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INVITED REVIEW: ADVANCES IN GOAT MILK RESEARCH

Subtitle: One hundred years of advancing goat milk research through JDS

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ABSTRACT

In the century of research chronicled between 1917 and 2017, dairy goats have gone from simply serving as surrogates to cows, to serving as transgenic carriers of human enzymes. Goat milk has been an important part of human nutrition for millennnia, in part because of the greater similarity of goat milk to human milk, softer curd formation, higher proportion of small milk fat globules and different allergenic properties compared to cow milk; however key nutritional deficiencies limit its suitability for infants. Great attention has been given not only to protein differences between goat and cow milk, but also fat and enzyme differences, and their impact on the physical and sensory properties of goat milk and milk products. Physiological differences between the species necessitate different techniques for analysis of somatic cell counts, which are naturally higher in goat milk. The high value of goat milk throughout the world has generated a need for a variety of techniques to detect adulteration of goat milk products with cow milk. Advances in all of these areas have been largely documented in the *Journal of Dairy Science* (JDS); this review summarizes such advances.

key words: adulteration, composition, nutrition, somatic cells, safety

INTRODUCTION

Previously considered the "poor man's cow", goats and goat milk products began gaining attention in the US in the 1960s because of health and nutritive values attributed to goat milk and milk products. Touted for its easy digestibility and lower allergenic properties compared to cow milk, goat milk has been considered a nutraceutical for decades, but many initial reports were anecdotal. The JDS played a large role in documented the true differences between cow and goat milk. Haenlein (1980) even credited JDS as "a major US research organ on dairy goats as well as on dairy cows". In the 100-year period since 1917, JDS has published more than 850 research manuscripts related to goat milk and milk products. However, these numbers do not reflect the full scope of research related to dairy goats, or the role that goat milk and milk products have played in advancing the global dairy industry in the past century. With particular focus on JDS publications, this manuscript is dedicated to those discoveries.

ADVANCES IN GOAT MILK RESEARCH FROM 1917 TO 2017

Goat milk and human nutrition

Likely since the beginning of domestication, the importance of goats for human nutrition has been recognized. Indeed, the first publications related to goat milk, published in *The Lancet*, tended to focus on infant feeding, and some of the risks and benefits associated with it (Blackham 1906; Cahill 1906; Dalebrook, 1902; Wright 1906). One letter to the editor of *The Lancet* claimed that "goats practically never have tubercle, therefore their milk can be given without pasteurizing… their milk is said to be better for infants than cow's milk because the curd is finer" (Edmunds, 1914). Prompted by the observation that goat milk rarely forms a cream layer, though fat content was similar to that of cow milk, Schultz and Chandler (1921) reported that 91% of goat milk fat globules were under 4 μm in diameter. Previous work by Bitting (1902) reported that 90% of cow milk fat globules were more than 4 μm in diameter. Although it soon became clear that goat milk was also susceptible to microbial contamination, the softer curd and higher proportion of small fat globules have been selling points of goat milk ever since these early works.

In the early 1900s, vitamins and minerals were almost exclusively studied in rats, chicks, and monkeys. Approximately 15 years before the early "Our Industry Today" report by Elvehjem (1953), work in his lab revealed that rats grew more slowly on goat milk than cow milk. By then, several cases of severe anemia had been associated with goat milk feeding of human infants, and the term "goat's milk anemia" was coined. Elvehjem (1953) reported that goat milk provided inferior amounts of vitamin B_{12} and that levels of folic acid in goat milk and cow milk were "about equal" (which has been since shown untrue). However, since improvement in rat growth was seen with folic acid supplementation, a sparing effect of folic acid on vitamin B_{12} was indicated. Still in the early days of understanding the role of folic acid and B_{12} in human health, Collins et al. (1953a and 1953b) published two companion papers in JDS, the former related to cow colostrum and milk, and the latter related to goat colostrum and milk. Because vitamin B_{12} levels in sheep milk could be increased by the addition of cobalt or trace-minerals (containing cobalt; Harper et al. 1951), they wanted to evaluate the impact of such diet supplementation in goats. Goats receiving trace-mineralized salt (containing cobalt) had a higher level of vitamin B_{12} in their colostrum and milk during the first week post-partum compared to those receiving only iodized salt. Trace-mineralized salt or a 50 mg supplement of cobalt per goat per day had no influence upon the level of B_{12} in goat milk after this time. The addition of trace-minerals to the diet of the goat did not influence the free folic acid level of the goat milk. The authors admitted that the information reported in the JDS work was "more accurate" than what the reported in their previous work (Collins et al. 1951).

It was not realized until later that goat milk was deficient, with respect to human nutrition, in folic acid, and vitamins B_{12} and B_6, nutrients that are essential for normal human baby development (Ford and Scott 1968; Parkash and Jenness 1968). Nonetheless, goat milk products gained considerable attention in the 1970s because of perceived health and nutritive value. Jenness (1980) provided a good review of goat milk nutritive value based upon literature of the time. Similar to cow milk, goat milk is an adequate to excellent source of protein, calcium, niacin, pantothenic acid phosphorus, potassium, riboflavin, thiamin and vitamin A to the human diet (Parkash and Jenness 1968; Jenness 1980). Neither cow nor goat milk is a good source of iron, vitamin C or vitamin D (unless fortified). In contrast to cow milk, goat milk contains less than adequate levels of vitamins B_6, vitamin B_{12}, and folic acid than cow milk for infant nutrition (Ford and Scott 1968; Parkash and Jenness 1968; Jenness 1980). Folic acid and vitamin B_{12} deficiencies became a focus of research in the 1970s, regarding megaloblastic anemia in children exclusively fed goat milk (Davidson and Townley 1977), and continue to be of concern today (Basnet et al. 2010; Ziegler et al. 2005).

One of the main characteristics of goat milk that has contributed to its appeal as an alternative to cow milk is its lower allergenic properties compared to cow milk. Even today, families are known to switch to goat milk or to buy a dairy goat to avoid cow milk consumption. Yet mostly antecdotal evidence for the lower allergenicity of goat milk was reported until the 1990s (Haenlein 2001; Loewenstein et al. 1980). With an incidence of 2 to 3% in the first year of life, cow milk allergy is the most common food allergy in early childhood, but the remission rate is approximately 85 to 90% by adulthood (Høst 2002). In an outstanding review published in JDS, Jenness (1980) noted that in many cases, allergy to cow milk proteins was not improved by shifting patients to goat milk, and he recognized that α_{s1}-casein may play a role. It was not until Ballabio et al. (2011) published in JDS that the clear relationship was established. By running individual milk samples from 25 goats with different α_{s1}-casein genotypes through SDS-PAGE and immunoblotting using monoclonal antibodies specific for bovine α-casein and sera from children allergic to cow milk, Ballabio et al. (2011) showed that goat milk allergenicity is a function of α_{s1}-casein genetic polymorphism. Lower reactivity was shown for samples with null α_{s1}-casein genotypes (0_10_1 or 0_1F). Their work confirmed that caution must be taken before goat milk is suggested as an alternative to cow milk for patients with cow milk allergy. They went further to indicate that goat milk from particular α_{s1}-casein genotypes could possibly serve as protein sources for hypoallergenic formulas (Ballabio et al. 2011). The findings were echoed by Lisson et al. (2014), who confirmed that although genetic variants of caseins differ in their allergenicity, cross-reactivity of IgE antibodies of goats and buffaloes with cow milk caseins limit feeding goat or buffalo products to cow milk-allergic patients.

In “Past, present, and future perspectives of small ruminant dairy research”, Haenlein (2001) provided an outstanding review of over 135 manuscripts related to, primarily, goats and sheep. Haenlein noted that research prior to 2001 was scarce on the unique qualities of goat and sheep milk compared to cow milk; largely it had been assumed that technical research on cows could be extrapolated to small ruminants. Haenlein summarized differences in anatomy, physiology, nutrition, metabolism, and pathology of goats and sheep, as well as differences in their milk and milk products and economic profitability. Although not mentioned in his manuscript, perhaps a dairy goat check-off program could help narrow the gap of disparity in research dollars spent on cows and dairy goats. Particularly compelling was Haenlein’s statement regarding the potential of goat and/or sheep milk to combat under- and malnutrition of people in poor areas and countries. Only 21 out of the 24 countries Haenlein included in his summary met the recommended level of calcium intake (1,000 mg/day). All but five countries met the recommended level of protein consumption (50 g/day) in the form of animal protein (developed countries); six countries had below or borderline levels of protein consumption even after plant sources of protein were added in. The bottom line is that many countries have room to improve animal protein and milk utilization. In his conclusion, Haenlein (2001) urged continued research, extension service, and public support to improve the productivity of small ruminant dairy animals, particularly in developing nations that rely on these animals to a much greater extent than developed nations.

