animals

Review

Recent advances in camel milk processing

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Simple Summary: The camel milk market was limited for long time by its almost exclusive self-consumption use in nomadic camps. A significant development is observed for the past two or three decades, including internationally, boosted by its reputation on its health effects for regular consumers. Such emergence leads the stakeholders in the sector to offer diversified products corresponding to the tastes of increasingly urbanized consumers, more sensitive to "modern" products. Thus, traditionally drunk under raw or naturally fermented form, camel milk has undergone unprecedented transformations such as pasteurization, directed fermentation, cheese or yoghurt processing and manufacture of milk powder for the export market. However, the specific characteristics of this milk (composition, physical properties) mean that the technologies applied (copied from technologies used for cow milk) must be adapted. In this review, some technological innovations are presented, enabling stakeholders of the camel milk sector to satisfy the demand of manufacturers and consumers.

Abstract: Camel milk is a newcomer to domestic markets and especially to the international milk market. This recent emergence has been accompanied by a diversification of processed products, based on the technologies developed for milk from other dairy species. However, technical innovations had to be adapted to a product with specific behavior and composition. The transformation of camel milk into pasteurized milk, fermented milk, cheese, powder, or other products was supported, under the pressure of commercial development, by technological innovations made possible by a basic and applied research set. Some of these innovations regarding one of the less studied milk are presented here as well as their limitations. Technical investigations for an optimal pasteurization, development of controlled fermentation at industrial scale, control of cheese technology suitable for standardized production, improvements in processes for the supply of a high-quality milk powder are among the challenges of research regarding camel milk.

Keywords: camel; milk technology; pasteurization; cheese making; powder milk; fermentation.

1. Introduction

For long time, only fresh camel milk was self-consumed by pastoralists and was regarded as a gift for the hosts coming under the tent of the nomads. Consequently, it was not considered a commodity and its sale was often taboo. Moreover, it did not undergo any transformation, except for fermentation [1] to prolong its shelf life in desert conditions where the cold chain could not be respected. The introduction of camel milk in regular market at national or even at international level is a recent feature [2]. Such development of camel milk market was concomitant with a deepening of knowledge on its fine composition [3] and on its transformation processes allowing the marketing of a more diversified dairy products [4]. Recent findings are effectively available, allowing this important product renowned for its true or supposed "medicinal" virtues [5] to put out camel milk from marginality. Indeed, the production of camel milk at world level is experiencing a considerable annual growth exceeding 8% in the period 2009-2019 [6], testifying of the growing interest for this product.

The present paper is proposing a 'state-of-art' regarding knowledge on camel milk processing by focusing on 4 main dairy products having different success on market i.e., pasteurized milk, fermented milk, camel cheese, and camel milk powder. Other products will be rapidly evoked.

2. Pasteurized milk

2.1. Current global conditions of pasteurization of camel milk

Pasteurization of camel milk became commonly used technique in camel-countries. But still now, the conditions of pasteurization by each holder were decided often without taking in consideration the specificity of camel milk, the rules being mainly based on the standard issued from pasteurization of cow milk. Some data regarding the conditions of pasteurization of camel milk in the scientific literature were quite variables: 60^{0}C for 30 minutes [7]; 75^{0}C for 15 seconds [8]; 63^{0}C for 30 minutes [9,10]. At the same time, many private companies in UAE, Saudi Arabia, Mauritania, Kazakhstan, Algeria, Tunisia, Morocco, Niger are producing and selling pasteurized camel milk on local market. All those companies applied different conditions for pasteurization. It is important to mention that national/regional/international standards are still not elaborated for camel milk or written just as "copy-paste" from cow milk. In some camel countries, no standard is proposed by government or, at minimum, it is suggested to apply the same conditions than for bovine milk.

2.2. Indicators of camel milk pasteurization

The question of pasteurization's procedure for camel milk should have its own conditions and indicators. Indeed, a preliminary study showed that alkaline phosphatase (ALP), traditionally used for cow milk [11], was not a convenient indicator of successful pasteurization of camel milk, because camel ALP is heat resistant showing still activity at 90^{0}C [12]. The heat resistance of camel ALP was later reported by [13]. Loiseau et al., [12] suggested to use glutamyltranspeptidase (75^{0}C for 30 seconds) or leucine arylamidase (75^{0}C for 28 seconds or 80^{0}C for 7 seconds) as indicator of pasteurization for camel milk. If camel milk must be pasteurized at 72^{0}C for 20 min, the most appropriate indicator could be gamma-glutamyl transferase (GGT) also according to Wernery et al. [13]. But later, in 2011 other results were published. Thus, Lorenzen, et al. [14] concluded that GGT was still present in pasteurized camel milk, and probably lactoperoxidase (LPO) could be a more appropriate indicator of pasteurization. Tayefi-Nasrabadi et al. [14] confirmed that camel LPO was less heat resistant than bovine LPO. Until now, not sufficiently in-depth studies were done in this field although pasteurized camel milk was introduced in

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international market. Such doubts on the convenient indicator of pasteurization of camel milk are a constraint for the establishment of an international standard. Probably, the pasteurization of camel milk at industrial scale is achieved in wrong way and its heat treatment maybe incorrect.

2.3. *Impact of pasteurization on physical properties of camel milk*

The characteristics of camel milk flow in pipes during pasteurization process, the cleaning procedures, the conditions of transfer and of pumping need to be studied also. The behavior of fat globule and of casein micelle in camel milk is different from cow milk, giving absolute viscosity 1.72 mPa*s at 20^{0}C, vs 2.04 mPa*s at same temperature in bovine milk. Thus, in dairy plant, the camel milk should be transferred not necessary at 20^{0}C. According to Kherouatou et al. [16], camel milk in fresh condition (without acidification) can resist to some mechanical strains without changing microstructure of starting milk. Apparent viscosity was quite stable (between 1.6 – 2.0 mPa*s) at pH value between 5.2 and 6.7. That is why camel milk can be manipulated in dairy plant as pumping, agitation, skimming, homogenization and bottling for producing pasteurized product.

