased to 5% in camels with free access to drinking water, while it decreased to 2.9% in dehydrated camels. Lactose concentration variation in CM has been considered one of the major reasons for the reported differences in its taste (occasionally sweet and occasionally bitter) (Yagil & Etzion, 1980). Interestingly, CM seems to be a safer and healthier option for patients suffering from lactose intolerance. One possible reason for the easy digestibility of CM is the lower concentration of casomorphin in CM that provokes reduced intestinal motility, thus exposing lactose more to lactase action over a longer period (Cardoso, et al., 2010). Another possible reason for low lactose intolerance of CM compared to bovine milk is due to the high content of L-lactate in raw CM which is 100 times more than that in bovine milk (Konuspayeva et al. 2019).

2.4. Minerals and vitamins

The average ash content in dromedary CM is similar to that in bovine milk but much higher than that in human milk (Table 1). The mean values (mg/100g) of major CM minerals are: calcium 111.4; magnesium 6.7; phosphorus 81.2; sodium 57.8; potassium 156.3, while the corresponding concentrations in bovine milk are 119.9, 13.4, 95.0, 49.7, and 147.0, respectively. The respective concentrations of these minerals are much lower in human milk: 32.4, 3.4, 14.0, 16.0, and 51.8 mg/100 g, respectively (Soliman, 2005). The Ca:P ratios for camel, bovine, and human milk are 1.5, 1.29 and 2.1, respectively. As a high level of phosphate in infant formula may cause hyperphosphatemia and low serum calcium, a CM-based formula is considered to be better for feeding infants (Kappeler, 1998). In addition, the iron concentration in CM is six times higher compared with bovine milk (Sawaya et al., 1984; Ziane et al., 2016).

Camel milk contains a wide range of vitamins, including vitamins A, C, D, E, and the vitamin B group. Camel milk is known for its high vitamin C content, which is three to

five times as high as that in bovine milk (Farah et al., 1992). The vitamin B3 concentration is also higher in CM compared with bovine milk, whereas bovine milk contains more vitamins A and B2 (Farah et al., 1992; Haddadin et al., 2008; Sawaya et al., 1984; Stahl et al., 2006). Camel and bovine milk contain similar levels of vitamins B1 and B6 (Haddadin et al., 2008; Sawaya et al., 1984). A comprehensive review about different types of vitamins in CM was recently published (Faye et al., 2019).

3. Biological functionalities of camel milk

3.1. Hypoglycaemic effect

The consumption of CM for treating diabetes has a long tradition in camel-rich regions (Mohamad et al., 2009). A significantly lower prevalence of diabetes was found in a CM-consuming community in Rajasthan, India compared with another community where CM was not consumed (0 vs. 5.5%) (Budania, et al., 2007). Dozens of clinical studies have confirmed the anti-diabetic effects of CM. According to Agrawal et al. (2003), type I diabetes patients required 30% less insulin after drinking CM for three months. Besides, the long-term efficacy and safety of CM as an adjuvant therapy for the treatment of type I diabetes were confirmed after 1- and 2-year trials (Agrawal et al., 2011; Saran, et al., 2007). Camel milk may also help control the insulin levels of patients with type II diabetes, as a significant increase in insulin levels was observed after two months of CM consumption (Ejtahed et al., 2015). The hypoglycaemic effect of CM was also investigated in animal models. The blood glucose levels in diabetic rabbits and dogs decreased by 78 and 47%, respectively, after receiving CM for four to five weeks (Sboui et al., 2010; Tantawy et al., 2010).

The anti-diabetic property of CM was previously considered to be mainly due to its high content of insulin and insulin-like proteins (Korish et al., 2015; Malik et al., 2012). However, in a recent study, Abou-Soliman et al. (2020) performed an *in vitro* digestion

of CM and found no insulin activity after 30 min of gastric digestion. Insulin digestion was further confirmed by negative results in enzyme-linked immunosorbent assay (ELISA) in their study. More *in vivo* studies are needed to confirm the absorption of orally administered CM insulin and insulin-like proteins. Other elements in CM may also potentially contribute to its anti-diabetic activity. For example, antioxidants in CM may also be capable of regulating hyperglycaemic states in humans (Limon et al., 2014).

3.2. Antimicrobial effect

Camel milk showed antibacterial activity towards both Gram-positive and Gram-negative bacteria such as *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Salmonella typhimurium*, *Klebsiella pneumonia*, and *Clostridium perfringens* (Benkerroum et al., 2004; Agamy & Ruppanneb, 1992; Othman, 2016). The antibacterial activity of CM offers help for diseases that are caused by bacterial infections, such as tuberculosis (TB) and Crohn's disease (Mal et al., 2000; Shabo et al., 2008). Besides eliminating pathogenic bacteria (*Mycobacterium tuberculosis* for TB and *Mycobacterium avium - subspecies paratuberculosis* (MAP) for Crohn's disease, respectively), bioactive proteins in CM, such as immunoglobulins, are believed to help boost immunity, which also benefits the healing process (Mal et al., 2006). Symptom alleviation is, therefore, usually regarded as the joint efforts of bactericidal and immunological effects of CM.

The antibacterial activity of CM is mainly due to its bioactive compounds, especially lactoferrin, lysozyme, and immunoglobulins, which are most abundant in CM (Benkerroum et al., 2004; Agamy & Ruppanneb, 1992). Besides, the antimicrobial activity of camel whey proteins was improved after enzymatic hydrolysis, suggesting that certain peptides with stronger antimicrobial activity may also be released after *in vivo* digestion (Salami et al., 2010). Lactoferrin in CM also exhibited antiviral activity towards hepatitis C virus genotype 4. Entry of the virus into the leucocytes was completely

inhibited in the presence of camel lactoferrin (Redwan & Tabll, 2007). Antifungal and antiparasitic activities in CM have also been claimed (Maghraby et al., 2005).

3.3. Immunological effect

Camels have a unique and powerful immune system. Camel antibodies are reportedly much smaller in size compared with their counterparts in humans. Additionally, IgG₂ and IgG₃ in CM are unique due to a natural absence of light chains (Riechmann & Muyldermans, 1999). The small size of camel immunoglobulins (Igs) is believed to be beneficial in targeting specific antigens. Camel IgG shows a complete neutralising activity against tetanus toxin and is recognized as a better inhibitor of enzyme antigens (Muyldermans et al., 2001; Riechmann & Muyldermans, 1999).

Camel milk therapy showed a surprisingly positive effect on the behaviour of autistic children. Though the cause of autism remains unknown, studies propose it to be related to an increase in oxidative stress. After two weeks of CM consumption, glutathione, myeloperoxidase, and superoxide dismutase concentrations were found to increase significantly in the plasma of autistic children, which benefits the control of oxidative stress (Shabo & Yagil, 2005). The immune system rehabilitative effect of Igs in CM is also regarded as a possible factor alleviating the potential dairy food allergy in autistic children (Al-Ayadhi et al., 2015).

3.4. Hypoallergenicity

Bovine milk allergy is one of the main food allergies reported in children and adults. The clinical symptoms vary and can be quite severe. Bovine milk contains over 20 proteins that can cause allergic reactions. Casein fractions (particularly α _{s1}-casein) and β -lactoglobulin are the two most powerful of these allergens (El-Agamy, 2007). A compositional analysis of human milk showed it to contain no β -lactoglobulin, and a low

concentration of α_{S1} -casein but a high concentration of β -casein (El-Agamy et al., 2009). The protein constituents in CM are similar to those in human milk, suggesting its high potential to serve as an alternative to bovine milk for children with allergies (El-Agamy, 2007). Encouraging results were also observed from clinical trials when CM was used to treat children with milk allergies (Shabo et al., 2005). Camel milk was even claimed to be a better choice for lactose-intolerant people, as they rapidly digested lactose in CM (Cardoso et al., 2010). Still, larger-scale trials are needed to make a stronger claim.

3.5. Angiotension I-converting enzyme (ACE) inhibitory activity

Angiotension I-converting enzyme (ACE) is a dipeptidyl carboxypeptidase that regulates blood pressure, and ACE inhibition results in a fall of blood pressure. Peptides that have ACE-inhibitory activity are found in various food proteins, including milk proteins (Minervini et al., 2003). ACE-inhibitory peptides were also found in CM hydrolysates and fermented CM (Soleymanzadeh et al., 2019; Tagliazucchi et al., 2016). In a study by Quan et al. (2008), an ACE-inhibitory peptide (AIPPKKNQD) was purified from fermented CM. This peptide maintained its ACE-inhibitory activity after either protease digestion or heat treatment, indicating its anti-hypertensive potential after *in vivo* digestion.