In recent years, epidemiological studies have led investigators to consider estrogen a factor that may contribute to reproductive system cancers (Farlow et al. 2009; Yager and Davidson, 2006). The World Cancer Research Fund/American Institute for Cancer Research (2007) demonstrated no relationships of importance for consumption of milk and cancer, with the exception of colorectal (decreased risk) and prostate (increased risk) cancers. Because of concerns about estrogen metabolites in milk, and consumption being associated with cancers of the reproductive system (Farlow et al. 2009), Farlow et al. (2012) compared estrone (E_1) and 17β-estradiol (E_2) levels in commercial goat and cow milk. Goat milk exhibited a lower combined concentration of E_1 and E_2 than cow milk.

Goats serve as surrogates to cows

The earliest JDS manuscript that specifically mentioned dairy goat milk was published in Volume 15, in May 1932, entitled "Fat Metabolism in the Lactating Goat" (Bender and Maynard, 1932). Similar to the sister manuscript, published in Volume 17, in March 1934, entitled "The Effect of Specific Dietary Fats on the Blood Lipids of Lactating Goats" (Williams and Maynard, 1934), authors of both manuscripts stated that dairy goats were selected for the research to save expense, rather than to study the dairy goat metabolism in particular. The authors explicitly stated an assumption that, physiologically, dairy goats and dairy cows would perform similarly. It is surprising that in those early works, adequate sample size and replication were not required for publication. Findings for four goats, who received four different dietary treatments, were reported in the Bender and Maynard (1932) manuscript. Cunningham and Addington (1935) destined goats to be "used more and more in fundamental research problems" because of their convenient size-equating them with five to seven dairy cows-and greater offspring potential. Since these early works, it has been realized that caution must be exercised when using the goat as a model for the dairy cow (Larson 1978), and dairy goats and their milk are worthy of study in their own right.

Advances in goat milk composition research

Bergman and Turner (1937) were among the first to report on the composition of dairy goat colostrum, in particular, the globulins (importantly associated with immune bodies). They reported a rapid transition of colostrum (characterized by high total solids, fat and total protein) from six Toggenburg does into nearly normal milk by the third and fourth day after parturition. At the time, total protein was composed of four groups of protein, namely casein, casein globulin, albumin, and globulin. They used the "newer methods of protein analysis", including precipitation with 8% trichloroacetic acid for determination of total protein, and casein precipitation with an acetate buffer solution, to quantitatively determine total protein, free from non-protein nitrogen and casein. By salting out with $MgSO_4$, Bergman and Turner (1937) were also able to track globulin and albumin separately, for the first time. The most rapid change was seen in globulin, which was reported to decrease from 1.76% on day one to 0.40% on day two, and 0.11% by day nine. Since albumin did not decrease to the same extent, globulin was determined to be the driver in protein transition between colostrum and normal milk.

Until 1940, only four research manuscripts reported goat milk composition data (Bosworth and Van Slyke 1916a, b, c; Lythgoe 1940). Lythgoe (1940) conducted proximate analysis on 335 samples from individual goats from 21 herds in MA, across a 16-month period. The results are summarized in Table 1. The work confirmed the high individual and seasonal variability in total solids (driven primarily by high variability of fat), which was more pronounced in goats than in cows. Fifteen years later, in another early JDS "Our Industry Today" literature reviews (Rusoff 1955) included a table comparing milk composition of various mammals (Table 2). The information was from the 2nd edition of a McGraw-Hill book, *The Market Milk Industry* (Roadhouse and Henderson, 1950). In subsequent years, a few manuscripts related to goat milk composition were published. Jenness (1980) compiled the mean total solids, fat, crude protein, lactose and ash from milk of international goat breeds from 11 references reported in nine countries between 1968 and 1979. At the time Jenness (1980) wrote his review, the composition of milk from individual US goat breeds had still not been reported; oddly, milk from pygmy goats was used to represent US goat milk composition. It wasn't until Alderson and Pollack (1980) summarized 3,481 milk and fat yield records of Alpine, LaMancha, Nubian, Saanen and Toggenburg goats from a cooperating herd in CA, that we gained an appreciation for the differences in milk composition and milk production of US dairy goat breeds. Milk and fat yield were influenced by age, month, and year of freshening, and Nubians had the lowest yields but highest fat content (3.8%). Haenlein (1981), who evaluated the production records of US dairy goats, also showed that milk from Nubians had the highest fat content (4.6%) and lowest yield (806 kg/305-day record).

[Table 1 near here]

[Table 2 near here]

More recently, Guo et al. (2001) collected commingled commercial goat milk shipments for an entire year to provide fundamental information for cheese making and milk cheese yield potential and pricing. Samples were collected weekly from bulk milk shipments to a commercial cheese plant from April, 1996 to March, 1997. The bulk milk was composed of milk from 12 dairy farms, composed of Saanen, Nubian, LaMancha, Alpine, and Toggenburg breeds, in New Hampshire and Vermont. Total solids (TS) and fat (F) contents decreased over the first 20 weeks from 12.7 and 3.6% to 11.3 and 3.0%, respectively, then increased to peak values of 13.4 and 4.4 in January. The contents of crude protein and casein also decreased in the first 20 weeks, from 3.5 and 2.7% to 3.2 and 2.3%, respectively, then increased gradually to 3.8 and 2.9% in February. The physicochemical properties of commingled goat milk, Table 3, was adapted from Table 1 from the manuscript (Guo et al. 2001). Summer milk had the highest yield potential per kg of protein, due to a higher proportion of casein in crude protein; late lactation milk from does that freshened in the summer had the lowest yield potential. Guo et al. (2001) also concluded that, because of the high lactational and seasonal variability, milk standardization, especially in February, will enable greater uniformity in cheese composition and functionality.

[Table 3 near here]

A viral disease that causes animal and economic losses in goat production throughout the world is caprine arthritis encephalitis (CAE) (The Center for Food Security and Public Health, 2007). The lentivirus responsible for CAE disease is caprine arthritis encephalitis virus (CAEV), which affects animals in the form of chronic progressive arthritis, pneumonia, chronic weight loss, encephalomyelitis, and indurative mastitis (Kaba et al. 2012). Because contradictory results have been shown for milk production studies, Kaba et al. (2012) investigated the influence of CAEV on milk yield, somatic cell count (SCC), and percent fat, protein and lactose in a 12-year cohort study with 177 does. No significant differences were found between infected and uninfected animals for daily milk yield or SCC (non-leukocytic epithelial cell-like particles). However, the milk of uninfected goats contained more total protein, fat and lactose than that of the infected goats. Martínez-Navalón et al. (2013) studied the Marciano-Granadina breed, which commonly carries CAEV. Longer lactations, higher milk yield, fat, normalized mean SCC and lactose content were found in seronegative goats. According to their findings, CAEV infection could be a major cause for decreased milk production in dairy goats, however they mentioned that transmission routes and potential causes of this disease are still unclear and need more research (Martínez-Navalón et al. 2013).

