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Review

Heat treatment of goat milk – A review

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A B S T R A C T

The behaviour of goat milk upon heating at various pH values differs from that of cow milk and the heat stability at natural pH is low. According to most studies, heat stability increases constantly from pH 6.7 to pH 6.9 and decreases thereafter. Modifications of the negative charge of the micelle and of the concentration of ionic calcium and soluble phosphate play an important role; both the increase and the decrease of ionic calcium can induce poor heat stability. A reduction of ionic calcium in goat milk to approximately 2 mM by appropriate calcium-sequestering agents may address the instability. The level of whey protein denaturation and the formation and profile of whey protein/whey protein and whey protein/casein aggregates are not similar at natural pH and at the pH of highest heat stability. Heat treatment influences the rennet clotting behaviour and gel properties of goat milk much less than those of cow milk.

Contents

1. Introduction

Heat treatment under varying conditions (IDF, 2022) is an indispensable step in the manufacture of dairy products aiming for the safety, extension of shelf life and configuration of particular textural features. The effect of heat treatments and heating methods on the components and particles of milk and their interactions at various physicochemical conditions have been constantly studied and updated. In this respect, the heat stability of various milk types has been the objective of numerous studies. Excellent review papers on the topic have been published for cow milk, which is the reference milk kind for the international literature, exhibiting the complexity of changes occurring upon heating (e.g., Anema, 2021; Deeth, 2021; Dumpler, Huppertz, & Kulozik, 2020; Huppertz, 2016; Nieuwenhuijse & Huppertz, 2022; Singh, 2004; Wiking, Gregersen, Hansen, & Hammershøj, 2022).

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The behaviour upon heating of non-cow milk kinds has been investigated to a much lesser extent. The aim of the present review is to present in a critical manner the scientific information about the heat stability of goat milk, the particular mechanisms for the changes that take place and interventions for the improvement of its behaviour upon heating. A very concise presentation of the main aspects related to heat treatment of cow milk before the discussion of goat milk particularities has been added in particular sections for the interpretation of the research findings.

2. Chemical and structural components of goat milk related to the behaviour upon heating

The gross composition of goat milk in comparison with reference cow milk is presented in Table 1. It is well established that the great variability of total solids content of milk from different goat breeds comes from the extended polymorphism of caseins that affect the protein and also the fat content. Particular characteristics of goat milk related to the behaviour upon heating, such as nitrogenous and mineral fraction, casein micelle, are presented in Table 2 in comparison with those of cow milk.

The unusual and very extended genetic polymorphism of casein in goat milk significantly affects the composition and technological properties. The most part of the genetic variability concerns α_{S1}-casein and consists of "strong", "medium", "weak" and even "null" alleles in terms of casein production (e.g., Amigo & Fontecha, 2011; Moatsou et al., 2008). The α_{S1}-casein polymorphism affects the characteristics of the goat casein micelles. Goat milk with strong α_{S1}-casein AA alleles that produce 7 g L^{-1} has casein micelles with smaller mean diameter compared with milk with weak FF alleles producing 0.9 g L^{-1}, i.e., 221 versus 268 nm. The same holds true for the mineralisation level, that is, 31.6 versus 34.3 mg Ca g^{-1} casein with similar hydration level: 1.71 versus 1.74 g water g^{-1} dry micelle (Remeuf, 1993). Mora-Gutierez et al. (1996) showed that goat casein micelles with high α_{S1}-casein content exhibit a higher degree of hydration. Later, Tziboula and Horne (1999) confirmed that the micelles of "weak" α_{S1}-casein milk were larger than "strong" counterparts without significant differences in the calcium and citrate content; however, total phosphorus content of "strong" milk was statistically significantly lower.

A consequence of the genetic polymorphism is that total casein content of goat milk varies extremely in the literature within 23–46 g L^{-1} while that of cow milk is within 24–28 g L^{-1}. The respective total whey protein contents are 3–12 and 5–7 g L^{-1}. The average ratio of casein to whey protein is lower in goat milk than in cow milk, i.e., 3.5–4 versus 4.5–4.7. Non-protein nitrogen (NPN) fraction of goat milk ranges from 3 to 8%, which is higher than that in cow milk (Alichanidis, Moatsou, & Polychroniadou, 2016; Claeys et al., 2014).

Goat milk is differentiated from cow milk in terms of the detailed composition of the casein and whey protein fractions (Table 2). It contains considerably more β-casein and less α_{S1}-casein than cow milk. Moreover, there are differences in respect to β-lactoglobulin (β-lg) and κ-casein contents, which are involved in phenomena related to the behaviour of milk upon heating, as reported previously. The average κ-casein on total casein of goat and cow milk are similar, 13 and 12.5%, respectively. However, the range in goat milk is very wide (34–62%) due to the aforenoted variability in the α_{S1}-casein content. As shown in Table 2, the average casein micelle size of goat milk is higher than that of cow counterpart. Goat milk contains less β-lg in its serum/whey fraction. In particular the average of the reported ratios β-lg to α-la are 1.74 and 2.35 for goat and cow milk, respectively (Alichanidis et al., 2016).

Non-centrifugal casein is 8.7% of total casein in goat milk, higher than the 5.7% in cow counterpart. The same holds true for the mineralisation of the micelle; on average the goat casein micelles contain 36 mg calcium g^{-1} protein, which is 25% more than that in cow micelles. The higher mineralisation level coincides with the lower hydration level of goat micelle compared with cow counterpart, i.e., 1.43–2.05 versus 1.92–3.7 or 1.77 versus 1.9 g H_2O g^{-1} protein (Park, Juarez, Ramos, & Haenlein, 2007; Roy, Ye, Moughan, & Singh, 2020).

Urea, which is the most abundant non protein nitrogenous (NPN) component, has been associated with the heat stability of milk (section 3.2.3). There are not many reports for the urea content of goat milk (Table 2). The urea content of milk from six different goat breeds has been found highly variable being on average 32.5 ± 11.2 mg 100 mL^{-1} (Mayer & Fiechter, 2012a). An influence of α_{S1}-casein genotype has been observed by Avondo et al. (2015), who report lower urea content of milk with "strong" than in counterpart with "weak" alleles, i.e., 57 mg versus 69 mg 100 mL^{-1}.

The fraction of ionic calcium that is of particular interest for the behaviour of milk upon heating is higher in goat milk compared with cow milk (Table 2). Holt and Jenness (1984) estimated 2.6 and 2 mM calcium ions in the ultrafiltrate of goat and cow milk, respectively. The same trend was true for magnesium ions, that is, 1.2 and 0.81 mM, respectively, and for the ionic strength that was 84 for goat milk and 73 for cow milk. Citrate concentration is higher in cow milk according to several studies (Table 2). Holt and Jenness (1984) reported that the citrate concentration of 5.4 mM of goat milk is 60% that of cow milk. From their findings a calcium to citrate ratio can be calculated as 4.28, higher than the 3.19 of cow milk. Since citrate binds a great part of calcium in the serum of milk, a high ratio could be related to the higher calcium ions concentration in goat milk. Moreover, the ratio of calcium plus magnesium to citrate in the soluble phase of goat milk was 2.28, i.e., 50% higher than in cow milk (Holt & Jenness, 1984).

3. The behaviour of goat milk upon heating

Goat milk at natural pH exhibits low stability upon high heat treatments. The objective of this section is the critical concise

Table 1
Gross composition (%) of goat milk compared with cow milk.

Total solids	Lactose	Fat	Ash	Protein	Reference (comment)
Goat milk					
13.2–11.6	4.3–4.8	3.5–5.6	0.7–0.8	2.6–4.1	Raynal-Ljutovac, Lagriffoul, Paccard, Guillet, & Chilliard, 2008 (various
13.2 ± 1.6	4.5 ± 0.2	4.5 ± 0.9	0.8 ± 0.06	3.6 ± 0.5	breeds and countries)
11.9–16.3	3.2–5	3–7.2	0.7–0.9	3–5.2	Claeys et al., 2014 (minimum and maximum values from the literature)
11.9–16.3	3.9–6.3	2.5–7.8	0.7–1.1	2.5–5.1	Alichanidis et al., 2016 (from selected sources)
13.2	4.4	4.3	0.8	3.6	
Cow milk					
10.5–13.7	3.6–5.5	2.5–6	0.6–0.9	2.9–5	Alichanidis et al., 2016 (from selected sources)
12.7	4.8	3.8	0.7	3.4	

Table 2
Comparative presentation of particular parameters of protein, nitrogenous and mineral fractions of goat and cow milk.[a]

Parameter	Goat milk	Cow milk	Reference
CN (g 100 mL^{-1})	2.33–4.63	2.4–2.8	Bornaz, Sahli, Attalah, & Attia, 2009; Han et al., 2021; Li, Ye, & Singh, 2019; Li et al., 2022; Moatsou et al., 2008; Raynal & Remeuf, 1998; Tamime, Wszolek, Božanić, & Özer, 2011; Verruck, Dantas, & Prudencio, 2019
α_{S1}-CN	0–28%	38%	
α_{S2}-CN	13.3–16.3%	10%	
β-CN	44.5–48.9%	33–39%	
κ-CN	13.3–16%	11–13%	
ø CNM (nm)	210–270	150–188	
WP (g 100 mL^{-1})	0.37–0.70	0.50–0.70	Moatsou, Hatzinaki, Samolada, & Anifantakis, 2005; Verruck et al., 2019
β-lg	43.5–47.8%	59.3–62%	
α-la	14.3–22%	18.4–19.2%	
Ca (g 100 mL^{-1})	0.113–0.129; 0.12–0.17†; 0.135–0.150§	0.111; 0.108–0.144‡	Gaucheron, 2005; Heilig et al., 2008; Guo, Liu, Zhao, Qin, & Zhang, 2021; Li et al., 2019, 2022; Mayer & Fiechter, 2012a,b; Raynal & Remeuf, 1998; Voutsinas, Pappas, & Katsiari, 1990
Soluble Ca	29.7–34.8%	37.3–40.5%	
Ionic Ca	10.8%	6.9–8.7%‡	
P (g 100 mL^{-1})	0.100; 0.10–0.16†; 99–122§	0.093–0.099	
Inorganic P	0.095%	0.075–0.092%‡	
Citrate (g 100 mL^{-1})	0.102–0.111; 81–145§	0.132–208	
NPN (g 100 mL^{-1})	0.4; 0.17; 0.24	0.2; 0.19	Avondo et al., 2015; Guo et al., 2021; Mayer & Fiechter, 2012a; Morgan et al., 2000; Walstra et al., 2006; Wojciechowski & Barbano, 2015
Urea (mg 100 mL^{-1})	4–54; 57–69	25	

