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Composition and aptitude for cheese-making of milk from cows, buffaloes, goats, sheep, dromedary camels, and donkeys

Giovanni Bittante,[1] Nicolò Amalfitano,[1] Matteo Bergamaschi,[1] Nageshvar Patel,[1] Mohamed-Laid Haddi,[2] Hamida Benabid,[3] Michele Pazzola,[4] Giuseppe Massimo Vacca,[5] Franco Tagliapietra,[1]* and Stefano Schiavon[1]

[1]DAFNAE—Department of Agronomy, Food, Natural resources, Animals and Environment, University of Padova (Padua), 35020 Legnaro (PD), Italy
[2]Laboratoire de Mycologie, Biotechnologie et Activité Microbienne, Université des Frères Mentouri, Constantine 25000, Algeria
[3]Institut de Nutrition, Alimentation et Technologies Agro-Alimentaires, Université des Frères Mentouri, Constantine 25000, Algeria
[4]Department of Animal Biology, University of Sassari, 07100 Sassari, Italy
[5]Department of Veterinary Medicine, University of Sassari, 07100 Sassari, Italy

ABSTRACT

Bovines produce about 83% of the milk and dairy products consumed by humans worldwide, the rest represented by bubaline, caprine, ovine, camelid, and equine species, which are particularly important in areas of extensive pastoralism. Although milk is increasingly used for cheese production, the cheese-making efficiency of milk from the different species is not well known. This study compares the cheese-making ability of milk sampled from lactating females of the 6 dairy species in terms of milk composition, coagulation properties (using lactodynamography), curd-firming modeling, nutrients recovered in the curd, and cheese yield (through laboratory model-cheese production). Equine (donkey) milk had the lowest fat and protein content and did not coagulate after rennet addition. Buffalo and ewe milk yielded more fresh cheese (25.5 and 22.9%, respectively) than cow, goat, and dromedary milk (15.4, 11.9, and 13.8%, respectively). This was due to the greater fat and protein contents of the former species with respect to the latter, but also to the greater recovery of fat in the curd of bubaline (88.2%) than in the curd of camelid milk (55.0%) and consequent differences in the recoveries of milk total solids and energy in the curd; protein recovery, however, was much more similar across species (from 74.7% in dromedaries to 83.7% in bovine milk). Compared with bovine milk, the milk from the other Artiodactyla species coagulated more rapidly, reached curd firmness more quickly (especially ovine milk), had a more pronounced syneresis (especially caprine milk), had a greater potential asymptotical curd firmness (except dromedary and goat milk), and reached earlier maximum curd firmness (especially caprine and ovine milk). The maximum measured curd firmness was greater for bubaline and ovine milk, intermediate for bovine and caprine milk, and lower for camelid milk. The milk of all ruminant species can be used to make cheese, but, to improve efficiency, cheese-making procedures need to be optimized to take into account the large differences in their coagulation, curd-firming, and syneresis properties.

Key words: milk coagulation, curd firmness, syneresis, cheese composition, dairy species

INTRODUCTION

The world's supply of milk is provided by just a few species. Aside from cattle, accounting for 83% of world milk production, buffaloes represent 13% of production, goats 2%, sheep 1%, and camels 0.4% (FAO, 2019). The remaining share is provided by other less-common dairy species, such as equines (horses and donkeys), yak, and reindeer (Park et al., 2017).

Cattle are raised in a wide range of environments. Some dairy species can be raised in what for others would be adverse environmental conditions, making dairying possible in environments that are often unable to support any other type of agricultural production. Milk can be produced from buffaloes in mainly wet tropical regions, goats in regions with poor soils such as in Africa but also in fertile areas of developed countries, sheep in semi-arid regions around the Mediterranean, camels in the very arid lands of North Africa and Asia, equines in the steppes of Central Asia, and yak and reindeer in environments that are very cold due to extreme altitudes or latitudes (FAO, 2019). The distribution of different dairy species around the world depends on

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*Corresponding author: franco.tagliapietra@unipd.it

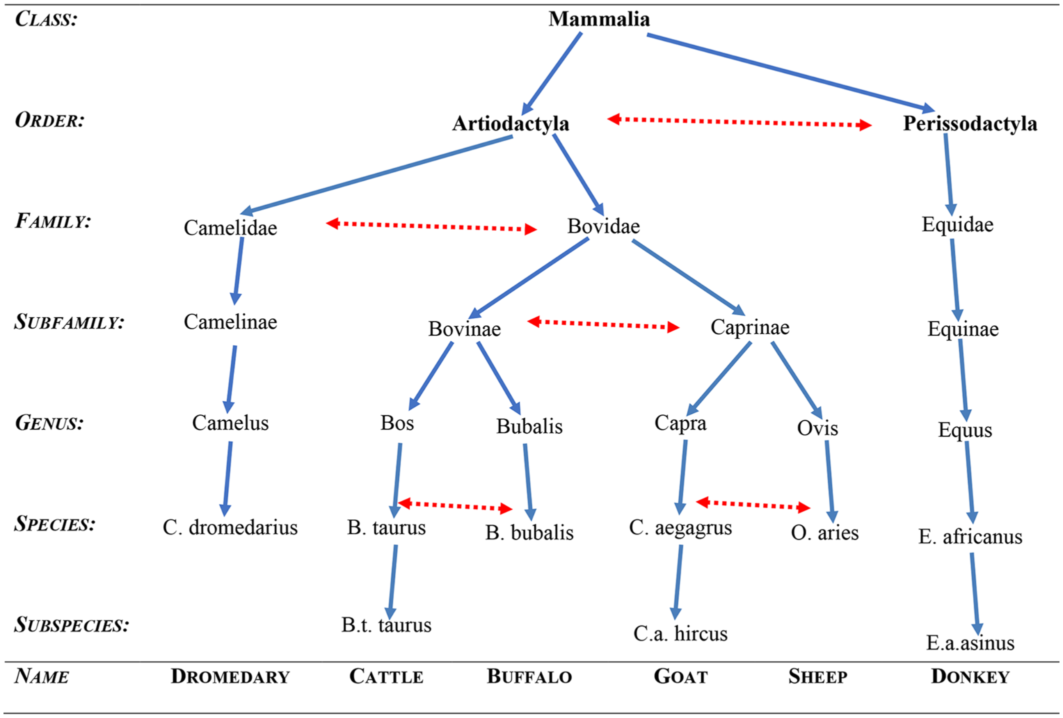

Figure 1. Evolutionary taxonomy of the 6 major dairy species and orthogonal contrasts among them (dashed red arrows).

their ability to adapt to harsh (cold, hot, arid, humid) environments, available feed resources, socioeconomic conditions, and human dietary traditions and cultural heritages. In developing countries, non-bovine species represent one-third of the milk consumed by the local population (40% in Asia) and probably about half of the milk fat and protein. As is well known, the main dairy species belong to the order Artiodactyla, the family Bovidae, and the 2 subfamilies Bovinae (cattle and buffalo) and Caprinae (sheep and goats), all of which are ruminants. As Figure 1 shows, camels belong to the same order but to a different family (Camelidae), and they are pseudoruminants, having 3 stomachs. Last, equines are very different from the other species, being monogastric and members of the order Perissodactyla and the family Equidae.

Processing allows milk to be preserved for periods ranging from days to years; it helps reduce food-borne illness (FAO, 2019) and often also the effects of lactose intolerance, which affects about two-thirds of the human population (Lomer et al., 2008). Cheese consumption is increasing worldwide (IDF, 2020). A wide range of cheese-making procedures are employed in different areas of the world and according to the species producing the milk. In the European Union alone, 238 different types of cheeses have protected designation of origin or protected geographical indication certification (Dias and Mendes, 2018). The authors are aware of only a few studies comparing the cheese-making aptitude of milk from different species (usually sheep and goats) using the same procedures, although large variability has been found according to breed within species (Cecchinato et al., 2015; Stocco et al., 2017, 2018a). The composition of milk varies greatly from species to species (reviewed by Alston-Mills, 1995; Medhammar et al., 2012; and Faccia et al, 2020a), as well as in relation to their phylogenetic pathways (Oftedal and Iverson, 1995). It is worth mentioning that the data reported in the original articles cited in these reviews were often obtained from a few samples taken from individual animals from a single or a few farms, and that the sampling, conservation, and analytical methods sometimes differ. Only a few original studies have directly compared the composition of milk from different species, usually bovine, ovine, and caprine (Gelè et al., 2014; Legarto et al., 2014; Roy et al., 2020).

Moreover, the technological properties (coagulation, curd firming, syneresis) of milk from different species have seldom been compared (Calvo and Balcones, 2000; Roy et al., 2020), and it is not known whether taxonomic distance also affects these traits. One problem that arises in evaluating the technological properties of milk from different species is that the methodologies commonly used in both research and industry have been established for testing bovine milk, and may not be always reliable when applied to other species.

Recently, it has been shown that modeling the dynamic patterns of milk coagulation, curd firming, and syneresis is more useful than using single-point traits to analyze the technological properties of bovine milk (Cecchinato et al., 2013) and could also be useful for analyzing the technological properties of milk from other species (Pazzola et al., 2018). Moreover, laboratory model cheese-making procedures mimicking those used in the dairy industry have been used to study cheeses made from milk from different species (Cipolat-Gotet et al., 2016a; Stocco et al., 2018a). Therefore, new opportunities are available for studying and comparing the cheese-making aptitude of milk from different dairy species. However, it should be borne in mind that where differences in species occur, there are also differences in environments and dairy systems, in farms within dairy systems, and in lactating animals within farms.

We therefore carried out a preliminary study on the 6 major dairy species in their typical environments and dairy systems, using bulk milk samples from different farms, each consisting of milk from many lactating females, with the aim of evaluating the variability in cheese-making efficiency found in practice. The specific aims of this study were to compare the different types of milk in terms of (1) chemical composition; (2) coagulation, curd-firming patterns, and syneresis properties; (3) recovery of milk nutrients in the curd; and (4) cheese yields, while also considering their phylogenetic pathways.