Studies with somatic cells

Similar to dairy cows, mastitis is the primary, and most costly infection of dairy goats, and dairy goat mastitis research published in JDS has been extensive in the past four decades (Contreras et al. 1997; Contreras et al. 2003; Gelasakis et al. 2016; Koop et al. 2010; Koop et al. 2012; Moroni et al. 2005; Timms and Schultz 1985). Summary of such work is beyond the scope of this manuscript. However, although high SCC are strongly associated with mastitis in cows, that is not always the case with goats (Dulin et al. 1983; Koop et al. 2012; Park and Humphrey 1986). It has long been known that the milk of goats naturally contains elevated levels of somatic cells compared to cows, because of the apocrine secretory system in the mammary gland, and that for cows, elevated SCC are associated with cheese quality defects (Dulin et al. 1982; Dulin et al. 1983; Poutrel and Lerondelle 1983; Park 1991; Zeng and Escobar 1996). But since bacterial cell counts do not explain high SCC in goat milk (Park and Humphrey 1986), the impact of SCC on goat cheese has been debated. Dulin et al. (1982) studied the differentiation and enumeration of SCC in goat milk. Results indicated that cytoplasmic particles that are similar in size to milk somatic cells, and commonly found in goat milk, can be mistakenly counted as somatic cells by milk quality machines, therefore it was recommended to use counting methods that are specific for DNA for estimation of somatic cells in goat milk to have an accurate differentiation of cells from cell-like material. Zeng (1995) compared SCC and chemical composition of goat milk using Fossomatic-300 and Dairylab II, calibrated either with goat milk or cow milk. In both machines, SCC estimation in goat milk was higher when cow milk was used as a standard than with goat milk as a standard. Moreover, results significantly exceeded legal limits established by the FDA (1,000,000 cells/mL for goat milk at the time, as opposed to the 750,000 cells/mL limit for cows (HHS, PHS, FDA, 2011). Zeng (1995) indicated that the natural differences between cow and goat milk can lead to SCC, protein, and fat reading errors by milk quality equipment when they are set up with cow milk as a standard. Therefore, he recommended to use goat milk as a standard when testing goat milk quality to collect reliable data.

Somatic cells, and their impact on cow milk quality, have been extensively studied. Factors such as milking methods, breed, age, stage of lactation, season, and management have been reported to affect SCC in cow milk, however it is not always the case in goat milk (Zeng and Escobar, 1996). Milk from Nubian and Alpine dairy goats and three milking methods (pipeline, bucket and hands) were tested to compare SCC, standard plate count (SPC) and chemical milk composition during a complete lactation (Zeng and Escobar 1996). There was no significant difference among milking methods, but SCC increased as lactation advanced and SPC was higher in Nubian milk than Alpine milk. Milk fat and protein of both breeds increased during the first 60 days of lactation and then decreased. Some milk samples contained over 1 million somatic cells/mL, which exceeded the legal limit for Grade “A”; nevertheless does did not experience mastitis symptoms such as swelling or redness of udder. A pathology test indicated that *Staphylococci* were the predominant bacteria, but there was no mastitis condition. Therefore, there was an indication that healthy does could produce milk with more than 1 million SCC/mL and the Grade “A” SCC rule should be reviewed to truly reflect goat udder health. In a more recent study with sixty Alpine goats not exhibiting clinical mastitis, Chen et al. (2010) demonstrated that milk composition did not change when SCC varied from 214,000 to 1,450,000 cells/mL. Milk with higher SCC actually had lower standard plate count. Coliform and psychrotrophic bacteria counts, milk components (fat, protein, lactose, casein and total solids), and yield of semisoft goat cheese, did not differ among low, medium and high SCC goat milk.

However, body and texture scores provided by trained panelists were lower and FFA were higher for high cheeses made with milk with highest SCC (Chen et al. 2010). Today, the Grade "A" Pasteurized Milk Ordinance allows 1,500,000 cells/mL for goat milk, 750,000 cells/mL for cow, sheep and camel milk (HHS, PHS, FDA, 2015). Albenzio et al. (2015) went deeper into the goat physiology with their research into activities of indigenous proteolytic enzymes in goat milk of different SCC. They identified 700,000 cells/mL as the threshold for changes in the immune status of the goat mammary gland. Similar to cow and sheep, plasmin appeared to be the predominant enzyme activity in goat milk, which was correlated to SCC, and macrophages in particular (Albenzio et al. (2015).

It is important to note that the other temperature, chemical, physical and bacteriological standards for Grade "A" raw milk and Grade "A" pasteurized milk and/or milk products do not differ for cow and goat milk (HHS, PHS, FDA, 2015). Goats, and goat milk and milk products are held to the same high standards for safety and quality that the dairy industry is known for.

Findings with fatty acids

By 1964, the overall significance of short-chain fatty acids (FA) of ruminant milk fat was not fully known, but it was recognized that goat milk had unique flavor properties. Efthymiou and Mattick (1964) developed a domestic feta cheese in order to provide uniformity to the unpredictable quality of feta cheeses that were being produced in the US at the time. Although feta cheese is traditionally made from goat and/or sheep milk, their method was developed to produce characteristics of "typical Greek Feta" using cow milk. The authors concluded that characteristic (desirable) rancid flavor, specifically from free fatty acids (FFA) C_2 to C_{10}, could be consistently produced using a mixed culture of *Streptococcus (*now *Lactococcus*) *lactis* and either *Lactobacillus casei* or *Lactobacillus acidophilus*, and lipase powder (either Capalase-KL (kid and lamb-derived) or Capalase-L (lamb-derived pregastric esterase)). Bitter, atypical rancid, and unclean flavors were associated with the use of Capalase-K or Italase, and FA of C_{12} or higher chain length predominated.

As the recognition of unique properties of goat milk grew, in particular FA, Dimick and Patton (1965) set out to understand the role of butyric acid, and its function in milk fat synthesis. It had previously been reported in JDS articles (Jack et al. 1963; Jensen et al. 1961), that butyrate was esterified in sn-1 and sn-3 positions in triglycerides. For their experiments, they utilized fresh raw milk from cows (herd milk) and goat (one animal) milk. Their work demonstrated similarities in mole percent distribution of FA from each of the triglyceride fractions, with butyrate concentrations topping out at 20.4 mole percent (goat) and 20.0 mole percent (cow), yet they determined few, if any, dibutyryl triglycerides exist in either type of milk. Ultimately, the authors concluded that butyrate exists predominantly as one mole per mole of triglyceride in both cow and goat milk. Freeman et al. (1965) later reported, in JDS, the distribution of FA in goat, sheep, Indian buffalo, cow and human milk using methyl esters via gas-liquid chromatography. Short-chain FA, $C_{4:0}$ and $C_{6:0}$, were determined to be esterified predominantly in the sn-1 and sn-3 positions in all species. The $C_{14:0}$ and $C_{15:0}$ FA were preferentially esterified at the sn-2 position, while $C_{18:0}$ was primarily esterified at sn1 or sn3 positions. Not long later, Breckenridge and Kuksis (1967), utilizing butyl esters in gas-liquid chromatography, revealed the FA distribution of milk from seven species (Table 4). Differences in the findings between Freeman et al. (1965) and Kuksis (1967) were attributed to methodology (methyl vs. butyl esterification) and milk sources.

Attaie and colleagues (1993) were the first to investigate FA profiles of cow and goat colostrum. Simultaneous distillation extraction was used to separate short-chain from long-chain FA, and the n-butyl esters of FA were quantified by gas chromatography and identities confirmed by gas chromatography-mass spectrometry. Table 5 displays the concentration of total FA in goat and cow colostrum. Similar to milk of goats and cows, significant differences in colostrum fatty acid profile were generally found between species. However, the amounts of hexanoic, octanoic, decanoic, 9-Decenoic, and dodecanoic acids also differed between goat breeds, with Nubians presenting more of each of the aromatic compounds.

[Table 4 near here]

[Table 5 near here]

Chilliard and colleagues (2003) provided an excellent review on the nutritional and physiological factors affecting goat milk lipid synthesis and lipolysis. In contrast to cows, goat milk fat content increases with almost all studied fat supplements, however, the response of fatty acid composition is similar in the two species. Although the LPL system of goat milk is lower than that of cow milk, it is more bound to the fat globules (vs. casein micelles in cows) and more strongly correlated to spontaneous lipolysis (lipolysis at 4°C) in goat milk. LPL activity is influenced by stage of lactation, milking frequency, fasting, and lipid supplementation (Chilliard et al. 2003). The lipolysis and characteristic goat milk flavor were attributed to a combination of goat milk fatty acid (FA) composition, triglyceride structure (i.e., high proportion of C_6 to C_{10} FA esterified on carbon 3) and LPL characteristics. The authors also suggested fat supplementation of diets to improve goat milk composition for greater control of cheese processing and sensory properties (Chilliard et al. 2003).