[a] Abbreviations are: CN, casein; CNM, casein micelle; WP, whey protein; β-lg, β-lactoglobulin; α-la, α-lactalbumin; NPN, non-protein nitrogen. Means or range of values are compiled from selected sources. CN, WP, Ca, P, Citrate, NPN and urea estimated on milk; values for urea lower in milk with strong α_{S1}-CN AA than in FF genotype (Avondo et al., 2015); α_{S1}-, α_{S2}-, β-, and κ-CN given as % total casein; β-lg and α-la given as % total whey proteins; soluble and ionic calcium given as % total calcium; inorganic P given as % total phosphorus; values indicated by †, ‡ and § are for throughout season as given by Guo et al. (2021), Li et al. (2019) and Voutsinas et al. (1990), respectively.

presentation of the findings of various research groups that utilise different heating conditions and systems to study the behaviour of goat milk upon heating. Therefore, some rather minor differences between the proposed patterns may exist. The publications are very limited compared with those for cow milk and the most part of them are studies involving high-heat treatment or UHT processing. They can be roughly classified as follows, considering that some of them can belong to more than one group:

(i) Several studies investigate the application of heat treatment, in particular of UHT processing and the improvement of the heat stability of goat milk (e.g., Anema & Stanley, 1998; Bouhallab, Leconte, Le Graet, & Garem, 2002; Bouhallab & Raynal-Ljutovac, 2005; Boumpa, Tsioulpas, Grandison, & Lewis, 2008; Chen, Grandison, & Lewis, 2012; De Raphael & Calvo, 1996; Heilig, Çelik, & Hinrichs, 2008; Montilla & Calvo, 1997; Morgan et al., 2003; Yuan et al., 2022; Zadow, Hardham, Kocak, & Mayes, 1983).
(ii) Some publications focus on the heat treatments of goat milk as an essential manufacturing step for dairy products (e.g., Alloggio, Caponio, Pasqualone, & Gomes, 2000; Calvo, 2002; Calvo & Balcones, 1998; Heilig et al., 2008; Hovjecki, Miloradovic, Rac, Pudja, & Miocinovic, 2020; Miloradovic et al., 2016, 2017, 2020; Moatsou et al., 2021; Montilla, Balcones, Olano, & Calvo, 1995; Raynal & Remeuf, 1998; Saipriya, Deshwal, Singh, Kapila, & Sharma, 2021).
(iii) A considerable number of studies investigate the factors and mechanisms that are responsible for the behaviour of goat milk upon heating (e.g., Anema & Stanley, 1998; Chen et al., 2012; Christodoulopoulos, Solomakos, Katsoulos, Minas, & Kritas, 2008; Han et al., 2021; Henry, Mollé, Morgan, Fauquant, & Bouhallab, 2002; Law et al., 1998; Li, Delger, Dave, Singh, & Ye, 2022; Montilla & Calvo, 1997; Morgan, Jacquet, Micault, Bonnin, & Jaubert, 2000; Pesic et al., 2012; Raynal & Remeuf, 1998; Tziboula, 1997; Zadow et al., 1983; Zhao, Zhang, Lu, & Lv, 2020).
(iv) Some comparative studies examine in parallel the behaviour of goat and cow milk (e.g., Alloggio et al., 2000; Calvo, 2002; Fox & Hoynes, 1976; Han et al., 2021; Heilig et al., 2008; Law, 1995; Li et al., 2022; Moatsou et al., 2021; Montilla et al., 1995; Pesic, Barac, Stanojevic, & Vrvic, 2014; Pesic et al., 2012; Raynal & Remeuf, 1998; Yuan et al., 2022; Zadow et al., 1983; Zhao et al., 2020).

An array of different types of changes of milk constituents and structural elements occurs upon heating. They depend on the heating parameters, temperature, time, method, and their combination. All milk components can be influenced, but modifications of protein structure and salt equilibria along with pH are crucial for the implementation of heat treatment and the heat stability of ruminants' milk. In this respect, the discussion of the behaviour of goat milk upon heating starts with the effect of treatments on the protein and mineral fraction of goat milk.

3.1. Protein and particle profile of heat treated goat milk

Of particular interest for the heat stability of milk are the composition of casein micelle and the modifications of its surface upon heating. Structural changes of whey proteins and of salt equilibria influenced by pH are involved in the behaviour of casein micelle upon heating. Therefore, heat induced changes of whey proteins and minerals in goat milk are presented before the

discussion of the behaviour of goat casein micelle. Main findings emerging from the detailed research on cow milk will be presented concisely for comparison reasons, when necessary.

3.1.1. Denaturation and complexation of whey proteins

A considerable number of studies have been performed on the heat induced changes of whey proteins of cow milk under various conditions. The behaviour of β-lactoglobulin upon heating of cow milk plays a major role since it is the most abundant heat-labile milk protein and in denatured form interacts with other whey proteins and caseins. It enhances the heat denaturation of other whey proteins, mainly of α-lactalbumin that does not contain free thiol-groups (Halabi et al., 2020). Heating of milk at temperatures higher than 65 °C induces unfolding and then denaturation of whey proteins. In turn, heat induced micelle-bound and serum aggregates through hydrophobic bonding and thiol/disulphide exchanges are formed (Donato & Guyomarc'h, 2009). Micelle-bound aggregates are whey protein/κ-casein complexes that are based on β-lactoglobulin and κ-casein covalent complexes (β-lg/κ-casein) resulting from thiol-disulphide exchanges with a molar or mass ratio of 0.5–3.5 whey proteins to one κ-casein. Whey protein/κ-casein complexes are also present in the serum phase of heated milk with a molar or mass ratio of 1–5 whey proteins to one κ-casein (Donato & Guyomarc'h, 2009). Among caseins, κ-casein and α_{S2}-casein can participate in intra- and inter-molecular disulphide bonding since they contain two cysteine residues each (Rasmussen et al., 1999). Under heating conditions frequently used for the majority of dairy products, the well-known complexes between κ-casein and denatured β-lactoglobulin in heated milk are favoured against complexes with α_{S2}-casein because κ-casein is on the surface and can be partially released into the milk serum upon heating; however, a low level of α_{S2}-casein/β-lactoglobulin interactions have been observed in UHT milk samples (Anema, 2021). Upon heating of cow milk at 70–90 °C, at pH 6.9, small denatured whey protein aggregates 60 nm in size are formed that remain dissolved in the serum and may contain κ-casein. At pH 6.7 about 30% of denatured whey proteins are in the dissolved aggregates and 70% are associated with micelles and at pH ≤6.5 all are associated with micelles (Walstra, Wouters, & Geurts, 2006). Moreover, upon heating at 65 °C for 30 min about 0.3 g β-lactoglobulin per g of milk fat are associated with milk fat globule membrane (MFGM) proteins, that is three times that estimated in unheated milk (Ye, Singh, Oldfield, & Anema, 2004).

The heat-induced denaturation of goat milk serum/whey proteins has been examined under various heating and pH conditions, considering their complexation with casein micelle surface and their tendency to form soluble aggregates. The estimation of whey protein denaturation is based on the reduction of the concentration either of soluble nitrogen or of major whey proteins. Various experimental conditions have been applied in the relevant studies, which in the present section are roughly classified as short time or batch treatments. Firstly, studies performed at the natural pH of goat milk are discussed.

Short time treatments were utilised by Calvo, Amigo, Olano, Martin, and Ramos (1989) to compare the level of denaturation of major whey proteins in goat, cow and sheep milk. The denaturation of β-lg in skim goat milk heated without pH adjustment at 90 °C for 15 s and 30 s was 20% and 3%, respectively, while α-la remained soluble. At 74 °C for 30 s, both whey proteins remained soluble. In the same study, the denaturation level in skim cow milk was slightly lower and in sheep milk higher than that in goat counterpart. Prasantha and Wimalasiri (2019) report that treatment of goat milk at typical pasteurisation conditions did not induce denaturation by means of change of the concentration of the soluble whey protein nitrogen. However, after treatment at 85 °C for 15 or 25 s, a reduction of 8.2 and 13.5%, respectively, was observed.

In flow-through heat treatments applied to in-line homogenised goat milk at natural pH 6.60, Moatsou et al. (2021) estimated higher denaturation level than the above-mentioned studies. In particular, 20, 35 and 43% reduction of soluble nitrogen was observed upon heating of milk at natural pH 6.60 at 78, 85 and 100 °C for 16 s, respectively. At 100 °C for 16 s, 89% and 8% of the initial native α-la and β-lg, respectively, remained soluble in goat milk; at 85 °C for 16 s the respective values were 90% and 45%. In the same study, the major whey proteins of goat milk exhibited higher heat tolerance compared with sheep counterparts. Zhao et al. (2020) examined the effect of heating from 65 to 137 °C for 7 s on the parameters of the secondary structure of whey proteins of goat milk, at natural pH. Their findings show that heating at 95 °C for 7 s decreased β-sheet structures from 56% in raw milk to 48%, increased α-helix from 35% to 48% and decreased β-turn from 9.5% to 3.1%.