4. Effect of heat treatment on the nutritional value of camel milk

4.1. Heat stability of camel milk

The heat stability of milk is an important parameter when considering its thermal processing. The heat coagulation time (HCT) of CM at 100, 120, and 130°C was investigated at pH 6.3–7.1 (Farah & Atkins, 1992). At 120 and 130°C, the milk was very unstable at all pH values, with HCT below 2–3 min. At 100°C, HCT initially increased to 12 min, then remained constant between pH 6.4 and 6.7, and increased progressively

with increasing pH, reaching approximately 33 min at pH 7.1. Camel milk seemed to be much less heat stable compared with bovine milk (Farah, 1993). In another study, the HCTs for bovine, buffalo, and CM were determined to be 1807.4, 1574.6, and 133.6 s, respectively, at 140°C (Shyam et al., 2016).

The presence of kappa-casein and β -lactoglobulin and their interaction during heating is believed to be critical in maintaining milk stability (Farah & Atkins, 1992). Therefore, the reduced level of kappa-casein (5% of total casein in CM compared with 13.6% in bovine milk) and the absence of β -lactoglobulin may be responsible for the poor stability of CM at high temperatures.

4.2. Heat stability of camel milk proteins

To develop a suitable heat processing technique for CM, it is necessary to study the heat stability of CM proteins to see whether their functionality can be maintained during heat treatment. Different heating conditions have been applied to CM proteins in different studies. Camel milk whey proteins were more heat resistant than bovine and buffalo milk proteins when the milk was heated to 63, 80, and 90°C for 30 min (Farah, 1986) or to 65, 75, 85, and 100°C for 10, 20, and 30 min (Elagamy, 2000). The heat stability of camel and bovine whey proteins was also measured indirectly by assessing the solubility change after the separated whey fractions at pH 4.0, 4.5, 5.0, and 7.0 were heated at 60–100°C for 1 h, given that the denatured proteins would precipitate after heating and cause a drop in whey protein solubility (Laleye et al., 2008). The effect of temperature on solubility depended on pH, and a major change in solubility occurred at pH 4.5, which is the isoelectric point of many whey proteins. Both bovine and camel whey proteins were most stable at pH 7, a level at which the aggregation process is inhibited by electrostatic repulsion between the unfolding globules. At pH 4.5 and 100°C, a decrease in solubility by 55 and 52% was observed for camel and bovine whey proteins, respectively. Camel

whey proteins were found to be more susceptible to acid denaturation, as solubility decreased by approximately 16% in camel and 9% in bovine whey as pH was dropped from 7 to 4. According to Felfoul et al. (2015), the bands of camel serum albumin, α -lactalbumin, and kappa-casein decreased after heating at 90°C. Bovine serum albumin was not seen in the electrophoresis patterns after heating bovine milk at 70°C, while β -lactoglobulin and α -lactalbumin bands were removed only at 90°C. In addition, the free thiol group concentration analysis results indicated that no significant camel protein denaturation happened at 70°C, while the complete denaturation of bovine milk occurred after heat treatment at 70°C for 30 min. Recently, Genene et al. (2019) also observed, through whey protein nitrogen analysis after heat treatment of the milk samples, that CM whey proteins were less heat-denatured compared with bovine milk whey proteins. SDS-PAGE results in the same study showed that 33% of α -lactalbumin was denatured in CM after heating at 90°C for 5 min, while the percentage was 95% in bovine milk.

Differential scanning calorimetry (DSC) has occasionally been used to measure the denaturation temperature of CM proteins. Concentrated CM and bovine milk showed denaturation peaks at 77.8 and 81.7°C, respectively (Felfoul et al., 2015). When liquid and dry, camel and bovine whey samples were analysed using DSC, dry camel whey showed three marginal thermal transitions at 139, 180, and 207°C, while the three peaks appeared at 81, 146, and 198°C for dry bovine whey. However, no significant differences were observed in the heat denaturation curves of camel and bovine whey proteins in liquid form (Laleye et al., 2008). As protein mixtures exist in these peaks, the numbers may not be reliable enough to draw conclusions on whey protein stability.

Overall, CM whey proteins seem to be more heat stable than bovine milk whey proteins, although differences in milk origin, test conditions, and assay methods may result in inconsistencies in the above results. These studies generally analyse whey proteins as a

whole, and protein gels are sometimes used to follow changes in major whey proteins. More detailed studies on how whey proteins, especially ones with antimicrobial activity (some are relatively minor in milk), behave during heat treatment will be helpful for providing comprehensive information for CM heating processing.

The thermostability of certain individual bioactive proteins in CM has also been investigated. Usually protein purification has to be performed prior to stability analysis. The heat resistance among these camel whey proteins was ranked as lysozyme > lactoferrin > IgG (Elagamy, 2000). The secondary structure of camel α -lactalbumin was better preserved than that of bovine α -lactalbumin during heat denaturation (Atri et al., 2010). Lactoperoxidase in CM exhibited lower heat stability compared with that in bovine milk when heated to 67–73°C (Tayefi-Nasrabadi et al., 2011).

Proteomic methods have also been applied in studies investigating the effect of heat treatment on CM proteins. Compared with traditional methods, they are able to efficiently quantify a large set of proteins simultaneously and provide a much more sensitive and accurate alternative for analysing the heat denaturation of individual CM proteins. The changes in CM proteins after freezing, pasteurisation and spray drying were investigated and compared with bovine and caprine milk (Zhang et al., 2016). A total of 129, 125, and 74 proteins were quantified in bovine, camel, and caprine milk sera, respectively. Protein concentrations changed at different rates with varied processing steps and among different species. Some immune-related proteins were heat sensitive, such as lactoferrin, GlyCAM 1, and lactapherin, with a loss of approximately 25 to 85% after pasteurisation and 85 to 95% after spray drying. Meanwhile, α -lactalbumin, osteopontin, and whey acidic protein were relatively heat stable, showing a loss of 10 to 50% after pasteurisation and 25 to 85% after spray drying. On the other hand, the concentrations of certain proteins originating from damaged milk fat globules and somatic cells increased after freezing.

Bovine and CM proteins before and after heat treatment at 80°C for 60 min were identified using liquid chromatography coupled with tandem mass spectrometry, LC-MS/MS (Felfoul et al., 2017). α -lactalbumin, PGRP, and serum albumin were identified as the major whey proteins in CM, in the following heat sensitivity order: α -lactalbumin < PGRP < serum albumin (100, 68, and 42% decrease observed after heating for α -lactalbumin, PGRP, and serum albumin, respectively). For the two major whey proteins, i.e. α -lactalbumin and β -lactoglobulin in bovine milk, 0 and 26% remained, respectively, after heat treatment. Moreover, a total of 19 protein bands were separated using SDS-PAGE and identified using LC-MS/MS. The results confirmed the vulnerability to heat treatment at 80°C of camel α -lactalbumin and PGRP, along with bovine α -lactalbumin and β -lactoglobulin. Meanwhile, casein fractions in both camel and bovine milk remained intact after being heated at 80°C for 60 min.

The denaturation of whey proteins in CM after heating at 63°C and 98°C for 1 h was investigated comprehensively by Quantitative 2D-difference in gel electrophoresis - mass spectrometry (Benabdelkamel et al., 2017). Compared with proteins in the non-heated milk samples, a total of 80 proteins significantly decreased in the milk samples heated at 63°C, while 25 proteins which remained stable in the 63°C-heated milk significantly decreased in the 98°C-heated milk samples. Enzymes were most severely damaged by heating, followed by binding proteins and cell adhesion proteins. Immune-related proteins comprised 5% of all the proteins affected by heat treatment.

