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ABSTRACT

The content, composition and variation of vitamin compounds in goat milk have been little studied. An experimental design was based on 28 commercial farms, selected considering the main feeding system (based on main forage and especially pasture access), goat breed (Alpine vs Saanen) and reproductive management (seasonal reproduction), in the main French goat milk production area. Each farm received two visits (spring and autumn) that included a survey on milk production conditions and bulk milk sampling. Milk vitamins (A, E, B_2, B_6, B_9, B_{12}) and carotenoid concentrations plus colour indices were evaluated. A stepwise approach determined the variables of milk production conditions that significantly altered milk indicators. The main forage in the diet was the major factor altering goat milk vitamin and carotenoid concentrations and colour indices. Bulk milk from goats eating fresh grass as forage was richer in α-tocopherol (+64%), pyridoxal (+35%) and total vitamin B_6 (+31%), and b^* index (characterising milk yellowness in the CIELAB colour space) was also higher (+12%) than in milk from goats eating conserved forages. In milk from goats eating fresh grass, concentrations of pyridoxamine, lutein and total carotenoids were higher than in milk of goats fed corn silage (+24, +118 and +101%, respectively), and retinol and α-tocopherol concentrations were higher than in milk of goats fed partially dehydrated grass (+45 and +55%). Vitamin B_2 concentration was higher in milk of goats eating fresh grass than in milk of goats fed hay or corn silage as forage (+10%). However, bulk milk when goats had access to fresh grass was significantly poorer in vitamin B_{12} than when fed corn silage (−46%) and in γ-tocopherol (−31%) than when fed conserved forage. Alpine goats produced milk with higher vitamin B_2 and folate concentrations than Saanen goats (+18 and +14%, respectively). Additionally, the milk colour index that discriminates milks based on their yellow pigment contents was 7% higher in milk from Alpine than Saanen herds, but milk from Saanen goats was richer in lutein (+46%). Goat milks were richer in vitamins B_2 and B_{12} and folates, but poorer in vitamin B_6 in autumn than in spring (+12, +133, +15 and −13%, respectively). This work highlights that goat milk vitamin and carotenoid concentrations and colour indices vary mainly according to the main forage of the diet and secondly according to the breed and season.

Implications

The main factors driving the vitamin composition and content of goat milk are still unknown, whereas current demands from consumers in particular and citizens in general are to send ruminants back to pastures. Indeed, consumers have high expectations regarding the quality of dairy products and their origin. This study highlights that the main forage in the diet is the major factor regulating the vitamin and carotenoid contents of goat milk under real farm conditions. Goats fed fresh grass produce slightly yellower milk richer in several vitamins and carotenoids that are of nutritional interest to the consumer. However, this milk contains vitamin B_9 and B_{12} concentrations that are very low in comparison with cow milk.

Introduction

Vitamins are essential nutrients in human nutrition and have fundamental roles in health (Graulet and Girard, 2017). Dietary

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intakes often remain below recommendations all over the world (WHO, 1995; 2008), including in Western populations (Troesch et al., 2012), and are at-risk factors in age-related degenerative or chronic diseases, as well as in certain forms of cancer (Graulet and Girard, 2017). Milk and dairy products are a very good source of vitamins for humans, especially in some parts of the world, depending on feeding habits (Graulet and Girard, 2017). However, the content, composition and variation of vitamin compounds in ruminant milk have been little studied (Graulet et al., 2013), except for vitamin A (retinol) for which differences have been highlighted according to diet composition, lactation stage, ruminant species and breed (Nozière et al., 2006). In general, data on small ruminants are lacking in the literature. Small ruminant milk is considered richer in vitamin A but poorer in carotenoids and consequently less yellow than cow milk. In sheep, this has been ascribed to more efficient conversion of β-carotene into retinol (Nozière et al., 2006). Although the original data are limited, it seems that milk vitamin concentrations are lower in goat or cow milk than in ewe milk and that milk from goats is poorer in folates (vitamins B_9) than cow or ewe milk (Park et al., 2007; Graulet et al., 2013).

Very few direct comparisons among breeds have been published, especially for goats. Michlová et al. (2014) did not detect any significant differences in vitamin A and E concentrations in milk between several breeds of ewes and goats. Milk β-carotene content is higher in Guernsey or Jersey cows than in Prim'Holstein or Friesian cows, whereas vitamin A concentration is lower (Nozière et al., 2006). Milk concentrations of β-carotene and vitamin A are similar among Prim'Holstein, Montbéliarde and Tarentaise cows (Nozière et al., 2006; Graulet et al., 2019), but levels of α-tocopherol (the major vitamin E found in milk) (Graulet et al., 2019) are higher in milk of Prim'Holstein than Montbéliarde cows, while levels of riboflavin (vitamin B_2) (Poulsen et al., 2015b) are higher in milk of Jersey (+38%) than Holstein cows.

Milk vitamin A and E concentrations are higher when ruminants are fed a complete pasture-based diet than when complemented with concentrate (Fedele et al., 2004; Martin et al., 2004). No such data are available for carotenoids and other vitamins in goat milk. Dairy cows at pasture produce a yellower milk richer in carotenoids, riboflavin and folates than cows fed maize silage, whereas the opposite is true for vitamin B_{12} (cobalamins) (Graulet and Girard, 2017). Conclusions are harder to draw for vitamins A and E because their usual supply in mineral and vitamin supplements masks vitamin intake from the rest of the diet (Martin et al., 2004; Agabriel et al., 2007; Chassaing et al., 2016). Moreover, milk riboflavin concentration is also lower when cows are fed hay in comparison to grass silage (Shingfield et al., 2005). Increasing the proportion of forage in dairy cow diets has no effect on milk concentrations of riboflavin, decreases niacin (vitamin B_3) and pantothenic acid (vitamin B_5) and increases vitamin B_6 (pyridoxal and pyridoxamine) (Graulet and Girard, 2017), especially when forages are based on grass. Milk vitamin B_{12} concentration is related positively to the percentages of chopped mixed silage and commercial energy supplement in the diet, but negatively to the percentages of baled mixed silage, corn and commercial protein supplement in the diet (Duplessis et al., 2019).