Few studies were focused on the sensory characteristics of heat-treated camel milk. Comparing 3 treatment (63°C for 30 min, 72°C for 15 sec and 100.5°C for 10 min), Lund, et al. [17] observed lower taste score, texture, overall acceptability in treated samples of camel milk compared to control (non-treated), but surprisingly there was no significant difference between pasteurization's protocol although the milk 63°C/30 min had the highest mean sensory score. However, these authors did not check the hygienic level of their samples. Indeed, to compare the different protocols, it is important to cross the data regarding pasteurization conditions and sensory characteristics with the hygienic level of the raw milk.

Some studies regarding behavior during heat treatment observed that camel milk could give an important amount of dry deposit on stillness steel plate during pasteurization process from 60 to 90^{0}C for 1h or 2h [18]. This study showed that such deposit is probably not protein origin, because free thiol groups are in lower quantity than for cow milk treatment. Similar design of experiment with camel whey protein showed that after 63^{0}C, whey proteins started to be denaturated; especially at 98^{0}C, a strong degradation was observed [19]. By the way, probably camel milk is producing higher quantity of "milk stones", the deposit of milk residues accumulated in insufficiently cleansed dairy equipment where bacteria can be multiplied, contributing to bad flavors in milk. At our knowledge, there was no available data in the literature regarding this aspect.

2.4. *Camel milk protein's behavior on heat treatment*

In-depth studies on the camel milk started relatively recently, especially on its technological properties. Even if some data on camel milk composition date from 1905 [20], research regarding heat treatment impact on camel milk components started to be implemented at the end of the 80ties only. Thus, in a first trial, camel milk was heated at 63, 80, 90^{0}C for 30 minutes. The rate of heat denaturation of whey proteins was twofold lower than for cow whey proteins [21]. After this study, another trial was focused on heat coagulation at 100-130^{0}C with pH range between 6.3-7.1. Only 100^{0}C variant showed relative stability at pH 7, comparable to cow milk [22].

Because milk stability during heat treatment is the most important point and because the size of casein micelles could impact the milk preservation under homogenous solution, camel milk micelles size was measured before and after pasteurization. They are broader than that of cow and human milk. However, an important point must be kept in mind: those samples were analyzed 36 hours after sampling [23]. Regarding the mineralization and citrate quantity in camel casein micelles, the proportions were significantly different than cow caseins micelles after pasteurization. It was observed that at pH 5, significant changes occurred in the structure from milk to coagulum [24].

Some studies [9, 25] stated that pasteurization of camel milk could change chemical composition. However, in these experimentations, microbial quality of raw camel milk was not assessed, no standardized starter culture was used, and finally, the microbial contamination risk was not taken in account. Yet, in trials where microbiological status was tested before processing, pasteurization at 63°C for 30 minutes improved bacteriological quality of camel milk without changes in the composition compared to raw camel milk [10, 26].

The observation of camel whey protein by SDS-PAGE shows that some proteins sensitively decrease after heat treatment, but in any case, less than for cows' proteins. The pattern of camel whey proteins, and globally, the composition of proteins is not the same for camel and cow milk. Thus, major proteins of whey in bovine are serum albumin (SA), α-Lactalbumin (α-La), β-Lactoglobulin (β-Lg) and for camel are SA, α-La and 3 fractions which are not reported in cow milk [21,27,28,29,30].

In a recent study [31], the effect of heat treatment according to different protocols (65°C for 30 min, 72°C for 30 sec, 75°C for 5 min, 85°C for 5 min, 90°C for 5 min) on camel whey proteins was assessed comparatively to cow milk. A lower denaturation of α-lactalbumin was observed in camel milk: after treatment at 90°C for 5 min, 67% of α-lactalbumin was un-denatured *vs* 5% only in cow milk. However, camel serum albumin (CSA) was not detected totally after treatment at 85°C for 5 min although it was less rapid than with cow serum albumin which disappeared after 75°C for 5 min [31]. Similar figures were observed in a previous paper [18].

Some authors tried to quantify the changes in the concentration of camel whey proteins during the pasteurization process. However, debatable results occurred especially because different methods were used, needing clarifications. Indeed, the quantification of the whey proteins in camel milk can be done by electrophoresis [32], radial immunodiffusion [28,33,34,35], HPLC [29], FPLC [33] and more recently by LC-MS/MS and LC-ESI.MS [30].

Heat resistance of camel milk could be revealed also by the heat coagulation time [22]. Compositional difference plays important role on heat resistance, in particularly, the absence of β-lg, the different ratio in casein complex (higher quantity of αs1-, αs2-, β-caseins and lower quantity κ-casein compared to cow milk [36]) and the presence in higher quantity of other whey proteins. Whey proteins include three proteins fractions described as common fractions of immunoglobulins (IgG1, IgG2, IgG3), α-lactalbumin, lactophorin which is closely related to the bovine proteose peptone component 3 (PP3), the innate immunity Peptido Glycan Recognition Protein (PGRP) and the Whey Acidic Protein (WAP) [37].

2.5. *Sterilized milk*

Concerning sterilization of camel milk by UHT treatment, the situation appears quite blocked. Still now there are no possibilities to produce UHT camel milk directly. All private companies are looking to find solution, but until now, there was no answer how to overcome this obstacle. Some studies for the heat resistance of whey and casein proteins, fat globule, vitamins or other compounds of camel milk were achieved and contributed to expect a technical solution [15,21,22,25,28,38,39,40].