MATERIALS AND METHODS

Herds, Animals, and Milk Samples

A total of fifty-four 2.5-L bulk milk samples (10–13 per species) were obtained after the morning milking from the milk tanks at various dairy farms rearing cows, buffaloes, goats, ewes, and donkeys in different regions of Italy. In addition, ten 2.0-L milk samples were obtained from free-ranging dromedary camels in 2 grazing areas of the province of Biskra in Algeria (Haddi et al., 2003): these animals were hand-milked and the samples immediately refrigerated. The farms were representative of the major dairy systems of the 5 species sampled in Italy and the dromedary camels sampled in North Africa. The main characteristics of the rearing environments, climatic conditions, farms, feeding systems, and animals (breed, size, production) are summarized in Table 1. This information is intended to give an overview of the major differences among the dairy species, as it is beyond the scope of this study to analyze these characteristics in detail.

All the milk samples, without preservative, were chilled at the farm and transported using a portable refrigerator (set at 6 ± 2°C) to the Milk Laboratory of the Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE) of the University of Padova (Legnaro, Italy). They were mixed, aliquoted, and processed within 48 h of sampling.

Analysis of Milk Samples

All milk and whey samples were analyzed using the following methods: percent fat content according to the Weibull-Stoldt method and Soxhlet extraction (VDLUFA, 2003); percent protein content according to the method 991.20 (nitrogen total content by Kjeldahl × 6.38; AOAC International, 1995); percent casein content according to AOAC International (1995) method no. 927.03; casein number, expressed as casein as percent of total protein; percent lactose content by HPLC (Schuster-Wolff-Bühring et al., 2011); percent ash content according to AOAC International (1995) method no. 945.46); percent total solids content according to AOAC International (1995) method no. 925.23. Energy content of the milk and whey samples (MJ/kg) was estimated by an equation based on their fat, protein and lactose contents, as proposed by NRC (2001); the results were then converted to megajoules. Sample pH was measured with a Titralab AT1000 Series analyzer fitted with a PHC805 pH electrode (Hach Company), and SCC was measured with a Fossomatic Minor (Foss A/S) and then log-transformed to SCS.

Single-Point Milk Coagulation Properties and Modeling of Curd Firmness and Syneresis

The milk coagulation properties of each milk sample were measured in duplicate (128 trials) by mechanical lactodynamograph (2 Formagraph instruments, Foss Electric A/S). Pendula calibration was carried out before each session of the trial. For each animal replicate, 10 mL of milk was heated to 35°C and then mixed with 200 μL of bovine rennet solution (Hansen Standard 215 with 80 ± 5% chymosin and 20 ± 5% pepsin; Pacovis Amrein AG) freshly diluted to 1.2% (wt/vol) in distilled water. All milk samples coagulated within 60 min of rennet addition, except for the donkey milk samples, none of which coagulated. At the same time, we carried out a small trial only on donkey milk, in which the experimental conditions were modified to stimulate milk gelation. Neither doubling the rennet concentration, lowering the pH (using citric acid) to a range of 5.3 to 5.5, or prolonging the time interval to 3 h from rennet addition, resulted in coagulation of donkey milk.

The following traditional single-point measurements of each coagulated milk sample replicate were obtained

Table 1. Geographical locations, climates, and characteristics of the farms and the lactating animals of the 6 major dairy species sampled

Item	Cow	Buffalo	Goat	Ewe	Dromedary	Donkey
Farm area						
Country	Italy	Italy	Italy	Italy	Algeria	Italy
Region	Veneto	Veneto	Veneto	Veneto/Sardinia	Biskra	Veneto/Emilia
Classification	Plains	Plains	Hills	Plains/hills	Plains	Plains
Geographic average coordinates						
Latitude	45°40′N	45°39′N	46°08′N	40°43′N	34°51′N	44°30′N
Longitude	11°36′E	12°15′E	12°12′E	8°33′E	5°43′E	11°15′E
Altitude, m above sea level	64	15	389	225	87	35
Climate classification[1]	Cfa	Cfa	Cfb	Csa	BWh	Cfa
Climate (monthly averages[2])						
Average temperature, °C	2.2–23.4	2.7–23.3	−0.7–18.7	8.1–23.7	11.8 – 33.8	3.0–24.6
Rainfall, mm/mo	56–131	63–148	64–229	7–106	2–20	42–119
Precipitation days, N/mo	5–10	6–9	6–18	1–9	1–4	4–8
Relative humidity, %	66–81	67–81	75–82	63–81	30–55	54–83
Prevalent farm characteristics						
Herd size class, N	100–300	50–200	20–150	100–1,000	50–200	40–200
Land destination	Arable land	Arable land	Pastures	Pastures	Pastures	Arable land
Irrigation	Yes	Yes	No	Yes/no	No	Yes/no
Barn	Modern	Modern	Traditional	Traditional	None	Traditional
Milking parlor	Yes	Yes	Yes	Yes	No	Yes
Prevalent feeding						
Main forage	Corn silage	Corn silage	Hay	Grass	Shrubs	Hay
Main concentrate	Corn	Corn	Compound	Compound	Bran	Compound
Main protein source	Soybeans	Soybeans	Soybeans	Grass	Shrubs	Hay
Feed distribution	TMR	TMR	On mangers/pasture	Pasture	Pasture	On mangers/pasture
Lactating animals						
Prevalent breed	Holstein	Mediterranean	Alpine	Sarda	Chaambi	Crossbreed
Live weight, kg	650	700	55	42	400	280
Metabolic weight, kg	129	136	20	16	89	68
Daily milk yield, kg	33	8	3	1.5	3	2

[1] Köppen-Geiger climate classification (Geiger, 1954). Cfa = humid subtropical climate (hot and humid summers and cold to mild winters); Cfb = oceanic climate (mild summers and cool winters); Csa = Mediterranean climate (dry hot summers and mild-wet winters); BWh = hot desert climate.

[2] Averages of the months with the lowest and with the highest climatic value.

directly from the instruments: rennet coagulation time (**RCT**, min) from rennet addition to gelation; time interval between gelation and reaching a curd firmness of 20 mm ($\mathbf{k_{20}}$, min); curd firmness at 30, 45, and 60 min after rennet addition ($\mathbf{a_{30}}$, $\mathbf{a_{45}}$, and $\mathbf{a_{60}}$, mm).

A data file of the 240 curd firmness (**CF**) observations (1 every 15 s for the 60 min of the test) for each milk replicate was also built for modeling CF over time following rennet addition ($\mathbf{CF_t}$). The 4-parameter model (Bittante et al., 2013) was chosen for this study because a preliminary inspection of the CF_t data showed an appreciable decrease in CF in the final part of the curve of almost all the coagulated milk samples, with the exception of some bovine and dromedary milk samples. This modeling uses all the information available to estimate 4 equation parameters for each sample replicate, which, unlike traditional milk coagulation properties, are not single-point measurements. The following model was adopted:

$$CF_t = CF_P \times \left[1 - e^{-k_{CF} \times (t - RCT)}\right] \times e^{-k_{SR} \times \left(t - RCT_{eq}\right)}.$$

The equation parameters estimated for each milk replicate were as follows: $\mathbf{CF_P}$ (mm), the asymptotical potential value of CF at an infinite time (mm) in absence of syneresis; $\mathbf{k_{CF}}$ (%/min), the curd-firming instant rate constant describing the increase in CF over time; $\mathbf{k_{SR}}$ (% /min), the syneresis instant rate constant describing the decrease in CF over time (an apparent decrease due to the increasing quantity of whey in the vat expelled from the curd); and $\mathbf{RCT_{eq}}$ (min), RCT estimated by the CF_t equation on the basis of all data points.

The CF_P is conceptually independent of test duration and is not intrinsically dependent on RCT (unlike $a_{30,}$ a_{45}, and a_{60}). In the initial phase of the test, after gelation, k_{CF} prevails over k_{SR}, such that CF_t increases to a point in time ($\mathbf{t_{max}}$) at which the effects of the 2 parameters are equal but opposite in sign; this is when CF_t reaches its maximum level ($\mathbf{CF_{max}}$). Thereafter, CF_t decreases, tending toward a null value.

Model Cheese-Making Procedure to Measure Nutrient Recoveries in the Curd and Cheese Yields

A total of 64 laboratory cheese-makings with complete material balances were carried out. The cheese-making apparatus consisted of 2 water baths fitted with a digital temperature controller and pumps to mix the water to ensure homogeneous heat distribution throughout the water baths. Five stainless-steel vats (capacity 2,000 mL) were filled with 1,500 mL of milk from each species and placed in a water bath (except for the buffalo milk, where 800 mL was used because of the higher cheese yield, and milk samples were analyzed in 2 replicates). The steps in the model cheese-making procedure adopted are summarized in Figure 2, and are described in detail in a previous study (Cecchinato et al., 2013) with a few modifications. Hansen Naturen Plus 215 bovine rennet (Pacovis Amrein AG) was added to the milk. The cheese wheels were ripened for 90 d in a climatic chamber at 15°C and 85% relative humidity. During ripening the wheels were vacuum-packed (7 d after cheese-making) until the end of ripening.

Cheese-making traits were calculated from the weights of the milk and the whey (in grams) and their chemical compositions, as proposed in a previous study (Cecchinato et al., 2015). The composition of the curd was calculated by subtracting the weight of each nutrient in the whey from the weight of the corresponding nutrient in the milk processed. In addition, ripened cheese yield was calculated from the weight of the ripened cheese wheels, according the method described by Cipolat-Gotet et al. (2020).

Briefly, the cheese-yield (**%CY**) and nutrient recovery (**REC**) traits measured were as follows:

- $\%CY_{CURD}$, $\%CY_{SOLIDS}$, and $\%CY_{WATER}$ (%), calculated as the percentage ratios of the weights (g) of the fresh curd, curd dry matter, and curd water, respectively, to the weight of the milk processed (g);
- $REC_{PROTEIN}$, REC_{FAT}, and REC_{SOLIDS} (%), calculated as the percentage ratios between the weights (g) of the protein, fat, and dry matter in the curd, respectively, and the corresponding components in the milk processed (g);
- REC_{ENERGY} (%), calculated as the percentage ratio between the energy content of the curd and the energy content of the milk processed;
- $\%CY_{CHEESE}$ (%), calculated as the percentage ratio of the weight (g) of each cheese wheel after ripening to the weight of the corresponding milk processed (g).