The present work tested the hypothesis that vitamin and carotenoid concentrations vary in goat milk, as in cow milk, and we investigated the main sources of these variations. Moreover, in line with the current expectations of consumers and citizens concerning ruminants feeding on grass, especially pasture, we explored whether this change in practice would lead to variations in the nutritional quality of the milk produced. Therefore, the present work compared vitamin and carotenoid concentrations and colour indices between bulk milk of goats of the two major breeds in France (Alpine vs Saanen) fed classical diets encountered in commercial conditions, in order to identify the main management factors affecting milk indicators.

Material and methods

Experimental design and collection of data on milk production conditions

The study was performed between April and December 2017 in 28 caprine dairy farms located in western France in the REDCap network (Caillat and Jost, 2015). Farms were selected considering the main feeding systems encountered in dairy goat farming (Legarto et al., 2014), the goat breed (Alpine vs Saanen) and the seasonality of reproduction. Each farm received two visits, in spring and autumn, so that goats were always eating fresh grass (grazing or fed indoors with fresh grass).

Each visit included a survey to characterise the farm, herd and diet, through information obtained from farmers and dairy control boards, and a milk sample. Data collected included the management of goats in groups (number of groups of goats (meaning herds) at the farm and number of goats per group) at the farm and their breed and, for each group, mean milk production yield, mean lactation stage, mean number of lactations per goat (lactation rank calculated as the number of parturitions), including the percentage of primiparous goats and the proportion of goats in extended lactation (goats producing milk continuously for more than 305 days, which is the usual maximum lactation period; Wolber et al., 2021), and finally the composition of the diet given to lactating goat groups (forages, concentrates, mineral and vitamin complements, other additives). The survey also collected information on forage such as pasture composition and diversity or the mode of grass conservation when applicable. In addition, when available at the farm, the DM content of forage was noted. Otherwise, DM content was estimated using mean values in INRA tables (Baumont et al., 2007). Data on the origin and composition of the concentrates (produced at the farm or provided by an animal nutrition company) completed the survey. To identify and quantify vitamin supplementation, we collected these data on commercial feeds (including mineral and vitamin complements and additives).

Dietary intakes (expressed in DM intake [**DMI**] per goat and per day) were estimated based on quantities the farmers reported they distributed. Refusals were also considered for these feeds and were reported by the farmers. For grass at pasture, the value of fresh grass intake was estimated from an equation considering the ingested quantities of distributed feeds, their nutritive value, performance of the dairy herd and the fill value of the fresh grass (Delagarde et al., 2017).

Milk sampling and analyses

Milk samples (1–2 L) were collected in the tank of the 28 herds at the farms once at each of the two periods (spring and autumn, one visit per season). All the tanks contained an even number of milkings at the time of sampling to ensure they were representative of the day, since systems were based on two milkings per day. Before sampling, the milk was stirred for 5 min. For each sample, one aliquot was placed in a tube with bronopol-B2 (Trillaud, Surgères, France) and stored at 4 °C until the determination of fat, protein and lactose contents and somatic cell count. Other aliquots were stored at −20 °C until analysis.

Fat, protein and lactose contents were determined by mid-infrared spectrophotometry (method NF ISO 9622 using FT+ by FOSS at Laboratoire Interprofessionnel Laitier Du Centre-Ouest, Surgères or FT6000 by FOSS at Mylab, Chateaugiron). Somatic cell count was determined by a fluoro-opto-electronic method

(NF ISO 1366-2; Fossomatic™, Foss, France). Colour (CIELAB) was determined by reflectance between 400 and 700 nm (Minolta CM 2600d, Minolta, Tokyo, Japan) according to Laverroux et al. (2021). We used two colour indices (a^*, b^*) of the CIELAB colour space. The values of these indices range from −120 to +120. A positive value of a^* and a negative value of a^* point to redness and greenness, respectively, whereas a positive value of b^* and a negative value of b^* point to yellowness and blueness, respectively. Additionally, the colour index (**CI**) was calculated as the upper area of the reflectance spectra from 450 to 530 nm (Nozière et al, 2006). Retinol, α- and γ-tocopherols, and carotenoids (lutein, zeaxanthin, β-carotene) were quantified according to Graulet et al. (2019). Milk folates and vitamin B_{12} were quantified with a radioassay kit (SimulTRAC B_{12}/Folate-S; MP Biomedicals, Solon, OH, USA) according to Duplessis et al. (2015). Vitamins B_2 and B_6 were quantified simultaneously by a method developed for vitamin B_2 by Laverroux et al. (2021), with the following modifications. After acidic and enzymatic extractions as reported, chromatographic analysis was performed on a Waters Acquity UPLC® system (Milford, USA) equipped with a fluorescence detector (FLR). Injection volume was set at 15 μL. Riboflavin, pyridoxamine, pyridoxal and pyridoxine were separated using the method developed by Laverroux et al. (2021) using an Acquity UPLC® HSS T3 column (150 × 2.1 mm, 1.8 μm particle size, Waters). Pyridoxamine, pyridoxal, pyridoxine and riboflavin were eluted at 1.9, 4.2, 6.1 and 14.1 min, respectively. Their fluorometric quantification was performed using the following respective excitation and emission wavelengths: 290/390 nm for pyridoxine and pyridoxamine, 300/370 nm for pyridoxal and 450/520 nm for riboflavin. Calibration curves were plotted with peak areas of standard solutions with five different concentrations. Each sample was analysed in duplicate.

Data treatment and statistical analysis

Data treatment and statistical analysis were performed with the Minitab 18 software (Minitab Inc, State College, PA). A combination of principal component analysis and hierarchical cluster analysis was performed on data from 56 diets (proportions of the different forages in the diet as % DMI; Coppa et al., 2012; 28 in spring and 28 in autumn, 56 statistical individuals) in order to establish groups based on the main forage in their diet. Goat herd characteristics, diet and milk composition were analysed by ANOVA using the GLM procedure including the fixed effects of main forage in the diet, season and breed and the interactions between main forage in the diet and season, between breed and season as well as main forage in the diet, breed and season. Tukey's honest significant difference test was used for pairwise comparisons of means ($P < 0.05$).

The relationships between the conditions of milk production and the vitamin and carotenoid concentrations as well as colour indices of bulk milk were explored through eleven exploratory variables clustered in two groups. The first group corresponded to five variables extrinsic to the animals: main forage in the diet, percentage of concentrate and alfalfa pellets included in the herd diet, level of vitamin A and E supplementation, mean DMI of the herd, and season. The other six variables, main breed of the herd, herd lactation stage or percentage of goats in extended lactation in the herd, percentage of primiparous goats in the herd or herd lactation rank (both being correlated), and mean milk yield of the herd constituted the second group of variables intrinsic to the animals. The modalities of these variables and their respective occurrence in the population of goat herds are presented in Table 1.