Recently, two new studies were published investigating protein profile changes in spray-dried CM powder. Zouari et al. (2020) spray dried skim CM and bovine milk and used HPLC-MS for protein identification and quantification before and after drying. Proteins were less denatured in CM powder compared with bovine milk powder. After spray drying, concentrations of camel serum albumin and α -lactalbumin decreased by 14.1 and

3.3%, respectively, while concentrations of camel PGRP and caseins remained constant or increased. The protein profiles of unprocessed CM, heated liquid CM (115°C, 15 min), and CM powder were compared by Li et al. (2020). Proteins were labeled with tandem mass tag and subjected to LC-MS/MS analysis. Among the 807 proteins identified, 246 and 170 proteins changed significantly in heated liquid milk and milk powder, respectively, compared with unprocessed milk. After processing, the most significantly decreased proteins included ARF GTPase-activating protein GIT1, elongation factor 1- α 1, Acyl-CoA desaturase, heat shock protein 90, and aldehyde oxidase 3-like protein. As bactrian CM was used in the study, the protein composition may be somewhat different from that of dromedary CM, which was used in other studies mentioned above.

Different processing conditions, along with analytical methods, may result in some of the inconsistent results described above. For example, α -lactalbumin was less heat stable than serum albumin in CM in Felfoul et al.'s study (2017) but more heat stable in Zouari et al.'s study (2020). Research concerning the influence of heat on CM proteome is still at an early stage. More studies are still required to show how various drying processes affect camel proteome, especially the bioactive proteins.

5. Possible food products produced from camel milk

5.1. Pasteurised and sterilised camel milk

Physically, CM is analogous to cow milk with its white colour, and slightly salty with a sweet aftertaste. Compared with cow milk, CM contains higher levels of minerals (*e.g.* iron), vitamin C, antibacterial and probiotic compounds, a higher ratio of whey proteins to caseins, and lacks allergy-inducing proteins (β -lactoglobulin). These factors make CM more readily digestible than cow milk, and closest to human milk in terms of nutritional values (El-Agamy, 2006). Due to higher concentration of antimicrobial components, raw (fresh) CM has a longer shelf life than cow milk (Faraz et al., 2013). Activating the natural

antimicrobial system (e.g. the lactoperoxidase system) in CM with hydrogen peroxide-producing lactic acid bacteria, such as *W. confusa* 22282, was reported as an alternative approach to maintaining the storage stability of raw CM (Dashe et al., 2020). From the nutritional aspect, it is feasible to process CM for human consumption similarly to cow milk. However, use of CM for daily human consumption is still limited although CM is available on the market in many countries. A list of suppliers for CM, which is obtained from the Alibaba sales platform, was described in study by Konuspayeva et al. (2021). Most CM products are pasteurised milks that are heated at approximately 72°C for 15 s to kill harmful pathogens, allowing the product to be kept for two weeks at refrigeration temperature (Ipsen, 2017). Studies show that pasteurising CM is possible under the same regimes used for cow milk without causing any significant alteration in its functionality. At temperatures less than 100°C, whey proteins and antimicrobial factors in CM were significantly more stable than those in cow milk (Elagamy, 2000; Farah, 1986), and the thermal inactivation of pathogenic bacteria (e.g. *Escherichia coli*) in CM and cow milk was similar (Sela et al., 2003).

Commercially pasteurised CM is unhomogenised. During its storage, a thin layer of white cream forms on top as a result of creaming. The creaming rate of CM is much slower than that of cow milk under the same conditions. At 4°C, creaming of CM after 24 h was twelve times less than that of cow milk (Farah & Rüegg, 1991). Homogenisation may therefore not be necessary for pasteurised CM, as its shelf life is quite short. The slow creaming of CM is attributed to its small fat globule size. As shown in Figure 1 (unpublished data), which exhibits the particle size distributions of raw cow milk and CM, the average particle size of CM derived from particle volume (D[4,3]) was 2.56 µm, while the average particle size of cow milk was almost double (4.16 µm). Moreover, a deficiency in agglutinin (a protein promoting the clustering of fat globules) in CM

contributes to its low creaming ability (Farah & Rüegg, 1991). Although there are many health benefits of drinking CM, extremely high retail price (*e.g.* USA: ~38 USD/L, Singapore: ~19 USD/L, Australia: ~15 USD/L, India: ~7 USD/L), due to low yield and high production costs, may be the main reason for its limited use for human consumption. Camel milk has very poor heat stability at high temperatures and cannot be sterilised at natural pH due to denaturation and protein sedimentation. Producing sterilised CM is therefore very difficult. It was described in section 4.1 that the coagulation time of CM was reduced from 12 min to less than 1 min with increasing heating temperature from 100°C to 140°C (Farah & Atkins, 1992). The low stability of CM at high temperatures is associated with a deficiency of kappa-casein and an absence of β -lactoglobulin. However, heat stability of CM at high temperatures increases with increasing pH and the presence of phosphate. Increasing to a pH of 6.9–7.2 or adding sodium phosphate (1 mmol/L) to CM did not cause any sedimentation of proteins or very little reversible sedimentation as it was heated at 121°C for 15 min (Alhaj et al., 2011). Compared to pasteurisation (72.5°C/15s) and high-pressure treatment (200–800 MPa), UHT (144°C/5s) led to the greatest colour change and highest whey protein denaturation in CM (Omar et al., 2018). The denaturation level of α -lactalbumin in UHT CM was approximately 66%, which is nearly double to that measured in high-pressure-treated CM (~33%) and pasteurised CM (~27%). Regarding colour, the total colour difference (ΔE) value (indicating colour differences between untreated and treated milk samples) of UHT milk was 6.5, while pasteurised and high-pressure-treated milk had ΔE 's of 1.5 and 2.26, respectively. Also, treatment with pressures higher than 400 MPa and UHT inhibited rennet coagulation in CM. This study reinforces the challenges faced in the sterilisation of CM and indicates high-pressure treatment (< 400 MPa) as a possible alternative for CM preservation because it has less negative effect on CM properties than UHT.

Future research directions for UHT of CM include studying the possibilities of various additives, such as disodium phosphate, kappa-casein from cow milk and calcium-chelating agents (*e.g.* ethylenediaminetetraacetic acid disodium salts) to stabilise CM proteins, and hydrocolloids to increase the viscosity and reduce the sedimentation of UHT CM (Alhaj et al., 2011). Small changes in pH seem to result in large effects on CM heat stability as kappa-casein and calcium content are the main factors affecting the heat stability of CM (Alhaj et al., 2011). Currently, Camelicious (Emirates Industry for Camel Milk & Products) is globally marketing a UHT CM product with a shelf life of 12 months when stored in a cool and dry place (Yirda et al., 2020). However, it is produced from reconstituted whole CM powder.

5.2. Foam agents

The top foam layer of many dairy products, such as cappuccino-style beverages, determines overall product quality and consumer acceptance. In most coffee shops, foam is prepared from cow milk, which may not be suitable for people with dairy allergies due to the allergy-inducing proteins in cow milk. Camel milk becomes a potential alternative for preparing foam because it lacks the allergen β -lactoglobulin. The foaming properties of CM and its proteins are comparable to those of cow milk under various temperature and pH conditions (Laleye et al., 2008).

The foamability and foam stability of camel sweet whey proteins (separated from rennet gels by centrifugation) at pH 7.0 were only slightly inferior to those of bovine sweet whey proteins (Laleye et al., 2008). However, after heat treatments were applied at 70 °C and 90°C, camel acid whey proteins (obtained after acidification of fresh CM until pH 4.3, followed by centrifugation) exhibited much higher foamability and foam stability than their bovine counterparts (Lajnaf et al., 2018). At pH < 5.0, camel α -lactalbumins lose their bound Ca^{2+} and exist in a molten globular state with high surface activity providing

better adsorption at the interface and higher intermolecular interactions to form a viscoelastic film (Lam & Nickerson, 2015). Camel α -lactalbumin accounts for a high proportion (> 70%) in acid whey proteins, thus acid whey proteins exhibited good foaming behaviour. In pure form, β -casein exhibited the higher foaming properties compared to α -lactalbumin (Lajnaf et al., 2017). Heat treatment of CM (70–100°C/30 min) also improved the foaming properties due to heat denaturation and aggregation of CM proteins, which led to an increase in surface hydrophobicity and a decrease in electronegative charge and interfacial tension. Also, changes in secondary structure and its high hydrophobicity induced by heating are other reasons for the improved foaming properties of CM proteins (Lajnaf et al., 2020). These findings will be beneficial to dairy processors, as they are helpful for evaluating the potential for commercial use of CM foam in cappuccino-style beverages.