Higher denaturation levels have been reported for batch treatments. Montilla et al. (1995) treated goat and cow milk at pH 6.68 at 65, 70, 75, 80, and 85 °C in a water bath for 5–35 min and they reported that the increase of heating time exhibited an effect on the denaturation level at 75 °C and thereafter. After treatment at 80 °C for 5 min, 40% of the initial α-la and 5% of β-lg remained soluble, while the respective values for cow milk were close to 50% and 40%. In the experiments of Law et al. (1998) performed in skim goat milk at pH 6.7, treatments of 5 min at 70, 80 and 90 °C caused approximately 10, 25 and 90% denaturation of β-lg, respectively. Below 80 °C, the denaturation of α-la was less than 10%, while it was close to 80% at 90 °C. Similarly, Moatsou et al. (2021) found almost no soluble β-lg and approximately 5% of the initial α-la in soluble form after batch treatment at 90 °C for 5 min.

In the comparative study of Raynal and Remeuf (1998), the denaturation level was expressed as soluble nitrogen. Denaturation occurred rapidly upon batch heating at 90 °C and its maximum, that corresponded to approximately 20% of whey proteins in the soluble phase, was reached during the first 2 min in goat, or cow or sheep milk. At 80 °C, heating for 5 min or more caused 70–80% whey protein denaturation, for all three milk kinds. At 85 °C, the maximum degree of denaturation was obtained in 1 min for goat milk, between 1 and 3 min for sheep milk and in 10 min for cow milk (Raynal & Remeuf, 1998). The results of Law (1995) showed that goat milk whey proteins were less readily denatured than cow milk counterparts at 80 °C for short heating times less than 5 min but more easily at 90 °C. Although the reaction orders for β-lg and α-la were the same, their rate constants in skim goat milk at 80 and 90 °C, at natural pH were much higher than in cow milk. The author suggests that the higher κ-casein concentration and the existence of three SH groups on goat κ-casein, i.e., one more than in cow counterpart, indicate that there is more availability for disulphide bonding with whey proteins. Moreover, β-casein that is more abundant than in cow milk may promote hydrophobic interactions between micelle and WP. Treatment at 90 °C for 10 min of defatted goat and cow milk at natural pH resulted in a very low quantity of native of β-lg that was less than 3% of the initial, for both milk kinds in the experiments of Pesic et al. (2012). However, cow α-la was found much more heat tolerant than goat counterpart; the respective native percentages were 30 and 4% (Pesic et al., 2012). Therefore, considering all above-mentioned findings of comparative studies, the heat induced denaturation level of the whey fraction of goat milk is higher than that of cow milk counterpart under similar conditions.

The effect of goat casein polymorphism on heat induced denaturation of whey proteins has been examined by Morgan, Micault, and Fauquant (2001). They found that non-soluble β-lg and α-la of goat milk with “strong” or “weak” α_{S1}-casein alleles heated at

natural pH 6.7, at 80 °C for 1 min were close to 40% and 10–15% of the initial, respectively.

The varying experimental and analysis conditions utilised in the investigations of the effect of pH on the level of soluble whey proteins upon heating of goat milk have not allowed firm conclusions to be drawn. Relevant studies are presented in Table 3, in brief. Morgan et al. (2001) found that the level of non-soluble β-lg is affected by pH upon heating of goat milk at 80 °C for 1 min. At pH 6.9, the level of non-soluble β-lg was almost 20% higher compared with that at pH 6.7, while the level of non-soluble α-la did not differ markedly between pH 6.7 and 6.9. They suggest that at pH 6.9, a large amount of β-lg/κ-casein complex is formed in the soluble phase contrast to cow milk, which is stabilised against heating by the complexation of β-lg with κ-casein occurring at its natural pH. On the other hand, the results of Montilla and Calvo (1997) show that at 135 °C for 20 s, the increase of pH from 6.8 to pH 7.2 did not exhibit statistically significant influence on the denaturation of α-la and β-lg. Similarly, in the comparative study of Pesic et al. (2014), the increase of pH from pH 6.5 to 7.1 did not essentially influence the levels of native β-lg and α-la in skim goat milk treated at 90 °C for 10 min, which were 1–3% and 3–4% of the initial, respectively. In the same study, under the same heating conditions, the increase of pH increased the level of native β-lg in cow milk from 2 to 7% and decreased native α-la from 30 to 24%. Apparently, the heat treatments applied in the later studies induced very high levels of denaturation that did not allow the emergence of different behaviours under different pH conditions.

The pH of goat milk before heating affects the partition of the denatured whey proteins in soluble complexes. On heating at 120 °C for 10 min of goat milk at pH <6.8, Anema and Stanley (1998) found very low levels of α-la and β-lg in non-sedimentable form, but an increase of pH from pH 6.8 to 7.6 caused a substantial increase, i.e., on average 20% of the total β-lg and 40% of α-la were in non-sedimentable form at pH 7.0. Also, Pesic et al. (2014) reported an increase of β-lactoglobulin in soluble complexes as pH increased. Under the same conditions, approximately 30% of each of denatured β-lg and α-la and of κ-casein were found in the soluble complexes in cow milk (Pesic et al., 2014). In particular, upon heating of goat milk at 90 °C for 10 min, at natural pH 6.7, denatured β-lg and α-la were not in soluble complexes. At pH 6.9 and 7.1, approximately 6 and 12% of total β-lg was in soluble complexes, respectively, but almost all α-la of heated goat milk remained associated with casein micelles under the same conditions. The increase of the pH from pH 6.7 to 7.1 of similarly treated cow milk increased both the β-lg and α-la in soluble complexes from approximately 30% to 50% (Pesic et al., 2014).

3.1.2. Salt equilibria

The forms and the partition of calcium and calcium-protein complexes are of paramount importance for the colloidal stability and the technological behaviour of heated milk. In brief, the highest proportion of calcium in milk is in the colloidal phase complexed mainly with phosphorus, that is, colloidal calcium phosphate (CCP). The most part of serum calcium exists in complexed forms mainly as calcium citrate followed by calcium phosphate and calcium chloride, while the concentration of free ionic form is 1.5–2 mM. A very small part of cations is bounded on whey proteins and two ions per mol are bound on α-lactalbumin. The very low concentration of ionic calcium is related to CCP through the equilibrium with calcium phosphate. It increases on acidification of milk, upon decrease of temperature or when soluble calcium salts are added. The opposite holds true for the increase of temperature. The inverse solubility of calcium phosphate, which is more soluble at low temperatures, induces calcium precipitation accompanied by release of hydrogen ions and decrease of pH (Barone, Yazdi, Lillevang, & Ahrné, 2021; Nieuwenhuijse & Huppertz, 2022). The pH of milk and the serum calcium and phosphorus of milk has been found inversely correlated with the temperature on heating from 20 to 80 °C of raw and condensed milk (Anema, 2009). Heating at 120 °C for <2 min followed by cooling down to 25 °C of cow milk protein concentrate reconstituted in simulated milk ultrafiltrate resulted in a decrease of pH from pH 6.65 to 6.37 due to re-equilibration of phosphates in the serum; moreover, calcium ion concentration was reduced from 2.36 to 1.47 mmol L^{-1} (Aydogdu, O'Mahony, & McCarthy, 2022).

Divalent calcium ions trigger protein aggregation at high temperatures by forming protein-calcium-protein complexes, by intramolecular electrostatic shielding of negative charges on the protein, or by ion-induced conformational changes that modify hydrophobic interactions (Petit, Herbig, Moreau, & Delaplace, 2011; Simons, Kosters, Visschers, & De Jongh, 2002). Barone et al. (2021) schematically depicted the phenomena involved in the aggregation of whey proteins mediated by ionic calcium. At first, calcium reduces surface potential of whey proteins, which in turn are associated via calcium bridges between the carboxylic group of aspartic and glutamic amino acids and attractive interactions between hydrophobic domains of protein.

Morgan et al. (2000) reported that samples of goat milk, stable upon heating at 120–150 °C for 1 min without pH adjustment, exhibited significantly higher pH, lower soluble calcium, i.e., 0.37 versus 0.44 g kg^{-1}, higher phosphorus, i.e., 0.96 versus 0.81 g kg^{-1}, and higher whey protein content, i.e., 7 versus 6 g kg^{-1}, compared with unstable counterparts. Heating of skim goat milk for 5 min in

Table 3
Partition of κ-casein and whey proteins in heat treated goat milk.[a]

Heating conditions		Preparation of serum/whey fraction	Phenomena	Reference
pH 6.7	70–80 °C for 5 min	50,000 × *g* for 120 min	Decrease of serum κ-CN from 45 to 20% of the initial; other caseins unaffected; reduction of β-lg up to 5% and of α-la up to 25% of the initial	Law et al., 1998
pH 6.9	80 °C for 1 min	Acid precipitation; then 3200 × *g* for 15 min	Large amount of soluble β-lg/κ-CN complex	Morgan et al., 2001
pH 6.4–6.8	>120 °C	65,000 × *g* for 60 min	30–45% of total κ-CN, 2–8% of total β-lg and 5–25% of total α-la in the serum	Anema & Stanley, 1998
pH 6.8–7.2	>120 °C		45–60% of total κ-CN, 10–20% of total β-lg and 25–50% of total α-la in the serum	
pH 6.7	90 °C for 10 min	Rennet induced or acid precipitation; then 3000 × *g* for 5 min	No κ-casein, β-lg and α-la in soluble complexes	Pesic et al., 2014
pH 6.9 and 7.1	90 °C for 10 min		10–20% of total κ-CN, 6 and 12% of total β-lg and no α-la in soluble complexes	
pH 6.9–7.3	140 °C	100,000 × *g* for 60 min	Increase of serum κ-CN from 4 to 24% of total	Yuan et al., 2022
pH 6.7	80–140 °C		Increase of serum κ-CN from 4 to 12% of total	

[a] Abbreviations are: κ-CN, κ-casein; β-lg, β-lactoglobulin; α-la, α-lactalbumin. In the work of Yuan et al. (2022), a dispersion of micellar goat casein concentrate was used in the experiments.

the range from 70 to 90 °C induced a slight increase of colloidal calcium and inorganic phosphate without changing their ratio that is close to 2 (Law et al., 1998). The results of Raynal and Remeuf (1998) showed that upon heating of goat milk at 90 °C for 1 min the concentration of diffusible calcium was decreased by 15%; this reduction was higher than that observed in sheep milk (≅10%) and cow milk (≅7%). A similar reduction of soluble calcium has been reported by Huang et al. (2022), who treated goat milk at natural pH for 10 min at temperatures from 45 to 95 °C. Soluble calcium decreased from approximately 430 mg kg^{-1} at to 400 mg kg^{-1} and 380 mg kg^{-1} upon heating at 75 °C and 95 °C, respectively; the reduction became statistically significant from 65 °C and thereafter.