After UHT treatment, the camel milk presents a separation on two phases. During heat treatment (at 63^0, 80^0, 90^0C for 30 minutes, 72^0C for 15 seconds), it was observed that the whey proteins were overly sensitive and start to be denatured [21,25]. To stabilize camel milk proteins after UHT treatment, different protocols as addition of chemicals (sodium hydroxide, calcium chloride, κ-CN from cow, sodium dihydrogen phosphate anhydrous, disodium hydrogen orthophosphate or EDTA salt) were tested but with disappointing results [41].

However, it is possible to get sterilized milk after reconstitution of liquid milk using camel milk powder. Such camel dairy product is available on market in the Middle East. Moreover, ultrafiltration for making camel concentrated skim milk was tested [42].

2.6. *Antimicrobial activity and pasteurized of camel milk.*

Many people (and even scientists) believe that camel milk has sufficient natural antimicrobial activity to preserve it from natural adulteration at ambient temperature for a long time. So, often, they consider that camel milk collection does not require the same requirements in hygiene practices. Therefore, in many cases, potential microbial contamination is not checked before implementing the trials. Yet, it is important to recall the results obtained by Sela, et al. [43] that thermal death time of *Escherichia coli* in camel milk is the same than in cow milk. Such presence of *E. coli* in camel milk is common [44] and the non-respect of hygienic rules will provoke digestive disorders in consumers, as it is observed in many camel milk degustation by naive persons. At the same time, raw and pasteurized camel milk has the capacity to inhibit *Cronobacter sakazakii*. As this bacterium can growth in powder milk, some authors think that it could be possible to use in the production of infant formula [45], but such possibility requires more investigations.

Obviously, pasteurization is prolonging shelf-life of milk and several data are available testing different protocols. In the study of Lund, et al. [17], the duration of keeping quality after storage at ambient temperature was 24 hours for raw milk, vs 76 hours with milk treated at 100°C/10 min, 64 hours for 63°C/30 min and 56 hours with the treatment 72°C/15 sec. The bacterial charge appeared higher (2.77 log CFU/ml) with a protocol 72°C/15 sec than 75°C/10 min (2.65 log CFU/ml) and 65°C/30 min (2.57 log CFU/ml), the lowest bacterial charge (2.45 log CFU/ml) being observed with a protocol 80°C/5 min [46].

In their study assessing the effect of two protocols (63°C/30 min and 72°C/15 sec), on total bacterial, coliform and moulds counts, Mohamed and El-Zubeir [47] found that the first protocol was non significantly more efficient on total bacterial and coliform count, but less on yeast and moulds count (Figure 1). However, the protocols were applied on highly contaminated milk. Still again, it is necessary to repeat that pasteurization is not a sterilization and requires the respect of the hygienic rules at milking, storage, and transport of the raw material to give a correct efficiency of milk processing.

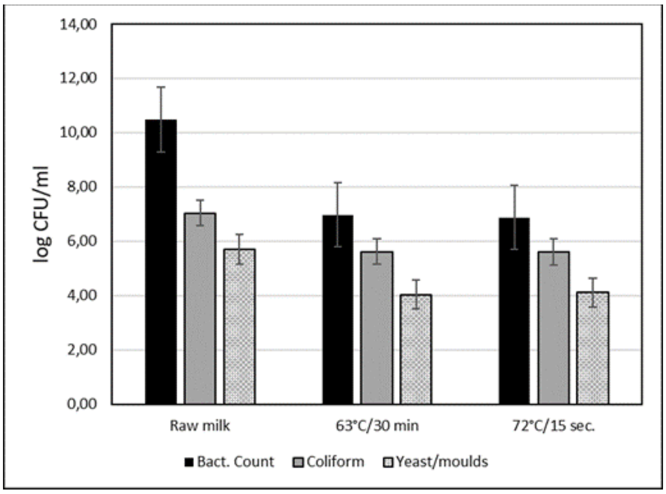

Figure 1. Changes in total bacterial, coliforms and yeast/moulds count in camel milk before (raw) and after heat treatments (from after [47])

Camel milk pasteurization is achieved at industrial scale, and pasteurized camel milk can be proposed directly to consumers within a shelf-life of around a week. Some dairy plants had a long experience to produce pasteurized camel milk, for example Tiviski (Mauritania), Camelicious (UAE), Al-Watania (KSA) or Tedjane (Algeria). However, further research is necessary, especially to study mainly the rheological properties of camel milk, poorly documented up to now. Further and in-depth studies need to be implemented before to be able producing UHT camel milk.

3. Fermented milk

The fermentation process is commonly used for the preservation of food. The process of fermentation of milk, including camel milk, is a traditional ancestral method all over the world. It consists of the transformation of lactose into lactic acid by the natural microflora of milk dominated by lactic bacteria and in some cases by yeasts. For understanding this process, numerous investigations on microflora of raw camel milk were performed. As many of fermented products from camel milk are made by spontaneous fermentation for centuries, it is key point to start our analysis of literature by global microflora (pathogenic or not) of raw camel milk.