Bouattour et al. (2008) showed that feeding a moderate level of soybean oil (6% as fed in the concentrate) to dairy goats increased total milk fat, conjugated linoleic acid (*cis*-9, *trans*-11 $C_{18:2}$ CLA), and *trans*-vaccenic acid (trans-11 $C_{18:1}$ VA) in milk without negative effects on intake, milk yield or protein content. In the same issue of JDS, Luna et al. (2008) reported increases in α-linolenic acid, CLA, VA, as well as minor conjugated linoleic acid isomers, in the milk of goats fed whole linseed and sunflower oil. Subsequently, Chen et al. (2009) demonstrated that feeding of a dietary supplement containing *trans*-10, *cis*-12 conjugated linoleic acid (3 to 6g/d/goat) reduced milk fat synthesis in dairy goats and decreased cheese moisture and yield. Martínez Marín (2012) fed increasing amounts of 3 plant oils (linseed oil, LO; high oleic sunflower oil, HOSFO; and regular sunflower oil, RSFO) to dairy goats. Oil supplementation decreased the level of saturated FA in milk fat (especially $C_{16:0}$) and increased mono-and polyunsaturated FA in a linear manner. LO supplementation appeared to be the most favorable alternative of the three because of the positive impact on rumenic acid and vaccenic acid and decrease in the omega-6 to omega-3 FA ratio in milk fat (Martínez Marín 2012). Even more recently, Toral et al. (2015) set out to compare lipid metabolism of goats and cows. Animals were fed diets containing no additional oil (control), or supplements of fish oil, sunflower oil and wheat starch, in a 3 X 3 Latin square design, with 26-d experimental periods. Their work demonstrated interspecies differences in mammary lipogenesis, suggesting a lower sensitivity to the inhibitory effects of *trans*-10, *cis*-12 CLA in goats and that ruminal biohydrogenation pathways are more stable and less prone to diet-induced shifts toward *trans*-10-containing intermediates in goats than cows.

With the emergence of biorenewable sources of fuel has come the production of by-products such as dried distillers grains with solubles (DDGS), a by-product of the ethanol industry. A good amount of literature is available on the impact of DDGS feeding on poultry, swine, beef, dairy cows, and even cow milk and cheese (Sankarlal et al. 2015, Testroet et al. 2015). Cais-Sokolińska et al. (2015) were the first to report on the impact of DDGS on goat and sheep milk and milk products, when they evaluated formation of volatile compounds in the fermented beverage, kefir. Their work showed that the increased polyunsaturated fats resulting from DDGS feeding resulted in significant changes to the fermentation process and aroma profile of the resulting kefirs Cais-Sokolińska et al. 2015).

Evolution of goat milk enzyme research

The enzyme composition of ruminant milk was not completely characterized by 1968, and is probably still not. Chandan et al. (1964) reported the lysozyme content of human milk in *Nature*, then proceeded to report on the composition of lysozyme, lipase and ribonuclease in the milk of five species in JDS (Chandan et al. 1968). There was interest in lysozyme due to the discovery that human milk had nearly 3,000 times the amount of lysozyme than that of cow milk, and potential implications to infant feeding and keeping quality of milk. The investigators confirmed the great discrepancy in lysozyme content of human milk (40,000 μg/100 mL) compared to cow (13 μg/100 mL), goat (25 μg/100 mL), sheep (10 μg/100 mL), and sow (0 μg/100 mL). Differences in lipase (13, 132, 39, 9, and 141 μM/min/100 mL, respectively) and ribonuclease (305, 1,100, 425, 300 and 30 μg/100 mL, respectively) were also notable, but not as extreme (Chandan et al. 1964). Later, with the emergence of genetic engineering, transgenic goats were developed to express human lysozyme at least 67% of the concentration found in human milk that enhanced the antimicrobial properties of goat milk to select mastitis and pathogenic microorganisms (Brundige et al. 2008; Maga et al. 2006). Maga et al. (2006) demonstrated that milk from the five transgenic goats had lower somatic cell count, but the overall component composition of the milk and milk production were not different from controls. Additional benefits included that milk from the transgenic goats had a shorter rennet clotting time and increased curd strength.

Milk xanthine oxidase (XO) was also a hot topic in the 80s. Oster (1971) proposed an association between XO and atherosclerosis. Because of such concerns, Zikakis and Wooters (1980) evaluated a total of 195 commercially processed dairy products, polarographically, for XO activity. Fluid milk, cream, powdered and evaporated milk, yogurt and ice cream, cheese, butter, as well as goat and sheep products, were evaluated. The authors reported XO activity of raw milk increased with storage, particularly frozen storage, and that commercial processing destroyed about 82% of XO activity compared to raw milk. Commercial processing allowed the release of XO from the milk fat globule membrane, enabling destruction. Cheeses made from goat and sheep milk (Feta and imported blue) were reported to contain low to no XO activity (Zikakis and Wooters 1980).

DeFeo et al. (1982) were among the first to distinguish differences in the lipoprotein lipase (LPL) system between goats and cows. The importance of the research lies in the fact that hydrolytic rancidity (lipolysis) aromas and flavors from volatile FFA are influenced by native LPL, and acceptability of goat milk products are largely influenced by rancid flavors. To characterize components of the lipolytic system in goats, in part because of the unique flavor characteristics of goat milk, Chilliard et al. (1984) activated spontaneous lipolysis in goat milk. Unlike for cow milk, LPL activity is correlated with spontaneous lipolysis in goat milk. Goat milk LPL was found to be distributed primarily in the cream (46%) and serum (46%), with little activity in the caseins

(8%), in comparison to cows (6, 17 and 78%, respectively). It has been shown that the LPL activity differs among several breeds of goat, with evidence of genetic polymorphism influencing the functional properties of this enzyme (Badaoui et al. 2007).

Plasmin is likely the most important proteases in milk because of its influence upon milk and cheese quality. Although a lot of research into the plasmin enzyme system had previously been conducted in cows, it was not until the early 1990s that anyone reported on the plasmin system in goats. Like in cow milk, the complex plasmin enzyme system, composed of plasmin (PL), plasminogen (PG), plasminogen activators (PA), plasminogen activator inhibitors, and plasmin inhibitors, is present in goat milk (Politis et al. 1994). For the first time, Politis et al. (1994) demonstrated that tissue plasminogen activators (t-PA) were present in the casein and serum fractions of goat milk; urokinase plasminogen activators (u-PA) were present in all fractions (i.e., casein, serum, and somatic cells). Electrophoretic studies by Trujillo et al. (1997) demonstrated that plasmin hydrolyzed the same regions in β-casein in cow and goat milk. The plasmin system is also involved in mammary involution, with higher PL and PA activity in late lactation cows (Baldi et al. 1996). Fantuz et al. (2001) evaluated the plasminogen activation system in goat milk and its relation with composition and coagulation properties toward the end of lactation. Compared to cow and sheep milk, goat milk PG activity was low, but consistent with the high activity of PA. The high PL and PA activity in goat milk was negatively correlated with coagulating properties in late lactation, which was likely related to degradation of casein (Fantuz et al. 2001).

The quality of cheeses largely depends on the rate, extent and nature of the two main biochemical processes involved in cheese aging, proteolysis and lipolysis. With the growing popularity of goat milk cheeses, and paucity of information regarding proteolysis and lipolysis specific to goat milk cheeses, Park (2001) published a review on the topic in JDS. Regarding proteolysis, one of the distinguishing differences between cow and goat milk is the ratio of caseins. Because of its naturally lower content of α_{s1}-casein, goat milk has a higher proportion of β-, α_{s2}- and κ-casein than cow milk. As a consequence, goat cheeses tend to be less firm, and less resistant to enzymatic degradation than cow cheeses (Park 2001). Earlier work published in JDS, by Fontecha et al. (1990), Ha and Lindsay (1991), Attai and Richter (1996a), and Jin and Park (1995), were also cited as being important for the characterization of lipolysis in goat milk cheeses.