De la Fuente, Olano, Casal, and Juarez (1999) found that the heat treatment of skim goat milk statistically significantly decreased the ionic calcium and the soluble calcium, phosphorus and magnesium contents of goat milk, as happened with cow milk heated under the same conditions. Indicatively, upon heating upon 75 °C for 30 min, soluble calcium of goat milk was 78%, soluble phosphorus was 89%, soluble magnesium was 87% and ionic calcium was 82% of those in non-treated milk. The respective percentages for similarly treated cow milk were 88, 92, 95 and 83%. In the same study, soluble mineral contents did not change when goat milk was treated at 85 °C for 20 s. Boumpa et al. (2008) did not observe change of the ionic calcium concentration in goat milk indirectly heated at 140 °C for 2 s; it was 2.3 and 2.2 mM before and after treatment, respectively. Later findings of Chen et al. (2012) showed that indirect UHT treatment at 140 °C for 5.6 s decreased ionic calcium from 1.9 to 1.7 mM, whereas in-container-sterilisation at 120 °C for 20 min reduced it markedly to 1.5 mM. According to Chen et al. (2012), the formation of calcium-mediated aggregates could explain the reduction occurred under in container-sterilisation conditions. The same group (Lin et al., 2006) had found that relatively small reductions in calcium induced larger reduction of ionic calcium in goat milk in a ratio of about 1:3.2.

The increase of pH from pH 6.5 to 7.3 decreased statistically significantly and linearly the calcium ion activity of a goat micellar casein dispersion (Yuan et al., 2022). A similar behaviour was observed in the same study for a cow counterpart that exhibited a lower calcium activity, by approximately 10%, at all pH values. Heating of goat milk without pH adjustment at temperatures higher than 95 °C for 7 s elevated significantly calcium and phosphorous in the sediment obtained by centrifugation. More specifically, UHT treatment at 137 °C for 7 s increased calcium and phosphorus in the sediment 3-fold and 2-fold, respectively compared with untreated milk. The addition of stabilising salts prevented their insolubilisation, in particular that of calcium (Zhao et al., 2020).

3.1.3. Changes and destabilisation mechanisms of casein micelles

The size and the native internal structure of the casein micelle size are modified upon heating due to the complexation of denatured whey protein and the deposition of calcium phosphate (Dumpler et al., 2020). Indicatively, cow casein micelle increases by 10 nm and 20 nm upon heating at 90 °C for 5 min and 10 min, respectively. The increase within the pH range of 6.5–6.7 is affected by small changes of pH values. At pH 6.5 more than 75% of the denatured whey proteins are associated with the micelles opposite to 30% occurring at pH 6.7 (Anema & Li, 2003). In fact, denatured whey proteins in the form of aggregates are associated with κ-casein on the surface of casein micelles inducing an increase in voluminosity and consequently in viscosity (Walstra et al., 2006). The modification of the native structure of casein micelles increases their sensitivity to low pH, high ionic strength and high calcium concentration due to the exposure of calcium sensitive caseins and the reduction of electrostatic and steric repulsion. On the other hand, the β-lg/κ-casein complexes on the cow micelle surface can act against casein heat aggregation at pH <6.7; under such conditions, complexed caseins and whey proteins aggregate together upon heating. At pH >6.7, heating generates aggregates of denatured whey proteins and κ-casein in the serum phase rather on the micelle surface and the κ-casein depleted caseins become susceptible to aggregation (Dumpler et al., 2020; Guyomarc'h, 2006). Interaction of cow denatured whey proteins with caseins at temperatures in the range 70–90 °C is differentiated according to pH as discussed in section 3.1.1 for whey proteins. After heating of cow milk at natural pH and subsequent acidification at pH 6.5 all denatured whey proteins are associated with casein micelle (Walstra et al., 2006).

The formation of β-lg/κ-casein in heat treated goat milk has been confirmed. Henry et al. (2002) investigated a high molecular mass complex of more than 100 kDa formed upon heating of goat β-lg and casein micelles at pH 6.7 or pH 6.9 at 80 °C for 10 min or at 115 °C for 20 s. They report that it was consisted of homopolymers of κ-casein and β-lg and a complex based on a disulphide bond between Cys_{160} of goat β-lg and Cys_{88} of goat κ-casein.

The behaviour of casein micelle upon heating at various pH is decisive for the heat stability of goat milk. Involved phenomena and factors, i.e., the dissociation of κ-casein, the increase in size, the interaction with minerals, the genetic polymorphism of caseins and the ratio of whey proteins, are discussed below. As mentioned before, the solubilisation of κ-casein upon heating and its relation to pH is one of the phenomena that affect the heat stability of milk. The reported values for heat treated goat milk summarised in Table 3 may differ due to different methods utilised for serum fractionation. Nevertheless, there is agreement that more κ-casein is dissociated from goat casein micelles upon severe heating at natural pH compared with cow milk.

Morgan et al. (2001) suggest that in goat milk the heat-induced interaction of β-lg with κ-casein is promoted at the pH 6.9 of maximum heat stability contrast to cow milk, which is stabilised against heating by the complexation of β-lg with κ-casein occurring at its natural pH. This suggestion is in accordance with the conclusion of Anema and Stanley (1998) who studied the heat induced dissociation of κ-casein from goat casein micelles on heating at 120 °C for 10 min and 140 °C for 2 min and at different pH levels. Under similar conditions, no α_{S2}-casein and low levels of α_{S1}-casein or β-casein were dissociated. Approximately 30–45% of κ-casein was in the non-sedimental form at pH 6.4–6.8, i.e., two to four times higher than the reported values for cow milk under the same conditions. Moreover, the increase of the level of the dissociation of κ-casein occurs at pH >6.8 while in cow milk occurs at pH >6.6. The high level of κ-casein dissociation from the micelle surface, combined with the high ionic calcium level of goat milk over pH range 6.4–6.7, accounts for low heat stability of goat milk under these pH conditions. The dissociation of κ-casein increased from 50% to 75% of total as pH increased from pH 6.8 to 7.4 along with increased amounts of non-sedimentable β-lg and α-la. Anema and Stanley (1998) propose that the combination of high amounts of non-sedimentable κ-casein and low levels of non-sedimentable β-lg at pH 6.8 in heated goat milk limits the interaction between these proteins – that seemed pH dependent in goat milk – and may result to the poor heat stability of goat milk at natural pH. The increase of heat stability at pH range 6.7–6.9 is assigned to the increase of net negative surface charge of the micelles and the decrease of ionic calcium level, in accordance to Zadow et al. (1983). Finally, at pH >6.9 and in particular at pH 7.2–7.6, the goat casein micelles excessively depleted from κ-casein have low surface charge, as happens in cow milk under similar conditions, and may be more sensitive to calcium compared with cow counterpart.

The amount of serum κ-casein in heat treated goat micellar casein dispersion has been found to be lower than that of unheated control in natural pH within the temperature range from 80 to 120 °C (Yuan et al., 2022). At 140 °C, κ-casein in the serum of goat milk was tripled from pH 6.9 to 7.3. Under the same temperature or pH conditions, the dissociation observed in cow casein dispersion was much lower. Finally, the conclusion of Yuan et al. (2022) was that the poor heat stability of goat milk casein dispersion was due to higher calcium ion activity and dissociation of κ-casein, that is in accordance with the suggestion of Zadow et al. (1983) and of Anema and Stanley (1998).

The findings of Pesic et al. (2014), mentioned before that in goat milk heated at 90 °C for 10 min at pH 6.9 and 7.1 much lower portion of β-lg was in soluble complexes than in cow milk, indicate that complexation on micelle surface is more favoured in goat milk at this pH range compared with cow counterpart. The same authors found differences in the micelle structure of the two milk kinds upon heating at pH range 6.5–7.1. The presence of α_{S2}- and β-casein on the surface of the goat casein micelle is suggested as a potential reason for the particular behaviour of goat milk upon heating. Seventy percent of total κ-casein, and 10% of α_{S2}- and β-casein, participated in micelle bound complexes of goat milk at pH 6.5. The increase of pH increased the percentage of α_{S2}- and β-casein to approximately 28%. Under the same heating conditions, κ-casein in the respective complexes of cow milk was increased from 8 to 52% of total κ-casein as pH increased from pH 6.5 to 7.1 (Pesic et al., 2014).

The distribution of whey proteins, caseins and minerals upon heating of goat milk at non-UHT conditions has been also investigated. The heating of goat milk from 70 °C to 90 °C, at pH 6.7 for 5 min had a limited effect on the concentration of α_{S1}-, α_{S2}- and β-casein in the serum obtained by ultracentrifugation. However, a 40% decrease of serum κ-casein was observed at 70 °C, which remained steady on treatments up to 90 °C (Law et al., 1998).

The role of the quantity of whey protein on the heat stability of goat milk was investigated by Bouhallab et al. (2002) by modifying the ratio of protein fraction using membrane processes. At natural pH, the decrease of the retention level of whey proteins increased the heat coagulation temperature, which was 135 °C and 141 °C for 95% and 15% retention, respectively. The casein to whey protein ratio of samples with enhanced heat stability was at least 1.4 times higher than in control natural milk. The increase of this ratio increased the heat coagulation temperature especially when casein content was higher than in natural milk. Interestingly, the most heat stable samples (≥146 °C) were those that had a low content of low molecular weight components and consequently of calcium in addition to a high casein to whey protein ratio. They suggested that the destabilising effect of whey proteins on the heat stability of goat milk at natural pH is similar to their destabilising effect observed in cow milk at pH 6.9.