5.3. Powder

The production of dried CM powder without impairing its bioactive components has emerged as an important approach to making CM available worldwide and extending its shelf life, reducing the transportation costs and expanding the applications of CM. Many CM powder products, some of which are non-branded, are available on the market. Most are produced using a freeze drying technique because the low drying temperature in freeze drying helps to protect the bioactive compounds in CM, especially the functional properties of its proteins. Freeze drying CM reportedly does not induce any significant alterations to nutritional properties (*e.g.* minerals, vitamins, amino acid composition, biological value, protein efficiency ratio, net protein utilization, and fatty acid profile) compared with those of fresh CM (Ibrahim & Khalifa, 2015). Other physicochemical properties, such as the colour, flowability, density, and composition of CM and cow milk powders did not differ when produced under similar freeze drying conditions and were

similar to those of commercial cow milk powders, except for CM powder insolubility, which was twice as high as cow milk powder (Sulieman et al., 2018). However, freeze drying is well known as a time consuming and expensive dehydration technique, and is not suitable for large-scale production of dried milk powders (Ortega-Rivas et al., 2005). Moreover, after freeze drying, CM powder must be ground and sieved to obtain desirable homogeneity in powder particle size. The high price of CM together with the high cost of freeze drying operations leads to the extremely high cost of CM powder.

Spray drying has been considered the most suitable unit operation for producing dairy powders. However, compared with bovine milk powders, the production of CM powders using spray drying is still at an early stage of research and development. Spray drying at a low temperature ($< 60^{\circ}\text{C}$) may be applicable for CM powder production, and there are a few spray-dried CM powder products available on the market. Due to a lack of information concerning nutritional facts and differences in the chemical composition of CM from various sources, performing a comparison of the nutritional values of CM powder produced by spray drying and freeze drying is impossible. Several reports exist regarding the spray drying of CM (Habtegebriel et al., 2018a; Habtegebriel et al., 2018b; Ho et al., 2019; Ho et al., 2021; Ogolla et al., 2019; Sulieman et al., 2014; Zouari et al., 2018). These studies are dedicated to observing the influences of spray drying operating conditions (inlet air temperature, outlet air temperature, drying air flow rate, feed flow rate, feed direction, and atomisation pressure) and feed material properties (solid concentration and fat content) on the physical, optical, and thermal properties of produced CM powders (yield, bulk density, colour, solubility, particle morphology, glass transition temperature, water activity, vitamin C recovery, fatty acid profile). Generally, spray drying CM with the concurrent flow direction yielded better results on CM powder quality in terms of water activity, degree of lightness, solubility, fluidity, and powder yield

(Sulieman et al., 2014). Moreover, the yield of spray-dried CM powder was also determined by inlet air-drying temperature, feed flow rate, and solid feed content. The yield increased with increasing inlet air-drying temperature and feed flow rate but declined with increasing solid content in the feed (Habtegebriel et al., 2018a; Habtegebriel et al., 2018b).

Spray drying CM at a higher temperature, higher feed flow rate, and with a high fat content declined the reconstitution properties of the powder (wettability, dispersibility, and solubility) (Habtegebriel et al., 2018a; Ogolla et al., 2019). Fresh CM powder produced by spray drying at 160 and 70°C of inlet and outlet air-drying temperature, respectively, had a very high solubility ($98.62 \pm 1.47\%$), and this solubility just slightly reduced during accelerated storage at 37°C and low relative humidity levels ($< 33\%$) over 18 weeks (Ho et al., 2019). During storage, increasing surface lipid content leading to the increase in surface hydrophobicity and slight agglomeration of the powder particles is the main cause for the decline of the CM powder solubility with increasing storage time and increasing RH (Ho et al., 2021). High solubility of spray-dried CM powder allows many applications in food processing, as rehydration is a prerequisite for the incorporation of milk powder in food products. Spray-dried CM powder has been investigated as a new functional source for replacing the cheese base in the manufacture of processed cheese sauces. An addition of 10% spray-dried CM powder significantly improved the quality attributes, especially the sensory properties of cheese sauces (Desouky et al., 2019).

In terms of particle morphology, spray-dried CM powders had a smooth surface covered with fat layers and no crystalline structure (Habtegebriel et al., 2018a; Ho et al., 2019a; Ogolla et al., 2019). Zouari et al. (2020a) found that the surface roughness of spray-dried CM was much lower than that of its bovine milk counterparts, and most of the CM fat globules were encapsulated by the proteins near the powder surface during droplet

formation. However, in a study by Ho et al. (2021), results of X-ray photoelectron spectroscopic analysis indicated that the surface of the fresh spray-dried camel milk powders was dominated by lipids (~78%), followed by proteins (~16%) and lactose (~6%). Increasing the surface lipid content during storage (*e.g.* 33% RH for 18 weeks) caused the agglomeration of powder particles which had wrinkled and folded surface with some dents and large vacuoles containing small, dried milk particles (Figure 2a and 2b). In addition, X-ray diffraction analysis of fresh spray-dried CM powders revealed some degree of crystallinity in the powders as some small sharp peaks were observed in their X-ray diffractogram (Figure 2c) (Ho et al., 2019). Analyses of the biochemical properties of spray-dried CM revealed that the α - and β -caseins were very stable during spray drying, while about 14% of serum albumin was denatured (Zouari et al., 2020b). Also, the whey protein nitrogen index of spray-dried CM (~11.5%) was similar to that of its bovine milk powder counterpart (~9.0%). These studies strengthen the possibility of producing CM powder via spray drying. However, further studies are required, particularly those examining the retention of bio-functionality in CM after spray drying.

There are many possible limitations for both laboratory- and factory-scale application of spray drying in CM powder production. Firstly, production of CM is limited to certain geographical locations, such as several Asian and Africa countries and Australia. Importantly, high temperature operation in the preconcentration (to increase the solids concentration of CM) and spray drying stages possibly will denature the nutritional and functional proteins in CM (Lajnaf et al., 2018). Due to the low solid concentration (~10%, w/w), it is not economical to perform spray drying of CM “as such”. In the production of milk powder, a preconcentration of milk to increase its solid concentration up to 40–50% (w/w) is an integral stage not only to reduce the energy consumption of the drying process, but also to help impart desirable characteristics to the dried powders (Roy et al., 2017).

Recent advancements in the concentration and spray drying techniques possibly allow the preconcentration and spray drying of CM powder at low temperatures.

5.4. Ice cream

Ice cream is a sweetened frozen product that is globally one of the most popular dairy desserts. It is typically produced from cow milk fortified with various ingredients. Due to the superior properties of CM to cow milk, the consumption of ice cream made from CM may be preferable to the cow milk product. Camel milk ice cream combines the benefits of both ice cream and CM to fulfil the requirements of the functional food (*e.g.* low-fat ice cream). Varieties of such products are currently available in the market. Basically, the production of CM ice cream is similar to that of cow milk counterpart, including the blending of ingredients, pasteurisation, homogenisation, cooling, aging ($\sim 4^{\circ}\text{C}$), freezing via a scraped surface freezer (-5°C) (or similar) under shear to incorporate air to form a foamed structure, adding flavouring ingredients (if applicable), packing, and blast freezing to temperatures of -25 to -30°C (Goff & Hartel, 2013). Camel milk ice cream has a lower melting point, lower dry matter content, and lower viscosity than cow milk ice cream when made with the same formulation. This is due to differences in the dry matter in CM and cow milk (10.02 and 12.30%, respectively). However, they are similar in fat and protein content, acidity, and sensory properties in terms of colour, flavour, texture, and mouthfeel (Jafarpour, 2017). Insignificant differences in consumer acceptance (texture, taste, flavour, and colour) were also reported for camel and cow ice cream (Hassan, 2009). Recent studies indicated that ice cream can be successfully processed from CM using various additives and flavourings to enrich the nutritional and health benefits, and to provide pleasant flavours to consumers (Ahmed & Zubeir, 2015; Salem et al., 2017). Fortifying CM ice cream with 2% CM casein and its hydrolysates increased its viscosity, consistency, and melting resistance, decreased its hardness and overrun, and

enhanced its sensory properties (Hajian et al., 2020). The excellent surface-active properties of camel caseins in the formulations of low-fat creams and emulsions were also reported (Ziaieifar et al., 2020).