Because the majority of goat milk cheese sold in the US are fresh, soft cheese (chevre), and because goats are largely seasonal breeders, availability is variable. Thus, Van Hekken et al. (2005) evaluated the impact of frozen storage on the proteolytic and rheological properties of soft goat cheese. The creation and removal of ice crystals in the cheese matrix and the limited proteolysis of caseins resulted in only slight changes to cheese texture. Thus, authors concluded that frozen storage of soft cheeses may be appropriate to enable year-round supply of soft goat cheese, but consumer evaluation was not conducted to confirm this.

Genetic variants of goat milk caseins

The five principal proteins in goat milk (α_{s1}-casein, α_{s2}-casein, β–casein, β–lactoglobulin and α–lactalbumin) were reported to closely resemble their homologs in cow milk (Jenness 1980). Research at the time suggested that goat milk lacked the homolog of bovine α_{s1}-casein, the most abundant protein in cow milk. Jenness (1980) attributed goat milk's reputed more easily digested, softer curd, to the lack of α_{s1}-casein in goat milk; yet he acknowledged that no direct experimental evidence was yet available on the subject. However, research in the late 1980s would reveal interesting findings about goat α_{s1}-casein. The JDS was one of the first journals to publish a manuscript on the topic in English, when Ambrosoli et al. (1988) reported that coagulation properties (coagulation time, rate of curd formation and curd firmness) and composition of goat milk with low and high α_{s1}-casein content differed. They reported that goat milk with low α_{s1}-casein had faster coagulation time, while milk with high α_{s1}-casein had higher levels of components and produced firmer curds. Later, Mora-Gutiérrez et al. (1991) demonstrated, using isoelectric precipitation and reversed-phase HPLC, that milk from Alpine and Nubian dairy goats could be divided into low, medium and high-α_{s1}-casein-producing groups. The authors proposed the idea of genetic regulation of α_{s1}-casein production, stopping short of suggesting it to be a breed-specific trait. In subsequent years, it was realized that at least ten different genetic variants influenced the α_{s1}-casein phenotype expressed, and genetic variants were associated with breeds, milk composition, and coagulation properties; those works were not presented in JDS (Martin and Addeo 1996; Clark and Sherbon 2000). Later, it was reported that at least 16 alleles are associated with different rates of α_{s1}-casein protein synthesis in goats (Caroli et al. 2006).

Cebo et al. (2012) demonstrated that genetic polymorphisms at the α_{s1}-casein locus affect both structure and composition of milk fat globules. At mid-lactation, goats displaying high-type α_{s1}-casein genotypes produced larger fat globules and had lower levels of polar lipids in the MFGM than goats with null α_{s1}-casein genotype. More work in this area should be expected in the coming years, since the authors suggest that genetic polymorphism in goats may be a tool to provide clues into lipid secretion pathways in the mammary epithelial cell (Cebo et al. 2012). Advances in metabolomics, using hyphenated gas chromatography-mass spectrometry and multivariate data analysis techniques, enabled Caboni et al. (2016) to characterize low molecular weight polar metabolites in milk of 28 goats with different α_{s1}-casein genotypes in Italy. Upregulated compounds associated with weak genotypes included sugars and polyols, while upregulated compounds associated with strong genotypes included citric and aconitic acids (Caboni et al. 2016).

Characterizations of caprine κ-casein genotypes were reported in JDS by several authors (Coll et al. 1993, 1995; Angiolillo et al. 2002; and Yahyaoui et al. 2003). Coll et al. (1995) characterized the nucleotide sequence of the cDNA and the promoter region of the κ-casein gene. Angiolillo et al. (2002) characterized three variants of goat κ-casein (designated A, B, and C) in Spanish, French, German and Italian goat breeds. Yahyaoui and colleagues (2003) proposed a nomenclature for the different alleles representing κ-casein variants. The full coding region of the κ-casein gene, including two new genetic variants were described, along with allele distribution among 210 animals representing different European goat breeds and 23 Spanish wild goats. The technique described by Yahyaoui et al. (2003) allowed the rapid and simultaneous genotyping of all known κ-casein variants; use of such a system could enable selection of milk for various industrial applications.

Growth in goat population and goat research

Goat milk research began to blossom in the 1970s, along with dairy goat populations in the US. According to Leach (1980), the number of registered dairy goats in the US increased from 3,611 in 1955 to 32,459 in 1976. Additionally, herds enrolled in the National Cooperative Dairy Herd Improvement Program (DHIP) increased from none in 1960 to 1,611 in 1978 (Leach 1980). By 1987, approximately 129,225 milk goats were counted (on 15,443 farms) in the USDA APHIS Census, with approximately 17 million kg of milk produced; however, it was acknowledged that the census does not always capture all animals (USDA, APHIS, CEI, 2003). Considering the number of dairy goats not on test in the US, Haenlein (1978) estimated that closer to 350 million kg of milk were produced by US dairy goats annually in the 1970s and 1980s. Assuming that the census captured only 60% of the true population, by 2002, the dairy goat population had grown to 407,105 in the US (USDA, APHIS, CEI, 2003). By 2012, the US dairy goat population was approximately 413,540 (USDA NASS).

It wasn't until Haenlein (1978) published "Dairy goat management" in JDS, that statistically significant published research about nutritional and breeding management, behavior, and economics of milk production of dairy goats was comprehensively reported. Around this time, Larson (1978) suggested caution to animal scientists for using the dairy goat as a model in lactation studies. Some of the most obvious differences, he pointed out, were the gross structural differences between goats and cows, and differing milk constituents. He also summarized the important differences in susceptibility to metabolic diseases associated with lactation and differing rates of metabolism affecting transfer of dietary and administered materials into milk.

A full issue of JDS was dedicated to dairy goats in 1980, resulting from the 1979 ADSA International Symposium on Dairy Goats (Haenlein 1980). Issue 10 contained 14 manuscripts related to dairy goats. Perhaps the most comprehensive summary of goat research at the time, "Composition and characteristics of goat milk: Review 1968-1979" (Jenness 1980) was one of them. Twenty-seven (11%) of the references cited were manuscripts published in the JDS. Some of the key findings during the period from 1968 through 1979 included the observance that although fat globules of goat milk resemble cow milk, goat milk lacks agglutinin, which causes fat globules of cow milk to cluster when cooled (Jenness and Parkash, 1971). This, coupled with the fact that goat milk contains a higher proportion of small fat globules than large (Schultz and Chandler, 1921; Jenness 1980), explains why goat milk is called "naturally homogenized". However, it was not until Cerbulis et al. (1982) that the lipid distribution of goat milk was formally investigated and reported. Goat milk resembled cow milk fat with respect to lipid fractions of whole milk and cream, containing 97 to 99% free lipid (97% of which was in the form of triglycerides) and 1 to 3% bound lipid (containing neutral lipid, glycolipid and phospholipid). However, goat skim milk contained more free lipid than cow milk, likely because of the higher proportion of small globules (Cerbulis et al. 1982).

In the same issue as Jenness (1980), a review of research on goat milk products was published (Lowenstein et al. 1980). Loewenstein and colleagues referenced 136 publications pertaining to preparation of consumer products from goat milk; an additional 183 manuscripts were included as "supplementary bibliography". Through their review, they concluded that, until that date, cheese was the only extensively-studied goat milk product, and additional research of goat milk products is needed. Perhaps partially in response, characterization of goat milk flavors surged in JDS in the 1980s and 1990s (Chilliard et al. 1984; Iverson et al. 1989; Ha and Lindsay 1991; Martín-Hernández et al. 1992; Jin and Park 1995; Attaie and Richter 1996a and b). The characteristic "goaty" aroma of goat milk products results from the volatile FA that are found in higher quantities in goat milk and milk products compared to cow milk. Branch-chain FA, including 4-ethylocatanoic (goat-like or "goaty") and 4-methyloctanoic (mutton-like) acids, from goat and sheep milks provide distinguishing flavors to varietal cheeses (Ha and Lindsay 1991). They reported an absence of 4-ethylocatanoic acid in cow milk cheeses, and suggested that the flavor compound, in particular, distinguished cow from goat and sheep cheeses. Additionally, the presence of phenols, particularly p-cresol and 3- and 4-ethylphenols (sheep-like flavors) were unique to sheep cheeses (Ha and Lindsay, 1991). Attaie and Richter (1996a) demonstrated that ripening time significantly affected the concentrations of FFA in Cheddar-like hard goat cheeses up to 12 weeks, and that the percentage of NaCl or the ratio of salt to moisture (S/M) did not affect FFA or lipolysis. In their companion paper (Attaie and Richter 1996b), it was shown that firmness of the Cheddar-like cheeses decreased up to 18 weeks, but no significant change occurred between weeks 18 and 24. Cheeses with higher salt (highest S/M) remained the most firm, explained by the lower hydration of the protein and less freedom of movement for the protein molecules, larger amount of intact casein, and firmer casein matrix (Attaie and Richter 1996b).