Goat milk micelle has a greater size than that of cow counterpart (Table 2). The size of casein micelle can play a role in the heat stability of milk. O'Connell and Fox (2000) observed that larger cow casein micelles had lower heat stability compared with smaller micelles and suggested that their low content of κ-casein makes them more susceptible to precipitation induced by the calcium ions. The high degree of κ-casein glycosylation in the larger micelles is also likely to enhance β-lg/κ-casein complex formation, which also reduces stability in heat coagulation time- (HCT-) pH profile minimum. The particular features of the goat casein micelle in relation to the behaviour of goat milk upon heating has been the objective of several studies. Early experimental results on the heat stability of goat milk at 135 °C taken by Thompson, Bosweij, Martin, Jenness, and Kiddy (1969) showed that one of the factors involved in the heat-liability of goat milk samples was their lower casein-pellet-solvation level compared with cow counterparts, which was, on average, 1.60 and 1.90, respectively. Moreover, they observed that the highest heat stability of 180 s among the goat milk samples corresponded to the sample with the highest solvation of 1.97. Zadow et al. (1983) connects the low α_{S1}-casein content with different distribution of calcium and increased concentrations of phosphorus and ionic calcium of goat milk compared with cow milk.

The influence of the composition of the goat milk casein micelles on the heat stability in terms of the genetic polymorphism at the α_{S1}-casein locus has been investigated with contradictory results. The behaviour of goat milk with “strong”- or “weak”- α_{S1}-casein content, i.e., 19% or 2% on total casein, at 140 °C within the pH range from 6.4 to 6.7 was examined by Tziboula (1997). “Strong” milk was considerably less heat stable from pH 6.6 to pH 7.1 despite its lower calcium and lactose content. Addition of “weak” to “strong” milk improved substantially the heat stability of the latter. When “strong” milk casein was resuspended in the serum of “weak” milk, the HCT at natural pH 6.6 increased ten-fold; the opposite was true when “weak” milk micelles were resuspended in “strong” milk serum. The findings of Tziboula and Horne (1999) indicated that “weak” α_{S1}-casein might be located on the surface of the micelles due to lack of a phosphoserine cluster.

In contrast to Tziboula (1997), Remeuf (1993) did not observe any influence of α_{S1}-casein genotype on the heat stability of goat milk under UHT conditions. Morgan et al. (2000) reported that the heat stable and heat unstable milks did not differ in terms of the composition of the casein fraction. Later, Manfredi et al. (2002) found that goat milk from goats homozygous for “strong” genotypes had higher heat stability than “medium” counterpart. “Strong” and “weak” goat milk with 26% and 2.2% α_{S1}-casein on total casein, respectively were heated at 120–150 °C, for 1 min in the pH range 6.5–7.2 by Morgan et al. (2001). The profile of heat stability expressed as °C in relation to pH were identical for both milk kinds with maximum at pH 6.9. However, it was the addition of whey protein that caused a statistically significant reduction of heat stability of “weak” milk at pH >6.9 while it did not affect “strong” milk. Although the level of denaturation of β-lg in goat whey protein concentrate was lower at pH 6.9 compared with pH 6.7, the opposite was true in the presence of both “strong” and “weak” goat milk casein micelles.

The effect of heating on casein micelle size has been found different between goat and cow milk although some findings are not in agreement with each other. This effect was investigated in the comparative study of Raynal and Remeuf (1998), who treated defatted goat, sheep and cow milk at 75, 89, 85 and 90 °C for variable intervals from 0.5 to 10 min, under batch conditions, at pH 6.5. In general, changes in the cow casein micelle size were not observed up to 90 °C whereas heating at 85 °C for 10 min and at 90 °C for 1 min increased goat casein micelle size by 25%.

The above-mentioned study of Heilig et al. (2008), after differential evaluation of the results with and without phosphate addition, concluded that graininess, sedimentation and occurrence of heat coagulation in ultrapasteurised and UHT goat milk are related to the increase of the casein micelle size. In contrast to mean cow milk micelle size that was 202 nm in pasteurised milk and 248 nm in UHT-steam injection milk, a substantial increase of the size of goat milk micelles was observed. Starting from 224 nm in pasteurised goat milk the size of micelles increased to 451 nm in ultrapasteurised milk and to 1260 nm in UHT-steam injection milk. Heilig et al. (2008) concluded that in the beginning the increase of micelle size results from the association of β-lg with κ-casein in the micelle surface, but under UHT conditions the formation whey protein-mediated-crosslinked casein clusters occurs. The findings of Chen et al. (2012) for in-container sterilised goat milk confirmed

that excessive sediment is related to heat-induced increase of casein micelle size followed by casein-mediated aggregation of casein micelles or further association of whey protein aggregates.

In the study of Zhao et al. (2020), heating above 85 °C increased the size of goat milk casein micelle significantly more than that of similarly treated cow milk. In particular, UHT treatment increased from 200 to 480 nm and from 190 to 287 nm the size of casein micelles of goat and cow milk, respectively. The treatment of goat milk at 90 °C for 5 min applied in yoghurt manufacture increased the mean micelle size in the experiments of Li et al. (2022) by 16% from 212 to 245 nm, which was higher compared with a 6% increase observed in similarly treated cow milk. At 120 °C the increase of micelle size was affected by the pH in the study of Yuan et al. (2022). A profound increase occurred at pH 6.5, 6.7 and 6.9 in a goat micellar casein dispersion while in cow counterpart an increase took place at pH 6.5 and 6.7.

Increase of goat milk micelle size was observed also after batch treatment at milder than UHT conditions (Hovjecki et al., 2020). Pasteurisation at 72 °C for 30 s had no effect. Heating at 85 °C and at 95 °C for 5 min increased the goat casein micelle size by approximately 42% and 27%, respectively. They suggested that the lower decrease observed at 95 °C implied a release of the aggregates into the serum phase. On the other hand, Han et al. (2021) did not observe any increase of casein micelle size of both goat and cow milk after treatment at 90 °C for 15 s. The diameter of goat milk micelle was 226 and 220 nm before and after heating and the respective values for cow milk were 179 and 165 nm.

3.2. Heat stability patterns of goat milk

Heat stability is the ability of milk to withstand high processing temperatures without visible coagulation or gelation. It is expressed as HCT in relation to pH and is largely affected by the concentration of calcium ions (Singh, 2004). Objective methods used for the determination of heat stability are grouped in two categories (Dumpler et al., 2020). The first category consists of methods based on the automated measurement of physical parameters such as viscosity that change upon coagulation. Alternatively, changes of the secondary structure of proteins can be correlated with the onset of coagulation and the quantity of aggregated protein. The second category consists of methods that determine the residual soluble proteins after heat treatment (Dumpler et al., 2020). Milk pH is the most important factor for the heat stability of milk, i.e., the temperature at which coagulation occurs decreases with the as pH decreases (Walstra et al., 2006). In general, heat stability of cow milk is improved by reducing calcium ion activity, by associating whey proteins with casein micelles, by reducing the sensitivity of casein to calcium ions and by the products of thermal degradation of lactose (Singh, 2004). Forewarming or preheating cow milk before concentration or sterilisation denatures whey proteins and shifts the maximum HCT when pH is lower than 6.6 (Dumpler et al., 2020). However, preheating has a very limited or no effect on the heat stability of plain milk (Walstra et al., 2006).

The heat stability of goat milk at its natural pH 6.6–6.7 has been proven to be low (e.g., Anema & Stanley, 1998; Fox & Hoynes, 1976; Raynal-Ljutovac, Park, Gaucheron, & Bouhallab, 2007; Zadow et al., 1983). The experiments of Fox and Hoynes (1976) showed that at 140 °C the maximum heat coagulation time of goat milk samples, with highly variable heat stability, was observed at pH close to 7.0. The stability was markedly decreased at higher pH, which is opposite to cow milk. Following the research on the heat stability of cow milk, Zadow et al. (1983) investigated the effect of pH on the heat stability of goat milk under UHT processing. They applied a preheating step at 75 °C, direct heating at 140 °C for 3 s and downstream homogenisation in two stages. At the pH range from 6.6 to almost 6.9, the sedimentation was severe and it was evident at pH higher by 0.3–0.4 of a pH unit compared with the appearance of sediment in cow milk. The higher ionic calcium content of goat milk than that of cow milk, i.e., 3.5 and 2.5 mM, respectively, was suggested as a factor for the inferior heat stability of the former. Instability at higher pH appeared when 0.05% calcium chloride was added in goat milk that increased the ionic calcium to 4.5 mM (Zadow et al., 1983). Accordingly, Montilla and Calvo (1997) found that goat milk directly heated at 140 °C for 2 s at natural pH 6.7 coagulated but withstood the same treatment at pH >6.8.

The low heat stability of goat milk at its natural pH 6.6 and in pH >6.9 has been also depicted in the experiments of Anema and Stanley (1998), who investigated the involved phenomena over a pH range. They report a differentiation of the shape of HCT-pH profile and a 7-fold increase of HCT as pH increased from pH 6.60 to pH 6.91. Unlike the HCT of cow milk, which increases from pH 6.4 to pH 6.7 then decreases at pH 6.9 and increases at pH >6.9, the heat stability of goat milk remained low from pH 6.4 to 6.7. Then, it increased constantly from pH 6.7 to pH 6.9 and then decreased under both the heating conditions that used in the experiments. A similar HCT-pH profile of goat milk at 140 °C has been also shown in the study of Tziboula (1997). The results of Saipriya et al. (2021) showed a maximum heat stability of goat milk at 140 °C in a lower pH range, i.e., within pH 6.7 and 6.8. Saipriya et al. (2021) also reported that pre-pasteurisation or boiling of milk before high-heat treatment increased the heat stability by approximately 10% and shifted its maximum to pH 6.8–6.9.

