



## Detailed mineral profile of milk, whey, and cheese from cows, buffaloes, goats, ewes, and dromedary camels, and efficiency of recovery of minerals in their cheese

Nicolò Amalfitano,<sup>1\*</sup> Nageshvar Patel,<sup>1</sup> Mohamed-Laid Haddi,<sup>2</sup> Hamida Benabid,<sup>3</sup> Michele Pazzola,<sup>4</sup> Giuseppe Massimo Vacca,<sup>4</sup> Franco Tagliapietra,<sup>1</sup> Stefano Schiavon,<sup>1</sup> and Giovanni Bittante<sup>1</sup>

<sup>1</sup>DAFNAE – Department of Agronomy, Food, Natural resources, Animals and Environment, University of Padova (Padua), 35020 Legnaro (PD), Italy

<sup>2</sup>Laboratoire de Mycologie, Biotechnologie et Activité Microbienne, Université des Frères Mentouri, Constantine 25000, Algeria

<sup>3</sup>Institut de Nutrition, Alimentation et Technologies Agro-Alimentaires, Université des Frères Mentouri, Constantine 25000, Algeria

<sup>4</sup>Department of Veterinary Medicine, University of Sassari, 07100 Sassari, Italy

### ABSTRACT

Milk and dairy products are important in the human diet not only for the macronutrients, such as proteins and fats, that they provide, but also for the supply of essential micronutrients, such as minerals. Minerals are present in milk in soluble form in the aqueous phase and in colloidal form associated with the macronutrients of the milk. These 2 forms affect the nutritional functions of the minerals and their contribution to the technological properties of milk during cheese making. The aim of the present work was to study and compare the detailed mineral profiles of dairy foods (milk, whey, and cheese) obtained from cows, buffaloes, goats, ewes and dromedary camels, and to analyze the recovery in the curd of the individual minerals according to a model cheese-making procedure applied to the milk of these 5 dairy species. The detailed mineral profile of the milk samples was obtained by inductively coupled plasma–optical emission spectroscopy. We divided the 21 minerals identified in the 3 different matrices into essential macro- and microminerals, and environmental microminerals, and calculated the recovery of the individual minerals in the cheeses. The complete mineral profiles and the recoveries in the cheeses were then analyzed using a linear mixed model with Species, Food, and their interaction included as fixed effects, and Sample within Species as a random effect. The mineral profiles of each food matrix were then analyzed separately with a general linear model in which only the fixed effect of Species was included. The results showed that the species could be divided into 2 groups:

those producing a more diluted milk characterized by a higher content of soluble minerals (in particular, K), and those with a more concentrated milk with a higher colloidal mineral content in the skim of the milk (such as Ca and P). The recoveries of the minerals in the curd were in line with the initial content in the milk, and also highlighted the fact that the influence of the brine was not limited to the Na content but to its whole mineral makeup. These results provide valuable information for the evaluation of the nutritional and technological properties of milk, and for the uses made of the byproducts of cheese making from the milk of different species.

**Key words:** essential minerals, environmental minerals, cheese-making efficiency, curd mineral recovery, whey composition

### INTRODUCTION

Milk and dairy products are important sources of essential nutrients for human nutrition and health in terms of the development of the organism and maintenance of a healthy metabolism (Haug et al., 2007; Pereira, 2014; Pereira and Vicente, 2017). They provide the organism with energy from the fat and lactose content, EAA from high biological value proteins, as well as other important compounds, such as vitamins and minerals (Fosset and Tomé, 2002). Although minerals represent only a small fraction of the nutrients in milk (less than 1% of milk composition), they have numerous roles in the organism, including the formation of structural components and biochemical functions, and therefore occur in different forms, such as inorganic salts and ions or the components of organic molecules, such as proteins. A classic example is represented by calcium in the blood, which is the basic constituent of bones and teeth in its inorganic salt form,

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\*Corresponding author: [nicolo.amalfitano@unipd.it](mailto:nicolo.amalfitano@unipd.it)

The list of standard abbreviations for JDS is available at [adsa.org/jds-abbreviations-24](https://adsa.org/jds-abbreviations-24). Nonstandard abbreviations are available in the Notes.

and is involved in neurotransmission, muscle contraction, and blood coagulation in its free ionic form (Pravina et al., 2013; Caroli et al., 2011). In its latter form, it can also be found linked to a reversible protein-bound form, which is important in regulating levels of ionic calcium in the blood and transporting it to other parts of the body (Taylor and Bushinsky, 2009). The same configurations are also found in milk, where some elements are exclusively dissolved as ions in the aqueous phase, whereas others are distributed between the soluble and colloidal phases, in the latter case associated with milk nutrients (Cashman, 2011; Sun and Li, 2021).

In addition to their nutritional role, minerals are also important for the technological quality of milk. In fact, calcium and phosphorus are crucial for the stability of casein micelles: calcium phosphate and calcium ions act as positively charged bridges between the negative phosphoserine residues of the caseins constituting the micelles (Gaucheron, 2005; Dalgleish and Corredig, 2012). In the cheese-making process, after the loss of stability due to the hydrolytic action of rennet, ionic calcium helps aggregate the micelles binding the caseins on calcium-sensitive sites. Adding calcium chloride to the milk exploits this mechanism and is a way of increasing the soluble calcium content and improving coagulation. In contrast, the drop in pH through the use of organic acid or through the fermentation of the lactose into lactic acid by the action of starter cultures increases the solubilization of colloidal calcium phosphate and reduces the stability of the micelles leading to their aggregation (Lucas et al., 2006; Dalgleish and Corredig, 2012). Magnesium also seems to play a role in the coagulation process, as it combines with calcium in binding the caseins (Cuomo et al., 2011), although our previous study showed a negative effect of high magnesium concentrations on cheese-making efficiency (Stocco et al., 2021).

Many studies have shown that the variation in milk macronutrients and mineral profiles is greatly affected by environmental factors, such as ration composition and feeding strategies, and factors linked to the animal, such as genetic makeup, parity order, lactation stage, and health status (Summer et al., 2009; Denholm et al., 2019; Stocco et al., 2019). Large fluctuations in milk components have been observed, in particular between different species: according to Gibson (1989) and Fox (2008), fat concentrations can vary by 2% to 55%, protein concentrations by 1% to 20%, and lactose concentrations by 0% to 10%, depending on the growth requirements of the offspring. However, these figures relate to comparisons of the composition of milk of all mammals, whereas the world's milk production for human consumption is provided by a few species, and the differences between them in composition are smaller, although still important (Alston-Mills, 1995; Medhammar et al., 2012; Faccia

et al., 2020). According to the Food and Agriculture Organization (FAO, 2021), cattle account for 83% of global milk production for human consumption, with the remaining percentage supplied by buffaloes (13%), goats (2%), ewes (1%), and camels (0.4%). A very small percentage is supplied by other less common dairy species, such as horses, donkeys, yaks, and reindeer (Park et al., 2017). The distributions of nonbovine species throughout the world depend on environmental conditions and the ability of the animals to adapt better than cattle species. In some cases, milk is the only form of agricultural production that harsh environments (hot, cold, arid, or humid) can support (FAO, 2021).

Several reviews have compared the milk from these dairy species (Alston-Mills, 1995; Medhammar et al., 2012; Faccia et al., 2020), although they have focused on studies based on a small number of individual or bulk samples from single or 2 to 3 species, and with often different conservation conditions and analytical methods. A few of these reviews also compared the mineral profiles (at least the macro-elements) of milk (Claeys et al., 2014; Pietrzak-Fiećko and Kamelska-Sadowska, 2020; Stobiecka et al., 2022). A few of the studies investigated and compared the milk mineral profiles of more than 2 species sampled at the same time (or within a year of each other), and included ruminants (Martín-Hernández et al., 1992; Rincón et al., 1994; Singh et al., 2019) and pseudoruminants, such as camels (Al-Awadi and Srikumar, 2001; Soliman, 2005). None of them investigated the mineral composition of the whey and the cheese, manufactured according to a standardized laboratory cheese-making process, from the milk of all the species analyzed.

Given this limited background knowledge, the aim of the present work was to compare the highly detailed mineral profiles of various dairy products (milk, whey, and cheese) obtained from cows, buffaloes, goats, ewes, and dromedary camels, following the fate of each mineral during the cheese-making process and to quantify the percentage recovery in the curd of the single minerals according to a standardized model cheese-making procedure applied to the 5 dairy species.

## MATERIALS AND METHODS

### *Experimental Design*

This work is part of the Good-Milk project, which included the aim to compare the composition, technological properties, and nutritional value of milk from ruminants (cattle, buffaloes, goats, and sheep) and pseudoruminants (dromedary camels).

In accordance with the aims of the study the experiment was a factorial combination of 5 species (cattle, buffalo, goat, sheep, and dromedary camel), and 3 food matrices

(whole milk, whey, and ripened cheese), and their interactions. Further details of the project, the herds and farming systems, animals, cheese-making procedures, and so on, are reported in a previous study (Bittante et al., 2022a). The farms were specifically chosen to represent the major dairy systems of the sampled species.

### **Animals and Milk Sampling**

Briefly, 10 bulk milk samples (about 2.5 L) per species were collected after the morning milking from the milk tanks of different Italian farms rearing either cows, buffaloes, goats, or ewes. As dromedary camels are mainly reared in free-ranging herds in extensive, very arid areas, 10 × 2.0 L individual milk samples were collected following hand milking of the animals, which were located in 2 grazing areas in the Province of Constantine (Algeria), under the supervision of the Institut de Nutrition, Alimentation et Technologies Agro-Alimentaires, Université des Frères Mentouri, Constantine 25000, Algeria. General characteristics, farming and feeding systems, and climatic conditions of the rearing environment for each species are described and discussed in our previous study (Bittante et al., 2022a).

All the samples were refrigerated immediately after collection and transported to the Milk Laboratory of the Department of Agronomy, Food, Natural Resources, Animals and Environment – DAFNAE (University of Padova, Legnaro, Italy) for milk analysis.

### **Sample Handling and Composition Analysis**

Milk samples were homogenized by gentle shaking, aliquoted, and analyzed for composition and technological quality within 48 h of collection. A 50-mL aliquot of milk was freeze-dried and used afterward to analyze the detailed mineral profile.