With the growing importance of dairy goats came the need for design of breeding programs. Iloeje et al. (1981) were among the first. They evaluated 21,845 records of dairy goats on Dairy Herd Improvement tests from 1965 to 1976. The relative importance of herd (22-31% of total variation in milk and fat yields and 15 to 25% of variation in fat%), doe (16 to 25% or total variation in milk yield, fat yield and fat%), sire (8 to 10% of the total variation), and year-season effects (8 to 14% of total variation) were found to be similar to those for dairy cattle. Ali et al. (1983) followed up, with a study of 42,618 records of goats with 125 days or more in milk, to examine relationships among lactation and reproduction traits. Milk and fat yields were affected by breed, parity, age after fitting parity, and month of conception. The authors recommended a reduction in the number of days dry since it was found to be negatively correlated with milk and fat yield in subsequent lactation (Ali et al. 1983).

Decades of adulteration detection

As the appreciation for and value of goat milk increased, methods to detect of goat milk with cow milk became necessary. Methods were published in Bulgaria (1929), Norway (1952), and France (1959) before the US. Aschaffenburg and Dance (1968) were among the first to publish methods to detect cow milk in goat milk by gel electrophoresis. Furtado (1983) utilized discontinuous polyacrylamide gel electrophoresis (PAGE) for detection of cow milk in pasteurized goat milk. Because of the naturally-lower amount of α_{s1}-casein in goat milk than cow milk, a frontal band, missing from the pattern of genuine goat milk and possessing the same electrophoretic mobility as bovine α_{s1}-casein, could be directly related to the amount of cow milk added to the goat milk. Iverson and Sheppard (1989) demonstrated that adulteration of sheep and goat cheeses was occurring throughout the world by evaluating the fatty acid profiles of 134 cheeses using programmed temperature gas-liquid chromatography of fatty acid butyl esters. Goat and sheep milk cheeses exhibited a characteristically different lower chain length fatty acid pattern than cow milk cheeses. The mean lauric:capric fatty acid (C_{12}:C_{10}) ratio became proportionally larger with increased substitution of cow milk for goat or sheep milk in cheese making. Later, Molina et al. (1996) reported on the use of Western blotting of native and denatured bovine β-lactoglobulin to detect addition of bovine milk to non-bovine milk cheeses. Native PAGE of whey or isoelectric focusing of β-lactoglobulin isolated from the casein fractions was followed by immunodetection with anti-bovine β-lactoglobulin antiserum. Immunoblotting of the native-PAGE plates of whey proteins from cheese allowed detection of heat-denatured whey proteins or pasteurized cow milk added to goat cheese at less than 1% adulteration. Even more recently, López-Calleja et al. (2004) utilized species-specific polymerase chain reaction techniques to detect sheep and goat milk adulteration with cow milk. The use of a forward primer complementary to a conserved DNA sequence, along with a reverse primer specific for cow, yielded a 223-bp fragment from cow milk DNA, whereas no amplification signal was obtained in sheep or goat milk DNA. When applied to raw, pasteurized, or sterilized milk mixtures of cow-sheep and cow-goat, the specific detection of cow milk had a good sensitivity threshold (0.1%). In follow-up work, López-Calleja et al. (2005) validated the effectiveness of the technique to authenticate the purity of sheep milk, with similar sensitivity threshold (0.1%). Adulteration continues to be of concern today. In Brazil, a study was requested by the association of small-holder producers to investigate and to inhibit adulteration practices (Rodrígues et al. 2012). A duplex PCR assay was developed, standardized and validated on 160 fresh bulk goat milk samples. The detection limit was 0.5% bovine milk in goat milk; 41.2% of the goat milk present in the market was adulterated with bovine milk at the time (Rodrígues et al. 2012). Also using PCR, Golinelli et al. (2014) reported that all locally produced goat cheeses tested (20 lots of 4 brands in Brazil) were adulterated with cow milk, even though labels did not indicate addition of cow milk. Additionally, almost half of the 102 regular consumers invited to participate in triangle tests were able to perceive adulteration of goat cheese with 10% (vol/vol) cow milk (Colinelli et al. 2014). Chen et al. (2016) used proteomics to quantify the percentage of cow milk added to goat or sheep milks or dairy products. Signature tryptic peptides in β-lactoglobulin were used as markers. The ultra-performance liquid chromatography triple quadrupole-mass spectrometry method was found to have high accuracy, selectivity, linearity and precision. Similar to many previous studies, adulteration was found in most of the commercial samples purchased (Chen et al. 2016).

Microbiology and safety

In the early part of the 20th century, livestock in the US were commonly infected with *Brucella* species. While cows were often carriers of *Brucella abortis*, goats carried *Brucella melintensis*. These were the early days of determining the current Federal Food and Drug Administration's "60-day rule", stating that cheesemakers use pasteurized milk, or age raw milk cheese for at least 60 days at not less than 35°F (1.5°C), which was established in 1950 (21 CFR 133; FDA HHS, 2016). Gilman et al. (1946) evaluated the length of time that *B. abortis* (the cow-borne source of Brucellosis) survived in Cheddar cheese. Uniquely, they also evaluated the survival of *B. melintensis* (the goat-borne source of Brucellosis) in goat cheeses, as fresh goat cheeses made from unpasteurized milk had been implicated in human undulant fever cases (Gilman et al. 1946). However, no documentation of cases was provided in the manuscript. Gilman et al. (1946) also reported, similar to other work of the day, that aging for about 60 days would provide "reasonable assurance of the absence of viable *B. abortus* in commercial Cheddar cheese." Surprisingly, although Gilman and colleagues did not conduct experiments with *B. melintensis*, based upon previous research, they reported that *B. melintensis* may live longer than 60 days in cheese, stating "goat milk cheese presents a special problem." Between 1965 and 1983, outbreaks of Brucellosis in Colorado and Texas in were linked to consumption of cheeses made from unpasteurized goat milk sourced from the US or Mexico, or consumed while US residents were visiting the Mediterranean basin, Far East, Middle East, and South

America (CDC, 1983; Eckman, 1975; Young and Suvannoparrat, 1975). Because of vaccination programs and vigilance, since the 1980s, *Brucella* species have essentially been eradicated from US livestock. There has only been one case of *B. melintensis* (not *B. abortis*) reported since, a single cow in Texas, in 1999 (USDA APHIS CEI. 1999).

Milk-borne infections were more common before pasteurization was discovered in the late 19th century and commonly implemented in the 20th century, but outbreaks related to consumption of unpasteurized milk remain a concern (Langer et al., 2012). In Scotland, milk pasteurization was mandated in 1983, but not England or Wales, and sale of unpasteurized sheep and/or goat milk was not prohibited anywhere in Great Britain at the time Sharp et al. (1985) wrote. Nonetheless, more cases of foodborne illness were related to cow milk than goat milk during that time (Sharp et al., 1985). In the US, Michigan was the first state to require milk pasteurization, in 1948; in 1987, interstate shipment of raw milk was prohibited by the FDA (Langer et al., 2012). In the period between 1993-2006, a disproportionate number (150-times higher incidence) of outbreaks of foodborne illness were associated with non-pasteurized than pasteurized dairy products, and in states that allow sales of raw milk (Langer et al. 2012). Between 2007-2012, 4 outbreaks were associated with goat milk compared to 77 associated with cow milk (Mungai et al. 2015). Goat milk and milk products have tended to stay out of the food safety news spotlight, with a few exceptions, again, typically associated with unpasteurized products, and mostly outside of the US (Bielaszewska et al. 1997; Hatchette et al. 2001; Hogerwerf et al. 2011; Lai et al. 2015; Méndez Martínez et al. 2003; McIntyre et al. 2002).