A descriptive analysis of concentrations of carotenoids and vitamins as well as colour indices was performed first to identify potential outliers. Then, the statistical analysis of carotenoid and vitamin concentrations and colour indices was a GLM where the eleven exploratory variables were tested. A stepwise approach determined the significant variables among them. Variables were considered significant at $P < 0.05$. Multicollinearity between variables included in the model was tested by factors of variance inflation. The threshold for model acceptance was set at factors of variance inflation <2, and the best model for each milk compound and colour index studied was the one with the best coefficient of determination (R^2).

Results

Goat herd characteristics, diet and milk gross composition according to main forage in the diet, season and breed

The first three axes of the principal component analysis explained 80% of the variability in the population. Four classes of main forage in the diet were defined, namely fresh grass (at pasture, as green feeding or both; **FG**), wet grass (grass preserved by the wet method meaning wrapped or ensiled; **WG**), hay (legumes, grasses or both, **H**) and corn silage (**CS**). Mean values regarding the characteristics of the herd, goats, diet and milk gross composition according to main forage, season or goat breed are presented in Table 2. The herd numbers in each of these classes were similarly distributed between the two seasons and the two breeds studied. The CS class was characterised by a diet containing a major percentage of corn silage (37 ± 6% of the DMI), whereas this forage was absent or very low for other classes ($P < 0.05$). Goat herds of the H class received hay as the major forage (46 ± 13% of the DMI), the percentage of the other forages being very low or null. However, each of the other classes received a proportion of hay in the diet, complementary to the main forage (16–20% of the DMI) but lower than for the H class ($P < 0.05$). It should be noticed that straw access was also higher for H than for the others (3 ± 4 vs 1 ± 2% of the DMI, $P < 0.05$). In the WG class, wet grass was greater (29 ± 12% of the DMI, $P < 0.05$) than in the other classes where it represented only 1 ± 4%. Finally, in the FG class, goat herds had significant access to fresh grass (from pasture or provided in troughs) because it was estimated that this feed represented 44 ± 18% of the DMI. In contrast, it was between 0 and 5% for other classes ($P < 0.05$). Five diets included alfalfa pellets (from 7 to 10% of the DMI) in addition to concentrates. The proportion of concentrates and alfalfa pellets varied significantly according to main forage in the diet classes, with the H class receiving a higher percentage than the FG class (49 ± 11 vs 35 ± 8% of the DMI, $P < 0.05$), the two other classes being intermediate. Mean supplementation in vitamin A was numerically higher for the CS class (132 ± 269 IU goat^{-1} day^{-}1) than for the three others, but the differences were not significant due to the large variabilities observed within groups (32 ± 33, 31 ± 42, 16 ± 14 IU goat^{-1} day^{-}1 for the H, GW and FG classes, respectively). The same was seen for supplementation in vitamin E. The mean DMI was not different among classes (around 2.8 ± 0.4 kg of DMI per goat and per day).

The herd size was 1.6- and 1.8-fold higher in the CS than in the WG and FG classes, respectively ($P < 0.05$). Goats of the H class were more advanced in lactation than those of the FG class (+77%; $P < 0.05$). In the FG class, herds had a lower mean percentage of primiparous goats than the other classes (−30%; $P < 0.05$) and a higher mean lactation rank than those of the CS and H classes (+25%; $P < 0.05$). The lactation rank was also on average higher in the WG than in the CS class (+17%; $P < 0.05$). The percentage of goats in extended lactation was greater in H since it reached 16 ± 15%, whereas it varied from 2 ± 2 to 4 ± 6% in the FG and WG classes, respectively ($P < 0.05$), the value being intermediate in the CS class. Milk yield and gross composition were similar among classes (Table 2). However, differences were observed

Table 1
Categorical variables describing conditions of goat milk production.

Variables group	Variable label	Variable modalities (mean values ± standard deviations)	Individuals number
Extrinsic variables	Main forage in the diet	Corn silage (37 ± 6% of DMI goat^{-1} day^{-1})	12
		Hay (legumes, grasses or both) (46 ± 13 of DMI goat^{-1} day^{-1})	19
		Wet grass (grass preserved by the wet method, meaning wrapped or ensiled) (29 ± 12 of DMI goat^{-1} day^{-1})	14
		Fresh grass (at pasture, as green feeding or both) (44 ± 18 of DMI goat^{-1} day^{-1})	11
	Percentage of concentrates and alfalfa pellets ingested	Low percentage in the herd diet (31 ± 4 of DMI goat^{-1} day^{-1})	14
		Medium percentage in the herd diet (40 ± 3 of DMI goat^{-1} day^{-1})	18
		High percentage in the herd diet (53 ± 8 of DMI goat^{-1} day^{-1})	24
	Level of supplementation in vitamins A and E	Low supplementation: – vitamin A: 2 892 ± 2 570 IU goat^{-1} day^{-1} – vitamin E: 6 ± 6 IU goat^{-1} day^{-1}	24
		Medium supplementation: – vitamin A: 11 669 ± 2 270 IU goat^{-1} day^{-1} – vitamin E: 35 ± 5 IU goat^{-1} day^{-1}	14
		High supplementation – vitamin A: 36 590 ± 57 619 IU goat^{-1} day^{-1} – vitamin E: 157 ± 246 IU goat^{-1} day^{-1}	11
		Unknown	7
	DM intake	Low level (2.2 ± 0.1 kg of DMI goat^{-1} day^{-1})	10
		Medium level (2.7 ± 0.2 kg of DMI goat^{-1} day^{-1})	34
		High level (3.3 ± 0.3 kg of DMI goat^{-1} day^{-1})	12
	Season	Spring	28
		Autumn	28
Intrinsic variables	Breed	Herd predominantly of Alpine breed (95%)	30
		Herd predominantly of Saanen breed (95%)	26
	Herd lactation stage	Herd in early lactation (73 ± 16 d)	11
		Herd in medium lactation (184 ± 48 d)	25
		Herd in late lactation (317 ± 72 d)	18
		Unknown	2
	Percentage of goats in extended lactation in the herd	Low percentage (0 ± 0% of the herd)	24
		Medium percentage (5 ± 2% of the herd)	16
		High percentage (26 ± 11% of the herd)	16
	Lactation rank in the herd	Low rank (2.3 ± 0.2)	31
		High rank (3.1 ± 0.4)	23
		Unknown	2
	Percentage of primiparous animals in the herd	Low percentage (22 ± 6% of the herd)	21
		Medium percentage (33 ± 1% of the herd)	16
		High percentage (40 ± 4% of the herd)	19
	Herd milk yield	Low level (2.1 ± 0.4 kg of milk goat^{-1} day^{-1})	15
		Medium level (3.0 ± 0.3 kg of milk goat^{-1} day^{-1})	23
		High level (4.0 ± 0.3 kg of milk goat^{-1} day^{-1})	17
		Unknown	1