A larger aliquot of each milk sample was used to manufacture the model cheeses. About 1,500 mL of milk (800 mL of buffalo milk, because of its higher cheese yield) was used to produce a model cheese with a diameter of 9.8 cm. The cheese-making procedure is given in detail in our previous study (Bittante et al., 2022a) and summarized in Figure 1. Briefly, the milk contained in a stainless steel vat was heated at 35°C for 30 min and, then, rennet was added to reach 0.051 international milk clotting units/mL of milk (Hansen Naturen Plus 215 bovine rennet, Pacovis Amrein AG). No calcium chloride or starter cultures were added to the milk to improve coagulation. After coagulation, the curd was cooked at 50°C for 10 min, and then cross-cut. After 10 min of syneresis, the curd was separated from the whey and drained for 30 min by suspension and handling in a mold over the whey. After draining, the curd was cut and placed in a 10 cm Ø

plastic mold for the final wheel shape formation. All the operations were executed over the whey collecting vat, and then a representative sample of the whey was taken for composition analysis. Then, the curd was pressed for a total of 30 min, with a turn every 10 min. The fresh cheese wheel was salted by immersion in a 20% saturated brine for 30 min. Finally, the cheese was ripened in a climatic chamber at 15°C and 85% RH for 7 d, then vacuum packed and kept under the same conditions for a total of 95 ± 5 d after cheese making (with a weight loss of 36% ± 6%). The chemical composition of the 3 food matrices obtained during the process is reported in Table 1. A 50-mL aliquot of whey collected during the cheese-making process was freeze-dried and stored at room temperature; the wheels of ripened cheese were ground and a sample stored at -80°C. Both the whey and the cheese samples were analyzed to determine their detailed mineral profile by the same method as that used for the milk samples.

### **Mineral Profiles of Milk, Whey, and Cheese Samples**

A Spectro Arcos EOP ICP-OES (Spectro A.I. GmbH, Kleve, Germany) with settings optimized for a 10% nitric acid solution was used to determine the mineral profiles of the samples according to the procedure described in detail by Stocco et al. (2019). Briefly, about 2 g of the food matrix sample (freeze-dried milk and whey, and ground ripened cheese) was diluted in a TFM vessel (Milestone S.r.l., Sorisole, BG, Italy) with 2 mL of hydrogen peroxide (30%) and 7 mL of nitric acid (65%; both reagents were Suprapur quality; Merck Chemicals GmbH). The mixture was then microwave digested in an Ethos 1600 system (Milestone S.r.l., Sorisole, BG, Italy) in 3 steps: (1) 25 to 200°C in 15 min at 1200 W, Pmax 100 bar; (2) 200°C for 15 min at 1200 W, Pmax 100 bar; (3) 200 to 110°C in 15 min. The mineralized sample was cooled at room temperature, and finally diluted with ultrapure water (resistivity 18.2 MΩ cm at 25°C) to a final volume of 20 mL. Standard solutions for instrument calibration, and blank solutions for accuracy and precision tests were prepared according to Stocco et al. (2019).

The minerals identified were classified into 3 categories according to their content and function in the human body, and their required intake in human diet (McDowell, 2003): (1) macrominerals, with a body content >0.01%, and an essential human intake >50 mg/d: sodium (Na), magnesium (Mg), phosphorus (P), sulfur (S), chlorine (Cl), potassium (K), and calcium (Ca); (2) essential microminerals, with a much lower concentration in the human body, and an essential intake <50 mg/d: chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), copper (Cu), zinc (Zn), selenium (Se), molybdenum (Mo), and iodine (I); (3) environmental microminerals, whose concentrations are similar to the essential microminerals,



**Figure 1.** Workflow diagram of the model cheese-making procedure. IMCU = international milk clotting units; RH = relative humidity; Ø = diameter.

and that have an as yet not well known role in the organism or that are the result of environmental contamination or both: lithium (Li), boron (B), aluminum (Al), silicon (Si), titanium (Ti), nickel (Ni), strontium (Sr), tin (Sn), and barium (Ba).

The concentrations of the individual minerals identified with this analysis were expressed as milligrams per kilogram of fresh product (mg/kg of fresh milk, whey, or ripened cheese). A limit of quantification (LOQ) for all the elements was determined by a signal-to-noise ratio of 10:1. For those elements with concentrations below the

LOQ in at least one sample, the limit was: 0.01 mg/kg for Cr, Mn, Li, Ba, Ti; 0.02 mg/kg for Cu, Mo, B, Ni; 0.1 mg/kg for Se. The values under the LOQ were imputed as half the minimum value found in the food matrix in question (Patel et al., 2020). In the case of Li, Ni, Se, and Mo, which were below the LOQ in a high percentage of samples ( $\geq 33\%$ ) from all the matrices, we did not use the actual concentrations obtained, but instead created a dummy variable that took the value 1 when the element was present in the sample above the LOQ, and 0 when below the LOQ (to calculate the percentage of samples

**Table 1.** Descriptive statistics (mean  $\pm$  SD) concerning the chemical composition of the 3 dairy products (milk, whey, and ripened cheese) across 5 species (cattle, buffaloes, goats, sheep, and dromedary camels; 10 samples per species)<sup>1</sup>

Chemical composition	Bovidae				
	Bovinae		Caprinae		Camelidae, Camelinae, Dromedary
	Cow	Buffalo	Goat	Sheep	
Milk					
TS, %	12.72 $\pm$ 0.59	17.93 $\pm$ 0.67	11.57 $\pm$ 0.76	16.86 $\pm$ 1.40	12.49 $\pm$ 1.37
Fat, %	3.87 $\pm$ 0.63	7.68 $\pm$ 0.46	3.07 $\pm$ 0.64	6.36 $\pm$ 0.70	3.74 $\pm$ 1.05
Protein, %	3.18 $\pm$ 0.20	4.38 $\pm$ 0.24	3.28 $\pm$ 0.22	4.95 $\pm$ 0.68	3.16 $\pm$ 0.55
Lactose, %	4.62 $\pm$ 0.24	5.01 $\pm$ 0.19	4.12 $\pm$ 0.32	4.67 $\pm$ 0.62	4.19 $\pm$ 0.38
Ash, %	0.68 $\pm$ 0.03	0.80 $\pm$ 0.03	0.79 $\pm$ 0.03	0.82 $\pm$ 0.08	0.85 $\pm$ 0.06
pH	6.63 $\pm$ 0.02	6.65 $\pm$ 0.04	6.50 $\pm$ 0.05	6.49 $\pm$ 0.20	6.44 $\pm$ 0.07
Whey					
TS, %	5.09 $\pm$ 0.87	8.00 $\pm$ 0.46	5.74 $\pm$ 0.98	8.18 $\pm$ 0.73	7.76 $\pm$ 1.07
Fat, %	1.01 $\pm$ 0.67	1.34 $\pm$ 0.42	0.79 $\pm$ 0.33	1.07 $\pm$ 0.33	1.97 $\pm$ 0.81
Protein, %	0.59 $\pm$ 0.09	1.17 $\pm$ 0.10	0.82 $\pm$ 0.15	1.42 $\pm$ 0.12	0.92 $\pm$ 0.17
Lactose, %	3.11 $\pm$ 0.50	4.46 $\pm$ 0.49	3.27 $\pm$ 0.65	4.88 $\pm$ 0.36	3.69 $\pm$ 0.46
Ash, %	0.32 $\pm$ 0.06	0.42 $\pm$ 0.03	0.44 $\pm$ 0.12	0.49 $\pm$ 0.03	0.58 $\pm$ 0.05
pH	6.62 $\pm$ 0.02	6.64 $\pm$ 0.06	6.44 $\pm$ 0.06	6.55 $\pm$ 0.04	6.42 $\pm$ 0.09
Ripened cheese					
TS, %	74.48 $\pm$ 2.18	77.37 $\pm$ 2.14	66.57 $\pm$ 1.97	70.40 $\pm$ 2.55	73.54 $\pm$ 3.45
Fat, %	36.97 $\pm$ 3.33	44.91 $\pm$ 1.19	30.00 $\pm$ 5.67	36.00 $\pm$ 2.82	30.79 $\pm$ 4.59
Protein, %	28.07 $\pm$ 1.79	23.14 $\pm$ 1.09	29.22 $\pm$ 1.43	26.20 $\pm$ 1.84	31.94 $\pm$ 3.18
Lactose, %	4.67 $\pm$ 0.71	4.48 $\pm$ 0.73	3.95 $\pm$ 1.17	4.12 $\pm$ 0.52	4.84 $\pm$ 0.90
Ash, %	4.77 $\pm$ 0.34	4.83 $\pm$ 0.41	4.95 $\pm$ 0.25	4.07 $\pm$ 0.44	5.98 $\pm$ 0.68
pH	6.01 $\pm$ 0.28	6.12 $\pm$ 0.33	5.44 $\pm$ 0.12	5.24 $\pm$ 0.41	6.19 $\pm$ 0.42

<sup>1</sup>Bovidae family includes cattle, buffalo, goat, and sheep species. Bovinae subfamily includes cattle and buffalo species. Caprinae subfamily includes goat and sheep species.

above the LOQ). We assigned these elements to the group “other trace minerals.”

### Recovery of Milk Minerals in Cheese

We took 2 approaches to calculating the recoveries of the milk minerals in the cheese, the first for fresh curd and the second for ripened cheese:

- $REC_{\text{MINERAL-CURD}}$ , %: the difference between the content of the mineral in the milk before processing and the content in the whey obtained from the cheese-making process, expressed as a percentage of the content of the same mineral in the milk before processing.
- $REC_{\text{MINERAL-CHEESE}}$ , %: the content of the mineral in the ripened cheese as a percentage of the content of same mineral in the milk before processing.

The content of each mineral in the relative dairy product was obtained multiplying its concentration (mg/kg of fresh product) by the weight of the dairy product (kg). It is evident that  $REC_{\text{MINERAL-CURD}}$  takes into account only the loss of the mineral in the whey, and assumes that the rest of the milk minerals are in the curd.  $REC_{\text{MINERAL-CHEESE}}$  takes into account the loss of the mineral in the whey, and

variations due to salting and ripening. The milk samples with minerals under the LOQ were excluded from the calculations of mineral recoveries.