Statistical Analyses

Nonlinear regressions were fitted to the 240 CF_t observations available for each milk sample replicate using the SAS version 9.4 nonlinear procedure (PROC NLIN; SAS Institute Inc.). The parameters of each individual equation were estimated by the Marquardt iterative method (350 iterations and a 10–5 level of convergence). Where milk samples showed convergence problems or bias in the estimation, the procedure was modified according to Stocco et al. (2018b): CF_P was obtained by multiplying the CF_{max} measured during the

60-min test by the regression coefficient between CF_P and CF_{max} of the non-problematic milk samples of the same dairy species. The other 3 CF_t model parameters (RCT_{eq}, k_{CF}, and k_{SR}) were estimated using the same nonlinear regression as that used for estimating the 4 equation parameters of the other milk samples.

A preliminary statistical analysis showed a small or null effect of the lactodynamographs and their individual pendula, so these effects were not included in the final analysis models. Experimental data from traditional and modeled milk coagulation properties (2 replicates per milk sample) of the 5 dairy species (donkey milk samples were excluded) whose milk coagulated within 60 min of rennet addition were analyzed using the MIXED procedure of SAS, according to the following base mixed model:

$$y_{ijk} = \mu + \text{Species}_i + \text{Sample(Species)}_{i:j} + e_{ijk},$$

where y_{ijk} is the trait with 2 replicates per milk sample (RCT, k_{20}, a_{30}, a_{45}, a_{60}, RCT_{eq}, CF_P, k_{CF}, k_{SR}, CF_{max}, t_{max}); μ is the overall intercept of the model; Species_i is

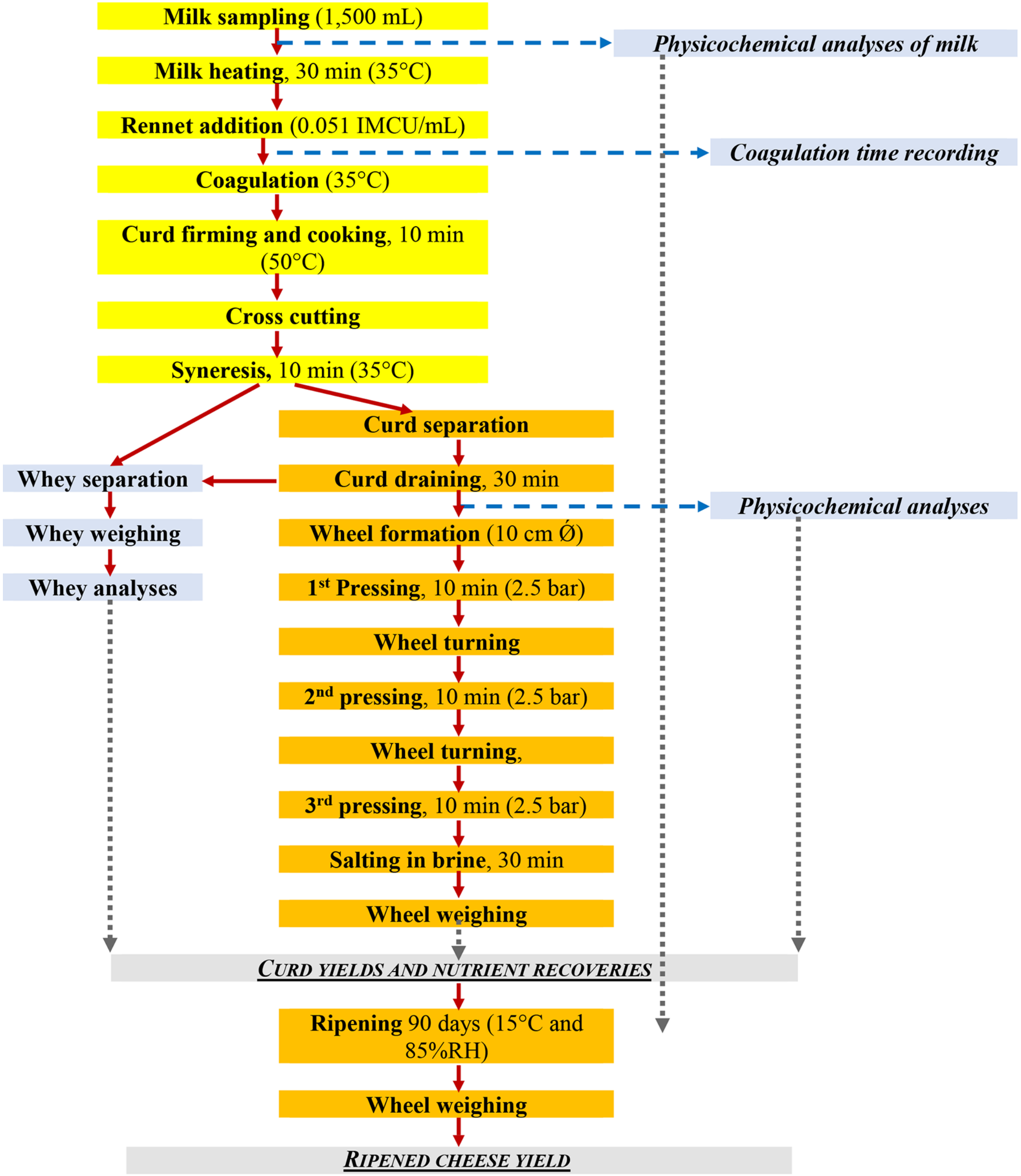

Figure 2. Schematic representation of the procedure adopted for model cheese-making using milk from the 6 major dairy species. IMCU = international milk clotting units; RH = relative humidity; ∅ = diameter.

the effect of the ith dairy species (i = 5 levels, donkey milk samples excluded); Sample(Species)$_{i:j}$ is the random effect of the jth sample within the ith species and is considered to be normally distributed (j = 1–51); e_{ijk} is the random residual $\sim N\left(0,\sigma_e^2\right)$ that quantifies the variability between the 2 replicates of each milk sample. In a first analysis, the Species$_i$ effect was treated as a random effect to obtain the variance components of species, samples, and residuals, and their relative proportions; in a subsequent analysis, it was treated as a fixed effect to obtain the least squares means (LSM) of the 5 species. The significance of the differences between the LSM of the 5 species was tested using the random effect of sample within species as the error line.

The traits with only 1 analytical value per milk sample (milk solids, fat, protein, casein, casein/protein ratio, lactose, ash, energy, pH, SCS, %CY$_{\text{CURD}}$, %CY$_{\text{SOLIDS}}$, %CY$_{\text{WATER}}$, %CY$_{\text{CHEESE}}$, REC$_{\text{PROTEIN}}$, REC$_{\text{FAT}}$, REC$_{\text{SOLIDS}}$, and REC$_{\text{ENERGY}}$) were analyzed using the same models but without the random effect of milk sample (reduced model). All 6 species were compared for milk chemical composition, and the 5 coagulating species (donkey excluded) for cheese-making traits; the significance of the differences between their LSM was tested using the residual as the error line.

Orthogonal contrasts between the LSM of the species were estimated considering their evolutionary taxonomic pathways (illustrated in Figure 1):

(a) Within the Mammalia class, the Perissodactyla order (donkey, monogastrics) vs. the Artiodactyla order (the other 5 species, ruminants and pseudoruminants);
(b) Within the Artiodactyla order, the Camelidae family (dromedary camels, pseudoruminants) vs. the Bovidae family (ruminants);
(c) Within the Bovidae family, the Bovinae subfamily (large ruminants: cattle and buffaloes) vs. the Caprinae subfamily (small ruminants: goats and sheep);
(d) Within the Bovinae subfamily, cows vs. buffaloes;
(e) Within the Caprinae subfamily, goats vs. ewes.

RESULTS

Descriptive Statistics and Main Sources of Variation of Milk Composition and Cheese-Making Traits

Descriptive statistics of the chemical compositions, traditional single-point coagulation properties, curd firming modeling (CF$_t$) equation parameters, milk nutrient recoveries in the curd, and cheese-yield traits of the milk samples obtained from the 6 major dairy species are summarized in Table 2. The distribution of the raw data showed significant skew or kurtosis for several milk traits, whereas the residuals obtained from the mixed models used to analyze the data were normally distributed, meaning that the distribution abnormalities were due to the fixed effect of some species.

The proportions of the main variances (species, milk sample within species, and replicates within milk sample or residual variance) of the single-point and modeled milk coagulation property traits analyzed in duplicate are illustrated in Figure 3. As can be seen, the effect of species explained 51% to 83% of the phenotypic variance in all the coagulation traits, and the effect of sample within species was responsible for most of the remaining variance. The modest incidence of residual variance is a confirmation of the high repeatability (93–99%) of direct lactodynamographic measures and of parameters of the CF$_t$ model, CF$_P$ excluded (87%). Figure 4 illustrates the proportions of the variances in traits measured only once per milk sample: chemical composition, nutrient recoveries in the curd, and cheese-yield traits. In this case, the effects of milk sample (different farms, dates, groups of animals, and more) and residual (sampling and analytical variability) are combined. As the graph shows, the effect of species explained more than 86% of phenotypic variance for milk composition and cheese yield traits, except for lactose, where it explained 70%, and ranged from 58 to 93% for nutrient recoveries in the curd. Note that the traits with the lowest species variances, lactose and REC traits, are those with the lowest overall coefficient of variation (Table 2). In the case of cheese-yield traits, species represented about 90% of total variance.