Abbreviation: DMI = DM intake.

between spring and autumn for these parameters. In line with higher DMI (+0.2 kg DMI per goat and per day; $P < 0.05$), the milk yield was 30% higher in spring than in autumn ($P < 0.001$). Spring milk was richer in lactose (+5%; $P < 0.001$) but poorer in fat (−8%), proteins (−13%) and the somatic cell count (−5%) than milk collected during autumn ($P < 0.001$). Finally, the mean number of days in lactation was twofold higher in autumn than in spring ($P < 0.001$), in line with the seasonal reproduction of goats on the studied farms. Other parameters did not differ between seasons.

Alpine and Saanen goat herds only differed in their lactation rank, which was higher for Alpine than Saanen goats (+12%; $P < 0.05$). Interactions were never significant.

Effects of production conditions on goat milk vitamin and carotenoid concentrations and colour indices

The models tested explained at least 50% of the variance for the concentrations of retinol, vitamins B_2 and B_{12}, lutein and total carotenoids (Table 3). For total α-tocopherol and tocopherols, pyridoxal, total vitamin B_6 (sum of pyridoxamine and pyridoxal, pyridoxine never being observed in goat milk, even at trace level), zeaxanthin and CI, they ranged from 40 to 49%. The lowest values of explained variance (20–34%) were for milk γ-tocopherol, pyridoxamine, folates, a^* and b^* colour indices.

The main forage in the diet was the variable that modulated the most the retinol, tocopherol, and total vitamin B_6 concentrations, and the a^* and b^* colour indices (at least 70% of the variance of the models explained by this variable). The main forage in the diet and the breed were the variables that most modulated the folate concentration, while for zeaxanthin concentration, it was the season (about 50% of the variance of the models explained by these variables taken separately). For the other indicators, no main variables but combinations of variables were identified. The vitamin supplementation, DMI, percentages of primiparous goats or goats in extended lactation and the interactions between these variables were not significant.

Variations according to diet composition and season

Among the variables characterising the diet composition and the season, the main forage in the diet is the major factor altering most of the goat milk vitamin and carotenoid concentrations and the colour indices (Table 4). Only folates and the CI were not affected by the main forage of diets. Bulk milk from goats eating fresh grass was richer in α-tocopherol (+64%; $P < 0.05$), pyridoxal (+35%; $P < 0.05$) and total vitamin B_6 (+31%, $P < 0.05$) than milk from the other classes. The b^* index was also higher (+12%; $P < 0.05$) for FG milk. Concentrations of pyridoxamine, lutein and

Table 2
Characteristics of lactating goat herds, mean bulk milk and diet composition according to main forage classes, season and breed (mean).

Item	Main forage in the diet (R)				Season (S)		Breed (B)		SEM	P-values		
	CS[1]	H[1]	WG[1]	FG[1]	Spring	Autumn	Alpine	Saanen		R	S	B
N	12	19	14	11	28	28	30	26				
Herd characteristics												
Herd size (number of goats)	345^{a}	284^{ab}	218^{b}	193^{b}	280	243	282	239	17.5	0.016	0.275	0.206
Herd lactation stage (day)	215^{ab}	249^{a}	179^{ab}	141^{b}	131^{b}	279^{a}	200	208	14.2	0.007	0.001	0.886
Herd lactation rank	2.4^{c}	2.5^{bc}	2.8^{ab}	3.2^{a}	2.7	2.6	2.8^{a}	2.5^{b}	0.1	0.001	0.499	0.050
Primiparous goats (%)	36^{a}	33^{a}	31^{a}	23^{b}	30	32	29	34	1.2	0.003	0.547	0.061
Goats in extended lactation (%)	8^{ab}	16^{a}	4^{b}	2^{b}	9	9	8	9	1.7	0.006	0.955	0.791
Herd milk yield (kg goat^{-1} day^{-1})	3.4	3.0	2.9	3.0	3.5^{a}	2.7^{b}	3.1	3.1	0.1	0.350	0.001	0.943
Consumed quantity (kg of DMI goat^{-1} day^{-1})	2.9	2.8	2.7	2.7	2.9^{a}	2.7^{b}	2.7	2.8	0.1	0.729	0.032	0.421
Diet (% of DMI goat^{-1} day^{-1})												
Fresh grass	0^{b}	1^{b}	5^{b}	44^{a}	13	7	14	5	2.6	0.001	0.256	0.076
Conserved forage												
Corn silage	37^{a}	0^{b}	0^{b}	2^{b}	8	8	7	9	2.1	0.001	0.953	0.705
Hay	20^{b}	46^{a}	20^{b}	16^{b}	26	30	26	30	2.4	0.001	0.320	0.471
Wet grass	2^{b}	1^{b}	29^{a}	2^{b}	7	10	7	10	1.8	0.001	0.384	0.281
Straw	1^{b}	3^{a}	1^{b}	1^{b}	2	2	2	2	0.4	0.050	0.934	0.519
Concentrates and alfalfa pellets	40^{ab}	49^{a}	45^{ab}	35^{b}	44	43	43	43	1.5	0.010	0.571	0.924
Vitamin supplementationVitamin E (IU goat^{-}1 day^{-1})	132	32	31	16	66	30	40	59	18.2	0.131	0.332	0.577
Vitamin A (10^3 IU goat^{-}1 day^{-1})	32	11	6	6	17	9	10	16	4.2	0.127	0.361	0.475
Gross composition of bulk milk												
Fat (g/kg)	38.9	36.4	38.0	38.2	36.1^{b}	39.3^{a}	38.2	37.1	0.5	0.269	0.001	0.312
Protein (g/kg)	34.5	33.7	33.8	33.3	31.4^{b}	36.3^{a}	34.4	33.2	0.4	0.831	0.001	0.101
Lactose (g/kg)	45.6	45.7	46.5	46.8	47.2^{a}	44.9^{b}	46.2	46.0	0.2	0.230	0.001	0.747
Somatic cell count (log_{10}/mL)	6.3	6.3	6.3	6.2	6.1^{b}	6.4^{a}	6.2	6.3	0.02	0.808	0.001	0.895

Values in the same row and for each group of traits (main forage in the diet, season and goat breed) without a common letter ($^{a-c}$) differed significantly ($P < 0.05$).
Abbreviations: CS = corn silage, H = hay (legumes, grasses or both), WG = Wet grass (grass preserved by the wet method, meaning wrapped or ensiled), FG = fresh grass (at pasture, as green feeding or both), DMI = DM intake.