### Statistical Analyses

All the data concerning the detailed mineral profiles were analyzed with the SAS MIXED procedure (SAS Institute Inc., Cary, NC) according to the following base mixed model:

$$y_{ijk} = \mu + \text{Species}_i + \text{Food}_j + \text{Species}_i \times \text{Food}_j + \text{Sample}_k(\text{Species}_i) + e_{ijk},$$

where  $y_{ijk}$  is the single mineral concentration (mg/kg of product);  $\mu$  is the overall intercept of the model;  $\text{Species}_i$  is the fixed effect of the  $i$ th level of animal species (5 species: cow, buffalo, goat, ewe, dromedary camel);  $\text{Food}_j$  is the fixed effect of the  $j$ th level of the food matrix (3 foods: Milk, Whey, Cheese);  $\text{Species}_i \times \text{Food}_j$  is the fixed effect of the interaction between Species and Food;  $\text{Sample}_k$  is the random effect of the  $k$ th sample within Species and is considered normally distributed  $\sim N(0, \sigma_{\text{sample}}^2)$ ;  $e_{ijk}$  is the residual random error and is considered normally distributed  $\sim N(0, \sigma_e^2)$ . The significance of

the Species effect was tested using the error line of the random Sample(Species), whereas the effects of Food and Species  $\times$  Food were tested using the error line of the random residual. As this model showed that the interaction between Species and Food was significant (from  $P < 0.05$  to  $P < 0.001$ ) for the large majority of the minerals analyzed, the mineral profile of each food matrix was analyzed separately with a simple linear model (GLM procedure in SAS) including only the fixed effect of Species and the residual random error.

The data regarding the recoveries of the milk minerals in the cheese were analyzed with the same above-mentioned factorial model, but substituting food matrix with cheese type (2 types: fresh curd and ripened cheese).

A check for outliers was performed for each studied trait (mineral profiles and recoveries) using as threshold the mean  $\pm$  3 SD units of residuals obtained from the first and more complex mixed models.

Orthogonal contrasts between the LSM of the species were performed according to the evolutionary taxonomic pathway of the 5 dairy species, as indicated in our previous study (Bittante et al., 2022a):

- (a) within the *Artiodactyla* order, the *Camelidae* family (dromedary camels, pseudoruminants) versus the *Bovidae* family (ruminants);
- (b) within the *Bovidae* family, the *Bovinae* subfamily (cattle and buffaloes) versus the *Caprinae* subfamily (goats and sheep);
- (c) within the *Bovinae* subfamily, cows versus buffaloes;
- (d) within the *Caprinae* subfamily, goats versus ewes.

## RESULTS

### Descriptive Statistics of Detailed Mineral Profile and ANOVA Results

Descriptive statistics of the detailed mineral profiles of the dairy foods (milk, whey, and cheese), and the results of the ANOVA of the effects of animal species, food matrix, and their interaction are summarized in Table 2. The minerals are listed according to their atomic number and category (Patel et al., 2019). All the mineral concentrations had a distribution with an important skewness or a large kurtosis or both, and a CV above 85%, except for K (CV = 29%) and B (CV = 55%). However, the distributions of the residuals obtained from the first linear model applied to each mineral tested as normal, attesting to the abnormal distribution of the raw data being due to important differences between species and food matrices.

Among the macrominerals, Ca, P, and Na had the highest concentrations in the milk, whey, and cheese,

followed by K and S, whose concentrations were less than half those of the first 3 minerals. The mineral with the lowest concentration in this group was Mg. Among the essential microminerals, Zn had the highest concentration, more than 10 times that of Fe, which had the second highest concentration. Cu, Mn, and Cr were present in much lower concentrations. Among the environmental microminerals, the most abundant were Si and Sr, while Al, Ba, B, and Ti were present in much lower concentrations. Four other trace minerals were present in concentrations greater than the LOQ in less than two-thirds of the samples of the 3 dairy foods: Mo was the most frequently quantified above the LOQ (in 58% of samples), followed by Ni (in 48% of samples), Se (36%), and Li (21%).

The ANOVA results ( $F$ -value and  $P$ -value) showed that food matrix had the highest impact on the mineral profile (Table 2), in particular on the essential macro- and microminerals. The effect was significant (from  $P < 0.01$  to  $P < 0.001$ ) also for the environmental minerals, except Ni and Mo. The effect of species was significant (from  $P < 0.05$  to  $P < 0.001$ ) for all the macrominerals, 3 out of the 5 essential microminerals, and 8 out of the 10 environmental microminerals. However, the  $F$ -value of the fixed effect of animal species was much lower than that of food matrix, except for K, Li, and Mo. Lastly, the interaction between food matrix and animal species was almost always significant (from  $P < 0.05$  to  $P < 0.001$ ), indicating important differences in the proportions of each milk mineral recovered in the cheese or lost in the whey. We therefore applied a simple linear model to the mineral profile of each food matrix with species included as a fixed effect.

### Differences Among Dairy Species on Milk Mineral Profile

The significance, LSM estimates, and results of the orthogonal contrasts testing the effects of dairy species on the detailed mineral profiles of milk are presented in Table 3. The most significant differences in the milk mineral profiles across the 5 dairy species regarded the macrominerals. All of these minerals in the milk of the pseudoruminant dromedary camels were very far from the mean of the ruminants. The dromedary camels had the highest concentrations of Na and K in milk (+37% and +32%, respectively, compared with the ruminants), and the lowest concentrations of P, S, and Ca (−16%, −19%, and −12%, respectively, relative to the mean of the ruminants), and especially Mg (−54%).

Among the ruminants, the *Bovinae* (large ruminants: cows and buffaloes) and the *Caprinae* (small ruminants: goats and ewes) subfamilies did not differ greatly in their macromineral contents, generally in the range of −5% to

**Table 2.** Detailed mineral profile of milk, whey, and cheese: descriptive statistics (each mineral concentration is expressed as mg/kg of fresh dairy products), and *F*-value of the effects of animal species, food matrix, and their interaction, and root mean square error (RMSE)

Trait	N	Mean	SD	Species	Food	Species × food	RMSE
Essential macrominerals, mg/kg							
Na	145	2,903	3,279	30***	3,192***	25***	459
Mg	147	266	226	99***	3,361***	70***	29
P	148	3,091	2,884	14***	5,692***	21***	317
S	148	1,001	938	16***	10,320***	50***	77
K	149	1,431	417	178***	121***	38***	104
Ca	146	4,473	4,467	19***	6,010***	23***	470
Essential microminerals, mg/kg							
Cr	148	0.11	0.11	0.3	250***	0.3	0.05
Mn	146	0.14	0.16	33***	1,693***	38***	0.03
Fe	146	1.18	1.21	7.1***	220***	6.9***	0.55
Cu	147	0.32	0.40	2.2	243***	7.1***	0.17
Zn	147	18.40	20.59	71***	3,729***	76***	2.70
Environmental minerals, mg/kg							
B	150	0.11	0.06	4.9**	48***	2.6*	0.03
Al	142	0.74	1.11	4.5**	54***	9.0***	0.64
Si	143	4.07	3.98	4.8**	81***	10***	2.26
Ti	147	0.06	0.06	2.3	331***	3.5**	0.02
Sr	146	2.47	3.46	63***	698***	59***	0.91
Ba	147	0.46	0.54	18***	892***	32***	0.12
Other trace minerals, <sup>1</sup> %							
Li	145	21	41	139***	5.0**	3.1**	18
Ni	151	48	50	0.9	1.8	1.1	50
Se	151	36	48	2.6*	15***	0.6	44
Mo	151	58	50	17***	1.2	1.3	39

<sup>1</sup>Percentage of samples with mineral content above the quantification limit (LOQ; Li <0.01 mg/kg, Ni <0.02 mg/kg, Se <0.1 mg/kg, Mo <0.02 mg/kg). \**P* < 0.05; \*\**P* < 0.01; \*\*\**P* < 0.001.

+5%, with the exception of K, which was higher in small ruminant milk (+20%) than in large ruminant milk.

Within the subfamilies, buffalo milk was richer in macrominerals than cow milk (ranging from +16% for Na to +68% for Mg), and sheep milk was richer than goat milk (from +10% for Mg to +53% for Ca), with the exception of K, which had a higher concentration in cow than in buffalo milk (+47%), and in goat than in ewe milk (+58%).

Regarding the microminerals, the differences between the species were less prominent. The major differences between the dairy species were in the essential microminerals Mn, Cu, and Zn, while only Sr and Ba among the environmental minerals differed significantly (*P* < 0.001) between species.

Dromedary camel milk was slightly richer in Zn (+12%), and much richer in Sr (+121%) than the mean of the ruminants' milk, and poorer in Mn (−14%), Cu (−70%), and Ba (−69%). Within the ruminants, the large ruminants' milk contained less Mn (−25%), Cu (−46%), Sr (−48%) and Ba (14%), and more Zn (+12%) and Si (+23%) than the small ruminants' milk. As with the macrominerals, buffalo and sheep milk tended to have higher concentrations of the microminerals, especially Mn, Cu, Zn, Sr, and Ba, whose concentrations were from 53% to 290% higher than in cow and goat milk.

Regarding the other trace minerals, it is worth noting that only in dromedary camel milk it was possible to

detect Li in concentrations that were always greater than the LOQ, and Mo almost always in concentrations lower than the LOQ.

### Differences Among Dairy Species on Whey Mineral Profile

The significance, LSM estimates, and results of the orthogonal contrasts testing the effects of dairy species on the detailed mineral profiles of whey are presented in Table 4. The mineral profiles of whey were still affected by species, but to a lesser extent than the milk profiles, also because of the smaller differences in the major nutrient contents of whey among the different dairy species.

As with milk, species mainly affected the macromineral concentrations. Compared with whey from the milk of ruminants, dromedary camel whey had higher concentrations of Na (+52%), K (+43%), and Ca (+34%), a lower Mg content (−45%), but the same concentrations of P and S. The whey of large ruminants (*Bovinae* subfamily) differed from that of small ruminants (*Caprinae* subfamily) in having lower concentrations of P (−21%), S (−17%), and K (−30%). Within the 2 subfamilies, sheep and buffalo whey (as with milk) had higher concentrations of macrominerals than goat and cow whey, with the exception of K.