Effects of Dairy Species on Milk Composition

The LSM of the fixed effects of dairy species on the chemical compositions of the milk samples, reported in Table 3, show large differences among the species compared. The orthogonal contrasts, built reflecting the evolutionary taxonomy of the species compared, were in large measure statistically significant. Note that, for all composition traits, the most significant difference is that between the milk from animals of the Perissodactyla order (donkey species, monogastric) and the Artiodactyla order (5 species, ruminants and pseudoruminants). Within these latter species, all contrasts were significant for the major milk components (solids, fat, protein, casein, lactose, and ash) and for energy content. The major differences, however, were not between the different families and subfamilies, but within the subfamilies. Within the Bovinae, cow milk had much lower contents of the major milk components than buffalo milk, and within the Caprinae, the contents were lower in goat than in ewe milk. The contrasts within the Artiodactyla order were generally not significant for the other milk traits, with a few exceptions: the casein/protein ratio and pH were lower in Camelidae milk than in the 4 species of Bovidae; and the 2 species of Bovinae (cows and buffaloes) had lower SCS and higher pH compared with the 2 species of Caprinae (goats and sheep).

Effects of Dairy Species on Milk Coagulation Properties

We observed a large variability in the patterns of coagulation and curd firming over time, both between different species and between milk samples from different farms within species, as the graphs in Figure 5 illustrate. It should be mentioned that none of the milk samples from the only monogastric species investigated (donkey) coagulated within the 60-min time limit.

Table 2. Descriptive statistics of the chemical compositions, traditional single-point coagulation properties, curd firming over time (CF_t) equation parameters and derived traits, milk nutrient recoveries in the curd (REC), and cheese yields (%CY) of the milk sampled from the 6 major dairy species

Trait	N	Mean	SD	CV, %	Minimum	Maximum
Milk chemical composition						
Total solids, %	63	13.04	3.54	27.2	7.46	19.27
Fat, %	64	3.99	2.53	63.3	0.10	8.54
Protein, %	63	3.29	1.24	37.6	1.19	5.95
Casein, %	62	2.48	1.17	47.1	0.38	4.57
Casein/protein, %	63	72.34	13.73	19.0	37.90	87.73
Lactose, %	63	4.76	0.61	12.9	3.67	6.20
Ash, %	62	0.70	0.20	28.5	0.21	0.93
Energy, MJ/kg	64	3.12	1.23	39.4	1.22	5.28
pH	63	6.67	0.26	3.8	6.29	7.22
SCS[1]	64	4.06	2.84	70.1	−2.64	8.41
Coagulation properties[2]						
RCT, min	101	16.99	8.70	51.2	1.45	39.30
k_{20}, min	87	5.04	5.17	102.6	1.30	37.15
a_{30}, mm	100	26.39	17.82	67.5	0.00	74.94
a_{45}, mm	99	26.60	14.94	56.2	2.50	70.32
a_{60}, mm	99	24.80	15.80	63.7	0.00	72.56
CF_t parameters[3]						
RCT_{eq}, min	101	17.69	8.43	47.7	2.69	39.00
k_{CF}, % per min	101	18.92	11.90	62.9	3.30	57.53
k_{SR}, % per min	99	1.73	1.58	91.3	0.00	5.95
CF_P, mm	100	46.43	14.36	30.9	7.36	82.86
CF_{max}, mm	100	37.57	14.42	38.4	4.20	72.56
t_{max}, min	101	34.88	15.00	43.0	7.75	60.00
Nutrient recovery[4]						
REC_{FAT}, %	61	78.13	12.87	16.5	42.08	90.78
$REC_{PROTEIN}$, %	62	79.04	3.87	4.9	67.57	89.80
REC_{SOLIDS}, %	62	59.46	8.33	14.0	36.15	78.52
REC_{ENERGY}, %	61	68.35	9.15	13.4	43.33	79.07
Cheese yields[5]						
$\%CY_{CURD}$, %	61	19.08	5.83	30.6	9.31	27.72
$\%CY_{SOLIDS}$, %	61	9.04	2.50	27.6	3.97	12.71
$\%CY_{WATER}$, %	61	9.67	3.38	34.9	3.26	14.35
$\%CY_{CHEESE\text{-}90d}$, %	62	12.01	3.90	32.5	5.16	19.12

[1] $SCS = 3 + \log_2 (SCC/100{,}000)$.

[2] RCT = rennet coagulation time; k_{20} = time interval between gelation and attainment of curd firmness of 20 mm; a_{30} (a_{45}, a_{60}) = curd firmness after 30 (45, 60) min from rennet addition.

[3] RCT_{eq} = RCT estimated according to curd firmness change over time modeling (CF_t); k_{CF} = curd-firming instant rate constant; k_{SR} = syneresis instant rate constant; CF_P = asymptotic potential curd firmness; CF_{max} = maximum curd firmness achieved within 60 min; t_{max} = time at achievement of CF_{max}.

[4] REC_{FAT}, $REC_{PROTEIN}$, REC_{SOLIDS}, and REC_{ENERGY}: nutrient (fat, protein, total solids, and energy, respectively) contained in curd as percentage of the corresponding nutrient contained in processed milk.

[5] $\%CY_{CURD}$, $\%CY_{SOLIDS}$, $\%CY_{WATER}$, $\%CY_{CHEESE\text{-}90d}$: cheese-yield traits, expressed as weight of the curd, curd total solids, water retained in curd, and fresh cheese after 90-d ripening, respectively, in percentage of the weight of processed milk.

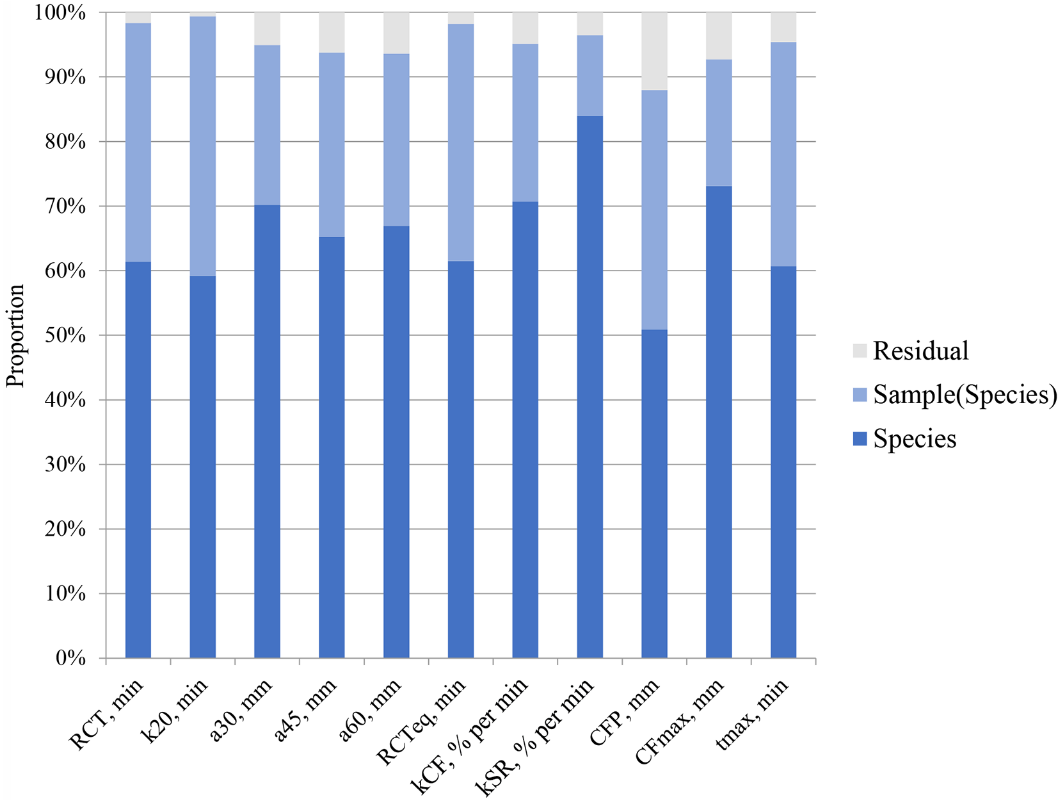

Figure 3. Relative proportions of the variances due to species, milk sample within species, and replicates or residuals within milk samples for traditional single-point milk coagulation property traits and for the curd firmness change over time modeling (CF_t) modeling equation parameters and derived traits, analyzed in duplicate. RCT = measured rennet coagulation time; k_{20} = time interval between gelation and attainment of curd firmness of 20 mm; a_{30} (a_{45}, a_{60}) = curd firmness after 30 (45, 60) min from rennet addition; RCT_{eq} = RCT estimated according to CF_t; k_{CF} = curd-firming instant rate constant; k_{SR} = syneresis instant rate constant; CF_P = asymptotic potential curd firmness; CF_{max} = maximum curd firmness achieved within 60 min; t_{max} = time at achievement of CF_{max}.

The LSM of the 5 dairy species exhibiting milk coagulation, curd firming, and syneresis, and the significance levels of the orthogonal contrasts between them for the traditional single-point coagulation properties are summarized in Table 4. Regarding the species belonging to the Artiodactyla order, the dromedary camel milk samples (Camelidae, pseudoruminants) did not differ from the average of the 4 species of Bovidae in coagulation time. Among the Bovidae, the milk samples of the 2 large ruminants coagulated more slowly than the milk from the small ruminants, due in particular to bovine milk having a much longer RCT than bubaline milk (29.7 vs. 13.3 min). Ovine and caprine milk, however, had similar RCT values (14.2 vs. 12.0 min).

Dromedary milk had a longer k_{20} and smaller a_{30}, a_{45}, and a_{60} than the average of the 4 ruminant species. The k_{20} of the milk from the large ruminants was longer than that of the small ruminants, again due to a large difference within the former. In the case of a_{30}, the 2 subfamilies did not differ from each other, but a large difference was detectable between the 2 large ruminant species (in favor of bubaline milk). Finally, in the case of a_{45} and a_{60}, differences were apparent between the large and small ruminants, and within the former, as well as a large difference within the latter (smaller in caprine than in ovine milk).