To avoid the instability appeared at 120 °C or 140 °C, the heat coagulation temperature at a fixed time (HCTEM) has been used in several studies instead of the heat coagulation time at a fixed temperature (e.g., Bouhallab et al., 2002; Manfredi et al., 2002; Morgan et al., 2001, 2003). HCTEM is the maximum temperature within the range from 80 to 140 °C, at which milk remains stable for 1 min. The heat coagulation temperature for 1 min treatment at natural pH of goat milk from various sources has been found highly variable ranging from 92 to 130 °C (Morgan et al., 2003).

The effect of heating conditions and of indirect or direct (steam infusion or injection) heating method on the stability and sensorial properties of goat milk has been investigated by Heilig et al. (2008) in comparison with cow milk. Skim or whole homogenised milk was pasteurised at 72 °C for 32 s. After a preheating step at 90 °C for 40 s, ultrapasteurisation was performed at 120 °C and UHT treatment at 140 °C for 4 s or for 10 s for steam injection or infusion, respectively. Cow milk was stable during the processing and storage while goat milk coagulated during indirect UHT treatment. Moreover, contrast to cow milk, the ultrapasteurised and in particular the UHT goat milk exhibited graininess that was very intense for the indirect process. A great amount of sediment was produced during the storage of UHT milk even when it had received lower heat load by means of steam infusion, i.e., 15.5% and 22% for skim and whole goat milk, respectively (Heilig et al., 2008).

The experiments of Yuan et al. (2022) point out the differences in the heat stability upon heating at 120–140 °C of goat and cow micellar casein dispersions, that is, in the absence of whey proteins. The HCT of goat micellar casein dispersion was markedly lower than that of cow counterpart, which was in accordance with the higher sedimentation of the former. At 70 °C the HCT was 100 ± 7 s and sedimentation estimated by centrifugation was observed after treatment at 70 °C for 90 s from pH 6.3 to pH 6.7. At pH >6.8–6.9 the sedimentation was markedly decreased while in cow milk a decrease was clearly evident at pH 6.7. The sediment of goat milk was substantially higher than that of cow milk and remained rather constant from 70 to 110 °C. Between 120 and 130 °C it increased significantly, while the increase in cow milk was much stronger.

Boumpa et al. (2008) analysed the sediment formed upon indirect UHT goat milk processing of goat milk at 140 °C for 2 s. The results showed that sediment formation was temperature dependent and was mainly consisted of fat and protein, at ratios from 1.48 to 1.63, while its mineral content was usually less than 5% of dry weight. The ratio of phosphorus to calcium was 0.96–1.50, that is, much higher than in milk and casein micelle fraction, i.e., 0.78 and 0.48, respectively.

Even at 80 °C for 20 s in plate heat exchanger, goat milk produced approximately 50% more deposit than cow milk, which contains 35% more ash and 50% more protein than cow milk (De Raphael & Calvo, 1996). Under different centrifugation conditions, the precipitate of goat milk heated at 70, 80 and 90 °C for 5 min was higher compared with cow milk (Miloradovic, Kljajevic, Jovanovic, Vucic, & Macej, 2015). In particular, treatment at 80 °C and 4500 × *g*, resulted in a precipitate of goat milk that was approximately three times higher than that of cow milk; after treatment at 90 °C it was four times higher. Skimming of heat treated goat milk increased protein precipitation whereas a similar effect was not observed in cow milk (Miloradovic et al., 2015).

3.2.1. Modification of the behaviour of goat milk upon heating

Various types of stabilisers-ion sequestering agents have been utilised for the improvement of the heat stability of goat milk. Also, supplementation with calcium chloride has been applied in some studies to investigate the effect of the increase of calcium ions (Table 4). The findings of these studies have been helpful for the understanding of the mechanisms involved in the behaviour of goat milk upon heating (section 3.1.3).

In the study of Zadow et al. (1983), goat milk supplemented with 0.2% sodium dihydrogen phosphate tolerated UHT processing at pH 6.72. The addition reduced the ionic calcium of raw goat milk from 3.2 mM to 1.4 mM, which was lower than 2.9 mM, above which instability was observed. Montilla and Calvo (1997) found that the addition of a commercial phosphate mixture at 0.3 and 0.5% caused a limited decrease of the level of denaturation and increased milk pH to pH 6.93. Although the effect of the experimental factors (pH and phosphates) on whey protein denaturation was limited, it was shown that the positive effect of added phosphates on heat stability at 140–145 °C was more profound compared with pH adjustment. However, at 135 °C the two factors had a similar effect.

Prakash, Datta, Lewis, and Deeth (2007) observed severe fouling upon UHT treatment of whole goat milk at 135 °C for 4 s, which was significantly decreased when ionic calcium was bound by 0.2% sodium hexametaphosphate (SHMP) or trisodium citrate (TSC) or by treatment with cation exchange resin at 30 g 10 L^{-1}. TSC decreased by more than ½ the ionic calcium, the decrease by SHMP was 3-fold, while cation exchange resin reduced it by $^1/_3$. The initial pH was 6.61 and the respective pH after the above-mentioned treatments was pH 6.80, pH 6.62 and pH 6.65, respectively. The results showed that a reduction of ionic calcium in goat milk to less than 2 mM by chemical bonding or ion exchange increases the run time in UHT plant from 10 min to about 30–35 min. The authors suggest that calcium-sequestering agents reduce the colloidal calcium phosphate and increase soluble phosphate that does not favour the tendency of micelles to coagulate and form deposits.

In the experiments of Bouhallab and Raynal-Ljutovac (2005) with skim goat milk that exhibited its highest heat stability at 137 °C, at natural pH, the addition of citrate had stronger stabilising effect in lower concentration compared with disodium hydrogenophosphate and to a neutral phosphate mix. In particular, the addition of 3 mM of trisodium citrate, disodium hydrogenophosphate and neutral phosphatase mix shifted the highest heat stability to 149, 147 and 141 °C, respectively. The addition of trisodium citrate apart from increasing the pH by 0.1 unit was more advantageous. The following facts have been suggested by the authors. Firstly, the addition of low quantity of trisodium citrate increased substantially more the soluble calcium by binding ionic calcium in pasteurised goat milk compared with phosphates. Moreover, citrate induces solubilisation of highly phosphorylated α_S- and β-caseins increasing thus the disintegration of casein micelles and viscosity that do not favour aggregation. On the contrary, the binding of ionic calcium by phosphates may result in the destabilisation of casein micelles due to the precipitation of calcium phosphate on them. They report that the addition of 1 mM

Table 4
Studies using additives in heat treated goat milk.[a]

Additives	Treatments	Estimated parameters	References
SDHP at 0.2%	Direct UHT 140 °C for 3 s	pH, reflectance, ionic calcium	Zadow et al., 1983
Commercial mixture of SDHP, DSHP and TSP at 0–0.09%	Direct 135–145 °C for 20 s; indirect 135–150 °C for 3–15 s at pH 6.7–7.2	pH, whey protein denaturation	Montilla & Calvo, 1997
DSHP at 1–6 mM; neutral mix of DSHP and SDHP at 1–6 mM; TSC at 1–4 mM	73 °C for 30 s and 85 °C for 1 min in water-bath	pH, heat stability, soluble calcium, soluble proteins	Bouhallab & Raynal-Ljutovac, 2005
SHMP or TSC at 0.2% or cation exchange resin in milk and then filtering	Indirect UHT at 135 °C for 4 s	pH, ionic calcium, ethanol stability, overall heat transfer coefficient (fouling)	Prakash et al., 2007
TSC, SHMP, DSHP or SDHP at 0.1–0.3%	Indirect UHT 140 °C for 2 s with upstream homogenisation	Total calcium and phosphorus, ionic calcium, dry sediment, composition	Boumpa et al., 2008
Commercial mixture of SPP and TSP at 0.05%	Ultrapasteurisation 120 °C for 4 s or 10 s, UHT 140 °C for 4 s or 10 s, indirect or direct heating (preheating 90 °C for 40 s)	Sensory analysis, sedimentation during storage, casein micelle size	Heilig et al., 2008
TCS or DSHP at 6.4–12.8 mM; calcium chloride 0.5–2 mM	Indirect UHT 140 °C for 5.6 s; in-container sterilisation 120 °C for 20 min	Sedimentation, pH, ionic calcium, ethanol stability, casein micelle size	Chen et al., 2012
DSHP, STPP and TCS (1:3:6) at 0–0.3%	Tubular heat exchanger 65–137 °C for 7 s	Sedimentation, particles distribution, protein structure, calcium and phosphorus	Zhao et al., 2020
TSC at 1–10 mM; sodium chloride at 25–600 mM; calcium chloride at 0.5 or 1 mM	140 °C in oil-bath until visible coagulation	HCT, sedimentation, serum caseins, particles distribution	Yuan et al., 2022

[a] Abbreviations are: DSHP, disodium hydrogen (ortho)phosphate; SDHP, sodium dihydrogen (ortho)phosphate; SHMP, sodium hexametaphosphate; SPP, sodium polyphosphate; STPP, sodium tripolyphosphate; TSC, trisodium citrate; TSP, trisodium (ortho)phosphate.

phosphates induces a limited increase of soluble calcium but decreases it when added at concentrations of 3 or 6 mM. Trisodium citrate induced less sedimentation than phosphates in UHT goat milk after 6- and 9-weeks storage. In the same study, it was shown that cold storage at 4 °C for 72 h before pasteurisation decreased substantially the heat stability of supplemented goat milk. As in a previous study of the same group (Bouhallab et al., 2002), the increase of casein to whey ratio from 4.8 to 6.7 increased the heat stability temperature from 135 to 141 °C.