Because of their particularly high virulence and negative consequences in humans contamination with shiga toxin-producing *Escherichia coli* (STEC) and *Listeria monocytogenes* are of particular concern to dairy producers and processors. Until the 1990s, there was a lack of information of *L. monocytogenes* in goat milk compared to the information available on cow and sheep milk. Because of the high mortality rate associated (30%) with listeriosis, Gaya and colleges (1996) evaluated incidence of *Listeria* species (spp.) in caprine milk in Spain. The incidence of *Listeria* spp. in samples from bulk tanks of 405 farms was 4.15%. There was a peak during autumn and winter months, compared to the reported spring peak for cows. The findings confirmed the risk for *Listeria* contamination of cheese made of raw caprine milk. Of 796 raw milk cheeses obtained in 2006 and 2007 in Switzerland, 3.7% and 6.3% were positive for pathogenic STEC, respectively (Stephan et al. 2008). Of the 63 goat cheeses evaluated, 4 goat milk soft cheeses and 1 goat milk semihard cheese (7.9%) were positive for STEC. The various serotypes were not enumerated in samples, so it is unknown if levels were high enough to cause foodborne illness. Nonetheless, authors concluded that raw milk cheeses continue to be a potential vehicle for transmission of pathogenic STEC to humans (Stephan et al. 2008).

D'Amico et al. (2008) studied the overall pathogen presence in 138 samples of cow, sheep and goat raw milk, from 11 farmstead cheese operations in Vermont, US. The study targeted *Staphylococcus aureus, Salmonella* spp., *L. monocytogenes*, and *E. coli* O157:H7. Goat milk samples had lower incidence (18.4%) of *S. aureus* than cow (27.4% or sheep (85.7%) milk samples. *S. aureus* was present at levels that could not lead to a risk to produce heat-stable enterotoxins (<100,000 CFU/mL); *S. aureus* is not considered a pathogen of high risk during cheesemaking due to competition with active starter culture. *E. coli* O157:H7, *Salmonella* spp., and *L. monocytogenes* were not found in goat milk at levels that could cause foodborne infections but outbreaks from these microorganisms could still occur if conditions allow. D'Amico and colleges (2008) concluded that since bacteria were found in very low levels in goat milk, improper storage could still facilitate pathogen growth, and some properties of raw milk cheeses could lead to the survival and growth of certain pathogens to risky levels.

Rahimit and Alian (2013) evaluated raw milk of buffaloes, cows, goats, sheep and camels, in Iran, to test for the presence of *S. aureus* and its different enterotoxins. Twenty-two samples of the total 200 tested positive for *S. aureus*, with the highest prevalence found in buffalo milk, followed by cow, sheep, goat and camel, respectively. The enzyme-linked immunoabsorbent assay (ELISA) technique was used to identify *S. aureus* enterotoxins; 45.6% of the samples produced an enterotoxin. Cow milk produced enterotoxin types A, B, and D; buffalo milk produced enterotoxin types A and D; sheep milk produced enterotoxin types A, and C; goat milk produced enterotoxin type D. They concluded that there is a high potential risk of staphylococcal food poisoning from drinking raw milk, especially if hygiene practices are not followed.

Of additional importance to the dairy industry are the many spoilage microorganisms, which compromise the organoleptic, nutritious, and biochemical characteristics. Because of their widespread occurrence and capability to grow in pipelines, bulk tanks and milking machines in dairy processing plants, Scatamburlo et al. (2015) characterized the proteolytic activity of *Pseudomonas* spp. isolated from 61 Brazilian goat milk samples from 12 farms. *Pseudomonas* spp. were confirmed by Polymerase Chain Reaction (PCR) by using a genus-specific region of the 16s DNA. Mean *Pseudomonas* spp. counts ranged from 3.0 to 4.8 log CFU/mL, a smaller range than previously reported for cow milk (1.0 to 6.6 log CFU/mL) (De Oliviera et al. 2006). The high proportion of proteolytic *Pseudomonas* spp. found in the analysis is indicative of a need for greater attention to sanitation along the production and processing chain.

Goat milk cheeses (n = 75) were among 273 cheeses included in a landmark piece of work presented by Trmčić et al. (2016), where it was proposed that coliform testing no longer be used to assess the safety of cheese. For decades, coliform bacteria have been used as indicator organisms for assessment of unsanitary conditions of manufacture. In fact, coliform testing in pasteurized milk was recommended by the US Public Health Service in the earliest edition of the Grade “A” Pasteurized Milk Ordinance (PMO) published in 1924 (Martin et al. 2016) and the current tolerance limit for coliforms in milk is no more than 10 CFU/mL (HHS, PHS, FDA, 2015). However, coliforms are a diverse group, and some research has shown that only a fraction have been identified as factors of fecal contamination and a wider fraction is environmental (Martin et al. 2016). Milk pasteurization, low pH, low water activity and other cheese characteristics were found to significantly contribute to lower prevalence of coliforms in cheese (Trmčić et al. 2016). Water activity was the only factor identified as determining the concentration at which coliforms are present in cheese. Although the prevalence of coliforms does not significantly differ in milk of cows, goats and sheep (D’Amico et al. 2008; D’Amico and Donnelly 2010), cheese manufactured from goat milk showed a higher risk of coliform detection (Trmčić et al. 2016). The authors proposed several reasons for higher coliform contamination or outgrowth: 1) intrinsic factors in goat milk and/or goat cheese (not including pH or water activity), 2) procedures involved in making goat cheese (not including pasteurization and cheese rind treatment), and/or 3) goat cheese producers may represent small facilities with reduced resources related to food safety (Trmčić et al. 2016).

International advances in goat milk products research

The value of goats was realized in many countries well before the US recognized their importance, and Haenlein (1980) documented some of the international symposia and references in his 1980 manuscript published in JDS. At the time, few international works related to dairy goats had been published in JDS. Since then, the international importance of goat milk and milk products has not been overlooked in JDS publications. Fundamental goat milk research, conducted by international authors, has been key to advancing dairy goat science. Additionally, JDS has been a reservoir for international work of regional interest, including works documenting chemical composition and nutritive value of the milk of native goat breeds in Saudi Arabia (Sawaya et al. 1984) and regional goat cheeses in Italy, Turkey, Spain and Portugal (Fontecha et al. 1990; Freitas and Malcata 2000; Martínez-Hernández and Juárez 1989; Martínez-Hernández et al. 1992; Trani et al. 2016; Yuceer et al. 2009).

Goat milk has not traditionally been used extensively for production of mozzarella or other pasta filata cheeses because the stretching process is not always successful. Italian investigators, Imm and colleagues (2003), were the first to investigate functionality and physic-chemical characteristics of goat milk mozzarella. Batches of cow or goat milk were standardized to 3.2% fat and pasteurized, then made into low moisture, part-skim mozzarella cheese using standard procedures (Kosikowski and Mistry 1999). No difference was noted in meltability between caprine and bovine mozzarella. The free oil was always lower in goat milk mozzarella, which was attributed to intrinsic differences in goat cheese fat and protein matrix. Although it improved by aging the cheese 3 to 4 weeks, it decreased in subsequent weeks of storage. Authors confirmed that structural degradation by proteolysis weakened gel matrix and improved melting characteristics; proteolysis occurred more quickly in bovine than caprine cheeses. The authors recommended additional research to better understand the contribution of fat globule size, polymorphic structure and casein micelle structure on melting properties. Recently, Niro et al. (2014) partially substituted cow milk with goat or sheep milks to produce acceptable Caciocavallo cheese. From a sensory standpoint, cow Caciocavallo cheeses were characterized by higher scores for sweetness, elasticity, adhesiveness and humidity (moisture). Mixed cow/sheep cheeses had higher scores for intensity of flavor, acidic, astringent, friability and salty attributes. Mixed cow/goat cheeses solubility (fast melt in mouth), intensity of aroma, and bitter attributes predominated (Niro et al. 2014). Faccia et al. (2015) reported satisfactory production of Fior di latte cheeses from sheep and goat milk after methodological modifications from the standard cow Fior di latte process.