Regarding the microminerals, compared with ruminant species, dromedary camel whey contained more Fe, Zn,

**Table 3.** Detailed mineral profile of milk: overall effect of the species, their LSM (each mineral concentration is expressed as mg/kg of fresh milk), their orthogonal contrasts (*F*-value), and root mean square error (RMSE)<sup>1</sup>

Trait	Species LSM										Orthogonal contrasts <i>F</i> -value						
	Bovidae										Camelidae vs. Bovidae	Bovinae vs. Caprinae	Cow vs. buffalo	Goat vs. sheep	RMSE		
	Bovinae			Caprinae			Camelidae, Camelinae, Dromedary										
Species effect <i>F</i> -value	Cow	Buffalo	Goat	Sheep	Cow	Buffalo	Goat	Sheep	Cow	Buffalo	Goat	Sheep					
<b>Essential macrominerals, mg/kg</b>																	
Na	17***	319	369	308	388	474	52***	0.1	5.0*	11**	49						
Mg	161***	101	170	136	150	64	423***	5.6*	217***	9.3**	10						
P	72***	901	1,284	985	1,316	946	48***	6.4*	137***	102***	71						
S	46***	308	425	307	460	302	36***	2.4	58***	92***	34						
K	154***	1,418	964	1,759	1,111	1,732	171***	71***	126***	243***	90						
Ca	111***	1,137	1,894	1,146	1,748	1,299	24***	4.2*	261***	156***	105						
<b>Essential microminerals, mg/kg</b>																	
Cr	2.1	0.03	0.04	0.03	0.05	0.04	0.1	1.0	0.3	7.1*	0.01						
Mn	17***	0.02	0.04	0.03	0.05	0.03	6.0*	24***	19***	21***	0.01						
Fe	1.3	0.49	0.56	0.39	0.50	0.56	1.1	1.8	0.6	1.5	0.20						
Cu	14***	0.05	0.09	0.07	0.19	0.03	16***	14***	4.8*	25***	0.05						
Zn	32***	3.52	6.05	3.13	4.80	4.91	5.6*	15***	74***	32***	0.64						
<b>Environmental minerals, mg/kg</b>																	
B	1.1	0.12	0.14	0.12	0.13	0.15	3.0	0.1	1.2	0.1	0.04						
Al	0.5	0.36	0.26	0.34	0.28	0.45	1.2	0.0	0.5	0.2	0.34						
Si	3.7*	3.17	2.96	2.38	2.59	2.08	7.1*	6.5*	0.5	0.5	0.70						
Ti	0.9	0.02	0.03	0.02	0.02	0.03	2.7	0.1	0.5	0.2	0.02						
Sr	39***	0.25	0.51	0.30	1.17	1.23	65***	21***	6.0*	64***	0.24						
Ba	40***	0.07	0.23	0.10	0.25	0.05	49***	2.2	59***	53***	0.05						
<b>Other trace minerals,<sup>2</sup> %</b>																	
Li	—	0	0	0	0	100	—	—	—	—	—						
Ni	0.2	40	40	40	22	40	0.1	0.3	0.0	0.6	50						
Se	1.4	20	0	40	33	20	0.1	4.0	1.2	0.1	42						
Mo	4.5**	90	50	60	33	10	9.4**	2.7	4.1	1.7	44						

<sup>1</sup>Bovidae family includes cattle, buffalo, goat, and sheep species. Bovinae subfamily includes cattle and buffalo species. Caprinae subfamily includes goat and sheep species.

<sup>2</sup>Percentage of samples with mineral content above the quantification limit (LOQ; Li < 0.01 mg/kg, Ni < 0.02 mg/kg, Se < 0.1 mg/kg, Mo < 0.02 mg/kg).

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

**Table 4.** Detailed mineral profile of whey: overall effect of the species, their LSM (each mineral concentration is expressed as mg/kg of fresh whey), their orthogonal contrasts ( $F$ -value), and root mean square error (RMSE)<sup>1</sup>

Trait	Species LSM										Orthogonal contrasts $F$ -value				
	Bovidae										Camelidae vs. Bovidae	Bovinae vs. Caprinae	Cow vs. buffalo	Goat vs. sheep	RMSE
	Bovinae			Caprinae			Camelidae, Camelinae, Dromedary								
Species effect $F$ -value	Cow	Buffalo	Goat	Goat	Sheep	Sheep	Sheep	Sheep	Sheep	Sheep	Camelidae vs. Bovidae	Bovinae vs. Caprinae	Cow vs. buffalo	Goat vs. sheep	RMSE
Essential macrominerals, mg/kg															
Na	40***	225	380	281	381	483	86***	2.4	37***	14***	48				
Mg	90***	48	101	73	85	42	175***	2.6	200***	9.2**	7				
P	11***	287	408	382	503	424	1.7	16***	14***	13***	61				
S	19***	99	151	112	189	124	3.4	11**	24***	49***	20				
K	42***	962	978	1,574	1,198	1,689	83***	51***	0.0	19***	151				
Ca	40***	216	358	213	323	372	51***	2.0	54***	31***	35				
Essential microminerals, mg/kg															
Cr	1.4	0.01	0.03	0.01	0.02	0.03	0.6	0.3	3.0	1.3	0.02				
Mn	0.6	0.00	0.00	0.00	0.00	0.01	2.0	0.2	0.2	0.1	0.01				
Fe	2.7*	0.21	0.27	0.18	0.21	0.31	6.6*	1.4	1.5	0.3	0.10				
Cu	18***	0.02	0.03	0.01	0.07	0.02	6.3*	12**	3.0	65***	0.01				
Zn	9.4***	0.16	0.25	0.10	0.21	0.27	12**	3.9	5.6*	8.9**	0.07				
Environmental minerals, mg/kg															
B	5.9**	0.09	0.17	0.11	0.15	0.16	4.8*	0.1	14***	2.1	0.04				
Al	1.7	0.12	0.36	0.11	0.14	0.17	0.0	2.1	5.2*	0.1	0.20				
Si	8.8***	1.51	1.81	1.47	1.80	1.05	31***	0.0	3.8	3.8	0.29				
Ti	2.7*	0.01	0.02	0.01	0.01	0.01	2.2	3.2	6.5*	0.2	0.01				
Sr	44***	0.03	0.06	0.04	0.13	0.25	143***	5.2*	1.8	15***	0.04				
Ba	3.5*	0.01	0.03	0.02	0.02	0.03	1.2	1.0	11**	0.3	0.01				
Other trace minerals, <sup>2</sup> %															
Li	27***	0	0	30	0	100	104***	2.6	0.0	5.0*	24				
Ni	0.3	67	50	40	60	50	0.1	0.2	0.4	0.5	52				
Se	0.3	11	17	30	20	20	0.0	0.5	0.1	0.2	42				
Mo	6.9***	89	67	70	60	0	23***	0.7	1.1	0.2	40				

<sup>1</sup>Bovidae family includes cattle, buffalo, goat, and sheep species. Bovinae subfamily includes cattle and buffalo species. Caprinae subfamily includes goat and sheep species.

<sup>2</sup>Percentage of samples with mineral content above the quantification limit (LOQ; Li < 0.01 mg/kg, Ni < 0.02 mg/kg, Se < 0.1 mg/kg, Mo < 0.02 mg/kg).

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

B, and especially Sr, and less Cu and Si. As with camel milk, Li was present in the whey in concentrations above the LOQ, Mo in concentrations below the LOQ.

### **Differences Among Dairy Species on Cheese Mineral Profile**

The significance, LSM estimates, and results of the orthogonal contrasts testing the effects of dairy species on the detailed mineral profiles of ripened cheeses are presented in Table 5. After the cheese-making procedure, the concentrations of almost all the minerals were greatly increased.

Dromedary camel cheese had higher concentrations of all the macrominerals (+18% to +67%) compared with the cheeses made from ruminant milk, with the exception of Mg (-38%). The large ruminant cheeses had slightly lower concentrations of all the macrominerals than the small ruminant cheeses (-7% to -24%), except Na (+27%) and K (no significant difference). The 2 ruminant subfamilies also exhibited large differences in cheese macromineral contents, although unlike milk and whey, they were not greater in sheep and buffalo cheeses. In contrast, among the small ruminants, sheep cheese had lower concentrations of the macrominerals than goat cheese (-13% to -31%), while among the large ruminants, buffalo cheese had higher concentrations of Na (+9%), Mg (+34%), and Ca (+9%), and cow cheese had higher K (+71%), but there was no significant difference in P content.

Regarding the microminerals, dromedary cheese again had higher contents of all the quantified essential and environmental minerals than ruminant cheese, with the exception of Cr (no difference), and Cu and Ba (higher in the ruminant cheeses). The other trace elements were also more often above the LOQ threshold in ruminants than in camel cheeses (Ni and Mo significantly so, with  $P < 0.01$  and  $P < 0.001$ , respectively), with the usual exception of Li, which was above the LOQ only in dromedary cheese. The *Bovinae* and *Caprinae* subfamilies differed principally in Zn content, which was higher in the former (+16%), and Mn, Cu, and Sr, which were higher in the latter (+82%, +45%, and +83%, respectively). As for the other trace minerals, Mo was more often above the LOQ threshold in large ruminants, and Se more often in small ruminants. Within the large ruminants, buffalo cheese had higher contents of Mn, Fe, Cu, Ti, and Ba than cow cheese, while within the small ruminants, goat cheese had higher contents of Mn and Zn, and sheep cheese higher Al, Sr, and Ba.