Table 3
Percentage variance of the indicators of goat milk explained by the full statistical model and the eleven exploratory variables.

Indicators of goat milk	Variance of full model (%)	Variance of the eleven exploratory variables (%)									
		R[1]	C[1]	S[1]	B[1]	MY[1]	LS[1]	LR[1]	R × S	S × B	R × S × B
Vitamin concentrations											
Retinol	55	47	–	–	–	–	–	8	–	–	–
γ-Tocopherol	20	20	–	–	–	–	–	–	–	–	–
α-Tocopherol	49	37	–	–	–	12	–	–	–	–	–
Total tocopherols	44	31	–	–	–	13	–	–	–	–	–
Vitamin B_2	58	14	–	18	26	–	–	–	–	–	–
Pyridoxal	40	28	–	12	–	–	–	–	–	–	–
Pyridoxamine	27	21	–	6	–	–	–	–	–	–	–
Total vitamin B_6	41	30		11							
Folates	34	–	–	18	16	–	–	–	–	–	–
Vitamin B_{12}	50	17	–	21	–	12	–	–	–	–	–
Carotenoid concentrations											
Lutein	50	18	19	–	13	–	–	–	–	–	–
Zeaxanthin	47	27	–	–	–	3	17	–	–	–	–
Total carotenoid	63	25	21	–	11	–	6	–	–	–	–
Colour indices[2]											
CI	45	–	16	8	11	–	–	10	–	–	–
*a**	21	21	–	–	–	–	–	–	–	–	–
*b**	21	21	–	–	–	–	–	–	–	–	–

[1] Abbreviations: R = main forage in the diet; C = percentage of concentrates and alfalfa pellets; S = season; B = main breed of the herd; MY = milk yield; LS = lactation stage; LR = lactation rank; CI = colour index.
[2] *a**: a negative value of *a** points to greenness. *b**: a positive value of *b** points to yellowness in the CIELAB colour space.

total carotenoids were higher in the milk of the FG class than in the CS class (+24, +118 and +101%, respectively; $P < 0.05$), the two other classes having intermediate values. The concentrations of retinol and total tocopherols were higher in milk of the FG class than for the H and WG classes (+45 and +55% on average, respectively; $P < 0.05$), the CS class having intermediate values. Vitamin B_2 concentration in milk of the FG class was higher than in the CS and H classes (+10%; $P < 0.05$). Milk zeaxanthin concentrations were equivalent between the FG and WG classes and were both higher than in milk of the H class (+147% on average; $P < 0.05$). However, bulk milk of the FG class was significantly poorer in vitamin B_{12} than bulk milk of the CS class (−46%; $P < 0.05$) and in γ-tocopherol than the three other classes (−31% on average; $P < 0.05$). The *a** index was also slightly lower for the milk of the FG class than for the milk of the CS and H classes (−10%; $P < 0.05$), the WG class having intermediate values.

Except for lutein, folates and vitamin B_{12}, the milk content of the other components secreted per day by the mammary gland varied according to the main forage classes (P ranging from 0.05 to 0.001; Table 5). Goats of the FG class secreted more retinol (+57.6%; $P < 0.05$) and total vitamin B_6 (+33.0%; $P < 0.05$) in milk than goats of the other groups. Those FG goats secreted more vita-

Table 4
Concentrations of vitamins and carotenoids and colour indices of goat bulk milk according to diet composition and season.

	Main forage in the diet (R)[1]				Concentrates and alfalfa pellets (C)[2]			Season (S)			P-values[3]		
Indicators of milk	CS	H	WG	FG	Low	Medium	High	Spring	Autumn	SEM	R	C	S
n	12	19	14	11	14	18	24	28	28				
Vitamins													
Retinol (mg/kg of fat matter)	6.5^{ab}	6.0^{b}	5.4^{b}	8.3^{a}	7.3	6.2	5.9	6.5	6.2	0.2	0.001	nd	nd
γ-Tocopherol (mg/kg of fat matter)	1.7^{a}	1.7^{a}	1.8^{a}	1.2^{b}	1.6	1.6	1.7	1.6	1.6	0.1	0.008	nd	nd
α-Tocopherol (mg/kg of fat matter)	7.7^{b}	5.8^{b}	6.2^{b}	10.8^{a}	9.7	6.7	6.1	6.8	7.6	0.4	0.001	nd	nd
Total tocopherols (mg/kg of fat matter)	9.4^{ab}	7.5^{b}	8.0^{b}	12.0^{a}	11.3	8.3	7.8	8.5	9.2	0.4	0.001	nd	nd
Vitamin B_2 (mg/L)	1.8^{b}	1.8^{b}	1.8^{ab}	2.0^{a}	1.9	1.8	1.8	1.7^{b}	1.9^{a}	0.04	0.024	nd	0.001
Pyridoxal (μg/L)	220^{b}	216^{b}	224^{b}	297^{a}	278	216	224	261^{a}	218^{b}	8.6	0.001	nd	0.005
Pyridoxamine(μg/L)	67^{b}	74^{ab}	72^{ab}	83^{a}	75	72	75	77^{a}	71^{b}	1.7	0.012	nd	0.044
Total vitamin B_6 (μg/L)	287^{b}	290^{b}	294^{b}	380^{a}	353	288	298	337^{a}	289^{b}	9.8	0.001	nd	0.004
Folates (μg/L)	13.4	13.2	13.9	13.6	13.3	14.0	13.2	12.5^{b}	14.4^{a}	0.3	nd	nd	0.001
Vitamin B_{12} (ng/L)	301^{a}	218^{ab}	224^{ab}	164^{b}	168	241	260	136^{b}	317^{a}	19.4	0.048	nd	0.001
Carotenoids (μg/kg of fat matter)													
Lutein	129^{b}	205^{ab}	204^{ab}	281^{a}	264^{a}	220^{a}	129^{b}	270	170	16.0	0.004	0.000	nd
Zeaxanthin	23^{ab}	19^{b}	46^{a}	48^{a}	50	32	9	32	21	5.2	0.047	nd	nd
Total carotenoids	160^{b}	242^{ab}	258^{ab}	321^{a}	311^{a}	261^{a}	163^{b}	239	190	18.6	0.001	0.001	nd
Colour indices[4]													
CI	308	303	303	350	338^{a}	313^{ab}	302^{b}	306^{b}	329^{a}	5.1	nd	0.005	0.008
a^*	-2.0^{a}	-2.1^{a}	-2.1^{ab}	-2.3^{b}	−2.2	−2.1	−2.0	−2.1	−2.0	0.03	0.008	nd	nd
b^*	5.8^{b}	5.9^{b}	5.8^{b}	6.5^{a}	6.3	5.9	5.8	5.8	6.0	0.1	0.003	nd	nd