The use of various stabilisers in the previously mentioned experiments of Boumpa et al. (2008) did not change the components of the sediment formed upon UHT treatment but, they increased the ratio of phosphorous to calcium in it. Sodium dihydrogen orthophosphate (SDHP) reduced the pH from 6.56 to 6.29, did not decrease the ionic calcium and increased sedimentation causing noticeable fouling within minutes from the start of UHT process. The addition of TSC, SHMP and disodium hydrogen orthophosphate (DSHP) reduced ionic calcium and sediment. DSHP was the most effective at similar levels of ionic calcium while SHMP increased substantially the ash and phosphorus content of the sediment. Interestingly, more sediment than expected was observed in some of the supplemented milk samples as observed also later by Chen et al. (2012). Boumpa et al. (2008) concluded that any factor, which change the negative charge on the micelle (e.g., calcium, hydrogen, sodium, potassium and magnesium ions) or modify ionic calcium activity (such as changes in phosphates and citrates) or the components of the casein fraction can influence the heat induced sediment formation. Similarly to Bouhallab and Raynal-Ljutovac (2005), Boumpa et al. (2008) suggest that an intense reduction of ionic calcium may destabilise casein micelles that become more susceptible to aggregation. On the contrary, a moderate reduction of ionic calcium increases the negative charge of casein micelles that does not favour their aggregation.

The experiments of Chen et al. (2012) were performed with semi-skim pasteurised goat milk subjected to UHT or in-container sterilisation, supplemented with TSC and DSHP, without pH control. In accordance with the previous work of this group (Boumpa et al., 2008) and the remarks of Bouhallab and Raynal-Ljutovac (2005), they report that both the increase and the decrease of ionic calcium can induce poor heat stability of goat milk as explained previously (section 3.1.2). In particular, the addition of both types of stabilising salts up to 6.4 mM decreased sediment down to 0.5–1% with DSHP being slightly less effective in UHT progress. Concentrations above 9.6 mM increased substantially the sediment. The pH increased from pH 6.71 to pH 6.81 and 6.98 for goat milk treated with 3.2 and 9.6 mM TSC. On the other hand, the increase of pH by DSHP at the same concentrations was much lower, i.e., to pH 6.77 and 6.98, respectively. Also, the UHT processing caused a small decrease of pH of treated milk samples by −0.05 and −0.07 pH units, on average. The suggested optimum concentration for both additives and processes was close to 6.4 mM. At this level of stabiliser, the ion activity was close to 55% of the initial, which was reduced further by 10% and 20% for UHT and in-container sterilisation treatments, respectively.

Heilig et al. (2008) report that the addition of a commercial sodium phosphate mixture at 0.05% inhibited graininess and sediment formation in ultrapasteurised and UHT skim and whole goat milk. In indirectly ultrapasteurised whole goat milk, the average decrease of graininess was from 5.7% to 1.2% (w/w), in steam infusion ultrapasteurised skim goat milk from 1.2% to zero and in whole milk from 2.4% to 0.2%, while in steam infusion UHT-heated skim milk the reduction was from 2.2% to 1%.

The addition of a mixture of stabilising salts consisting of DSHP, sodium tripolyphosphate (STPP) and TSC at a ratio of 0.15% decreased the aggregation in UHT goat milk in the study of Zhao et al. (2020). The induced changes were the reduction of the size of the micelle size, chelation of calcium ions, reduction of the amounts of calcium and phosphorus in the sediment, change of the charge of proteins and control of the changes of their secondary structure caused by UHT treatment, i.e., limitation of the reduction of β-sheets and β-turns and increase of random coil and α-helix in whey proteins (Zhao et al., 2020). The addition of calcium chloride up to 1 mM in a goat micellar casein dispersion at the natural pH 6.9 decreased the HCT at 120 °C by approximately 50%, similarly to cow counterpart. The result of TSC addition was a strong increase of HCT of goat milk, i.e., 5 mM citrate doubled the HCT; nevertheless, under the same conditions, the increase of HCT of cow counterpart was higher (Yuan et al., 2022).

Therefore, the effect of stabilising salts on the heat stability and the behaviour of goat milk upon heating at natural pH depends on the type and the concentration of salt and the conditions of processing and their interactions.

3.2.2. Ethanol stability and heat stability

Ethanol stability of milk is the maximum concentration of an ethanol solution added at equal quantities to milk, that does not induce coagulation. Before the presentation of the limited findings about ethanol stability profile of goat milk, a very concise presentation of important facts about the ethanol stability of reference cow milk follows. The primary use of ethanol stability test was the rapid assessment of the microbiological quality of milk and it has been proposed as predictor of the stability of milk to UHT processing. However, its reliability is under question, since many factors, such as season, diet, and stage of lactation can affect the outcome of the test (Horne & Muir, 1990). For example, the experiments of Chavez, Negri, Taverna, and Cuatrín (2004) showed that ethanol unstable cow milk samples, precipitation observed at ≤72% ethanol, of good microbiological quality, at natural pH had significantly lower casein number (73.5% versus 74.45), higher chloride, sodium and potassium contents, higher Na/K ratio (0.34 versus 0.30) and lower pH (pH 6.68 versus 6.71), while ionic calcium was similar to that of samples stable at 78% ethanol. Although the mean heat stability of ethanol unstable milk samples was lower than that of stable samples, there was a large range of intersection between the heat coagulation times of the two groups indicating that alcohol test was not successful predictor of heat stability.

Donnelly and Horne (1986) concluded that the major factor determining alcohol stability at any pH is the level of divalent cations. Salt balance is correlated with the ethanol stability at natural pH of cow milk, while usually soluble inorganic phosphorus contributed substantially to the variable salt profile throughout lactation. According to models constructed by Chavez et al. (2004), the content of chloride, potassium and ionic calcium along with somatic cell counts play a role in the ethanol stability of cow milk with good microbiological quality at natural pH. On the other hand, the pH and the concentrations of calcium, ionic calcium, phosphorus and urea were included in the heat coagulation model obtained by heating at 140 °C until the appearance of clots. Although the ionic calcium was in both models, it was more important for heat coagulation than for alcohol stability. As concluded by Horne and Muir (1990), the mechanism of ethanol-induced coagulation is dominated by physical interactions, while heat coagulation is controlled mainly by chemical reactions especially upon prolonged heating; a similar behaviour in alcohol and heat stability tests can be achieved if there is a reduction in the chemical reactions.

A possible connection between ethanol and heat stability of goat milk has been investigated. Horne and Parker (1982) observed much lower ethanol stability of skim goat milk in comparison with cow counterpart at a wide pH range (40% versus 85%, at natural pH). Increase of pH from pH 6.0 to pH 7.6 induced a sigmoidal increase of

ethanol stability that was shallower in skim goat milk compared with cow counterpart. The reduction of available calcium shifted the ethanol stability profile to lower pH for both milk kinds. Based on experiments with resuspended micelles, applying chemical modification of proteins and diafiltration treatment, they suggested that the low heat stability of goat milk is rather related to micelle particularities, such as low charge and low α_{S1}-casein content, than to effects of any combination of serum ions.

The results of Guo et al. (1998) confirmed the lower ethanol stability of goat milk and its shallow sigmoid increase as pH increases. At natural pH, the average ethanol stability of goat and cow milk was 44% and 72%, respectively. In goat milk, it increased from approximately 45% at natural pH to 70% at pH 7.1. They connect the low ethanol stability with potential instability at UHT processing. According to their findings the increase of Na/K ratio by adding NaCl considerably increased ethanol stability of goat milk, e.g., ethanol stability almost doubled at natural pH by adding 2% NaCl. The addition of KCl had an opposite effect. Recently, de la Vara et al. (2018) confirmed that ethanol stability behaviour of goat milk is clearly different from that of other ruminants milk. They report a mean ethanol stability of 50%, 63% and 83% for goat, sheep and cow milk, respectively. Moreover, the positive effect of the increase of pH was lower compared with cow and sheep milk.

Zadow et al. (1983) related the decrease of ionic calcium content of goat milk as pH increased from pH 6.5 to 6.9 to a possible increase of ethanol stability and UHT-stability as had been reported for cow milk. Prakash et al. (2007) observed that the reduction of fouling upon UHT processing (135 °C for 4 s) of whole goat milk induced by the addition of calcium sequestering agents coincided with a substantial increase of ethanol stability. More specifically, a 2-fold or 3-fold decrease of ionic calcium increased the ethanol stability from 58% in raw milk to 82% and 98%, respectively in UHT treated milk. Considering previous findings, the authors attribute the low ethanol stability of goat milk to reduced negative charge of casein that tends to collapse in the presence of alcohol. The increase of pH increases ethanol stability since calcium ions are reduced by sequestration by phosphates in the milk serum. The addition of calcium sequestering agents reduces calcium ions and colloidal calcium phosphate and increases the level of soluble phosphates in milk serum.

Boumpa et al. (2008) estimated ethanol stability before and after UHT processing of goat milk supplemented with various stabilisers. Similarly to the previous study, the addition of stabilisers reduced ionic calcium and changed ethanol stability but not in a consistent manner. Small improvements in ethanol stability were more effective with DSHP than with TSC and especially SHMP. Moreover, there was a significant correlation between calcium ions and ethanol stability before heating while the opposite was true for pH and ethanol stability. The conclusion was that ethanol stability was not reliable for the prediction of sediment formation upon UHT processing of goat milk, in accordance with the results of Chen et al. (2012). However, these publications propose that when determination of ionic calcium cannot be performed, the ethanol stability test could be useful, in particular for indirect UHT sterilisation if milk is not in the region of poor heat stability occurring at low concentrations of ionic calcium (sections 3.1.2 and 3.2.1).