Effects of Dairy Species on Modeled Curd-Firming and Syneresis Patterns

Despite the large variability among the different milk samples (different farms and sampling dates), each species presented a typical pattern of curd firmness over time (Figure 5); this affects the LSM of the parameters of the CF_t model equation and the traits of the dairy species, as well as the significance levels of their orthogonal contrasts (summarized in Table 4). The averages of the 2 RCT (RCT and RCT_{eq}) values were very similar to each other (and differed from species to species), as were the significance levels of the comparisons between the various species, with the exception of dromedary milk compared with the milk from the 4

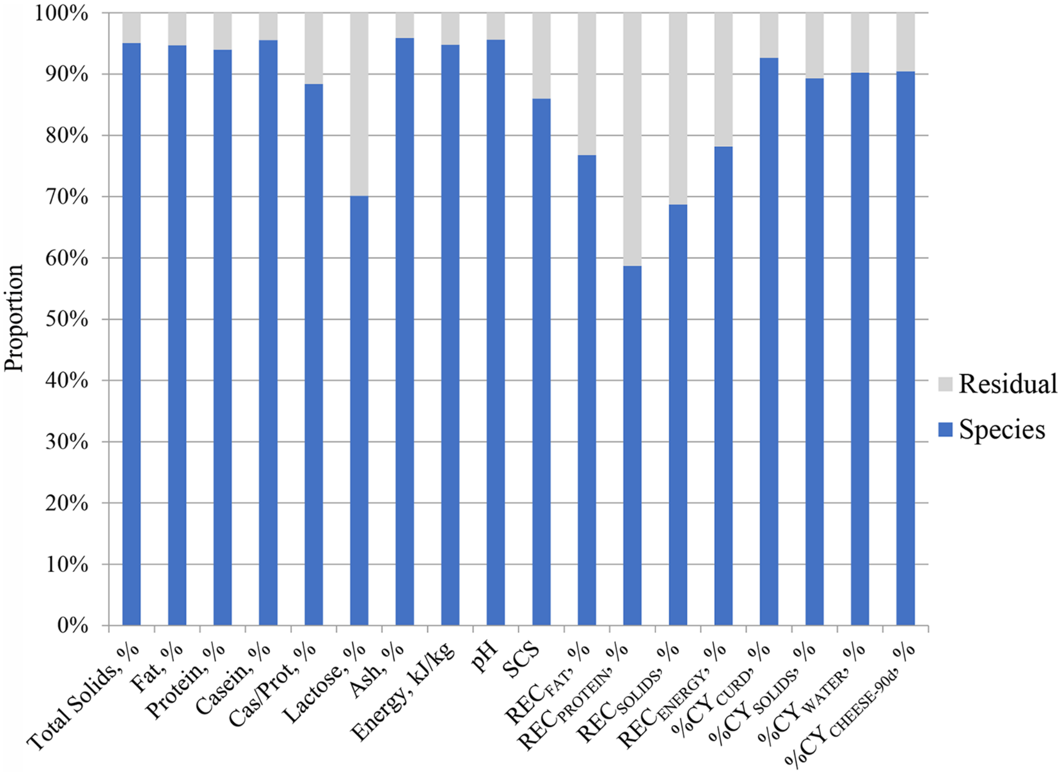

Figure 4. Relative proportions of the variances due to species and milk sample within species or residuals for milk composition, nutrient recovery in the curd, and cheese-yield traits, analyzed once per milk sample. Cas/Prot = ratio of casein to protein; REC_{FAT}, $\text{REC}_{\text{PROTEIN}}$, $\text{REC}_{\text{SOLIDS}}$, and $\text{REC}_{\text{ENERGY}}$ = nutrient (fat, protein, total solids, and energy, respectively) contained in curd as percentage of the corresponding nutrient contained in processed milk; $\%\text{CY}_{\text{CURD}}$, $\%\text{CY}_{\text{SOLIDS}}$, $\%\text{CY}_{\text{WATER}}$, $\%\text{CY}_{\text{CHEESE-90d}}$ = cheese-yield traits expressed as weight of the curd, curd total solids, water retained in curd, and fresh cheese after 90-d ripening, respectively, in percentage of the weight of processed milk.

ruminant species, which did not reach the significance threshold in the case of RCT, but was below it in the case of RCT_{eq}.

The curd-firming instant rate constant (k_{CF}) was slower in the Camelidae than in the Bovidae family and in the Bovinae than in the Caprinae subfamily, and within the subfamilies it was slower in bovine compared with bubaline milk and in caprine compared with ovine milk. The syneresis instant rate constant (k_{SR}) was the same in the Camelidae and Bovidae families but differed greatly between the Bovinae and Caprinae subfamilies (in favor of the latter), and within the Caprinae subfamily between goats and ewes (in favor of the former).

Both the CF_{P} asymptotical value and the CF_{max} were smaller for camel milk than for ruminant milk but similar for large and small ruminants. However, they were larger in buffalo and ewe milk compared with cow and goat milk. The time to CF_{max} (t_{max}) was similar between Camelidae and Bovidae families but longer in large ruminants compared with small ones, because of the longer time taken by bovine milk samples.

Effects of Dairy Species on the Recovery of Milk Nutrients in the Curd

The LSM of the fixed effect of dairy species and the levels of significance of the orthogonal contrasts of the recovery coefficients of milk nutrients retained in the curd are shown in Table 5. Nutrient recovery was affected by dairy species: it was null for donkey milk, as it does not coagulate at all, and regarding the other species, REC_{FAT} was modest in dromedary milk, and was greater for large ruminants than for small ruminants. Among the large ruminants, REC_{FAT} was greater in bubaline than in bovine milk, and among the small ruminants the difference was not significant.

The $\text{REC}_{\text{PROTEIN}}$ presented much smaller differences among species (donkey excluded); the average value was slightly lower for dromedary milk than for ruminant milk, whereas among the ruminants, it was higher for large ruminants, especially bovine milk, than for small ruminants. The $\text{REC}_{\text{SOLIDS}}$ and $\text{REC}_{\text{ENERGY}}$ were much more influenced by REC_{FAT} than by $\text{REC}_{\text{PROTEIN}}$; the statistical analysis therefore showed dromedary

Table 3. Least squares means and their orthogonal contrasts (F-value) of the milk composition of the 6 dairy species

Item	Dairy species, LSM						Orthogonal contrasts, F-value					Residual root mean square
	Cow (C)	Buffalo (B)	Goat (G)	Sheep (S)	Dromedary (Dr)	Donkey (Do)	Perisso- vs. Artiodactyla (Do vs. C+B+G+S+Dr)	Camelidae vs. Bovidae (Dr vs. C+B+G+S)	Bovinae vs. Caprinae (C+B vs. G+S)	Cow vs. buffalo (C vs. B)	Goat vs. sheep (G vs. S)	
Solids, %	12.81	17.93	11.57	17.22	12.49	8.11	584.5***	65.7***	13.5***	196.9***	216.7***	0.84
Fat, %	3.83	7.71	3.07	6.36	3.74	0.32	586.9***	48.0***	30.2***	208.5***	143.1***	0.61
Protein, %	3.20	4.38	3.28	5.12	3.16	1.39	596.3***	53.2***	16.2***	71.4***	156.4***	0.32
Casein, %	2.55	3.61	2.59	4.01	2.15	0.63	870.6***	120.5***	7.4**	89.9***	145.6***	0.26
Casein/protein, %	79.9	82.4	79.2	78.3	72.0	46.7	418.1***	21.7***	2.5	1.4	0.2	4.83
Lactose, %	4.65	5.01	4.12	4.81	4.19	5.56	87.5***	14.1***	11.4**	5.6*	18.8***	0.35
Ash, %	0.68	0.80	0.79	0.85	0.85	0.34	1,294.3***	26.9***	33.4***	43.4***	10.9**	0.04
Energy, MJ/kg	3.02	4.88	2.66	4.43	2.90	1.37	569.2***	64.5***	19.0***	203.0***	177.5***	0.30
SCS[1]	4.07	4.46	6.46	6.62	5.00	−0.80	329.8***	1.1	44.9***	0.7	0.1	1.09
pH	6.62	6.65	6.50	6.53	6.44	7.14	1,228.8***	49.9***	48.6***	1.0	1.1	0.05

[1] $SCS = 3 + \log_2 (SCC/100{,}000)$.

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

milk to be inferior to ruminant milk, small ruminants inferior to large ruminants, and cows and goats inferior to buffaloes and ewes (only for $\mathrm{REC}_{\mathrm{ENERGY}}$).

Effects of Dairy Species on Cheese-Yield Traits

The LSM of the fixed effect of dairy species and the significance levels of their orthogonal contrasts of cheese-yield traits are summarized in Table 5. The various dairy species presented very large differences in cheese yield, which encompasses milk composition, coagulation, curd-firming and syneresis patterns, and milk nutrient recoveries in the curd. For all the cheese-yield traits, dromedary milk was inferior to the average of the milk from the 4 ruminant species, small ruminants were slightly inferior to large ruminants, and, within subfamilies, bovine and caprine milks were inferior to bubaline and ovine milks.

DISCUSSION

In this section we will discuss the results for each non-bovine dairy species and make some comparisons with bovines, which are taken as the reference. To reduce variability due to individual animals and to obtain results representative of a variety of farms, we used bulk milk samples from different farms, with the only exception of dromedary milk (milk samples from free-ranging females in 2 different grazing areas). Obviously, the results obtained reflect the prevalent climatic conditions, farming and feeding systems, and prevalent breeds of the sampled areas, as summarized in Table 1.