5.5. Butter

Although CM fat content is quite similar to that of bovine milk (~ 2.30–3.95%), butter production from CM is very difficult, and the butter-making process from cow milk cannot be applied to CM due to differences in the physical and chemical nature of their fats and proteins. Certain authors, therefore, claimed that butter cannot be made from CM (Yagil et al., 1994). Camel milk shows little tendency to creaming because of its lack of agglutinin (a protein promoting the clustering of fat globules) together with a small fat globule size and strong bonding of fat and proteins. In addition, the high melting temperature of CM fat, which is caused by the high proportion of long-chain fatty acids in the fatty acid profile and thicker fat globular membrane, makes the churning process of CM cream only accomplishable at higher temperatures than those commonly used for bovine milk (10–14°C) (Asresie et al., 2013; Berhe et al., 2017; Farah & Fischer, 2004; Fuquay et al., 2011).

In fact, nomads in Sudan, Kenya, Egypt, Algeria, and Pakistan manually produced CM butter approximately 2 or 3 decades ago using fresh, soured or fermented CM, and CM cream. However, these manual processes were unable to obtain high yields of butter (El-Agamy, 2006). Actually, controlled processes of CM butter making with improved butter yields were developed within the last two decades (Farah et al., 1989), as shown in Figure 3. In this process, CM was initially heated to 65°C and centrifuged to separate the cream. After standardisation to 20–30% fat content, the cream was optionally inoculated with a 2% starter, to produce either a sour or sweet cream. Both sour and sweet creams were churned at 15–36°C and the butter grains were washed in water at 27°C. Results indicated

that at the same fat content and churning temperature, the butter yield obtained from sour cream was markedly lower than that achieved from sweet cream. For sweet cream, highest butter yields (80–85.3%) are obtainable with cream at 20–25% fat content and churning temperatures of 15–20°C, corresponding to a churning time of 10–18 min. In addition, no butter grains were obtained at a low churning temperature (< 12°C), while the butter yield significantly declined as cream was churned at a temperature higher than 36°C. Berhe et al. (2013) reported on another procedure to increase the butter yield from fermented CM (Figure 3). Camel milk fermented at room temperature until pH 4.10 was subjected to vigorous churning in a vertical direction at 22–23°C, rather than the back-and-for movement used in the traditional method. This method resulted in a high butter yield (~80%) due to the high churning force but very long churning time (~ 120 min). Although producing butter from CM is possible from a scientific viewpoint, competing with cow milk butter requires extensive further studies to address the limitations in the churning process and butter yield.

In terms of butter quality, CM butter is characterised with a white colour, stickiness, greasiness, high melting point, low content of short-chain fatty acids, and less flavour intensity. Camel milk butter is not only used as food for eating, as oil for food preparation and cooking, but also for medicinal purposes due to the probiotic characteristics of microflora used in traditional CM butter making (Ipsen, 2017; Muraad & Meriem, 2008; Muraad & Nour-Eddine, 2006).

5.6. Cheese

Producing cheese from CM is more difficult and complicated than from other mammalian milks (cow, buffalo, sheep, and goat) because of the long coagulation time, low yield, and weak coagulum (Ramet, 2001). Cheese firmness is determined by the ratio of kappa-casein to total caseins. The higher this ratio results in the firmer the cheese. However, this

ratio is about 3.5% in CM, which is much lower than in bovine milk (~13%) and buffalo milk (13–20%). In addition, camel kappa-casein has completely different cleavage sites for hydrolysis compared with its bovine counterpart. Chymosin cleavage sites of camel kappa-casein are at the Phe⁹⁷-Ile⁹⁸ amino acid sequence sites, while those of bovine milk are at Phe¹⁰⁵-Met¹⁰⁶. All these characteristics, together with high resistance of CM to bacterial growth due to its high content of antibacterial compounds, result in delaying the coagulation of CM and the production of soft coagulum. The large size of casein micelles is another feature of CM associated with its poor rennetability. Camel casein micelles are approximately 380 nm in size, nearly double to that of bovine milk casein micelles (150 nm) (Berhe et al., 2017; El-Agamy, 2006). Despite these limitations of CM, numerous efforts have been made to produce various types of CM cheeses, and they are summarised in Table 3. Details about production of CM cheeses at household scale by nomads are reviewed by El-Agamy (2006). Recently, Konuspayeva (2020a) well described challenges in the production of CM cheeses regarding technological development, cultural satisfaction, and commercialisation.

A simple approach to producing CM cheese is to use a mixture of CM and other non-bovine milks, such as buffalo milk, to increase casein content. Soft unripened buffalo milk cheese had a higher yield (12.22% for buffalo milk vs. 5.49–7.68% for CM) and was superior in sensory and physical properties than its CM counterpart under the same processing conditions (Inayat et al., 2007). Therefore, mixing 30% (w/w) buffalo milk with CM improved the rennetability and firmness of curds, increased the yield, decreased weight loss during pickling, and enhanced the microbiological quality and sensory properties of the resultant cheese (Shahein et al., 2014). For similar reasons, mixing sheep milk with CM for the production of soft cheese has also been reported (Saadi et al., 2020). Soft cheese is the most popular CM cheese. Several procedures are used to produce CM

soft cheese using various coagulation agents. Mohamed et al. (2013) found that fresh soft cheese with acceptable sensory properties could be simply prepared from CM via coagulation by direct acidification (60% acid acetic, pH 4.3). However, in a recent study by Mbye et al. (2020), the use of acetic acid (30% acid per liter of milk) as a coagulant in the production of soft unripened camel cheeses was reported to cause a pungent odor and sour taste of the product. In addition, Mehaia (1993) claimed that making CM cheese without using starter cultures was not encouraged, as this resulted in high moisture and pH, low yield, and poor sensory properties of the cheese. Ahmed and Kanwal (2004) also stated that using starter cultures (*S. cremoris* and *S. lactis*, isolated from CM) provided higher-quality CM soft cheese. Abu-Tarboush (1996) recommended using mixed cultures (*S. thermophilus* and *L. delbrueckii* ssp. *bulgaricus*) to archive desirable properties when producing CM cheese and yoghurt. These studies indicate the importance of starter cultures in CM cheese making. Different starter cultures were found to have various effects on the physicochemical and texture properties, and on consumer's preferences of the product. Non-aromatic cultures, such as STI-12, RST-743, and R-707, result in better curd firmness, cheese yield, cheese compositional quality, and texture, while aromatic cultures, such as XPL-2 and CHN-22, impart higher consumer preference for taste and aroma (Bekele et al., 2019).

The quality of CM soft cheese is dependent on many factors, ranging from processing conditions to the types of coagulants used. Studies concerning CM cheese making have, therefore, focused on optimising these factors. By varying heat treatments, pH, CaCl₂ content, and buffalo milk ratios, Qadeer et al. (2015) reported that optimal processing conditions for producing soft CM cheese at high yields (~22%), with short coagulation times (~30 min) and good texture included heating at 65°C for 30 min, pH 5.5, 0.06% CaCl₂, and 10% buffalo milk. In addition, CM soft cheese quality was also determined

according to lactation stage (Konuspayeva et al., 2014) and bovine chymosin (Chy-Max™) concentration (Benkerroum et al., 2011), with corresponding optimal conditions being 25 days postpartum and 1020 IMCU chymosin/L of milk.

Camel chymosin is not easily affordable as a coagulant in CM cheese making, especially for households and small-scale processors, due to its high cost and limited availability. Thus, alternative coagulants with cheaper prices and from easily accessible sources are encouraged. Using ginger crude extract to coagulate CM for cheese production is one alternative, due to the proteolytic activity of the protease enzymes in the extract, although the yield and quality of CM cheese produced from ginger crude extract are lower than those made from camel chymosin (Hailu et al., 2014). Organic acids were also effective coagulants for producing CM cheese. Mbye et al. (2020) reported that soft unripened cheeses prepared from citric acid (30% acid per litter of milk) had a higher yield and better sensory attributes than those prepared from camel chymosin.

Brined cheeses with salty, sour, and firm sensory descriptors are other types of cheese that can be successfully produced from CM (Hailu et al., 2018; Konuspayeva et al., 2017). After drainage, the curds are ripened in NaCl solution for several months to induce the development of flavour compounds in the cheese.