3.1. Microflora of raw camel milk

3.1.1. Non-pathogenic microflora in raw milk

Normal microflora in camel milk is widely investigated, and the results testify to their high diversity according to different countries. In Tunisia, [48] found in raw camel milk $2.7x10^2$ CFU/mL of total mesophilic aerobic bacteria, 1.7 CFU/mL$x10^2$ of yeasts/moulds and $1.3x10^3$ CFU/mL of LAB. In total, 60 LAB strains were isolated. In camel milk samples from Morocco [49,50], 120 bacterial strains were isolated and identify as LAB by morphological and biochemical characterizations, then with 16S rRNA gene amplicon sequencing. Among described strains, some having probiotic properties were detected. Some of those strains were isolated in raw camel milk [51]. They belong to the genus *Lactobacillus* (*L. acidophilus, L. rhamnosus, L. gasseri, L. delbrueckii*) [52]. Other strains belonging to the same genus (*L. plantarum, L. pentosus and Lactococcus lactis lactis*) were reported by Yateem, et al. [53]. The diversity of microflora in camel milk is involving yeast also as observed in Algeria where 12 species, dominated by *Trichosporon asahii, Pichia fermentans* and *Rhodotorula mucilaginosa*, were identified [54].

Some strains isolated from raw camel milk as *Leuconostoc mesenteroides* have shown specific antimicrobial activity against Listeria [55]. Similar finding was observed with *Enterococcus feacium* [56]. Abo-Amer [57] described ability of *Lactobacillus acidophilus* strains isolated from raw camel milk to produce substances with antimicrobial activities. In a study achieved in Iran, among 64 LAB strains, 11 (belonging to genus *Enterococcus, Lactobacillus* or *Pediococcus*) presented significant antibacterial activity against *S. aureus subsp. aureus* or *B. cereus* [58]. In Kenya, the predominant strains belonged to species E. *faecalis, S. agalactiae, Weisselia confusa; Rhodotorula mucilanginosa, Cryptococcus albidus, Candida lusitaniae* [59,60]. In Kazakhstan, natural microflora including lactic bacteria (*E. durans, E. faecalis, E. faecium, Lb. casei, Lb. curvatus, Lb. kefiri, Lb. paracasei, Lb. sakei, Lc. lactis, Lc. mesenteroides*) and yeasts/moulds (*Kazakhstania unispora, Saccharomyces cerervisiae, Kluyvermyces marxianus*) identified in dromedary and Bactrian milk [61,62]. In Bactrian milk collected in China [63], 72 strains of lactic bacteria were isolated including *Lb. paracasei, E. italicus, E. durans, Lc. Lactis, W. confuse* and *E. faecium.*

Such diversity has high technological interest, this microflora playing important role both for antimicrobial activity as emphasized above and on acidification which is essential for cheese processing. However, due to the antimicrobial properties of camel milk proteins in higher quantity than in cow milk [64], and, in some cases, to the low hygienic status of the camel milk samples, the acidification process appears slower than for cow milk [65]. The starters used in camel milk processing for fermentation or cheese making (mesophilic, thermophilic or their mixtures) lead to an acidification rate at 37°C between 33 and 79% lower than for cow milk [60].

3.1.2.Pathogenic microflora of raw camel milk

Many data exist dedicated to preliminary bacteriological description of raw camel milk using different methods from all camel countries. Sela, et al. [43] already reported that camel milk could contain *E. coli* if elementary rules of hygiene were not applied. Camel milk could contain also all other pathogenic strains such as *Streptococci* or *Staphylococci* genus [66]. According to this last study in Algeria, 58% of commercialized samples of raw camel milk were satisfactory quality, 8.33% were acceptable and 33.3% were unacceptable. However, in their samples, they did not find any *Salmonella sp*. and *Shigella sp*. Another study achieved in Sudan reported presence of *E. coli, Klebsiella spp., Pseudomonas spp., Proteus spp., Enterococci spp., Micrococcus spp., Streptococcus spp., Staphylococcus spp*. [67]. The presence of coliforms can be observed despite the concurrent development of lactic bacteria. In Tunisia for example, a monitoring of raw camel milk focused on numeration of mesophilic count, total Lactic Acid Bacteria (LAB) and Coliforms reported values of 7x103; 1.37x102 and 1.8x101 CFU/mL respectively [68]. That is why it is important to verify all raw camel milk samples for microbiological quality before processing. Indeed, when significant changes in camel milk composition are observed during the process, it could be linked to the microbiological status of the raw samples. The lack of systematic checking microbiological quality in initial raw milk could impact all the processing trials

3.2. Diversity of fermented camel milk

The microflora biodiversity leads to a rich diversity of fermented beverages prepared from camel milk. Moreover, fermented form is one of the oldest ways of consumption of camel milk. Camel milk producers living in different regions of the world have their own varieties of fermented product with their specific taste, texture and flavor. Nowadays each camel country describes their traditional fermented milk by microbiological, physico-chemical, chemical properties and sometimes volatile organic compound profiles. The most known fermented camel milks described in the literature are *shubat* in Kazakhstan [69] and China [70], *khoormog* in Mongolia [71], *garris* in Sudan [72,73], *suusac* in Kenya [74], *laben* (lben) in Arabic countries [48], *ititu* and *dhanaan* in Ethiopia [75,76] (Table 1). Other traditional fermented beverages based on the mixture of camel milk and water are available in Mauritania under the name of *zrig* [79], in Morocco as *Lfrik* [80], and *chal* in Iran and Turkmenistan [81].