Composition and Cheese-Making Ability of Donkey Milk

Equine milk from both mares and donkeys is traditionally consumed in some areas of the world, especially the steppes of Central Asia, although it is gaining attention worldwide because of its composition. Our results confirm donkey milk as very different from the milk of Artiodactyla dairy species: the low fat and protein contents and high lactose content make it more similar than ruminant milk to human milk (Salimei, 2011; Salimei and Fantuz, 2012). Not only does it have less than half the protein content of other species, its composition is also very different, being characterized by much less casein and more whey proteins (Vincenzetti et al., 2008; Salimei, 2011). It should be mentioned that the analytical methods used can affect or bias the results (Oftedal and Iverson, 1995). The method most frequently used for analyzing milk, Fourier-transform infrared spectrometry, is not calibrated nor validated for equine milk, and using calibrations developed for milk from dairy cows or other ruminants can give rise to biased results (G. Bittante unpublished data, University of Padova, Padua, Italy). Moreover, the reference methods for determining milk casein content are based on the use of bovine rennet (Ribadeau-Dumas and Grappin, 1989), which is not specific for the casein

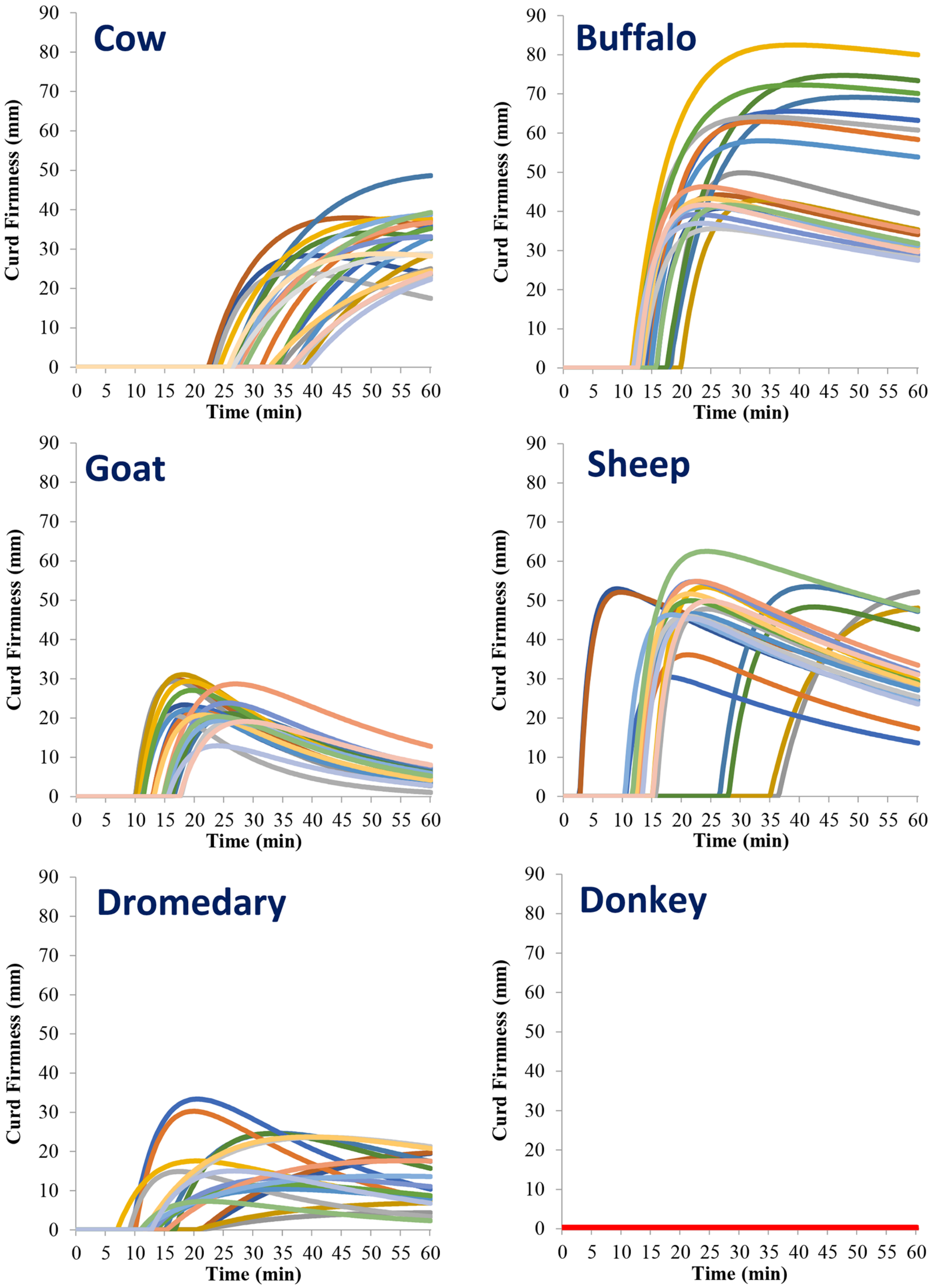

Figure 5. Plots of the modeled equations obtained from the 240 single-point curd firmness observations recorded over 60 min (1 every 15 s) for each milk sample replicate, grouped according to dairy species, showing the patterns of each species and the within-species variability.

Table 4. Least squares means and their orthogonal contrasts (*F*-value) of traditional milk coagulation properties (MCP) and parameters of the curd firming over time model (CF_t) of the 6 dairy species

	Dairy species, LSM						Orthogonal contrasts, *F*-value						
Item	Cow (C)	Buffalo (B)	Goat (G)	Sheep (S)	Dromedary (Dr)	Donkey (Do)	Perisso- vs. Artiodactyla (Do vs. C+B+G+S+Dr)	Camelidae vs. Bovidae (Dr vs. C+B+G+S)	Bovinae vs. Caprinae (C+B vs. G+S)	Cow vs. buffalo (C vs. B)	Goat vs. sheep (G vs. S)	Sample root mean square	Residual root mean square
Traditional MCP[1]													
RCT, min	29.7	13.3	12.0	14.2	14.2	>60.0	—	2.5	23.1***	44.7***	0.8	5.5	1.2
k_{20}, min	9.4	2.4	3.4	2.2	15.9	—	—	23.4***	4.7*	12.2**	0.4	4.5	0.6
a_{30}, mm	8.1	48.5	26.8	35.8	14.5	—	—	19.0***	0.9	86.6***	4.2*	9.5	4.3
a_{45},mm	25.0	45.1	14.8	35.6	13.8	—	—	25.2***	11.8**	25.0***	25.7***	8.7	4.1
a_{60}, mm	31.0	42.4	8.8	31.0	11.3	—	—	26.1***	32.6***	7.7**	27.9***	8.9	4.3
CF_t modeling[2]													
RCT_{eq}, min	30.0	14.3	13.3	15.5	13.8	>60.0	—	5.5*	21.1***	44.0***	0.8	5.4	1.2
k_{CF}, % per min	7.7	25.2	19.9	33.4	8.7	—	—	30.1***	24.0***	36.3***	20.7***	6.3	2.8
k_{SR}, % per min	0.5	0.6	4.5	1.4	2.0	—	—	0.6	126.9***	0.2	105.3***	0.6	0.3
CF_P, mm	43.2	57.4	42.2	58.4	31.2	—	—	28.3***	0.0	10.3**	12.9***	9.4	5.3
CF_{max}, mm	32.2	50.3	36.9	50.9	17.8	—	—	83.5***	1.3	29.0***	16.8***	7.0	4.3
t_{max}, min	55.2	32.4	22.9	26.2	36.2	—	—	0.3	41.0***	29.4***	0.6	9.3	3.4

[1] RCT = measured rennet coagulation time; k_{20} = time interval between gelation and attainment of curd firmness of 20 mm; a_{30} (a_{45}, a_{60}) = curd firmness after 30 (45, 60) min from rennet addition.

[2] RCT_{eq} = RCT estimated according to curd firmness change over time modeling (CF_t); k_{CF} = curd-firming instant rate constant; k_{SR} = syneresis instant rate constant; CF_P = asymptotic potential curd firmness; CF_{max} = maximum curd firmness achieved within 60 min; t_{max} = time at achievement of CF_{max}.

$*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

Table 5. Least squares means and their orthogonal contrasts (*F*-value) of milk nutrient recoveries in the curd and % cheese yields of the processed milk of the 6 dairy species

	Dairy species, LSM						Orthogonal contrasts, *F*-value					
Item	Cow (C)	Buffalo (B)	Goat (G)	Sheep (S)	Dromedary (Dr)	Donkey (Do)	Perisso- vs. Artiodactyla (Do vs. C+B+G+S+Dr)	Camelidae vs. Bovidae (Dr vs. C+B+G+S)	Bovinae vs. Caprinae (C+B vs. G+S)	Cow vs. buffalo (C vs. B)	Goat vs. sheep (G vs. S)	Residual root mean square
Curd recovery[1]												
REC_{FAT}, %	79.8	88.2	77.6	80.6	55.0	—	—	126.5***	6.2*	9.9**	1.0	6.8
$REC_{PROTEIN}$, %	83.7	80.1	77.8	77.7	74.7	—	—	29.6***	28.7***	12.4***	0.0	2.7
REC_{SOLIDS}, %	64.8	64.6	56.4	60.2	46.0	—	—	76.0***	19.2***	0.0	3.1	5.1
REC_{ENERGY}, %	71.2	75.9	65.5	69.7	52.4	—	—	125.6***	19.1***	6.6*	4.5*	4.7
Cheese yields[2]												
$\%CY_{CURD}$, %	15.4	25.5	11.9	22.9	13.8	—	—	76.6***	40.4***	253.0***	227.7***	1.7
$\%CY_{SOLIDS}$, %	8.3	11.7	6.5	10.5	5.8	—	—	130.9***	33.3***	104.7***	112.6***	0.9
$\%CY_{WATER}$, %	6.9	13.1	5.2	12.2	7.8	—	—	17.0***	15.4***	209.7***	202.4***	1.1
$\%CY_{CHEESE\text{-}90d}$, %	9.0	16.0	8.5	15.1	7.6	—	—	103.4***	3.0	207.7***	144.2***	1.3

[1] REC_{FAT}, $REC_{PROTEIN}$, REC_{SOLIDS}, and REC_{ENERGY} = nutrient (fat, protein, total solids, and energy, respectively) contained in curd as percentage of the corresponding nutrient contained in processed milk.

[2] $\%CY_{CURD}$, $\%CY_{SOLIDS}$, $\%CY_{WATER}$, $\%CY_{CHEESE\text{-}90d}$ = cheese-yield traits expressed as weight of the curd, curd total solids, water retained in curd, and fresh cheese after 90-d ripening, respectively, in percentage of the weight of processed milk.

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

fractions of equine milk, and the methods for separating different casein and whey proteins have not been optimized and validated for equine milk.