Values in the same row and for each group of traits (main forage in the diet, concentrates and alfalfa pellets, and season) without a common letter ($^{a, b}$) differed significantly (P < 0.05).
[1] Abbreviations: CS = corn silage, H = hay (legumes, grasses or both), WG = grass preserved by the wet method, meaning wrapped or ensiled, FG = fresh grass (at pasture, as green feeding or both), CI = colour index.
[2] Concentrates and alfalfa pellets (% DM intake goat^{-1} day^{-1}): Low, 31 ± 4; Medium, 40 ± 3; High, 53 ± 8.
[3] nd: not determined because variable not retained in the model; interactions were not significant.
[4] a^*: a negative value of a^* points to greenness. b^*: a positive value of b^* points to yellowness in the CIELAB colour space.

Table 5
Amounts of vitamins and carotenoids secreted daily in milk according to goat feeding.

	Main forage in the diet (R)[1]					
Indicators of milk	CS	H	WG	FG	SEM	P-value[2]
Number of samples	12	19	14	11		
Vitamins						
Retinol (μg secreted/day)	677^{b}	620^{b}	517^{b}	969^{a}	35.5	0.0001
γ-Tocopherol (μg secreted/day)	204^{a}	177^{ab}	185^{ab}	136^{b}	8.9	0.012
α-Tocopherol (μg secreted/day)	880^{ab}	575^{c}	588^{bc}	$1\,152^{a}$	48.1	0.0001
Total tocopherol (μg secreted/day)	$1\,049^{ab}$	760^{c}	768^{bc}	$1\,294^{a}$	50.9	0.0001
Vitamin B_2 (mg secreted/day)	5.33^{ab}	5.08^{b}	4.99^{b}	5.84^{a}	0.2	0.019
Pyridoxal (mg secreted/day)	0.68^{b}	0.65^{b}	0.63^{b}	0.90^{a}	0.04	0.003
Pyridoxamine (mg secreted/day)	0.20^{b}	0.22^{b}	0.20^{b}	0.25^{a}	0.01	0.027
Total vitamin B_6 (mg secreted/day)	0.88^{b}	0.87^{b}	0.83^{b}	1.15^{a}	0.05	0.005
Folates (μg secreted/day)	45.1	38.7	37.0	40.9	1.59	nd
Vitamin B_{12} (ng secreted/day)	1 066	709	640	411	66.4	nd
Carotenoids						
Lutein (μg secreted/day)	15.4	16.8	18.2	29.5	1.77	nd
Zeaxanthin (μg secreted/day)	0.78^{b}	1.77^{ab}	3.97^{a}	4.84^{a}	0.51	0.005
Total carotenoid (μg secreted/day)	16.2	18.0	21.5	35.6	2.00	nd

Values in the same row without a common letter ($^{a-c}$) differed significantly (P < 0.05).
[1] Abbreviations: CS = corn silage, H = hay (legumes, grasses or both), WG = grass preserved by the wet method, meaning wrapped or ensiled, FG = fresh grass (at pasture, as green feeding or both).
[2] nd: not determined because variable not retained in the model.

min B_2 (+20%; P < 0.05), α-tocopherol (+103%; P < 0.05) and total tocopherols (+74%; P < 0.05) in milk than goats of the H and WG classes. Finally, goats of the FG class secreted more zeaxanthin (+520%; P < 0.05) and lessγ-tocopherol (−33%; P < 0.05) than goats of the CS group.

The percentage of concentrates and alfalfa pellets only had a significant effect on milk carotenoid concentrations and CI index (Table 4). Indeed, goats receiving a high proportion of concentrates and alfalfa pellets had lower milk concentrations of lutein (−47%; P < 0.05) and total carotenoids (−43%; P < 0.05) than goats of the other classes. Moreover, the CI values of bulk milk from goats fed the highest proportion of concentrates and alfalfa pellets were lower (−11%; P < 0.05) than those of bulk milk from goats of the lowest class.

The season had a significant effect on milk concentrations of B vitamins and the CI value, but not on other variables. Milk concentrations of vitamin B_2, folates and vitamin B_{12} were greater in autumn than in spring (+12%, +15%, +133% respectively; P < 0.001). Similarly, the CI value of milk was 7.5% (P < 0.01) higher in autumn than in spring. Concentrations of the two vitamers of vitamin B_6 and their sum were, however, significantly higher in spring than in autumn (+20% for pyridoxal, +8% for pyridoxamine, and +17% for total vitamin B_6; $P < 0.01$, 0.05 and 0.01, respectively).

Variations according to herd characteristics: breed, milk yield, lactation stage and rank

There were few differences related to breed (Table 6). Milk concentrations of vitamin B_2 and folates were higher in Alpine than in Saanen goats (+18 and +14%, respectively; $P < 0.001$). Additionally, the CI value of milk was also 7% higher in milk from Alpine than Saanen herds ($P < 0.05$), but milk from Saanen goats was richer in lutein (+46%; $P < 0.01$) and total carotenoids (+34%, $P < 0.001$).

Goat herds with the lowest mean milk yield exhibited the highest milk α-tocopherol and total tocopherol concentrations and the lowest milk vitamin B_{12} concentration in comparison to the classes with medium and high milk yields (+38, +32 and −46%, respectively; $P < 0.05$). Zeaxanthin concentration was also significantly lower (−66%; $P < 0.05$) in milk of goats with the highest milk yield.