Table 1. Some main characteristics of fermented camel milk from different countries

Product	References	TVM	LAB	YM	Coli.	pH
		In log10CFU/mL				
Suusac	Lore et al. [84]	9.03	6.77	2.05	1.00	6.0- 4.25
	Jans et al. [78]	ND	7.2 – 8.5	ND	ND	4.9
Garris	Hassan et al. [9]	ND	ND	ND	ND	6.2- 3.8
	Adelgadir et al. [77]	7.11 – 8.36	7.34 – 8.66	6.05 – 7.79	ND	3.79 – 4.32
Shubat	Rahman et al. [70]	ND	6.8–7.6	4.3–4.7	ND	ND

TVM: total viable microorganisms; LAB: lactic bacteria; YM: yeasts and moulds; Coli: coliforms
ND: non determined

However, in most of the cases, the fermentation process is occurring spontaneously by using previously fermented milk to inoculate raw milk [82]. Microflora in fermented product is consequently more diversified than raw milk samples [83]. For example, traditional *suusac* (Kenyan fermented camel milk) contained 45 LAB and 3- yeasts identified by API50CHL and API20AUX. LABs mainly represented by *Lactobacillus curvatus, Lb. plantarum, Lb. salivarius, Lactococcus raffinolactis* and *Leuconostoc mesenteroides subsp. mesenteroides*, and yeasts – *Candida krusei, Geotrichum penicillatum* and *Rhodotorula mucilaginosa*

[84]. Other strains as *E. faecalis, Lb. fermentum, Lc. lactis, Cryptococcus laurentii, Candida lusitaniae, Saccharomyces cerevisiae, Trichosporon mucoides* and *T. cutaneum* were also identified more recently [60]. Traditional *garris* from Sudan is containing following LAB based on API39CHL identification system: *Lactobacillus animalis, Lb. brevis, Lb. divergens, Lb. plantarum, Lb. rhamnosus, Lb. gasseri, Lb. paracasei, Lb. fermentum, Lactococcus raffinolactis* and *Lc. alimentarium* [85].

Such complex microflora ecosystem in fermented milk could lead to very variable final products, hardly compatible with the necessity to get product with standard organoleptic quality. For example, *shubat* which is prepared mainly by Kazakh people from Kazakhstan, Uzbekistan, Russia, Xinjiang region of China and Western part of Mongolia, is made by spontaneous fermentation leading often to the production of gas and foam, and sometimes particularly very acid leading to some reluctance on the part of urban consumers [86]. Moreover, spontaneous fermentation can be affected by the presence of pathogenic strains of *E. coli* because the initial pH is not sufficient to suppress their growth [87]. To solve these problems, a convenient way is the use of starter cultures, i.e., a preparation containing limited numbers of identified live microbial strains (single or mixed) inoculated in raw milk. Such management of controlled fermentation can lead to expected sensorial properties of the final product by contributing to flavor and texture adapted to the urban consumers' taste. It contributes also to propose a standard and safer product on the market. Unfortunately, despite the high biodiversity of camel milk microflora, starters cultures used in camel industry are mainly coming from bovine milk. In Kazakhstan, among 104 isolates from *shubat* samples, coming from different regions of the country, 79 were maintained in pure culture (71 bacteria and 8 yeasts), then three of the strains were selected because their biochemical properties (*Lactobacillus fermentum* K5, *Lactobacillus fermentum* K6 and *Lactobacillus plantarum* K7) for testing their growth kinetic and characteristics, notably for measuring their produced biomass [88,89]. This point was important for developing industrial culture in fermenters. Then, each culture was tested for technological suitability, acidity, bacterial colonization, and organoleptic properties [89]. The transfer to industrial level was achieved thanks to the acquisition of high-capacity bioreactor wherein the media used were selected on the base of bacteria optimal growth and convenient ratio cost/growth potential. The final product (packaged starters in powder after lyophilization) was commercialized in two volumes (5 and 10 grams per pack). However, industrial transfer remains difficult and requires supplementary studies regarding technological properties of the numerous strains available in natural fermented milk [90]. Yet, beyond the commercial interest for the development of fermented milk with standardized organoleptic properties, there is also the public health benefit of such products thanks to their potential probiotic effect. For example, camel milk inoculated with LAB strain *Lactococcus lactis* KX881782 isolated from raw camel milk shows highest α-glucosidase inhibitions (antidiabetic effect), antioxidant activity, angiotensin-converting enzyme inhibition (antihypertensive effect) and antiproliferative activity (anticancer effect) than with cow milk [91].

4. Camel cheese

Technical innovations regarding fermented camel milk are applied on a beverage known from prehistoric times to extend its shelf-life [92]. At reverse, the making of camel cheese itself was an innovation. Indeed, the difference in casein proportions (notably the low part of κ-casein) between cow and camel milk should explain the clotting difficulties observed in this last: 3-4% of κ-casein only *vs* 13-15% in cow's milk [93]. Moreover, bovine chymosin used in dairy industry does not allow the optimal clotting of casein micelles of camel milk, leading to a weak curd. Thus, obtaining a firm coagulum was the first challenge of the camel scientists and dairy factories processing camel milk [94].

4.1. *The challenge of the coagulation*

The first trials were achieved in the years 80 by using bovine rennet enriched in chloride and calcium phosphate and *Rhizomucor miehei* as coagulant (commercialized under the name of Camifloc ®), but the coagulum remained fragile and brittle [95]. Different vegetal coagulants were tested also as extracts from *Zingiber officinale* [96] or from *Moringa oleifera* [97] as well as abomasum extracts from young or adult camel [98]. The solution to get a firm curd followed the sequencing of camel chymosin achieved by Kappeler, et al. [93] by introducing the coding gene for camel chymosin into a mould (*Aspergillus niger*). Later, this recombinant enzyme was produced by Chr. Hansen© at industrial scale and marketed from 2008 under the trade name Chymax-M1000®. However, if getting a good curd was a necessary condition, it was not sufficient to get a "good" cheese adapted to the consumers' preference for taste, especially because most of the camel cheese making were set-up by scientists in their laboratory rather by cheese technicians in dairy plants, except in Mauritania [99].