### **Descriptive Statistics of Recovery of Milk Minerals in Cheese and ANOVA Results**

Descriptive statistics of the recoveries of individual milk minerals in the cheeses, and results of the ANOVA

of the effects of species, cheese type, and their interaction are summarized in Table 6. The recovery data were less skewed than the mineral concentration data, but the CV were still often high. The CV of the macromineral recoveries ranged from 9% to 83%, for the essential microminerals from 8% to 48%, and for the environmental microminerals from 18% to 175%. The macromineral with the highest recovery in cheese was Na, which exceeded 100% retention (because of cheese salting), followed by Ca, P, and S at between 68% and 80% of the content of the initial milk. Mg recovery was 50%, K only 19%. The essential microminerals generally had high retentions: close to or above 100% for Mn, Zn, and Cu, 57% for Fe, and 67% for Cr. With regard to the environmental microminerals, almost all the Sr and 83% of the Ba was retained in the cheese, while 56% of Al, and 64% of Ti were recovered. Lastly, the recovery of Si was 39%, B only 13%.

The results of the ANOVA of the effects of dairy species, cheese type, and their interaction showed that, in general, the recoveries of the macrominerals were more affected than the recoveries of all the microminerals. The significance of the effect of cheese type on the recoveries of the minerals highlights important differences between 2 stages of the cheese-making procedure in terms of mineral retention in the cheese. The direct approach represents the actual content of the minerals in the ripened cheese in relation to the contents in the milk processed (i.e., it represents the recoveries at the end of the cheese-making and ripening procedures). The indirect approach, in contrast, which calculates the mineral content of the curd as the difference between the contents in the milk and in the whey, represents the theoretical recovery of minerals in the fresh curd before the salting phase with brine and ripening. Cheese type, therefore, indicates the effect of salting and ripening on the recovery of the minerals. A simple linear model with species included as a fixed effect was applied to the mineral recoveries calculated according to the 2 approaches separately to study the effect of species before and after the salting phase and ripening.

### **Differences Among Dairy Species on Milk Mineral Recoveries in Fresh Curd (Indirect Approach)**

The significance, LSM estimates, and results of the orthogonal contrasts testing the effect of dairy species on mineral recoveries in the fresh curd are presented in Table 7. It is worth noting that no minerals had a recovery higher than 100%, suggesting that the minerals retained by the curd are only those of the initial milk. It is also interesting that, aside from Na, the only mineral with a much higher recovery estimate in the ripened cheese (Table 8) than in fresh curd was Mn. The effect of species

**Table 5.** Detailed mineral profile of cheese: effects of Species, their LSM (each mineral concentration is expressed as mg/kg of ripened cheese), their orthogonal contrasts (*F*-value), and root mean square error (RMSE)<sup>1</sup>

Trait	Species LSM						Orthogonal contrasts <i>F</i> -value					
	<i>Bovidae</i>						<i>Camelidae</i> , <i>Camelinae</i> , Dromedary	<i>Camelidae</i> vs. <i>Bovidae</i>	<i>Bovinae</i> vs. <i>Caprinae</i>	Cow vs. buffalo	Goat vs. sheep	RMSE
	<i>Bovinae</i>		<i>Caprinae</i>									
	Species effect <i>F</i> -value	Cow	Buffalo	Goat	Sheep							
Essential macrominerals, mg/kg												
Na	33***	6,830	7,471	6,059	5,216	9,042	70***	51***	5.4*	7.0*	729	
Mg	96***	410	551	750	518	346	145***	116***	59***	114***	48	
P	22***	5,944	6,107	7,279	6,272	7,582	38***	27***	0.7	22***	499	
S	47***	2,102	1,918	2,321	2,014	2,562	100***	19***	15***	32***	123	
K	194***	1,780	1,039	1,657	1,209	2,372	425***	0.4	218***	60***	132	
Ca	22***	8,891	9,700	10,619	9,227	12,027	56***	8.7**	8.2**	19***	745	
Essential microminerals, mg/kg												
Cr	0.4	0.22	0.21	0.24	0.25	0.23	0.0	1.2	0.1	0.0	0.08	
Mn	51***	0.21	0.25	0.45	0.39	0.40	19***	174***	4.8*	7.6**	0.05	
Fe	9.1***	1.42	2.34	1.96	2.59	3.72	26***	2.3	7.7**	2.6	0.88	
Cu	5.9***	0.44	0.80	0.92	0.88	0.43	8.6**	8.8**	8.4**	0.1	0.32	
Zn	93***	39.66	40.08	37.89	30.88	67.07	337***	20***	0.1	14***	4.27	
Environmental minerals, mg/kg												
B	3.8**	0.05	0.07	0.05	0.09	0.13	11**	0.3	1.2	3.0	0.05	
Al	9.2***	0.69	1.13	0.62	1.77	3.38	30***	0.7	1.0	5.0*	1.15	
Si	9.5***	4.40	6.02	4.70	7.57	13.96	34***	0.6	1.1	2.7	3.87	
Ti	4.0**	0.10	0.14	0.12	0.12	0.17	9.6**	0.1	7.0*	0.0	0.04	
Sr	71***	3.31	3.36	4.20	7.99	14.10	199***	39***	0.0	33***	1.54	
Ba	38***	0.83	1.34	0.78	1.47	0.45	67***	0.3	32***	47***	0.23	
Other trace minerals, <sup>2</sup> %												
Li	26***	0	0	0	0	70	105***	0.0	0.0	0.0	20	
Ni	2.7*	64	53	70	67	10	10**	0.6	0.4	0.0	48	
Se	3.2*	36	37	70	83	80	2.1	9.1**	0.0	0.5	47	
Mo	11***	82	95	60	67	0	35***	5.7*	0.9	0.2	37	

<sup>1</sup>*Bovidae* family includes cattle, buffalo, goat, and sheep species. *Bovinae* subfamily includes cattle and buffalo species. *Caprinae* subfamily includes goat and sheep species.<sup>2</sup>Percentage of samples with mineral content above the quantification limit (LOQ; Li <0.01 mg/kg, Ni <0.02 mg/kg, Se <0.1 mg/kg, Mo <0.02 mg/kg).\**P* < 0.05; \*\**P* < 0.01; \*\*\**P* < 0.001.

**Table 6.** Percentage recovery (REC) of milk minerals (shown as subscripts) in cheese; descriptive statistics, *F*-value of the effect of species, cheese type and their interaction, and root mean square error (RMSE)

Trait	N	Mean	SD	Species	Cheese type	Species × cheese type	RMSE
Essential macrominerals, %							
REC <sub>Na</sub>	95	145.0	119.9	28***	781***	20***	29.94
REC <sub>Mg</sub>	97	49.9	8.9	18***	77***	13***	4.78
REC <sub>P</sub>	97	68.4	8.6	22***	21***	7.1**	4.42
REC <sub>S</sub>	97	68.5	6.4	10***	17***	7.3***	4.44
REC <sub>K</sub>	98	19.3	11.1	32***	225***	19***	4.93
REC <sub>Ca</sub>	95	79.5	7.5	14***	57***	3.2*	4.46
Essential microminerals, %							
REC <sub>Cr</sub>	88	67.3	24.3	4.1**	4.4*	2.2	20.44
REC <sub>Mn</sub>	58	105.7	33.0	0.7	36***	5.1*	21.63
REC <sub>Fe</sub>	94	57.0	20.1	6.9***	2.9	4.6**	16.32
REC <sub>Cu</sub>	75	92.0	43.7	1.7	8.3**	0.6	39.83
REC <sub>Zn</sub>	94	101.0	7.8	1.4	20***	0.6	6.92
Environmental minerals, %							
REC <sub>B</sub>	52	13.4	23.4	6.3***	4.7*	1.5	19.85
REC <sub>Al</sub>	89	55.7	37.8	2.2	0.1	2.6*	34.53
REC <sub>Si</sub>	91	39.1	17.6	11***	144***	9.6***	9.54
REC <sub>Ti</sub>	70	63.6	27.5	2.5	1.5	3.6*	23.66
REC <sub>Sr</sub>	95	97.9	17.5	5.2**	31***	4.5**	13.01
REC <sub>Ba</sub>	88	83.3	27.5	9.9***	1.7	1.2	22.30

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

on mineral recoveries was not quite as great in fresh curd as in ripened cheese.

The contrasts showed that the recoveries of all the macrominerals in dromedary camel fresh curd was always lower than the recoveries in ruminants' curd. Within the ruminants, most of the differences were between the *Bovinae* (large ruminants) and *Caprinae* (small ruminants) subfamilies, with the former group having higher recoveries than the latter. Within the 2 groups, there were hardly any significant contrasts, and they were generally in favor of sheep and buffalo, except for B which had a higher recovery in cow and goat curds.

#### Differences Among Dairy Species on Milk Mineral Recoveries in Ripened Cheese (Direct Approach)

The significance, LSM estimates, and results of the orthogonal contrasts testing the effects of dairy species on the mineral recoveries in ripened cheese are presented in Table 8. It is worth noting in this case that the recoveries of some of the minerals in the ripened cheeses of some species are estimated at over 100%, but in all the cases the difference from the theoretical 100% is lower than the root mean square error (RMSE) of the recovery. Only in the case of Na was the recovery much higher than 100% (and the RMSE); in the case of ripened buffalo cheese it amounted to more than 3 times the content in the processed milk, about twice the content in the case of cow and sheep cheeses, and more than 1.5 times in the case of goat and dromedary camel cheeses. Dairy species had a significant effect (from

$P < 0.05$  to  $P < 0.001$ ) on the recovery of almost all the minerals, except Cu and Zn.

The contrasts indicated that, even in ripened cheese, compared with ruminants, dromedary camel exhibited lower recoveries of all macrominerals (excluding S resulted not significant), as well as Cr and Ba, showing instead higher recovery of Si. There were a few differences between the ripened cheeses obtained from milk of the *Bovinae* (large ruminants) and *Caprinae* (small ruminants) subfamilies, and these were mostly in the macrominerals, similar but not identical to the curds. In particular, after salting and ripening, cheeses from the *Bovinae* subfamily had higher recoveries of Na and K, whereas the *Caprinae* had higher recoveries of Ca and Mg. Within the subfamilies there were bigger differences, but, in general, the cheeses from buffalo and sheep milk had still higher recoveries of minerals than cow and goat cheese; the only significant exception ( $P < 0.001$ ) was Sr in small ruminants.