Only concentrations of zeaxanthin and total carotenoids varied according to lactation stage, decreasing as lactation progressed (from 63 ± 10 to 20 ± 7 mg/kg of fat matter and 309 ± 29 to 214 ± 22 mg/kg of fat matter, respectively; $P < 0.05$).

Finally, bulk milk where the goats had the greatest lactation rank had higher a retinol concentration (+22%; $P < 0.01$) and CI value (+8%; $P < 0.01$) than that from herds where the goats had the smallest lactation rank.

Discussion

Effects of herd characteristics on goat milk vitamin and carotenoid concentrations and colour indices

Folate [13.5 μg/L] concentration was at the lowest levels of previous reports (10 μg/L according to Park et al., 2007; 33–183 μg/L for Lucas et al., 2006). Vitamin B_{12} [231 ng/L] concentration was 3-fold lower than that found by Park et al. (2007; 650 ng/L). This confirms that goat milk is extremely poor in these two vitamins in comparison to cow milk for which values range from 52 to 347 μg/L for folates (Lucas et al., 2006) and 684 to 21,576 ng/L for vitamin B_{12} (Duplessis et al., 2019). This suggests that the origin of milk, especially the species, should be considered more in human nutrition, since dairy products are considered to be among the primary sources of folates and vitamin B_{12}. We have no data on cheese or yogurt, but the present results highlight that raw milk supplies very different amounts of folates and vitamin B_{12} depending on whether it is from cows or goats. It would be interesting to study whether microbial activity during goat cheese ripening increases the concentrations of these vitamins to levels equivalent to those observed in cow cheese.

In the present study, the distribution of the two breeds was well balanced within the experimental design. Only the lactation rank was slightly higher in Alpine than in Saanen goats, but milk yield was similar between the breeds suggesting that the concentrations of vitamin B_2 and folates and the CI value were higher in bulk milk of Alpine than in Saanen goats, whereas the opposite was observed for lutein and total carotenoids. This is the first report highlighting a between-breed difference in these parameters. In ruminants, B vitamins in milk originate from the diet and from bacterial synthesis in the rumen, except vitamin B_{12} which is entirely supplied by rumen bacterial synthesis. Consequently, our results could be explained by rumen specificities in the bacterial profile between the two breeds, as already observed in sheep (Chang et al., 2020), but never studied in goats. Another hypothesis could be genetic differences between breeds in vitamin intestinal absorption, metabolic use or mammary transfer from blood to milk. Indeed, B vitamin circulation in the body and across tissues depends on regulatable protein transporters, according to literature data mainly available in monogastric animals (Montalbetti et al., 2014). The genetic dependency of milk vitamin B_{12} concentration

Table 6
Vitamin and carotenoid concentrations and colour indices of bulk milk according to goat herd characteristics.

	Main Breed of the herd (B)		Milk Yield (MY)[1]			Lactation Stage (LS)[2]			Lactation Rank (LR)[3]			P-values[4]			
Indicators of milk	Alpine	Saanen	Low	Medium	High	Early	Medium	Late	Low	High	SEM	B	MY	LS	LR
N	30	26	15	23	17	11	25	18	31	23					
Vitamins															
Retinol (mg/kg of fat matter)	6.6	6.1	6.9	6.1	6.2	7.1	6.1	6.3	5.9^{b}	7.2^{a}	0.2	nd	nd	nd	0.005
γ-Tocopherol (mg/kg of fat matter)	1.5	1.7	1.7	1.6	1.6	1.6	1.5	1.7	1.7	1.4	0.1	nd	nd	nd	nd
α-Tocopherol (mg/kg of fat matter)	7.2	7.2	9.4^{a}	7.0^{b}	6.6^{b}	7.9	7.3	6.8	6.3	8.5	0.4	nd	0.005	nd	nd
Total tocopherols (mg/kg of fat matter)	8.7	9.0	11.0^{a}	8.5^{b}	8.2^{b}	9.4	8.8	8.5	8.0	9.9	0.4	nd	0.005	nd	nd
Vitamin B_2 (mg/L)	2.0^{a}	1.7^{b}	1.9	1.9	1.7	1.8	1.8	1.9	1.8	1.9	0.04	0.001	nd	nd	nd
Pyridoxal (μg/L)	236	233	230	234	244	286	234	204	215	261	8.6	nd	nd	nd	nd
Pyridoxamine (μg/L)	75	73	74	74	74	80	73	72	70	79	1.7	nd	nd	nd	nd
Total vitamin B_6 (μg/L)	311	306	304	308	318	366	307	276	285	341	9.8	nd	nd	nd	nd
Folates (μg/L)	14.4^{a}	12.6^{b}	13.9	14.1	12.4	13.1	13.3	14.2	13.5	13.6	0.3	0.001	nd	nd	nd
Vitamin B_{12} (ng/L)	226	236	144^{b}	264^{a}	272^{a}	124	213	329	274	179	19.4	nd	0.007	nd	nd
Carotenoids (μg/kg of fat matter)															
Lutein	166^{b}	243^{a}	252	150	184	294	180	137	163	224	16.0	0.005	nd	nd	nd
Zeaxanthin	29	24	46^{a}	41^{a}	15^{b}	63^{a}	28^{b}	11^{b}	22	35	5.2	nd	0.019	0.001	nd
Total carotenoids	210^{b}	281^{a}	290	179	200	309^{a}	217^{b}	210^{b}	185	260	18.6	0.001	nd	0.020	nd
Colour indices															
CI[6]	328^{a}	307^{b}	327	319	295	322	307	319	305^{b}	330^{a}	5.1	0.013	nd	nd	0.004
a^*[5]	−2.1	−2.0	−2.1	−2.1	−2.0	−2.2	−2.1	−2.0	−2.0	−2.2	0.03	nd	nd	nd	nd
b^*[5]	6.0	5.8	6.1	6.1	5.7	6.0	5.9	6.0	5.8	6.2	0.1	nd	nd	nd	nd

Values in the same row and for each group of traits (main breed of the herd, milk yield, lactation stage, and lactation rank) without a common letter (^{a,b}) differed significantly ($P < 0.05$).

[1] Herd Milk Yield (kg of milk goat^{-1} day^{-1}): Low, 2.1 ± 0.4; Medium, 3.0 ± 0.3; High, 4.0 ± 0.3.