The variety of possible cheese being considerable, many trials are necessary to propose a large panel of products to the consumers. Different cheeses based on technology of gruyere [100], mozzarella [101] or feta and halloumi making [102] were tested, but the texture, the taste and flavor of the final product were not corresponding to the bovine equivalent. Indeed, the behavior of the camel "proteinic-lipidic matrix" during cheese processing differs from cattle milk. Such discrepancies between the milk from different dairy species require more fundamental investigations on rheological properties, and for understanding the changes during the different steps of coagulation, acidification, draining, brining, and refining as well as the effect of various starters and thermal treatment.

4.2. *Rheological and microstructural studies*

Camel cheese making being a recent achievement all over the world, more basic studies on rheology or microstructure of the final products remain scarce. Investigations on curd tension and syneresis were achieved on soft camel cheese [103]. Gel firmness and gelation properties were tested according to different levels of temperature and pH [104]. The parameters of cheese viscosity (storage and loss moduli, loss tangent) after camel milk coagulation by camel chymosin were also reported [105]. At our knowledge, if several studies on texture measurements (hardness, adhesiveness) were published (for example, [106], the microstructure properties of camel cheese require more investigations. In Iran, different mixtures of coagulants (*Rhizomucor miehei* protease and camel chymosin) on microstructure and rheological properties of white cheese were compared, reporting a more compact protein network and firmer structure in the cheeses made with camel chymosin, but they used cow milk as model [107]. In other studies, the comparison of the viscoelastic structure and globally of the gelation properties at different temperatures between cow and camel milk show higher difficulties to get cheese with pasteurized camel milk [107].

However, only studies at laboratory scale are available. True investigations at industrial scale are lacking. Moreover, in the published literature regarding physico-chemical and rheological characteristics of camel cheese, the microflora (pathogenic or not) was not taken in account systematically.

4.3. *Comparative "behavior"*

Comparison of the changes observed in the "proteinic-lipidic matrix" of camel and cow milk during the cheese processing is a common feature in scientific literature to understand their respective "behavior" specificity. However, the comparison is of low interest when the gross composition of each specific milk differs significantly. To avoid this problem, Konuspayeva et al. [102] adjusted cow milk for obtaining the same fat and total protein concentrations. Although they got similar cheese raw yields (7.4±0.15 vs 7.3±0.55 kg/100kg for camel and cow milk, respectively) and calcium recovery, camel cheese presented higher recovery in total nitrogen, and cow cheese in fat. Significant differences were observed also in lactoserum composition: camel lactoserum contained more fat and total nitrogen (9.0±1.73 g/kg and 9.21±0.23 g/kg, respectively) compared to cow (7.7±1.61 g/kg and 7.30±0.02 g/kg, respectively) despite similar dry matter (68.9±3.2 and 68.1±1.15% in camel and cow whey, respectively).

Two main technological difficulties in camel cheese processing are occurring: (i) the continuous removing of serum from curd, and (ii) the slow acidification of the curd. Indeed, contrary to cow cheese where ripening is started after curdling with rapid appearance of crust formation, camel cheese is characterized by a weak crusting and a continuous loss of wet, due to serum release, leading often to very dry curd what hinders correct ripening. Such behavior can be favorable for some types of cheese (as Feta type), but not for hard cheese [94]. The slow acidification was reported firstly by Farah and Bachmann [108] who reported that 10 hours were necessary to decrease pH from 6.6 to 5. Such delay can be reduced at 36°C compared to 20°C [101]. Starters as thermophilic ones containing *Lactobacillus helveticus*, and *L. lactis* or *Streptococcus thermophilus*, known for their high-acidifying power can be used to also improve the acidification process [101]. However, as for the management of fermentation to get specific fermented products, camel cheese manufacturing is not using starters made with lactic bacteria isolated from camel milk. The challenge for scientists and cheese makers could be the identification of LAB strains specific to camel milk allowing to provide typic aroma of cheese and to enrich the camel cheese variety proposed to the consumers.

Investigations on the interactions between minerals and camel cheese processing are also lacking. It has been established that there was no effect of addition of phosphate or calcium chloride to improve gelation by camel chymosin [101] contrary to cow milk [109]. Another lacking information regarding camel cheese is the analysis of volatile organic compounds responsible for aroma which are supporting the typicity of the cheeses. Nowadays, such analytical approach was developed for cow cheese [110].

4.4. The challenge of the industrial development

Up to now, it seems that scientists and cheesemakers aim to make cheese by using the same methodology than for cow cheese. But when Feta or Mozzarella-type cheese are prepared with camel milk, the results are often disappointing because taste, texture and consistency appear far away from the same cheese made with cow milk. In the Middle East, where the consumers prefer products with neutral taste, it is difficult to expect the development of cheese with strong character as in Western Europe. To achieve products adapted to the local consumers, different trials were reported to propose for example spread cheese [111] or white soft cheese [112,113]. However, few cheese tunes have given rise to sensory analyzes to assess the acceptability of the product by the local consumers [102]. Yet, such research would be useful for the dairy industry to develop a convenient cheese production. At our knowledge, few industrial initiatives have seen the light of day [99].

The industrial development of camel cheese making is limited not only by the technological difficulties, but also by the hygienic quality of raw milk as mentioned above, notably because it is difficult to coagulate camel milk after pasteurization forcing manufacturers to work with raw milk. The use of halloumi-type cheese technology [102] is an interesting alternative because the coagulum is pasteurized in lactoserum for 10 minutes at 80°C after pressing. A second difficulty is linked to the cost of camel cheese due to the high price of the primary matter [114]. An alternative could be the valorization of lactoserum which represents 88 to 90% of the initial milk volume.