5.7. Yoghurt

Similar to CM cheese, manufacturing CM yoghurt is quite difficult due to the poor coagulation ability of CM, which results in thin consistency and weak product structure (Berhe et al., 2017). Texture is the most important attribute determining the appearance, mouthfeel, and overall consumer acceptability of yoghurt. However, the traditional approach to producing cow milk yoghurt is inapplicable to CM. Camel milk fermentation via starter cultures (*S. thermophilus* and *L. delbruckii* subsp. *bulgaricus*, 2.5%) and incubation at 37°C up to 16–18 h did not form a desirable curd structure, but instead lead

to fragile and heterogeneous dispersed flakes with watery texture (Zubeir et al., 2012). Most attempts to make CM yoghurt have extensively concentrated on increasing firmness and preventing syneresis of the product during processing and storage. Similar to producing CM cheese, mixing CM with other mammal milks, such as sheep milk (Ibrahim & Zubeir, 2016), buffalo milk (Khalifa and Zakaria, 2019), and bovine milk (Kamal-Eldin et al., 2020), is a simple approach to making CM yoghurt. However, mixing CM with other milk types reduces its inherent functionality, values, and properties, and therefore using single stabiliser and hydrocolloid or their combinations has been investigated to improve the consistency of CM yoghurt (Table 4). Al-Zoreky and Al-Otaibi (2015) reported that CM yoghurt containing 0.6% carboxymethyl cellulose, gum acacia, or alginate with 0.06% CaCl_2 had a thin and soft texture (semi-liquid). Adding either 2.5% bovine non-fat dry milk or 0.08% Na_2EDTA did not result in a proper coagulum of CM yoghurt. In particular, the use of 0.6% of either pectin or carboxymethyl cellulose led to an unacceptable taste and flavour of the product. Similarly, Hashim et al. (2009) reported that carboxymethyl cellulose at concentrations of 0.5–1.0% had no effect on the texture of CM yoghurt. Kavas (2016) also reported an inability to produce yoghurt from CM added with bovine whey protein isolate (3%), samphire molasses (3%), and κ -carrageenan (0.1%). The interaction between κ -carrageenan and bovine whey protein isolate resulted in unacceptable properties (physiochemical, rheological, microbiological, and sensory) of yoghurt. However, these properties were significantly improved and highly accepted when κ -carrageenan was replaced by xanthan gum (0.5%) under the same processing conditions. Likewise, Mohsin et al. (2019) reported that adding 0.75% of biosynthesized xanthan from orange peels to CM date yoghurt markedly improved the texture, firmness, and sensory attributes of the product. Added biosynthesised xanthan resulted in homogenous and compact microstructure with a dense network of casein

micelles.

Hashim et al. (2009) reported that the addition of either alginate or gelatin (0.5–1.0%) in combination with CaCl_2 (0.05–0.1%) markedly improved the texture of CM yoghurt. Consumer testing indicated that CM yoghurt containing 0.75% alginate and 0.075% CaCl_2 had sensory properties and acceptability similar to that of cow milk yoghurt. Also, this formulation was successfully applied to CM yoghurt flavoured with various fruits. Similarly, Mudgil et al. (2018) reported that using gelatin at concentrations of 0.75–1.0% improved the texture, rheological properties, and appearance of CM yoghurt, and made them comparable to those of their commercial and cow milk counterparts. However, the sensory properties of CM yoghurt, taste and flavour in particular, were only mildly acceptable compared with cow milk yoghurt. Studying arabic gum (1–2%), Jasim et al. (2018) found that adding it led to increased viscosity, decreased syneresis, and enhanced texture and appearance, but high concentrations (~2%) of arabic gum led to an off-taste in CM yoghurt. Another formulation to produce maple strawberry syrup-flavoured CM yoghurt with acceptable quality was also reported by Galeboe et al. (2018) using 1.2% gelatin, 5.0% bovine skim milk powder, 0.15% CaCl_2 , 4.0% maple strawberry syrup, and 6% yoghurt culture (YF-L811), and by incubating the milk at 42°C for 18 h.

Moreover, modified starch (E1422) at appropriate concentrations (e.g. 3%) was found to reduce syneresis, increase the water holding capacity, and improve chemical, sensory, and microstructural properties, with high overall acceptability of the product (Khalifa & Ibrahim, 2015). However, using a mixture of this modified starch (E1422) and mono- and diglycerides at a 1:1 ratio (0.5–1.5%, w/w) for CM yoghurt production was not preferred due to the ropy structure of the product, resulting in low sensory acceptance. Poor structure of CM yoghurt was also reported for the mixture of guar gum, sodium carboxymethyl cellulose, and mono- and diglycerides at a ratio of 1:1:1. Nevertheless, at

a concentration of 1.5% (w/w), the mixture of a 1:1 ratio of gelatin and mono- and diglycerides significantly stabilised the texture without affecting product flavour (Ibrahim & Khalifa, 2015).

Polymerised bovine whey protein is another stabiliser that has been investigated for use in CM yoghurt, and it was obtained through the heat treatment of whey protein solution (10%, pH 7) at 85°C for 30 min (Sakandar et al., 2014). At a concentration of 8.0%, polymerised whey protein gave CM yoghurt desired characteristics in terms of texture and sensory properties. Furthermore, to enhance the therapeutical values of CM yoghurt, several studies have investigated the addition of various herbal water extracts (Shori, 2013; Shori, 2013; Shori & Baba, 2012, 2014) and oat β -glucan (Ladjevardi et al., 2016). The aforementioned studies show that, although the production of CM yoghurt is achievable with desirable attributes for some formulation of stabilisers and hydrocolloids, utilising the products available on the market and acceptable by consumers is still complicated and requires further investigation. Rather than focusing on only choosing stabilisers and hydrocolloids, combining them with the alteration of CM properties, such as a reduction in fat global size (homogenization and microfluidization) and partially denaturising the proteins in CM (heat treatment) possibly warrant subsequent studies.

6. Conclusion

This review discussed the compositions, bioactive components, and functionalities of CM compared with bovine milk. High nutritional value, together with a lack of allergy-inducing β -lactoglobulin and a high content of β -casein, enables CM to be used as a daily drink for human consumption like bovine milk or to be converted into powder that can be incorporated into infant formula. However, preserving the functionalities of the bioactive components in CM during heat treatment or other processes is very challenging for food processors. In addition, CM shows little tendency to coagulate primarily because of a lack

of kappa-casein and β -lactoglobulin interactions, which causes many difficulties in the production of cheese, butter, and yoghurt from CM. Deficiency of agglutinin (a protein promoting the clustering of fat globules), small fat globule size and strong fat and protein bonding are other hurdles in CM butter production. Despite the difficulties in processing CM, studying and developing food products from CM remains an interesting topic, and several CM food products are being investigated and some are commercially available such as pasteurised CM, CM powder, cheese, butter, and yoghurt. However, improving the quality of these products to make their properties at least similar to their bovine milk counterparts requires further extensive investigation.

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Author contribution

All authors contributed to planning the contents of the manuscript. **Thao Ho:** Conceptualization, methodology, writing – original draft, writing – review & editing, visualization. **Zhengzheng Zou:** Conceptualization, methodology, writing – original draft, writing – review & editing, visualization. **Nidhi Bansal:** Conceptualization, methodology, writing – review & editing, supervision.

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1241 high-throughput fluorescent method for determination of oxidase activities in
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1 **Figure captions**

2 **Figure 1:** Particle size distribution of raw camel and cow milk (Ho et al., 2021).

3 **Figure 2:** SEM of fresh spray-dried camel milk powder (a) and the powder kept at 33%
4 RH for 18 weeks (b); and XRD of fresh spray-dried camel milk powder (c).
5 Adapted with permission from Ho et al. (2019).

6 **Figure 3:** Process for making butter from camel milk.