The low content of protein, especially casein, and possible differences in the types of protein fractions, their characteristics and genetic variants on one side, and the use of bovine rennet with unknown affinity for equine milk on the other, could account for the absence of milk gelation, curd firming, and syneresis in donkey milk. It is worth mentioning that other authors (Doreau and Martin-Rosset, 2011) have also observed little or no coagulation of equine milk, as reviewed by Faccia et al. (2018). Iannella (2015) obtained a curd from donkey milk only by using a procedure very different from those commonly used in commercial cheese production: the milk was not heat-treated, and the temperature was maintained at 37°C; thermophilic starter culture was added; after 90 min camel chymosin was added; and the curd was separated after 5 h. The average curd yield was as low as 3.3% of the milk processed, and the dry matter content was 35.7%, which means that the curd solids obtained represented only 1.18% of the milk processed. Other authors have used vegetal (Sampaio, 2017) or microbial (Faccia et al., 2020b) rennet and other adjuvants (D'Alessandro et al., 2019).

Although donkey milk is unsuitable for cheese-making, and despite its low fat and protein contents, it is nonetheless gaining interest in human nutrition, as it has other valuable nutritional characteristics. Particularly attractive is its similarity to human milk, which favors its use with infants and also preterm babies (Monti et al., 2007; Martini et al., 2018; Bertino et al., 2019). Recent studies claim that the propensity of donkey milk to provoke digestive intolerance in children is low (Murgia et al., 2016; Souroullas et al., 2018). Moreover, because equines are monogastric, donkey milk does not contain phytanic acid, which is produced from chlorophyll in the rumen, so it is suitable for individuals with Refsum disease (Wanders et al., 2011; Devle et al., 2012; Roca-Saavedra et al., 2017). Further studies are needed to characterize in greater detail the chemical composition of donkey (and mare) milk, to study its coagulation behavior in the human stomach and intestine, and to evaluate its effects on the health of infants, children, and adults.

Composition and Cheese-Making Ability of Dromedary Camel Milk

Camelid milk is an essential provider of high-quality nutrients to humans in very arid environments (Alhadrami, 2011; Sakandar et al. 2018). Few studies have been conducted on the production of cheese from camel milk (Ramet, 2001), and even fewer have compared the results with milk from ruminants. In this study, we found that dromedary milk, like goats' milk, was similar in composition to bovine milk, confirming the results reviewed by Medhammar et al. (2012).

Although the composition of camel milk is similar to cow milk, the coagulation, curd-firming, and syneresis patterns are profoundly different, as observed by Bornaz et al. (2009) and Qadeer et al. (2019) and as reviewed by Faccia et al. (2020a). The orthogonal contrasts based on evolutionary taxonomy, which clearly separates the Camelidae order from the Bovidae order (Figure 1), revealed highly significant differences in almost all the traits related to the cheese-making aptitude of milk. The practical meaning of the observed differences in the CF_t equation parameters among the species is clearly illustrated in Figure 6, which shows the average coagulation, curd-firming, and syneresis patterns characterizing the milk of the 6 major dairy species on the basis of the LSM values of their equation parameters. The graphs show clearly that dromedary milk coagulates much earlier than cow milk (RCT_{eq}), and after a similar time interval to the other ruminant species. However, the rising part of the curve (k_{CF}) for dromedary milk is similar in steepness to that of cow milk, and much less steep than the other ruminants. The patterns for both dromedary and cow milk observed here are very similar to those for skim milk observed by Omar et al. (2018): RCT values were almost identical (29.7 vs. 31.2 min for whole vs. skimmed cows' milk, and 14.2 vs. 16.2 min for whole vs. skimmed dromedary camel milk). Very different were the results obtained by Bouazizi et al. (2021), who, using dromedary chymosin, obtained with dromedary milk a coagulation much delayed compared with cow milk (72.3 vs. 27.5 min). The k_{SR} of dromedary milk found in our study is about 3 times greater than that of bovine milk, which explains why the descending phase of the curve (syneresis) begins 36 min after rennet addition, whereas it is not yet clearly distinguishable at the end of the test (60 min) in the case of cow milk. The greater k_{SR} also explains why, even though the asymptotical potential curd firmness (CF_P) is similar in the 2 species, the CF_{max} observed within 60 min is much lower in camelid milk than in bovine milk. These differences could be related to differences in the proportions of protein fractions, and particularly to the low proportion of the κ-casein-type fraction in camel milk (Omar et al., 2016), as it is well known that the concentrations and relative proportions of different caseins and whey proteins in milk affect its coagulation properties (Amalfitano et al., 2019) and cheese-yield efficiency (Cipolat-Gotet et al., 2018).

In this study, the milk samples of all species were mixed with the same rennet of bovine origin (80% chymosin and 20% pepsin). It should be noted that the chymosin enzyme produced by camels gives their milk greater coagulation efficiency compared with bovine

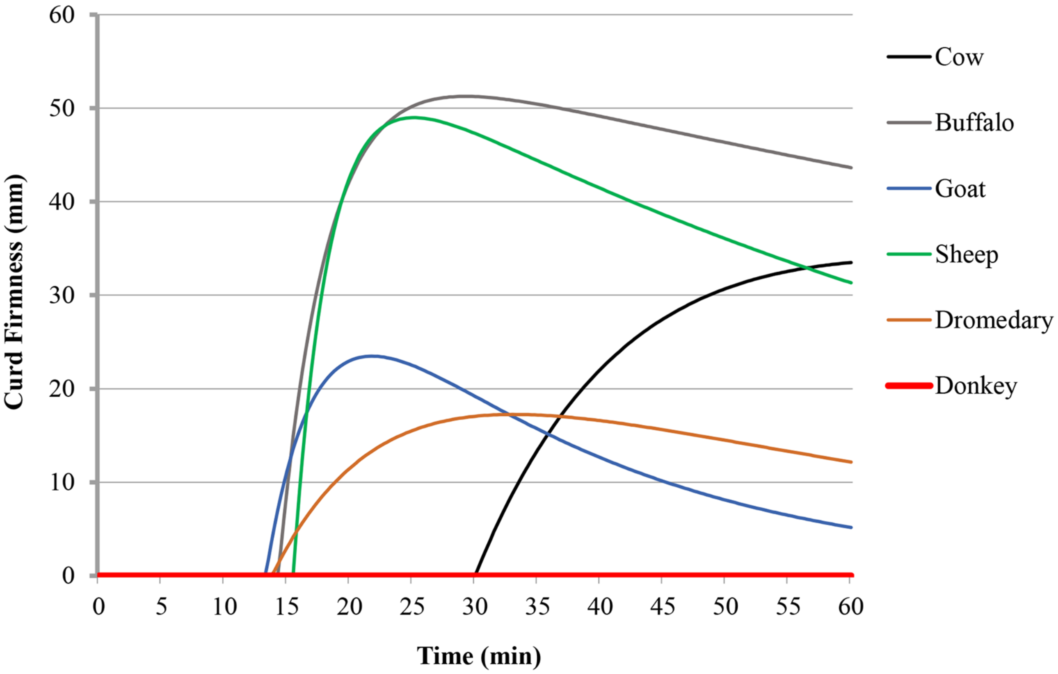

Figure 6. Average modeled pattern of curd firmness over time after rennet addition, obtained using the LSM of the equation parameters of the 6 major dairy species.

chymosin (Kappeler et al., 2006; Sørensen et al., 2011; Langholm Jensen et al., 2013) and may compensate for the "weakness" of camel curd. Camel chymosin is, in fact, sometimes used in the dairy industry for producing bovine cheeses, especially when coagulation is slow and curd weak.

Composition and Cheese-Making Ability of Sheep Milk

Sheep milk is used almost exclusively for cheese production, especially in countries of the Mediterranean basin (Fahmy and Shrestha, 2002; Noce et al., 2016), a preference that is clearly related to its excellent cheese-making ability (Bittante et al., 2014; Leitner et al., 2016). Its rapid coagulation after rennet addition and very fast increase in CF compared with bovine milk is well known (Gelè et al., 2014; Pazzola et al., 2014; Pazzola, 2019). In fact, sheep milk had the highest k_{CF} of the different species investigated here. The syneresis instant rate constant was at an intermediate level and similar to dromedary camel milk. A large variability in k_{SR} among milk samples of different individual ewes has sometimes been observed. Vacca et al. (2015) found that the CF_t curve of milk produced by about one-third of ewes had no descending phase, and that the milk also had no estimable k_{SR} value. The milk samples in the present study were not obtained from individual ewes within a flock but were rather bulk milk from different flocks, so they represent the average pattern of many ewes from different farms, which can explain why the CF_t curve of all but one of the sheep milk samples had a clear descending phase.

The REC traits of sheep milk were intermediate with respect to the milk samples from the other ruminants. This, combined with the very high fat, protein, and casein contents, explains the very high cheese-yield traits characterizing ewe milk, which confirms previous results obtained with similar methodologies (Cipolat-Gotet et al., 2016a). Note that other model cheese-making procedures separate the curds and whey through centrifugation, although the separation is not satisfactory with this process (Cipolat-Gotet et al., 2016b) and it leads to overestimation of the cheese yield (Othmane et al. 2002; Manca et al., 2016). This suggests the need for a common methodology to more accurately compare different species, although the drawback would be that it could not be adapted to the specific characteristics of milk from different species.

Composition and Cheese-Making Ability of Goat Milk

Different breeds of goat present very different milk composition characteristics (Devendra and Haenlein, 2011). The fat and protein contents of milk from goat breeds of Alpine origin, like those sampled in this study, differ little from cow's milk, whereas breeds of Mediterranean origin are characterized by much greater milk nutrient contents (Vacca et al., 2018a), similar to sheep milk. Coagulation and curd-firming abilities are also largely affected by breed (Vacca et al., 2018a; Pazzola, 2019), in part due to differences in the genetic variants of milk protein fractions (Pazzola, 2019). In most cases, goat milk falls between the patterns typical of ovine and bovine milk (Gelè et al., 2014; Leitner et al., 2016). It is worth noting that goat milk exhibited the highest k_{SR} instant rate (Table 5), which explains the large difference between CF_P and CF_{max} (the former similar to sheep milk, the latter similar to cow milk; Table 5) and why CF_{max} was reached at the earliest t_{max} compared with all the other species. A high k_{SR} is often interpreted as the result of rapid syneresis expelling the whey from the curd, which can then float freely in the vat, giving less resistance to the pendulum of the lactodynamograph (Bittante et al., 2013). However, in the case of goat milk, fragile curds are frequently obtained (Leitner et al., 2016; Roy et al., 2020), especially in Alpine breeds (Pazzola et al., 2018; Vacca et al., 2018a), which means that the descending phase of the CF_t curve (and the high k_{CF}) can be interpreted not as the result of increasing syneresis and actual curd firmness but instead as fragmentation caused by the pendulum in the curd (Vacca et al., 2020). This also explains why the milk of Alpine goats is often coagulated by acidification instead of renneting to produce very fresh cheeses (Moatsou and Park, 2017). In any case, it is the differences in milk nutrient contents that are responsible for the substantial differences in the cheese yields of goat and sheep milk (Leitner et al., 2016), and of different goat breeds, especially between those of Alpine and Mediterranean origin (Vacca et al., 2018b; Pazzola et al., 2019).