## DISCUSSION

### Essential Macrominerals in Milk

Milk and dairy products are important sources of macrominerals. Although there are plenty of other food sources of these minerals in developed countries, it is uncertain whether these alternatives have equivalent levels of bioavailability, even with fortification (Chalupa-Krebzdak et al., 2018). Dairy cows are the major source of milk and dairy products on the planet, accounting for

**Table 7.** Recovery (REC) of milk minerals (shown as subscripts) in fresh curd calculated as difference between the content of the mineral in processed milk and in the obtained whey as percent of the content of the same mineral in processed milk (indirect approach): effects of species, their LSM, their orthogonal contrasts (*F*-value), and root mean square error (RMSE)<sup>1</sup>

Trait	Species LSM										Orthogonal contrasts <i>F</i> -value					
	Bovidae										Camelidae, Camelinae, Dromedary	Camelidae vs. Bovidae	Bovinae vs. Caprinae	Cow vs. buffalo	Goat vs. sheep	RMSE
	Bovinae			Caprinae												
Species effect <i>F</i> -value	Cow	Buffalo	Goat	Sheep	Goat	Sheep										
Recovery essential macrominerals, %																
REC <sub>Na</sub>	14***	39.9	33.7	19.3	25.1	11.7	29***	18***	1.7	1.4	8.90					
REC <sub>Mg</sub>	14***	59.5	61.7	52.6	58.7	43.4	50***	5.3*	0.5	3.9	5.61					
REC <sub>P</sub>	15***	73.0	79.8	65.9	73.7	60.9	39***	10**	6.0*	7.4*	5.28					
REC <sub>S</sub>	12***	74.2	77.1	67.8	70.3	64.2	30***	17***	1.7	1.3	4.02					
REC <sub>K</sub>	17***	42.5	35.3	20.9	29.2	15.6	32***	21***	3.1	3.7	7.74					
REC <sub>Ca</sub>	25***	83.9	87.9	83.6	87.1	74.9	95***	0.2	5.9*	4.8*	2.98					
Recovery of essential microminerals, %																
REC <sub>Cr</sub>	1.1	63.1	66.0	57.2	58.9	50.6	2.8	1.3	0.1	0.1	14.05					
REC <sub>Mn</sub>	0.2	40.6	—	—	—	13.8	—	—	—	—	58.72					
REC <sub>Fe</sub>	3.4*	62.9	68.4	57.7	64.1	43.6	12**	0.7	0.5	0.7	14.05					
REC <sub>Cu</sub>	9.0***	67.1	80.8	76.5	83.8	46.2	31***	1.2	3.7	0.8	11.73					
REC <sub>Zn</sub>	7.7***	96.1	97.3	97.2	97.2	95.7	18***	2.7	8.5**	0.0	0.78					
Recovery of environmental minerals, %																
REC <sub>B</sub>	5.2**	37.4	2.0	16.3	-15.6	9.6	0.0	5.1*	8.9**	6.7*	22.41					
REC <sub>Al</sub>	0.3	61.9	54.8	46.0	42.9	48.8	0.0	0.8	0.1	0.0	37.11					
REC <sub>Si</sub>	3.1*	59.4	61.0	45.1	52.8	51.6	0.5	7.1*	0.1	1.5	10.65					
REC <sub>Ti</sub>	1.6	64.9	61.1	52.5	90.1	68.1	0.0	0.7	0.2	4.8*	16.00					
REC <sub>Sr</sub>	20***	88.1	92.6	88.9	91.5	81.6	73***	0.0	9.2**	3.0	2.73					
REC <sub>Ba</sub>	10***	78.0	91.2	82.6	93.6	49.0	38***	0.3	2.2	1.6	15.42					

<sup>1</sup>Bovidae family includes cattle, buffalo, goat, and sheep species. Bovinae subfamily includes cattle and buffalo species. Caprinae subfamily includes goat and sheep species. \**P* < 0.05; \*\**P* < 0.01; \*\*\**P* < 0.001.

**Table 8.** Recovery (REC) of milk minerals (shown as subscripts) in ripened cheese calculated as content of minerals in cheese as percentage of the content in the processed milk (direct approach): effects of species, their LSM, their orthogonal contrasts (*F*-value), and root mean square error (RMSE)<sup>1</sup>

Trait	Species LSM											Orthogonal contrasts <i>F</i> -value			
	Bovidae											Goat vs. sheep	Goat vs. buffalo	Goat vs. buffalo	RMSE
	Bovinae			Caprinae			Camelidae, Camelinae, Dromedary		Camelidae vs. Bovidae	Bovinae vs. Caprinae	Cow vs. buffalo				
	Cow	Buffalo	Sheep	Goat	Sheep	Goat	Sheep								
Recovery essential macrominerals, %															
REC <sub>Na</sub>	46***	194.4	327.5	168.4	200.1	154.5	16***	45***	79***	3.4	38.31				
REC <sub>Mg</sub>	19***	36.9	51.6	46.5	53.5	41.7	8.1**	13***	51***	8.8**	5.20				
REC <sub>P</sub>	20***	58.8	75.1	63.1	73.1	60.8	9.6**	0.5	52***	16***	5.68				
REC <sub>S</sub>	8.9***	61.1	72.5	64.3	68.5	67.0	0.1	0.1	30***	3.4	5.28				
REC <sub>K</sub>	98***	11.2	17.1	8.0	17.2	11.0	20***	13***	114***	213***	1.43				
REC <sub>Ca</sub>	9.8***	69.7	81.4	78.9	80.7	68.4	11**	5.4*	22***	0.5	6.24				
Recovery of essential microminerals, %															
REC <sub>Cr</sub>	6.5***	51.7	87.7	69.5	85.3	50.4	8.0**	1.1	13***	2.3	23.26				
REC <sub>Mn</sub>	3.0*	88.7	111.5	116.1	118.1	120.2	2.1	6.4*	6.3*	0.1	21.42				
REC <sub>Fe</sub>	9.9***	30.6	70.5	46.0	66.1	53.2	0.0	1.0	33***	5.9*	17.64				
REC <sub>Cu</sub>	1.5	72.4	117.5	116.0	99.0	93.8	0.1	0.7	4.9*	0.7	47.23				
REC <sub>Zn</sub>	1.5	100.1	104.9	104.0	108.2	100.2	1.3	1.9	1.9	1.2	8.86				
Recovery of environmental minerals, %															
REC <sub>B</sub>	5.3*	—	20.4	—	13.0	9.1	—	—	—	—	5.20				
REC <sub>Al</sub>	6.7***	25.6	83.0	30.7	58.2	71.1	3.2	0.9	18***	3.2	32.85				
REC <sub>Si</sub>	19***	13.1	33.2	16.9	34.8	44.1	34***	1.0	31***	20***	8.70				
REC <sub>Ti</sub>	6.0***	37.8	89.1	59.2	56.6	49.8	1.0	0.3	18***	0.0	26.67				
REC <sub>Sr</sub>	6.4***	115.7	105.2	119.4	88.1	93.6	3.5	1.9	2.6	18***	16.65				
REC <sub>Ba</sub>	5.5***	95.7	106.0	72.9	90.6	61.6	10**	6.0*	0.9	2.4	25.51				

<sup>1</sup>Bovidae family includes cattle, buffalo, goat, and sheep species. Bovinae subfamily includes cattle and buffalo species. Caprinae subfamily includes goat and sheep species.\**P* < 0.05; \*\**P* < 0.01; \*\*\**P* < 0.001.

81.3% of global milk production according to FAOSTAT (FAO, 2021), although other dairy species are also important in some parts of the world. Buffaloes produce 15% of the world's milk, and are particularly important in hot, humid environments. Goats (2.3% of global milk supply) are particularly important in arid temperate zones and mountains, and dairy ewes (1.1%) are reared mainly around the Mediterranean basin. Lastly, in very hot, arid areas, camelids (0.3%) have become a valuable source of milk (Zarrin et al., 2020; Narayanan, 2023). Other species (reindeer, donkeys, mares, yaks) are also used around the world for milk production, but they are niche sources of dairy products (Park et al., 2017). Unfortunately, comparisons of the composition of milk from different dairy species (using the same sampling and analytical procedures) are few and far between, especially for mineral profiles. The data reported in articles reviewing studies on milk composition refer to single or few (2–3) species.

**Macromineral Profile of Dromedary Camel Milk.** The macromineral profile of dromedary camel milk assessed in the present study is close to the range found in the literature (Elhassan et al., 2016; Mostafidi et al., 2016; Konuspaveva et al., 2022). A certain level of variability compared with other studies can be explained by differences in farming systems (in this case nomadic herds), feeding management (mainly grazing of shrubs), lactation stage, parity order, season, and the hydration level and general health of the animal. The high concentration of Na found in dromedary milk compared with the other dairy species can be explained by the grazing behavior of this species, which prefers to consume halophilic plants, such as *Atriplex* and *Acacia*, which are very rich in salt (Yagil, 1982; Medhammar et al., 2012; Elhassan et al., 2016). Regarding the other macrominerals, some review articles found dromedary milk to be similar to cow and goat milk (Barłowska et al., 2011; Medhammar et al., 2012; Gaucheron, 2013), as we also found in the present study through direct comparison. Low levels of Mg were found by Soliman (2005) and Felfoul et al. (2016), but not by Chen et al. (2020). The information they provide suggests that this low value may be due in part to the genetics of the species, and in part to a low dietary intake or dehydration (Yagil and Etzion, 1980). It is worth noting that camel milk varies in composition and nutritional value according to breed (Mudgil et al., 2023).