3.2.3. Other factors

HTC variability among different lots of cow milk and often throughout season may arise from the variation of urea concentration. Urea is the most abundant component of the NPN fraction of milk with mean concentration 250 mg kg^{-1} ranging from 84 to 280 mg kg^{-1}. The increase of the urea content results in the increase of milk heat stability partially by limiting the reduction of pH (Walstra et al., 2006). Heat stable and unstable goat milk samples did not differ in terms of urea composition (approximately 700 mg L^{-1}, on average), according to Morgan et al. (2000). The removal of urea from "weak" α_{S1}-casein goat milk decreased by half the HCT at 140 °C at pH 6.7–7.1, despite the concomitant increase of pH. Based on this finding, Tziboula (1997) suggested that the lower urea content of "strong" goat milk than that of "weak" counterpart could be related to its inferior HCT.

Physiological factors that affect the pH and the fine composition of raw goat milk has been found important for the heat stability of cow milk. In the study of Christodoulopoulos et al. (2008), the heat stability in terms of heat coagulation temperature was negatively affected by oestrus. During this period, goat milk pH decreased from 6.65 to 6.45 while SCC increased from 8×10^5 mL^{-1} to more than 10^6 mL^{-1}, which coincided with a substantial decrease of heat coagulation temperature from approximately 125 to 95 °C.

Manfredi et al. (2002) report that heat stability increased from kidding up to 150 days of lactation and decreased thereafter. However, Anema and Stanley (1998) found that the lactation season had no significant effect on the behaviour of goat milk upon UHT processing. According to the results of Li et al. (2022), the level of whey protein denaturation and whey protein–casein micelle association were the highest in winter and the lowest in spring whereas the heat-induced increase in casein micelle size was not affected by the season. The viscosity of the heated goat milk treated at 95 °C for 5 min was the lowest in the summer, being correlated with the contents of fat and total solids and not to the heat-induced change in micelle size.

4. Effect of heat treatment on technological properties of goat milk

The behaviours of milk upon treatment with rennet or upon biological acidification are technological properties of major importance for the manufacture of dairy products, such as cheese and yoghurt. Since heat treatment is an essential step in the manufacture of these products, the formation of rennet- and acid-induced gels from heat treated goat milk has been studied often in parallel to similarly treated cow milk.

In the early study of Montilla et al. (1995), the rennet clotting time (RCT) of cow milk increased linearly with heating time for treatment up to 70 °C and then markedly at higher temperature, as expected, i.e., treatment for 5 min at 70 °C and 80 °C corresponded to an RCT of approximately 20 and 40 min. On the other hand, the RCT of goat milk remained almost steady within 6–7 min, for heating up to 85 °C for 5–35 min. Accordingly, the curd forming rate of goat milk was slightly affected, i.e., for 5 min treatment it was 3.6 at 70 °C and 6.3 at 85 °C. This parameter could not be estimated in cow milk treated at >75 °C since extremely weak curds without detectable consistency were produced. The level of denaturation of whey proteins was not correlated with RCT of goat milk opposite to cow milk. Interestingly, dialysis of cow milk against goat milk resulted in a substantial decrease of RCT of the former. While the addition of calcium chloride in heated cow milk at 70 °C for 30 min decreased markedly the RCT (approximately 6-fold upon 4 mM calcium chloride), a much lower reduction close to 10% was observed in goat milk under similar conditions. The authors (Montilla et al., 1995) assign the different behaviour in the differences of individual casein composition and casein micelle size.

Calvo (2002) confirmed that treatment at 70 °C for 30 min does not affect the RCT and rate of curd firming of goat milk, opposite to cow milk. Moreover, they observed that the glycomacropeptide (GMP) formation was slower in goat milk compared with cow milk, despite the lower RCT of the former. They ascribed the lower RCT of goat milk to faster micelle aggregation. Heating slowed down the

GMP formation in cow milk, while there was no effect of on goat milk. A significantly higher drainage rate of rennet induced curds was found by Calvo and Balcones (2000) for heat treated goat milk at 70 °C for 5 or 30 min than cow and sheep counterpart. The heating conditions 70 °C for 30 min decreased drainage rate by approximately 25%, while in cow milk the decrease was 50%. The same group (Calvo & Balcones, 1998) found that heating of goat milk at 75 °C, 80 °C and 90 °C for various time intervals increased significantly the cheese yield, expressed as the pellet weight obtained by centrifugation of the curd. The increase was significantly more than in the respective cow counterpart at 75 °C; nevertheless, at ≥80 °C, cow milk did not coagulate.

In accordance with the above-mentioned findings, Raynal and Remeuf (1998) observed that RCTs of goat and sheep milk were much less impaired by heat treatment compared with cow milk, which could not form gel after treatment at 90 °C for 1 min. On the contrary, the RCT of goat milk treated at 90 °C for 5 or 10 min or higher was close to the RCT of untreated milk. The gel strength was impaired after treatment at temperature equal or higher than 80 °C, especially for long heating times. For example, at 80, 85 or 90 °C for 5 min, the gel strength was 74, 64 and 52% of the initial, respectively. The respective values for cow milk were substantially lower, i.e., 47, 52 and 17%, respectively. The theoretical maximum gel strength considered as firmness of goat milk was not affected by heating at 90 °C even for 10 min, while in cow milk it could not be estimated after 1 min heated at 90 °C. Raynal and Remeuf (1998) proposed, similarly to Montilla et al. (1995), that the level of whey protein denaturation may not be a limiting factor for the secondary phase of rennet clotting, in contrast to cow milk; the correlation coefficient between RCT and percentage of denatured whey proteins in cow and goat milk was 0.65 and <0.01, respectively. The decrease of whey draining capacity due to heating was much lower in goat milk compared with cow milk. In particular, after 1 min treatment at 80, 85 or 90 °C, it was approximately 90, 60 and 55% of the initial, while the respective values for cow counterpart were 60, 35 and 25%. Considering that the cross-linking capacity within the goat milk was not affected by heating, Raynal and Remeuf (1998) proposed whey draining of heated goat milk was hindered only by the increased water holding capacity of denatured whey proteins.

Alloggio et al. (2000) found that heating at 80 or 90 °C for 1, 3 or 10 min decreased significantly the RCT of goat milk, but at a different level in respect to the duration of heating; however, there were differences among the RCT of heat treated milk from different goat breeds. A dramatic increase of RCT of cow milk analysed under the same conditions was observed. In contrast, pasteurisation at 63 °C for 30 min or 72 °C for 10 s and especially boiling at 100 °C increased more than two times the rennet gelation time of goat milk and reduced the coagulum strength in the study of Saipriya et al. (2021).

High heat treatment at 80 or 90 °C for 5 min of goat cheese milk increased the yield in fresh cheese by more than 30%, although moisture on non-fat substances at day 40 was similar to that of control. Changes of some textural parameters were observed but not in a consistent manner during ripening. Moreover, cheese pH at day 10 and thereafter was lower when high-treated cheese milk was used, which was assigned to the initially higher moisture levels of the curd (Miloradovic et al., 2017). The cheese whey resulted under these cheesemaking conditions had significantly lower total solids when cheese milk was treated at 85 or 90 °C for 5 min compared with control treatment at 65 °C for 30 min, i.e., lower by 10% or 15%, respectively. Accordingly, there was a severe reduction of total protein by 22 and 45%, respectively since a considerable amount of denatured whey proteins is expected to be retained in the curd.

The RCT of heat treated goat milk was affected by flow-through heat treatments, in the experiments of Moatsou et al. (2021). Treatments more intense than 73 °C for 16 s increased the RCT of goat milk significantly but inconsistently and decreased curd firmness. Heating at 100 °C for 16 s increased the RCT by 40% and 20% as compared with raw and pasteurised goat milk, respectively; consequently, gel firmness was substantially reduced. Interestingly, the rennet clotting parameters of control goat milk batch heated at 90 °C for 5 min were similar to those of pasteurised milk. A similar finding is presented by Raynal and Remeuf (1998), who found that the RCT and gel firmness of rennet gels from goat milk heated under batch conditions at 90 °C for 1–10 min were close to pasteurised counterpart.

The course of acidity development during the thermophilic fermentation of heat treated goat milk was not affected by flow-through heating from 73 to 100 °C for 16 s or by batch heating at 90 °C for 5 min (Moatsou et al., 2021). The acidification course of reconstituted cow skim milk powder treated at 90 °C for 5 min was significantly slower compared with goat milk counterparts. In the same study, the water holding capacity (WHC) of yoghurt-type gels was significantly affected by the conditions of heat treatment. The WHC of the gels from goat milk treated at 85 and 100 °C for 16 s and at 90 °C for 5 min was significantly lower than in those heated at 73 °C and 78 °C for 16 s, despite the higher level of whey protein denaturation of the former group. Hovjecki et al. (2020) reported that an increase in the heat treatment of goat milk, from 72 °C for 30 s to 85 °C for 5 min, substantially decreased the fermentation and gelation time of the resulting acid gels, while the highest firmness and consistency were estimated for yoghurt produced from milk heated at 85 °C for 5 min. Inferior rheological and texture properties were observed in gels from goat milk heated at 95 °C for 5 min.

5. Conclusion and future perspectives

The majority of the studies on the behaviour of goat milk upon heating have exhibited important differences in respect to cow milk. Moreover, the effect of physicochemical conditions on the heat stability and the heat-induced mechanisms is differentiated in certain points between these two milk kinds. A great part of the goat milk behaviour upon heating is due to the particularities of the interaction of denatured whey proteins with goat casein micelles at natural pH as well as the formation and partition of various types of aggregates. Heat instability is also connected to the increased ionic calcium content goat milk that facilitates the formation of aggregates and sediment. The use of adequate stabilisers, when allowed, can deal with the problem to a satisfactory degree.

The most part of research in the field concern high-heat or UHT treatments, whereas studies on high-pasteurisation or ESL treatments are limited. The same holds true for the method used for heating; often the results of various studies cannot be compared or supplemented due to non-equivalent heating means. Thorough research is necessary for the optimisation of the heat treatment, both the heating conditions and method, of goat milk from various animal breeds to meet the interest of modern societies for the goat dairy products and for less processed food. Moreover, specific attention should be given to the effect of treatment on minor components of goat milk with biological activity that are exploited in baby or other specific formulae.

Declaration of competing interest

None.

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