5. Camel milk powder

As said in the introduction, the contribution of camel milk to international dairy market is very recent and was possible thanks to the development of powder milk production which is the best way to preserve this highly perishable product for later consumption. Moreover, camel milk being produced often in remote places far away from consumption basin, it is the only solution to transport high quantity of milk by removing the water it contains (88 to 90% of the weight). The advantage is also the conservation of the nutritive value of the liquid milk. To make camel milk powder, two main modern technologies were used: spray-drying (hot-drying) and lyophilization (freeze-drying).

5.1. *The drying technologies*

The first reported trial aiming to make camel milk powder is recent, used freeze-drying technology to study the thermal characteristics of camel milk and its main components [7]. However, these tests were carried out in laboratory (not on an industrial scale) with a laboratory freeze-dryer allowing drying from -40 to 20°C with vacuum of 100 Pa. The resulting powder was stabilized at 11.3% humidity. A second, more recent reference [115] pursues similar objectives, namely, to assess the effect of freeze-drying on the nutritional properties of camel milk, i.e., to test the procedure on the fine composition of camel milk in comparison with fresh milk. Analyses indicate a relative stability of most components (including minerals and vitamins) and conclude that the nutritional properties of camel milk powder are maintained. However, it is also a laboratory equipment with limited capabilities. Moreover, nothing is said about the solubility of the powder thus obtained.

The spray-drying process was also the subject of few scientific publications. In their study comparing the physical properties of powdered camel and cow milk obtained by spraying, [116] used a two-step process: milk is first concentrated up to 20-30% of dry matter by a rotating evaporator at 80°C, then passed through a sprayer. The equipment used (FT80/81 Tall Form Spray Dryer) can treat small amounts with the same effects of an industrial sprayer. In their protocol, the drying conditions were air intake temperature at 200-220°C, air outlet temperature between 98 and 105°C, pump speed at 3-5 arbitrary units, air outlet humidity between 1.2 and 5.8%. In their conclusion, the authors indicate that this process allows getting powder with less than 1.8% water, thus allowing a long shelf life. The drying temperature should be well controlled, as too high a temperature results in an increase of the insolubility index due to protein denaturation. Overall, the solubility of camel milk powder is lower than that of cow milk. Another criterion used by manufacturers to assess the quality of a milk powder is fluidity. This is the ratio between the density of the un-tamped powder and its density when compacted. This fluidity appears lower for camel milk compared to cow milk but remains in fairly good proportions [117]. In a recent study regarding acid gelling of fresh and powdered camel milk acid [118], the dry-spraying process also used a laboratory sprayer (Buchi B-290), allowing an air entry temperature of 190°C and an output temperature of 90°C with an input flow of 600ml/h. In their publication, [118] aimed also to test the effect of spray-drying, in particular the temperature of the air intake (160, 140 and 120°C), atomization pressure (800, 600, and 400 bars) and feeding flow (5.4 and 3 arbitrary units/s) on the nutritional components of camel milk (vitamin C, fatty acid profiles). The equipment used was the same mini-laboratory sprayer cited in previous publications. Powder yield increased with the highest air intake temperatures and the lowest feed flows. High temperatures and high spray pressures reduced vitamin C levels. Finally, the atomization pressure increased the fatty acid content.

5.2. *Interests and limits of the technologies used for spraying camel milk*

The spray-drying method seems preferable to make camel milk powder for a better reconstitution of liquid milk, but the investment for dairy industry is more important as it requires the procurement of a costly milk drying tower and sprayer. However, the powder obtained by freeze-drying (lyophilization) could be used by agro-food industries (pastry and chocolate factories).

Nevertheless, the main limit is that drying is consuming high level of energy. In dairy industry, spray-drying process has a higher energy demand per tonne of end product, even if recent technical improvement and the equipment has decreased the energy consumption per tonne of finished product. Moreover, the high investment to get and to use a drying tower for making milk powder requires a sufficient volume of raw matter which is only possible in certain contexts as big camel dairy farm or collecting centres with a large network of camel farms.

Finally, it appears that trials on camel milk (in any case, those that are published) are limited in number and that industrial trials are poorly documented. It is also apparent that the spraying of camel milk requires an optimization of the input parameters (temperature, pressure, flow) to maintain the nutritional properties of the product and the functional characteristics (solubility, hygroscopy, fluidity) of the powder. As camel milk studies were all carried out with materials dealing with small quantities, the "translation" of these results on industrial scale face to large volumes is not available, although the practice of industrial hot spraying of camel milk is implemented in the United Arab Emirates, China and Europe.

5.3. The challenge for camel milk powder development

The main problem with camel milk during a high-temperature heat treatment, as happens during spraying, is the denaturation of proteins (especially whey proteins), which explains the difficulty to obtain UHT milk. To keep powder milk in the best possible conditions, and to facilitate the solubility of the powder to replenish the liquid milk, the surface composition of the powder is essential [119]. This surface is naturally composed mainly of fat. The denaturation of serum proteins at high temperature increases the fatty surface part of the powder and makes it difficult to replenish liquid milk. For a better emulsion during this reconstruction, it is proposed to perform an "encapsulation" by sodium caseinates that ensure a stability of the powder. Such encapsulation is improved with the presence of lactose. For example, surface fat decreases from 30 to less than 5% if lactose is 1:1 related to sodium caseinate.

In the following description (Table 2), possible improvements are reported to obtain a quality powder of stable quality due to the specificities of camel milk.