In Ethiopia, a research project was initiated in 2007 to address the increasing demand for goat milk cheese (Mestawet et al. 2013). The goat breeds, adapted to the climatic conditions of Ethiopia, had high casein content and good milk coagulating properties. The new mutation in the α_{s1}-casein gene that they identified, which yielded milk with very high α_{s1}-casein, may provide opportunities for genetic improvements (Mestawet et al. 2013). Because of interest in intensive dairy goat production and value-added goat milk products in Brazil, Fonseca et al. (2013) evaluated the influence of lipolytic bacteria in raw goat milk upon goat milk powder during storage. Although lipolytic psychrotrophs did not increase during 5 d of raw milk storage, and psychrotrophs were killed by pasteurization, peroxide value, C_8 and C_{10} FA concentrations and total FFA content of milk powder increased and rancid flavors increased during 180 d of powder storage. Authors concluded that raw goat milk intended for powder should be processed within 3 days of collection (Fonseca et al. 2013).

In Norway, as consumption of the brown whey cheese (Brunost) has decreased, the interest in rennet- and acid-coagulated cheeses has increased (Inglingstad et al. 2014). As a result, the need for higher quality goat milk has increased in recent years. Inglingstad et al. (2014)

examined the effect of two different types of pasture (cultivated and rangeland) and two different hay qualities (high and low quality) on goat milk composition and renneting properties. Milk from pastured goats was superior (higher casein and fat) to those on hay, and goats on cultivated pasture had the highest yield; cultivated pasture yielded milk with higher α_{s1}-casein and κ-casein (better renneting properties) compared to other treatments (Inglingstad et al. 2014). Providing additional support to the findings, Revilla et al. (2016) analyzed the antioxidant capacity of 224 cheese samples in Spain, prepared using mixtures of milk from cows, sheep and goats, in two manufacturing seasons (winter and summer) and over 6 months of ripening. Although animal species was not a significant factor correlated with total antioxidant capacity, statistically significant correlations were found between total antioxidant capacity and season of manufacturing (higher antioxidant activity in summer cheeses), time of ripening, retinol, % fat, % protein, and some minerals (K, Mg, Na, and P) (Revilla et al. 2016).

SUMMARY AND FUTURE DIRECTIONS

One of the earliest domesticated animals in the world, goats will always be an important part of human culture. Their compact size (compared to cows) makes them appealing from a herd management and milking standpoint. Additionally, physiological differences render unique physical characteristics to goat milk in terms of flavor profile, fat globule size, coagulation properties and allergenicity, making goat milk the dairy product of choice for many consumers. Economic demand for goat milk and milk products, based on the differences between goat and cow milk and milk products has advanced methods to detect adulteration across the globe. It is expected that such work will continue.

Although the track record of safety of goat milk and milk products is good, research must be continued to ensure the safety and quality of these products, particularly with the emergence of new foodborne pathogens and spoilage microorganisms. When Casper et al. (1998) first looked at seasonal changes in goat whey, and promoted food industry applications of goat whey, sustainability was not yet a buzz word. But now, and into the future, additional research into methods to sustainably feed goats, responsibly improve productivity, ecologically manage effluents, and creatively utilize goat whey will be essential to responsibly manage the global dairy industry.

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Table 1. Analysis of 355 individual goat milk samples from 21 herds, collected across 16 months (adapted from Lythgoe (1940)).

Month	% Total solids	% Fat	% Solids nonfat	% Lactose	% Proteins	% Ash	Protein-fat ratio
December and January	14.5	5.08	9.42	4.78	3.99	0.84	0.78
February	14.56	5.13	9.43	4.87	3.97	0.85	0.78
March	14.08	4.80	9.28	5.03	3.74	0.76	0.80
May, June and July	12.24	3.79	8.45	4.66	3.34	0.77	0.86
August	11.44	3.37	8.07	4.32	2.99	0.78	0.89
September	12.29	3.98	8.31	4.49	3.16	0.79	0.82

Table 2. Average composition of milk of various mammals (adapted from Roadhouse and Henderson, 1950).

Species	% Total solids	% Fat	% Lactose	% Protein	% Ash
Human	12.57	3.70	6.98	1.63	0.21
Cow	13.10	4.00	4.90	3.50	0.70
Goat	12.86	4.09	4.20	3.71	0.78
Camel	12.39	5.40	3.30	3.00	0.70
Ewe	16.43	6.18	4.17	5.15	0.93

Table 3. Physicochemical properties of commingled goat milk (adapted from Guo et al. 2001).

	N	X $\pm$ SD	Range
Fat (%)	50	3.61 $\pm$ 0.47	3.00-4.40
Lactose (%)	50	4.47 $\pm$ 0.15	4.13 – 4.73
Crude protein (%)	50	3.47 $\pm$ 0.21	3.19 – 3.86
Casein (%)	50	2.57 $\pm$ 0.15	2.34 – 2.86
Non-protein nitrogen (% of crude protein)	49	5.04 $\pm$ 0.34	4.40 – 5.65
Total solids (%)	50	12.38 $\pm$ 0.71	11.17 – 13.44
Ash (%)	50	0.82 $\pm$ 0.04	0.79 – 0.89
Calcium (%)	50	0.15 $\pm$ 0.01	0.12 – 0.17
Phosphorus (mg/kg)	50	0.13 $\pm$ 0.02	0.10 – 0.16
Sodium (mg/kg)	49	672 $\pm$ 125	380 – 977
Magnesium (mg/kg)	49	160 $\pm$ 24	100 – 217
Zinc (mg/kg)	49	4.59 $\pm$ 1.93	1.30 – 9.50
Specific gravity	50	1.0235 $\pm$ 0.0007	1.0224 – 1.0262

Table 4. Fatty acid composition (mole %) of milk fat triglycerides of five species, up to $C_{20:0}$ (adapted from Kuksis (1967)).

Fatty acid	**Human**	**Jersey cow**	**Holstein cow**	**Goat**	**Sheep**
4:0	-	9.8	8.5	8.2	10.3
6:0	-	5.0	2.9	6.9	3.4
8:0	-	2.4	1.4	5.8	2.3
10:0	0.6	4.8	2.3	7.9	3.4
12:0	3.0	4.1	2.1	1.9	1.8
14:0	5.3	11.8	7.5	2.6	5.0
15:0	0.6	1.7	1.2	0.7	0.9
16:0	26.5	36.5	28.0	16.0	20.9
16:1	4.0	1.1	1.6	1.2	1.2
16:2	-	-	-	-	-
17:0	1.1	0.8	0.7	2.4	2.9
18:0	7.8	8.6	14.6	14.3	15.5
18:1	37.6	13.0	26.5	30.4	27.2
18:2	10.0	0.4	1.5	1.7	2.9
18:3	0.6	-	-	-	2.4
20:0	-	-	Trace	-	Trace

Table 5. Concentration of total fatty acids in colostrum of goats and cows (adapted from Attaie et al. 1993).

Fatty acid	Nubian goats[1]	Alpine goats[1]	Holstein cows[2]
	Mean (µg/g of fat)[+]		
Butanoic acid	304.51^{A}	202.67^{A}	226.12^{A}
Hexanoic acid	385.66^{A}	239.44^{B}	235.45^{B}
Heptanoic acid	5.31^{A}	4.63^{A}	4.46^{A}
Octanoic acid	520.68^{A}	297.80^{B}	162.28^{B}
4-Ethyloctanoic acid	13.66^{A}	12.52^{A}	10.46^{A}
Decanoic acid	1513.70^{A}	766.99^{B}	256.10^{C}
9-Decenoic acid	36.22^{A}	18.34^{B}	19.66^{B}
Undecenoic acid	10.07^{A}	7.26^{A}	3.69^{B}
Dodecanoic acid	792.72^{A}	437.79^{B}	302.35^{B}

$^{A, B, C}$Means in a row with the same superscript are not different ($P > 0.05$).
[1]Means are average of seven samples with duplicate and triplicate determinations.
[2]Means are average of four samples with triplicate determinations.