**Macromineral Profile of Milk from Ruminant Species.** Within the ruminant group, differences between the more productive species (cows and goats) and the species with a more concentrated milk (buffaloes and sheep) are expected (Barłowska et al., 2011; Gaucheron, 2013; Chia et al., 2017). Calcium, P, S, and Mg have the highest percentages in colloidal form in association with the protein fraction of milk (Toscano et al., 2023). Two-

thirds of milk Ca is found in the casein micelles interacting with P, the second most prevalent mineral in this phase. Total P in the casein micelles is divided between the phosphoserine residues of casein molecules and inorganic phosphate. Calcium interacts with both forms, and with inorganic phosphate creates small granules called nanoclusters, which contribute to the structure of the micelles. Magnesium is also present in this structure, with about 30% to 40% of its total content associated with nanoclusters, while the remaining part is present in the aqueous phase in association with inorganic phosphate and citrate. Finally, most of the S in milk is associated with the protein fraction as the latter is rich in sulfur-containing AA (Toscano et al., 2023). We therefore expect to find higher concentrations of these minerals in milk with a higher protein content (i.e., in buffalo and sheep milk compared with cow and goat milk). Sodium and K, instead, are the macrominerals with the highest percentages in the aqueous phase of milk (>90% of their total content). In ionic form they contribute to the osmotic equilibrium of milk with blood, so changes in their concentrations are often considered a sign of impaired udder health. According to Rook and Wood (1958), Wheelock and Rook (1966), and Rook and Wheelock (1967), where the concentration of K is higher and the concentration of Na is lower in milk than in blood it indicates water moving from the potassium-rich intracellular fluid to the secretory mammary alveoli. In cases of mastitis, along with a reduction in lactose and other milk solids, there will be a reduction in the K concentration and an increase in Na to compensate the osmotic pressure (Giannuzzi et al., 2024). Considering that the milk samples used for the present study were obtained from healthy animals, it is not surprising to find high K concentrations in the species that yield a more diluted milk, (i.e., with more water, such as cows, goats, and dromedaries). Sodium concentrations, however, were higher in buffalo and sheep milk than in cow and goat milk. Other studies have found bovine milk generally to have a high Na content, lower only than dromedary milk, and followed by buffalo and sheep milk. Various studies (Barłowska et al., 2011; Gaucheron, 2013; Chia et al., 2017) have found goat milk generally to have the lowest value, as we found here. An interesting observation, and in agreement with Park et al. (2007), was the difference between the *Bovinae* and the *Caprinae* subfamilies, where the concentrations of the macrominerals tended to be higher in the latter one, except for Ca (higher in the *Bovinae*) and for Na and S (not statistically different).

### Essential Microminerals in Milk

Microminerals have an important role in the metabolism of the organism, even in concentrations lower than

100 mg/kg (McDowell, 2017). Except for Zn, milk is a minor source of these minerals, and their contents are more variable than the macrominerals, because they are more influenced by environmental factors not directly linked to the animal, such as contamination. The rankings of the different species in the literature are not as consistent as those for the macrominerals (Konuspayeva et al., 2022). This could partly explain the smaller effect of species on micro- than on macrominerals. Only Zn seems more affected by species, although still with high variability, which could be explained by the fact that it is present mostly in colloidal form and associated with the casein fraction of milk (80%–90% of total content), as with most of the macrominerals (Toscano et al., 2023). In fact, it follows the same pattern as the colloidal macrominerals, being higher in the more concentrated milks (from buffalo and sheep) and lower in the more diluted ones. The only exception is dromedary milk, which is similar to buffalo and sheep milks in Zn content, but not in protein content. Some comparative studies found a higher concentration of Zn in dromedary milk than in other dairy species, particularly goat and cow (Fantuz et al., 2016; Konuspayeva et al., 2022). The situation is not very different from the other essential microminerals; some studies on different species found higher concentrations in buffalo and sheep milk than in cow and goat milk. Dromedary milk again seems to be often the exception for these minerals. Regarding Fe and Cu, dromedary milk has been found to have a higher content of these elements compared with the other species (Soliman, 2005; Barłowska et al., 2011; Medhammar et al., 2012). Other authors found it to have the lowest amount (Fantuz et al., 2016). Pietrzak-Fiećko and Kamelska-Sadowska (2020) found, as we did, no significant difference in Fe content between the ruminants, but unfortunately, they did not include camel milk in their study. As with Zn, Fe, and Cu are to a large extent associated with the protein fraction of milk (both caseins and whey proteins, such as lactoferrin) and to inorganic P and citrate (Gaucheron, 2013). Manganese is also strongly associated with milk protein and has comparable contents in cow, goat, and dromedary milk. Finally, there is very little information on the Cr content in milk and its role in human nutrition, and it differs little between the dairy species.

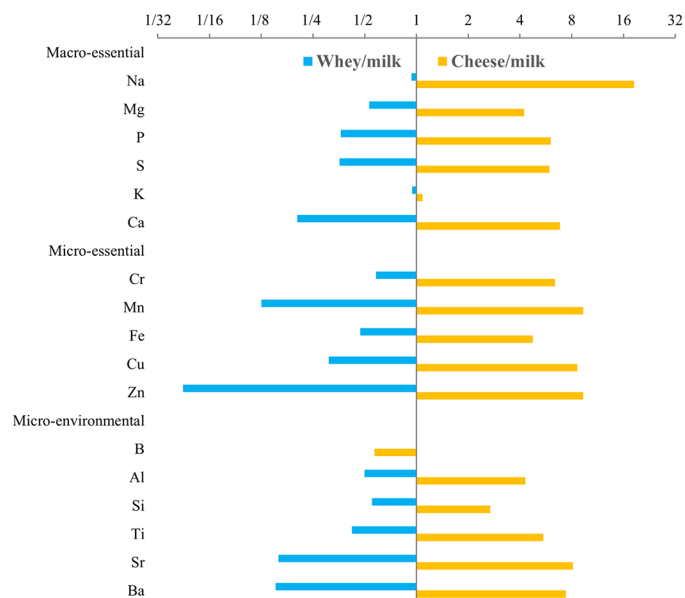
### **Environmental Microminerals in Milk**

Environmental microminerals are those elements that seem to have no physiological role in the organism. Their presence in milk is derived generally from direct contamination from the environment, or as the result of excretion of these elements by the organism, having ingested them with their feed, or the animal's interaction with the environment, as in the case of pica (Payne and Livesey,

2010). These minerals are of particular interest for their possible toxicity at low dose (As, Cd, F, Pb, Hg), and, for some of them (Li, B, Ti, Rb, Sr), their imputed positive bioactive effects on human nutrition (Hejna et al., 2018). The literature contains few studies on the concentrations of environmental microminerals in different species, and most have been carried out on grazing species, such as goats and sheep, as potential bio-indicators of environmental pollution (Miedico et al., 2016). All the studies agree that the contents of these trace minerals in milk are highly variable due to the different environments in which the animals are reared, as we observed in the present study. Few studies have been carried out in Italy on large and small ruminants. With regard to cows and buffaloes, Fantuz et al. (2022) found higher concentrations of B, Ti, and Sr in the milk of both species than we did, but like us, they found higher levels of these minerals in buffalo milk, although in our study the only significant difference was in Sr ( $P < 0.05$ ). With regard to goats and sheep, Miedico et al. (2016) found higher concentrations of Al and Sr in the 2 species, although the difference was not statistically significant, whereas in the present study, only Sr was significantly higher ( $P < 0.001$ ) in sheep milk with a similar concentration to the afore-cited study.

### **Cheese-Making Effect on Mineral Recoveries in Cheese and Losses in Whey**

Minerals have a strong effect on cheese making, which in turn has a strong effect on the minerals, from both a nutritional (the partition of milk minerals and other nutrients between cheese and whey) and a technological point of view (efficiency of coagulation, curd firming, syneresis, and nutrient retention in the cheese). One gram of cheese can have from 1 to more than 20 times the content of a single mineral than the milk, and this together with its fat and protein contents makes cheese a nutrient-dense food (O'Callaghan et al., 2017). Mineral concentrations are an important factor in cheese production as they influence the final yield of the product, particularly Ca. The addition of calcium chloride to the milk during the cheese-making process is known to improve coagulation by increasing the ionic Ca in solution and stimulating aggregation of the casein micelles. Some studies have pointed out that the concentrations of P and Mg are also important (Lucas et al., 2006; Dalgleish and Corredig, 2012; Stocco et al., 2021). For the whey, minerals have a different meaning; whey can only be used in infant formulas (particularly those for 0- to 6-mo-old infants) after it has been demineralized. Nanofiltration of the whey yields whey salt powder which can be used to produce diet supplements and to fortify foods, juices, and drinks (Anand et al., 2013). Acid coagulation of milk in cheese making increases mineral losses in the whey, but in the



**Figure 2.** Concentration of minerals in whey and cheese expressed as ratio respect to milk in a logarithmic scale (milk = 1.00, i.e., the vertical bar).

present study we used presamic coagulation, which produces a “sweet” whey.

**Comparisons of the Mineral Concentrations in Milk, Whey, and Cheese.** The very different outcomes of minerals during cheese making is evident when we compare their concentrations in whey and cheese with the original concentrations in milk. This is visualized in Figure 2, which shows the ratios between the concentrations of each mineral in whey and in milk, and between the concentrations in cheese and milk. As the 2 ratios have very different scales, they were expressed in logarithmic scale to help visualization. Thus, milk, taken as the reference (denominator of the ratios), has a value of 1.00 (0.00 logarithm) and is represented by the vertical black bar. The ratios  $<1.00$  (generally whey to milk) are to the left of the reference bar (negative logarithm) and those  $>1.00$  (generally cheese to milk) are to the right (positive logarithm).

Figure 2 shows clearly that the only mineral that has similar concentrations in milk, whey and cheese (ratios close to 1.00) is K. This means that the quantity of K found in cheese is similar to the cheese yield, and the rest is lost with the whey. It is worth noting that the average cheese yield of these 5 dairy species was 19.1%, so the whey loss was on average 80.9% by volume of the milk processed (Bittante et al., 2022a).

The concentrations of all the other macro- and micro-minerals, except B, were lower in the whey (blue bars in Figure 2) than in the milk, and, conversely, their concen-

trations in cheese (dark yellow bars) were higher. This is clear evidence that there is active partitioning of all these minerals in favor of the curd and cheese during cheese making. We expect that the higher the cheese/milk ratio, the lower the whey/milk ratio, and this is true for the majority of minerals, the most evident exception being Na, which had the highest cheese/milk ratio, but no corresponding decrease in the whey/milk ratio. The reason, of course, lies in the salting of the fresh cheese. The tap water used to make the brine could be one reason for the apparent discrepancy between the 2 ratios observed for some microminerals. An example of a mineral profile of tap water and brine used in cheese making is reported in Supplemental Table S1 (see Notes) for reference. Lastly, B was the only element with a cheese/milk ratio lower than 1.00, and a whey/milk ratio close to 1.00.