Table 2. Possible improvements to get camel milk powder with high quality

Process	Activity	Particularities	Comments
Raw camel milk (raw material)	Limit the number of suppliers or implement collecting centers with quality control	Low bacterial load (ideally <100 CFU/ml coliforms) Titrable Acidity <16°Dornic	Without respect for hygiene, the milk may clot during powder processing and cause harmful fouling of the equipment.
Concentration to remove a part of the water (on average 88% water in camel milk)	Remove at least 30% of the water by the principle of the "pressure cooker" less expensive in energy, saving atomization time and improving quality of the final product.	If hygienic standards are insufficient, risk of clotting	Clotted products are difficult to be reused, not only for the reconstruction of liquid milk, but even for the transformation into other products (cheese, yoghurt, fermented milk)
Homogenization to better emulsify	Make the fat and caseins' micelles in small size for getting	Optional for better powder quality, add a stabilizer of the emulsion	This non-compulsory phase would result in a powder of better physical quality

	a good quality emulsion	(caseinates), and possibly remove lactose to obtain an optimal ratio 1:1 caseinates/lactose	(solubility, fluidity, low hygroscopic capacity) and stable over a longer period (preservation time)
Spray-drying	Optimize temperature (inlet/outlet), atomization pressure, input flow to minimize energy costs and preserve the nutritional properties of camel milk	If hygienic standards are insufficient, the risk of appearance of poorly dried agglomerates will impact the commercial quality of the product	Data is available from suppliers
Packaging of camel milk powder	To preserve the quality of the finished product, it is advisable to use automated bagging.	Working in a sterile atmosphere under strictly controlled humidity	This is a main step because any anomaly can involve all the previous steps (critical point in a HACCP approach). Minimize people with access to this part of the chain

6. Other products

6.1. *Yogurt*

Ample literature is available on the possibility of making yoghurt with camel milk [120,121]. Several strains of conventional lactic bacteria have been tested such as *Lactobacillus bulgaricus* or *Streptococcus thermophilus* [122], but also *L. acidophilus*, *L. casei* and *Bifidobacteria* [123].

However, the manufacture of camel milk yoghurt poses a texture problem, the product appearing sticky and ultimately unpleasant to the palate [124]. Indeed, the viscosity of the product does not change during the gelling process compared to the milk of other dairy species. This constraint is related to the protein composition [125], and to antibacterial factors naturally present in camel milk [126]. Another reason could be linked to the foaming properties of camel milk. The foam in this milk is stable, but it leads to a weak structure of the gel which becomes unstable [127].

To obtain a better texture, trials with the addition of gelatin, alginate or calcium were attempted [128] or using ferments producing exo-polysaccharides [129]. The application of high-pressure treatment could have positive effect on the texture, but no trials have been conducted to date with camel milk [130].

Other authors have attempted to improve the manufacture of camel milk yoghurt by mixing with milk from other species [131] or by introducing 0.75% biosynthesised xanthan, however with medium results in terms of organoleptic properties [132]. In any case, the final product corresponds at best to a "drinking yoghurt" without having the taste qualities, even when natural or synthetic aromas are added [133]. These difficulties explain why there is not really industrial production of camel milk yoghurt at present. Some researchers have proposed frozen yogurt to produce a product that is between yogurt and ice cream [134]. The optimal composition from a texture point of view would be allowed with several ingredients such as fat (5%), sugar (13%), gelatin (0.5%) and 14% banana [135], but again, such a proposal has never come out from the laboratories.

6.2. *Butter and sweet*

The fat in camel milk contains less than 0.5% butyric acid [136] compared to almost 5% in cow's milk. In addition, fat cells are smaller than in cow's milk [137]. As a result, butter yield is low [138] and disappointing organoleptic property [124,139]. To obtain fat cells at the time of butter production, it is necessary to make vigorous hot shaking (22-23°C), which allows to recover about 80% of the fat [138]. *Ghee* (clarified butter), a popular product in India, has also been attempted from camel milk [140] but in addition to very low yield compared to buffalo or cow's milk, the final product has been found to be more susceptible to rancidity. Transformation into butter therefore does not seem fundamentally interesting in the context of an industrial valuation of camel milk. In fact, apart from trials in Ethiopia where butter consumption, including rancid for certain recipes, is important, the production of camel butter has little future.

Making ice creams with different flavours is an easy technology. Ice-cream made of camel milk are commercialized in the United Arab Emirates, Morocco or Kazakhstan. The same technology is used than for other milks. Ice cream is very popular among consumers and, above all, with less reluctance than for other products. However, very few studies on texture and sensory properties have been conducted [141].

There are no references on processing camel milk into sweets. However, traditional products are available. For example, in Kazakhstan, a caramel called *Balkailmak* is obtained after a long thermal treatment of about ten hours at boiling temperature. The introduction of milk powder in chocolate as proposed in the Emirates can be recalled also. A study on the acceptance of camel milk in a panel including 470 Emiratis students showed higher score in chocolate flavoured milk [142]

6.3. *Non-alimentary processing of camel-milk*

The manufacture of soaps and other cosmetic creams with camel milk is now a common practice in many countries (Morocco, Mauritania, Saudi Arabia, India, Holland, China, Australia...), either on a semi-industrial scale or on handicraft scale. China sells cabinets containing various cosmetic products from lipstick sticks to moisturizers, shampoos, and various lotions. The interest in the use of camel milk for cosmetic industry benefits from the hypo-allergen properties of its proteins [143].

7. Conclusion

The "modernized" processing of camel milk is a recent feature compared to the milk from other dairy species. However, the technologies used to transform milk into pasteurized or fermented products, cheese or yoghurt, powder or various sweets face to two main challenges: (i) the systematic application of already proven technologies for cow's milk is not necessarily suitable for camel milk, and requires adaptations based on more fundamental research on the behaviour of milk components during processing; (ii) the transfer of laboratory results already relatively numerous to industrial scale remains insufficient, especially for products such as cheese or yoghurt, and requires additional technical and economic analyses. The worldwide keen interest for camel milk, which is largely due to its expected health effect for consumers, is prompting basic research and development to continue investigations in order to translate technological innovations into products available on a large scale.

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