Composition and Cheese-Making Ability of Buffalo Milk

The milk produced by buffaloes has the highest content of total solids and fat, and the second-highest protein content (but the greatest casein/protein ratio) of the 6 major dairy species (Table 3; Aspilcueta-Borquis et al., 2010; Roy et al., 2020). The coagulation and curd-firming patterns of the milk of this species are also excellent (Ariota et al., 2007; Cecchinato et al., 2012) and compete with ovine milk for first place (Figure 6). Buffalo milk had the highest recoveries in the curd of fat and energy (Table 5), so not only did it have the highest cheese yield (Zicarelli, 2004; Dettori et al., 2009), it also had the highest cheese-making efficiency,

Table 6. Average daily production of milk, milk energy, ripened cheese, and ripened cheese energy of the 6 major dairy species, expressed per lactating head, per unit of live weight (LW), and per unit of metabolic weight (MW)

Item	Cow	Buffalo	Goat	Ewe	Dromedary	Donkey
Milk yield						
Per head, kg/d	33	8	3	1.5	3	2
Per unit of LW, g/kg	51	11	55	36	8	7
Per unit of MW, g/kg	256	59	150	91	34	29
Milk energy yield						
Per head, MJ/d	100	39	8	7	9	3
Per unit of LW, kJ/kg	153	56	145	161	22	10
Per unit of MW, kJ/kg	773	287	399	410	98	40
Cheese yield						
Per head, kg/d	2.97	1.28	0.26	0.23	0.23	0.00
Per unit of LW, g/kg	4.6	1.8	4.6	5.4	0.6	0.0
Per unit of MW, g/kg	23.0	9.4	12.8	13.7	2.6	0.0
Cheese energy yield						
Per head, MJ/d	71.0	29.6	5.2	4.7	4.6	0.0
Per unit of LW, kJ/kg	109	42	95	111	11	0
Per unit of MW, kJ/kg	550	218	261	283	51	0

retaining as much as 76% of milk energy in the cheese. In a previous study, using the same model cheese-making procedure and a large number of individual buffalo milk samples, Cipolat-Gotet et al. (2015) found an average $\text{REC}_{\text{ENERGY}}$ of 79.3%, compared with 67.2% for bovine milk. Cheese-making efficiency was found to be unaffected by the buffalo's parity, but it increased with advancing stage of lactation.

The fact that the cheese yield in solids of buffalo milk was much larger that of cow milk compensates in part for the much lower daily milk yield of this species compared with cows, and explains why buffalo are the second most important producers of milk in the world (Sun et al., 2014). Buffalo are well suited not only to tropical (hot, humid) environments, where specialized dairy cows have difficulty adapting to the conditions and can develop health problems (Khan, 2002), but also to temperate climates in developed countries (Arora and Khetra, 2017). In Italy, which has the largest dairy buffalo population in Europe, a combination of very high cheese yield and products of excellent quality (i.e., buffalo mozzarella cheese) mean that buffalo milk fetches a price 3 to 4 times higher than cow milk (Addeo et al., 2007).

Cheese Production of the 6 Major Dairy Species

Direct comparison of the 6 dairy species in terms of daily cheese production and cheese production efficiency is beyond the scope of this study, but some considerations can be made on the basis of the average daily milk yields and live weights of the lactating females in the farms sampled. The variability in milk quality and technological properties due to different farms and animals within species is generally much lower than the variability in daily milk yield (Bittante et al., 2015; Stocco et al., 2018a). However, the differences among the dairy species are so large that some inferences can be drawn, albeit cautiously. The differences in terms of average daily milk yield between the most productive species (cows) and the others ranges from about a quarter (buffalo) to a twentieth (sheep). This is explained firstly by the differences in animal size and, second, by differences in dairy systems. To aid discussion of the differences among the species, in Table 6 we summarize some of the raw ratios obtained from the milk yields and live weights recorded or estimated, and the milk energy contents, ripened cheese yields, and milk energy recoveries in the cheese measured in this study. The daily productions of milk, milk energy, ripened cheese, and cheese energy are expressed per lactating head, per unit of live weight, and per unit of metabolic weight.

If the milk yield is divided by the live weight of the animal (grams of milk per kilogram of live weight) (Table 6), goats produce about the same amount of milk as cows, and sheep produce an amount that is intermediate between cows and buffaloes. The milk production of dromedary camels and donkeys remains in the order of 6 to 7 times lower than cows.

One of the most important determinants of production efficiency is the ratio between the nutrient requirements for milk production and for animal maintenance (Tempelman and Lu, 2020). It seems, however, that a scaling factor based on average metabolic weight (**MW** $= \text{LW}^{0.75}$, where LW = live weight) could be more informative, as it would in some way represent production per unit of net energy required for animal maintenance. It should be borne in mind that the concept of MW was first proposed for comparing species of very different sizes (Brody, 1945). Scaled for MW, the bovine species remained about 8 to 10 times more productive than the 2 less-productive species, with caprine species intermediate.

However, the differences among the dairy species are, to a large extent, explained by differences in milk composition. The metabolic burden of lactation is first represented by the quantity of energy secreted with milk. The energy content of buffalo milk, the species with the highest net energy content, is 3.5 times that of the species with the lowest net energy content (donkey). Therefore, a need exists for a proxy for milk production efficiency in terms of milk energy, and not only of milk volume, especially when comparing very different species. As can be seen from Table 6, after taking into account the energy content of milk, the superiority of the bovine species over the asinine species increases about 35-fold when milk energy secreted is expressed per head, 16-fold when expressed per unit of LW, and 20-fold when expressed per unit of MW. However, the values for the small ruminants are now similar because the higher energy content of sheep milk tends to compensate for the higher milk production of goats (Table 6). When scaled on LW, the daily milk energy production of small ruminants appears to be comparable to that of cows, whereas scaled on MW, the values for these 2 species are about half that of the bovine species. It worth noting that, although buffaloes differ little in size from cows, their energy production values are about one-third those of bovines, regardless of the scaling factor. The energy output of dromedary camels remained much lower than that of cows (8–12 times), although much larger than that of donkeys.

As this study focuses on the cheese-making ability of different dairy species, we can conclude with some considerations on the daily cheese production of the different species. We can exclude the equine species from this discussion, not only because of their low daily milk production and very low content of coagulating solids (fat and casein) in the milk, but also because of the difficulties in getting the milk to coagulate.

Cheese productivity of the ruminant and pseudoruminant species is more a reflection of the values in terms of milk energy than in terms of milk volume (Tempelman and Lu, 2020), given the strong relationships between the energy content of milk and cheese yield per unit of fluid milk. Therefore, the considerations regarding daily milk energy secreted by the different species could also apply to daily cheese production, with the difference that the values for buffaloes and, in part, sheep are slightly greater, and values for dromedary camels are lower due to differences in the milk nutrient recoveries in fresh cheese.

The final consideration, which takes daily milk production, animal size, milk composition, and cheese-making efficiency of different species together, is summarized by the daily production of cheese energy per unit of MW. As can be seen from Table 6, the productivity of cows seems to be 2 times that of small ruminants, 2.5 times that of buffaloes, and 11 times that of dromedary camels. Obviously, these differences are related to the cheese-making procedures used in this study, which are optimized for bovine milk. Cheese-making conditions, especially coagulant type and concentration, have been shown to interact with dairy species (Liburdi et al., 2019). Moreover, the differences observed reflect the genetic specificities of the different species, as well as the animals' different environmental conditions and the different dairy systems. Note that, whereas in Italy cows and buffaloes are mainly raised on intensive dairy farms on the plains, small ruminants are often managed semi-intensively in the hills. In these hilly conditions, cows' productivity is much lower than on the plains, so the daily cheese energy production per unit MW can be expected to be not much different from that of the small ruminants. The productivity of dromedary camels is much lower than the 4 ruminant species, although their environmental conditions are the harshest and management is the most extensive. In these very hot and arid conditions, cows probably could not survive, and small ruminants would have difficulty adapting. Thus, despite their low productivity, dromedary camels can provide humans with a highly nutritious food (milk, dairy products, and meat) in areas where no alternative type of production is sustainable (Zarrin et al., 2020).

Regarding the rearing of dairy species in developed countries, it should be borne in mind that, aside from production efficiency and technological properties, the economics of dairy farms rearing "minor" species is strongly affected by the price paid for the milk in local (niche) markets. In Italy, milk from small ruminants generally fetches a price in the range of 1.5 to 2 times that of cow milk, buffalo milk 2.5 to 3 times, and donkey milk up to 10 times.

CONCLUSIONS

The 6 major dairy species produce milk with very different compositions and abilities of the milk to coagulate and of the curd to firm and expel whey and to retain milk nutrients. Asinine milk is the most similar to human milk but is not a valuable source of cheese because it does not coagulate and has very low fat and casein contents. Camelid milk, compared with the other species, has a similar coagulation time but a less favorable curd-firming process, with lower nutrient recovery and cheese yield, and requires specific cheese-making conditions and the use of camel chymosin. Bubaline and ovine milks have better cheese-making aptitudes (nutrient contents, coagulation and curd firming properties, nutrient recovery in the curd, and cheese yield) compared with bovine and caprine milks. Bovine milk is characterized by a late coagulation and caprine milk by a rapid decrease in curd firmness after attaining the maximum.

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