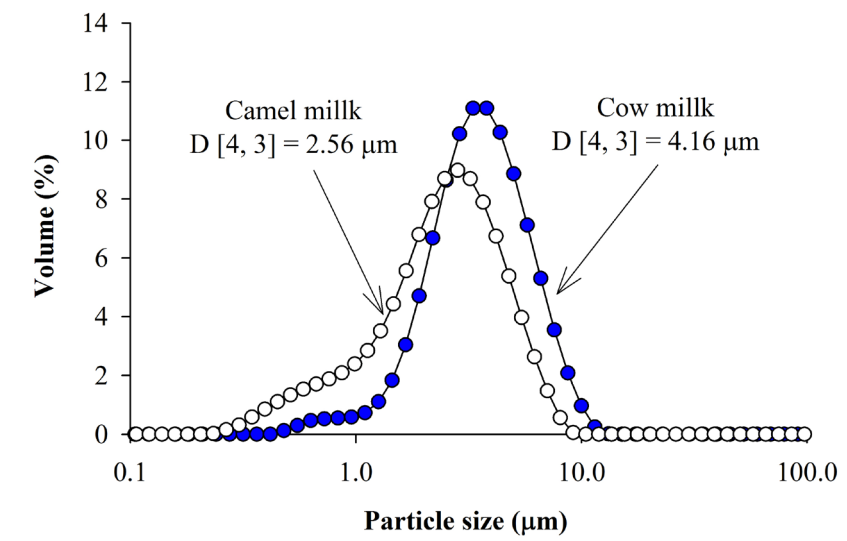
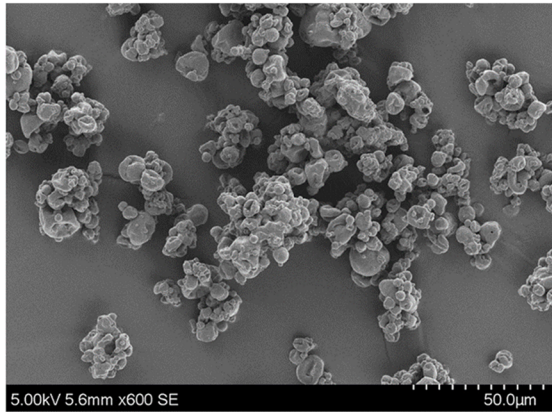
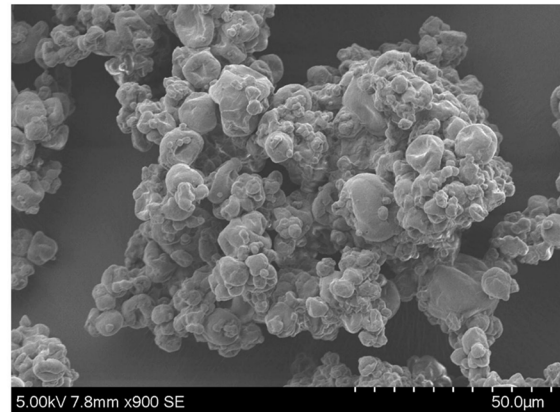


Figure 1: Particle size distribution of raw camel and cow milk (Ho et al., 2021).

(a): SEM of fresh powder



(b): SEM of powder - 33% RH & 18 weeks



(c): XRD of fresh powder

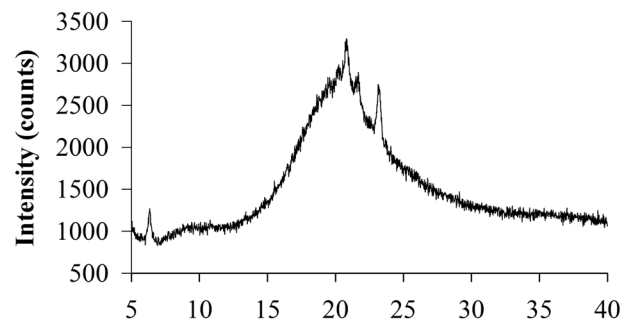


Figure 2: SEM of fresh spray-dried camel milk powder (a) and the powder kept at 33% RH for 18 weeks (b); and XRD of fresh spray-dried camel milk powder (c). Adapted with permission from Ho et al. (2019).

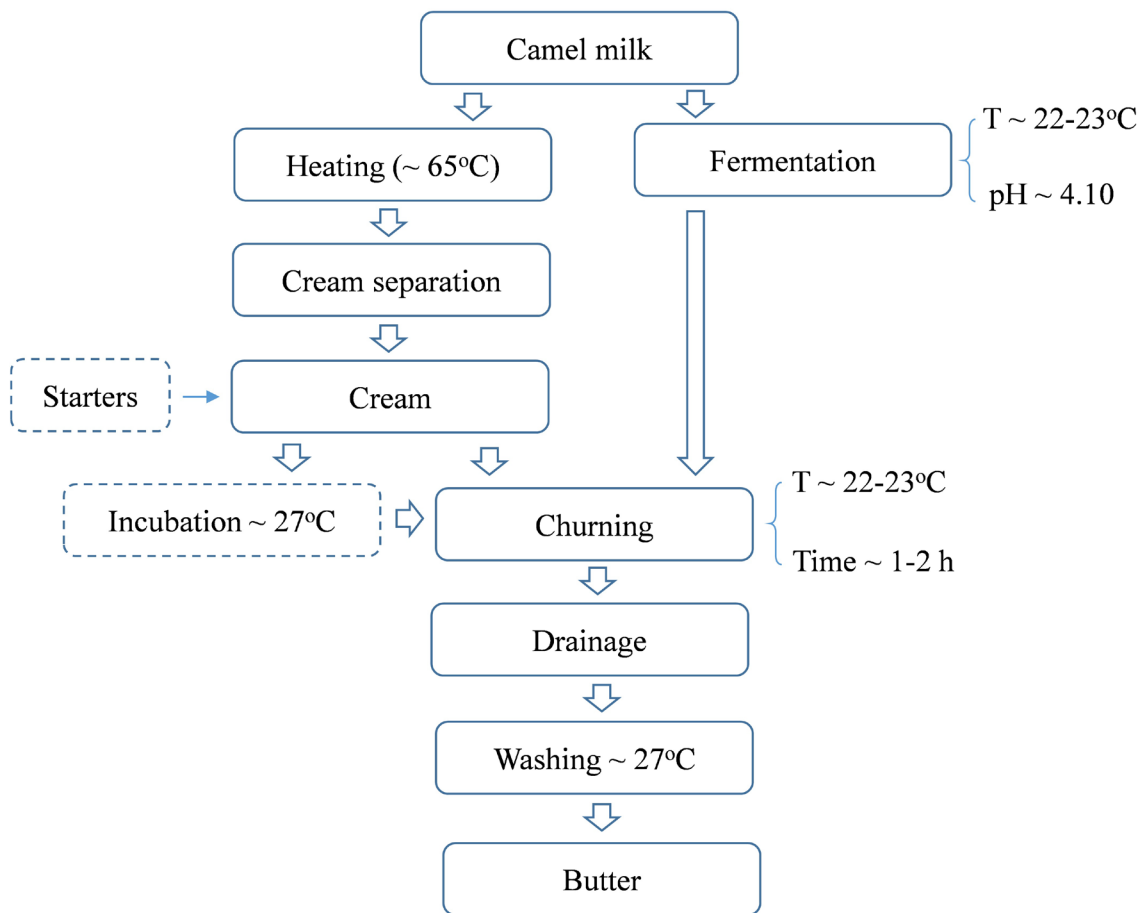


Figure 3: Process for making butter from camel milk.

1 **Table captions**

2 **Table 1:** Composition of camel, bovine and human milk.

3 **Table 2:** Physico-chemical properties and bioactivities of bioactive proteins in camel
4 milk.

5 **Table 3:** A summary of the research studies regarding camel milk cheese, with
6 emphasis on cheese types and processing conditions.

7 **Table 4:** A summary of studies concerning camel milk yoghurt using different stabilizers.

8 **Table 1:** Composition of camel, bovine and human milk.

Milk type	Composition (% w/v)			
	Protein	Fat	Lactose	Ash
Camel milk				
- East Africa	3.33 ± 0.52	4.14 ± 0.80	4.18 ± 0.72	0.76± 0.09
- North Africa	3.21 ± 0.60	3.50 ± 1.01	4.65 ± 0.67	0.84± 0.08
- Indian subcontinent	3.36 ± 0.64	3.49 ± 0.85	4.45 ± 0.74	0.77± 0.07
- Western Asia	3.10 ± 0.62	3.31 ± 1.03	4.45 ± 0.40	0.78± 0.05
- Undetermined	3.34 ± 0.53	3.62 ± 0.81	4.49 ± 0.77	0.72 ± 0.07
Bovine milk	3.20–3.80	3.70–4.40	4.80–4.90	0.70–0.80
Human milk	1.10–1.30	3.30–4.70	6.80–6.90	0.20–0.30

9

10 **Table 2:** Physico-chemical properties and bioactivities of bioactive proteins in camel
 11 milk.