**Recovery of Milk Minerals in Fresh Curd and Ripened Cheese.** We used the data on the mineral contents of milk and whey to estimate the recovery of each mineral in the fresh curd (assuming it will be equal to the difference between the mineral content of the milk processed and the whey yielded). We also used the data on the mineral content of cheese and milk to estimate the recovery of each mineral in the ripened cheese (the ratio between the quantity of the mineral in the cheese and in the milk processed).

The average recoveries of each mineral with the 2 procedures are listed in Tables 7 and 8. To facilitate comparison of the 2 series of values, they are represented graphically in Figure 3. It is evident that the values obtained with the 2 procedures differ very little for the large majority of minerals. It is also evident that the recovery of minerals in the cheese depends on the cheese-making procedure adopted. Only in our area 37 different categories of cheeses are produced (Bittante et al., 2022b), so we adopted a standardized laboratory cheese-making technique based on the most frequent procedures adopted in practice, conscious of the need for future studies on interaction between cheese-making procedure and species for the recovery of minerals.

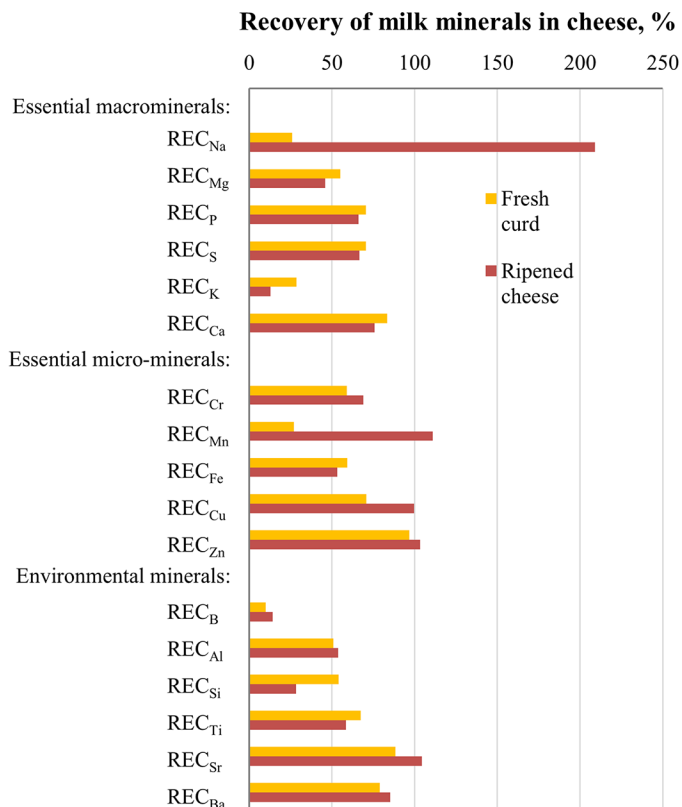
The largest difference, as expected, concerns Na recovery; the recovery in fresh curd is measured before it is salted in brine, whereas the recovery in ripened cheese is measured after, which also explains why  $REC_{Na}$  in cheese is much larger than the theoretical maximum value of 100% (also taking into account the RMSE). The second largest difference between the recoveries in fresh curd and in ripened cheese concerns Mn, the third Cu. In both cases, we cannot exclude the possibility that the cause is the water or the salt used to make the brine. As Figure 3 also shows, the recoveries of K and B differ little from the cheese yield, and there is no evident active process whereby the concentrations increase in the curd at the expense of the whey.

In discussing the recovery of the minerals in cheese, it is worth keeping in mind that most of them are mainly present in their colloidal and ionic forms, and mainly in the skim of the milk, so their recoveries are strongly connected to protein recovery (colloidal forms) and the water retained in the curd (ionic forms).

Before brining, Na and K have the lowest recoveries in the curd, and are, in fact, mostly present in the aqueous phase of milk, so more than half their content in milk is lost in the whey. A certain level of recovery is expected, because almost half the fresh cheese yield is constituted by the whey retained in the curd (Cipolat-Gotet et al., 2013; Stocco et al., 2018). Magnesium generally has a recovery close to 60%, even though its colloidal form associated with the casein micelles represents only one-third of the total content in milk (Oh and Deeth, 2017). Calcium has the highest recovery in this group of minerals because two-thirds of its content is in the casein micelles, while the remaining part is present in the whey in its free ionic form, or associated with citrate and inorganic phosphate, or bonded to the whey proteins (Gaucheron, 2013). Phosphorus and S have similar recoveries of around 70%, but although 50% of P is in colloidal form together with Ca, and 50% is in the aqueous phase, S is mostly bound to casein and whey proteins rich in sulfur-containing AA (cysteine and methionine; Anand et al., 2013; Toscano et al., 2023).

After brining, all the recoveries of the macrominerals change. Except for Na, which increases drastically, the recoveries of the other minerals tend to decrease. This may be due to partial substitution of the whey retained in the curd (after pressing) with the brine in which the fresh cheese is submerged. This would mean a loss mainly of the soluble minerals in the whey, and an uptake of Na and other minerals in the brine. This seems plausible, in particular with respect to the lower recovery of K.

Regarding the microminerals, essential or otherwise, they seem to be mostly present in milk associated with other compounds, such as fat, protein, and to a small extent other salts (Toscano et al., 2023). Hence, over 50% of their content in milk is generally recovered in cheese. For example, 95% of Zn in milk is associated with casein micelles though interaction with casein phosphoserine residues and inorganic phosphate (Gaucheron, 2013), so a recovery rate of over 90% is expected. However, the chemical form in which these elements appear in milk is not always well known. Analyzing the recovery of these microminerals before and after brining seems to confirm their presence mainly in the colloidal phase of milk. The Mn content in whey was often under the LOQ, making it impossible to calculate its recovery using the indirect approach, and meaning that most of it is allocated to the solid part of the cheese. Only B has a recovery rate close to Na and K, suggesting its presence mainly in the aque-



**Figure 3.** Percentage recovery (REC) of milk minerals (shown as subscripts) in cheese calculated indirectly (processed milk whey/curd) or directly (cheese/processed milk).

ous phase of milk. This is also clear from the analysis after brining, as the recovery of Mn is so high that it exceeds 100% due to contamination from this element in the salt and tap water constituting the brine. Although the other elements do not exceed 100%, their recoveries tend to increase after brining (unlike the macro-elements). Boron, instead, is so low, having been washed away by the brine, that is under the LOQ in the cheese matrix.

**Mineral Recoveries in Cheeses from the Milk of Different Dairy Species.** This distribution of minerals between the colloidal and aqueous phases is based on bovine milk as the reference. The other species investigated are not very far from these proportions, but there are some differences. Goat milk is known to have a higher proportion of ionic Ca than cow milk, but there is no difference between these 2 species in the actual soluble Ca content in the aqueous phase of the milk (~33%); in sheep milk, however, a lower proportion of Ca is soluble, close to 20% (de la Fuente et al., 2013). Sixty-six percent of Mg is soluble in goat milk, 64% in cow milk, and 56% in sheep milk (de La Fuente et al., 1997; Oh and Deeth, 2017). In buffalo milk, ~20% of Ca and ~50% of Mg are soluble (Singh et al., 2019). It seems, therefore, that the species with the higher concentrations of nutrients have

lower amounts of soluble macrominerals, except for Na and K, which are completely soluble. However, in the present work, most of the differences between the species in mineral recoveries seem to be linked more to the efficiency of the cheese-making process. It is worth noting that the lowest recoveries of all the essential macrominerals are in dromedary milk, which could explain its poor coagulation properties, which we observed during cheese making using bovine rennet in our previous study (Bittante et al., 2022a), and also reported by Farah (1993). Moreover, the lower pH observed in the milk and whey of this species can indicate a higher solubilization of the colloidal minerals and, so, possible higher losses into the whey (Lucey and Horne, 2009). Within the ruminants, the higher recoveries in the *Bovinae* subfamily compared with the *Caprinae* family are in line with the former's higher cheese solids yield and water retention. Within these subfamilies, the only significant differences ( $P < 0.05$ ) were in Ca and P recoveries, which were higher in the species with higher colloidal proportions of these minerals (buffalo and sheep).

## CONCLUSIONS

The detailed mineral profiles of the 5 major dairy species studied in the present research varied significantly between each other. Generally, the species producing more diluted milk (cow, goat, dromedary camel) presented lower concentrations of minerals linked to the colloidal phase of milk, and higher contents of soluble minerals in the aqueous phase. The species with more concentrated milk (buffalo, sheep) presented the opposite pattern. Dromedary camel milk had a distinctive mineral profile, influenced by their diet and rearing environment, particularly for macrominerals and partially for the essential microminerals. Environmental microminerals seemed to have closer connections with the environmental and farming conditions characterizing each species. The recovery of minerals in cheeses manufactured according to the same cheese-making procedure depended on the initial mineral content and its chemical form, with brining further affecting results. This information will be useful in evaluating the nutritional and technological qualities of milk from these 5 major species, and to better characterize the byproducts of the cheese-making process.

## NOTES

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by an Institutional Animal Care and Use Committee or Institutional Review Board. The authors have not stated any conflicts of interest.

**Nonstandard abbreviations used:** IMCU = international milk clotting units; LOQ = limit of quantification; REC = recovery; RH = relative humidity; RMSE = root mean square error.










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## ORCID

- Nicolò Amalfitano  <https://orcid.org/0000-0001-6030-1620>
- Nageshvar Patel  <https://orcid.org/0000-0002-0726-408X>
- Mohamed-Laid Haddi  <https://orcid.org/0000-0003-2081-0425>
- Hamida Benabid  <https://orcid.org/0000-0003-4802-1380>
- Michele Pazzola  <https://orcid.org/0000-0001-5685-0416>
- Giuseppe Massimo Vacca  <https://orcid.org/0000-0003-3110-5211>
- Franco Tagliapietra  <https://orcid.org/0000-0002-0593-1600>
- Stefano Schiavon  <https://orcid.org/0000-0002-5539-8947>
- Giovanni Bittante  <https://orcid.org/0000-0001-7137-7049>