Bioactive protein	Accession No. or NCBI reference No.	Molecular mass (kDa)	pI	Amino acid residues	Bioactivities
<i>Lactoferrin</i>	Q9TUM0	75.3	8.63	689	Immunomodulation; Antibacterial activity; Antiviral activity
<i>Immunoglobulins</i>					
IgAs_light and heavy chains	n.d.*	22.5 and 55.5	n.d.	n.d.	
IgMs_light and heavy chains	n.d.	27.0 and 80.0	n.d.	n.d.	Maternal immunity transfer;
IgGs1_light and heavy chains	n.d.	30.0 and 50.0	n.d.	n.d.	Toxin-neutralizing activity; Enzyme antigen inhibitor
Heavy-chain IgGs2	n.d.	46.0	n.d.	n.d.	
Heavy-chain IgGs3	n.d.	43.0	n.d.	n.d.	
<i>GlyCAM-1</i>					
Variant A	P15522	15.4	5.2	137	Antibacterial activity; Mastitis prevention
Variant B	P15522	13.7	5.93	122	
<i>PGRP-1</i>	Q9GK12	19.1	9.02	172	Antibacterial activity; Microbiome modulator; Anti-inflammatory activity
<i>Lactoperoxidase</i>	NP_001290481	69.7	8.87	613	Antibacterial activity
<i>Lysozyme</i>	XP_010984684	14.9	6.33	130	Antibacterial activity
<i>WAP</i>	P09837	12.6	4.86	117	Antibacterial activity; Anticancer activity; Protease inhibitor

12 * not determined.

13 Source: Elagamy et al. (1996; Hamers-Casterman et al. (1993); Mati et al. (2017).

14 **Table 3:** A summary of the research studies regarding camel milk cheese, with emphasis
 15 on cheese types and processing conditions.

Type of cheese	Processing conditions	References
Fresh soft cheese	- Heating at 63°C, 30 min - Acidification with 60% acid acetic, pH = 4.3 - CaCl₂, 3-4%	Mohamed et al. (2013)
Soft unripened cheese	- Heating at 65°C, 30 min - CaCl₂, 0.15% - Yogurt starter culture, <i>S. thermophilus</i>, 3% - Ginger crude extract	Hailu et al. (2014)
	- Heating at 65°C, 30 min - CaCl₂, 3.0% - Chymosin (1000 IMCU/ML milk), or citric or acetic acid (30% acid/L milk) - Thermophilic yoghurt starter culture (<i>Streptococcus thermophilus</i> and <i>Lactobacillus delbrueckii subsp. bulgaricus</i>), 3% (w/v)	Mbye et al., (2020)
Fresh soft white cheese	- Milk fat, 0–3% - Salt, 0–3% - CaCl₂, 0.03% (w/v) - Yogurt B-6 starter (<i>S. thermophilus</i> and <i>L. delbrueckii subsp. bulgaricus</i>), 1.0% (w/w) - Lactic fermentation starter (<i>L. lactis ssp. cremoris</i>, <i>L. lactis ssp. lactis</i>, and <i>L. lactis ssp. diacetylactis</i>), 1.0% (w/w) - Rennet, 0.004% (w/w)	Mehaia (1993)
Fresh cheese	- Camel milk isolated LAB (<i>S. cremoris</i> and <i>S. lactis</i> in a ratio of 95:5): 5.0% (w/v) - Rennet, 0.03% (w/v)	Ahmed and Kanwal (2004)
	- CaCl₂, 0.03% - Camifloc**	El Zubeir and Jabreel (2008)
Soft cheese	- CaCl₂ 0.02% (w/v) - Yogurt starter cultures (<i>S. thermophilus</i> and <i>L. delbrueckii subsp. bulgaricus</i>), 3.0% (w/v)	Benkerroum et al. (2011)

	- Chymosin Chy-Max TM , 0.15–15% (v/v)	
	- CaCl ₂ , 0.1 mL/kg or Ca phosphate, 1 g/kg	Konuspayeva et al. (2014)
	- Rennet Chy-Max M, 50 µL/L	
	- CaCl ₂ , 0.02–0.08%	Qadeer et al. (2015)
	- Pasteurization conditions, 60–75°C/30 min	
	- pH 5.5–6.5	
Fresh soft white cheese	- Camel milk retentate	
	- CaCl ₂ 0.02% (w/w)	Mehaia (2006)
	- Salt, 1.05% (w/w)	
	- Yoghurt starter cultures (B-6), 0.5% (w/w)	
	- Rennet**	
	- CaCl ₂ 0.05% (w/v)	
	- 10% citric acid solution, pH = 5.5 or starter culture, 5%	Khan et al. (2004)
	- Rennet, 0.15 mL/L	
Soft white cheese	- CaCl ₂ , 0.02 g/L	
	- Starter culture (STI-12, RST-743, R-707, XPL-2, CHN-22), 50U/500 mL	Bekele et al. (2019)
	- Camel chymosin, 85 IMCU/L*	
Dry-salted soft cheese	- Starter (<i>S. thermophilus</i> , CHOOZIT star24 TM), 3.0%	
	- Chymosin Chy-Max M1000, 50 µL/L	
	- Salting in NaCl, 3% (w/w)	Konuspayeva et al. (2017)
Brine-salted soft cheese	- Starter (<i>S. thermophilus</i> , CHOOZIT star24 TM), 3.0%	
	- Chymosin Chy-Max M1000, 50 µL/L	
	- Salting in saturated NaCl	
Soft brined cheese	- CaCl ₂ 0.02% (w/v)	
	- Starter culture (<i>Str. thermophilus</i> STI-12), 75 U /1000 L	Hailu et al. (2018)
	- Camel chymosin Chy-Max TM , 55–85 IMCU/L*	
	- Curd brine NaCl, 2 and 5% (w/w)	

16 *IMCU: International milk clotting units; **: no data on concentration.

17 **Table 4:** A summary of studies concerning camel milk yoghurt using different stabilizers.

Type of yoghurt	Gelation agents	References
Set-type yoghurt	- Stabilizers: CMC, pectin, gum acacia and alginate, 0.6% (w/v) - Non-fat dry milk, 2.5% (w/v) - Na₂EDTA, 0.08% (w/v) - CaCl₂, 0.06% (w/v) - Yoghurt starters (<i>S. salivarius</i> ssp. <i>thermophilus</i> and <i>L. delbrueckii</i> ssp. <i>Bulgaricus</i>), 2% (v/v)	Al-Zoreky and Al-Otaibi (2015)
Set-type yoghurt Flavored yoghurt	- Milk solid non-fat, 2.5–5.0% (w/v) - Stabilizer (Grindstred ES255), 0.6–1.2% (w/v) - Yoghurt culture (Yo-Fast-88)* - Gelatin, CMC, alginate, 0.5–1.0% (w/v) - CaCl₂, 0.05–0.1% (w/v) - Flavored with various fruits	Hashim et al. (2009)
Set-type yoghurt	- Arabic gum, 0–2% (w/w) - Yoghurt starters (<i>S. salivarius</i> ssp. <i>thermophilus</i> and <i>L. delbrueckii</i> ssp. <i>Bulgaricus</i>)**	Jasim et al. (2018)
Flavored yoghurt	- Gelatin, 1.2% (w/v) - Bovine skim milk powder, 5% (w/v) - CaCl₂, 0.15% (v/v) - Maple strawberry maple syrup, 4% (v/v) - Yoghurt culture (YF-L811), 3% (v/v)	Galeboe et al. (2018)
Set-type yoghurt	- Modified starch, E1422, 1–5% - Yoghurt cultures (DVS-ABY-1 Nu-TRISH), 2%	Khalifa and Ibrahim (2015)
Set-type yoghurt	- Whey protein isolate, 3% (w/v) - Samphire molasses, 3% (w/v) - κ-carrageenan, 0.1% (w/v) - Xanthan gum, 0.05% (w/v) - Starter culture (<i>Lb. bulgaricus</i> and <i>Str. thermophilus</i>), 3% (w/v)	Kavas (2016)
Set-type yoghurt	- Gelatin, 0–1.5% - Yoghurt cultures (Yo-Flex Express 1.0), 0.2%	Mudgil et al. (2018)

Stirred yoghurt	- Polymerized whey protein isolates, 2–8% - Yogurt cultures**	Sakandar et al. (2014)
Set-type yoghurt	- Combined stabilizers: 0.5–1.5% (w/w) 1) Gelatin (E441) and mono- and diglyceride of fatty acid (E471) = 1:1 2) Guar gum (E412), sodium carboxymethyl cellulose (E466), and E471 = 1:1:1 3) Modified starch (E1422) and E471 = 1:1 - Freeze dried ABY-1 culture, 2%	Ibrahim and Khalifa (2015b)

18 **The level recommended by the dairy company (x), 1.5x, and 2x. **: no data of*
19 *concentration.*