[2] Herd Lactation Stage (LS): Early, 73 ± 16; Medium, 148 ± 48; Late, 317 ± 72.

[3] Herd Lactation Rank (LR): Low, 2.3 ± 0.2; High, 3.1 ± 0.4.

[4] nd: not determined because variable not retained in the model; interactions were not significant.

[5] a^*: a negative value of a^* points to greenness. b^*: a positive value of b^* points to yellowness in the CIELAB colour space.

[6] Abbreviation: CI = colour index.

is suggested by previous results obtained in Holstein Friesian cows (Rutten et al., 2013; Gavan, 2020). These authors failed to relate this phenotype to genes known to be involved in cobalamin transport in the gastrointestinal tract, the blood, intracellular processing, or reabsorption by the kidneys. They proposed that the genes involved in the variability in milk vitamin B_{12} concentration may be linked to vitamin B_{12} mammary secretion, but these genes are still not clearly identified (Rutten et al., 2013). We can hypothesise that differential expression of those genes between breeds could explain the interval between values observed for Saanen and Alpine goats. In agreement with this hypothesis, Poulsen et al. (2015b) highlighted the genetic variation of vitamin B_2 concentration in cow milk (between Holstein and Jersey breeds) and observed an association with the *SLC52A3* gene coding for a vitamin B_2 tissue transporter.

As previously observed (Lucas et al., 2006; Nozière et al., 2006), the present study confirmed that carotenoids in goat milk are mainly lutein (85–90%) with a small fraction of zeaxanthin, whereas β-carotene is not present. This remains true even in goats fed fresh grass, which is rich in carotenes (Nozière et al., 2006). Surprisingly, milk lutein concentration varied with the breed and was significantly higher for the Saanen than for the Alpine goats. Differences in milk concentrations are known for β-carotene between Guernsey and Holstein breeds (Nozière et al., 2006) and for β-cryptoxanthin and 13cis β-carotene between Holstein and Montbéliarde breeds (Graulet et al., 2019), but not lutein or zeaxanthin. Since the mean dietary intake did not differ between herds of the two breeds, this suggests that the discrepancy was of genetic origin.

In the present study, milk zeaxanthin concentration decreased significantly with the lactation stage. Variations of carotenoid concentrations according to lactation stage have only been reported in bovine milk for β-carotene, which increased during the first half of lactation (Nozière et al., 2006), resulting from the increase in DMI (enrichment effect) combined with the decrease in milk yield after the peak (concentration effect). The decrease in milk zeaxanthin concentration in the present study cannot be attributed to DMI, but to diet composition and its corresponding zeaxanthin intake.

Additionally, we observed that retinol concentration increased with lactation rank in goat milk, which has not been clearly demonstrated in cows. The colour index was also slightly higher in the milk of goats of high lactation rank in comparison to low lactation rank, in agreement with numerically higher carotenoids (lutein and zeaxanthin) and vitamin B_2 concentrations because all these yellow pigments contribute to the milk's yellow colour (Laverroux et al., 2021). Carotenoid concentrations have already been reported to increase in the milk of multiparous cows according to lactation rank (Nozière et al., 2006), but the corresponding data are lacking in the literature for vitamin B_2. In the present study, these increases in retinol, carotenoid, and vitamin B_2 concentrations and in colour indices are likely partially due to higher lactation rank in goat herds fed with a large proportion of fresh or wet grass in comparison to others.

Differences in milk yield between herds participated in the enrichment or the depletion of several compounds. When milk yield increased, α-tocopherol and zeaxanthin concentrations were reduced by a dilution effect. For other vitamins like B_2, B_6 and folates, retinol or γ-tocopherol, the concentrations did not differ whatever the milk yield, indicating that their secretion may be driven by milk secretion rather than a proper regulatory process. In agreement, we observed that the total amounts of these vitamins secreted daily increased significantly with milk yield. By contrast, vitamin B_{12} concentration increased according to milk yield ($P < 0.001$) and the amount secreted was almost 6-fold higher for herds with the highest milk yield compared to herds with low production. This result is unexpected and in contrast to results reported in cows (Duplessis et al., 2019). The reasons for this divergence between the two species should be explored in detail in appropriate studies.

Effects of forage composition on goat milk in vitamin and carotenoid concentrations and colour indices

Among the studied variables, we observed that the main forage in the diet generally explained most of the variance in milk concentrations of vitamins and carotenoids as well as in colour indices. The FG group especially differed from the other groups due to its higher yellowness (b^* index), retinol, α-tocopherol, pyridoxal, pyridoxamine, total vitamins B_6, vitamin B_2, and carotenoid concentrations and lower a^* index, vitamin B_{12} and γ-tocopherol concentrations. This resulted from increased amounts secreted daily of retinol, α-tocopherol, pyridoxal, pyridoxamine, total vitamin B_6, vitamin B_2, and zeaxanthin. Our results on milk enrichment in retinol, α-tocopherol, and carotenoids according to the increase in the proportion of grazed pasture in the diet agree with previous observations made in milk or cheese (Fedele et al., 2004; Pajor et al., 2014; Lucas et al., 2008). As in dairy cows (Calderon et al., 2007; Graulet et al., 2019), it is likely that the milk enrichment with carotenoids and tocopherols observed in the FG group is related to their higher intakes through fresh grass consumption at pasture. Moreover, milk α-tocopherol concentrations depend on the grazing period (Calderon et al., 2007; Gutiérrez-Peña et al., 2018). Indeed, compared to feeding hay, while no difference was shown during spring grazing (Pajor et al., 2014), a higher milk α-tocopherol concentration was observed when goats were grazing in September and October (Delgado-Pertíñez et al., 2013).

In ruminants, milk retinol derives naturally from endogenous synthesis in the intestine and from β-carotene in feedstuffs, with the possibility of liver storage (Nozière et al., 2006). However, direct dietary supply is often achieved in livestock through vitamin supplement and/or a commercial concentrate, but these practices vary greatly between farms, including in goat-rearing systems, as highlighted by the high variations around means for the levels of vitamin A and E supplementation. The reasons for these discrepancies in dietary vitamin supplementation in ruminants remain unknown, and we hypothesise that they depend on the sociotechnical background (farmer's knowledge and perception of vitamin requirements in ruminants, farming advice, etc.). However, in the present study, there was no statistical relationship between dietary retinol supplementation and milk enrichment, probably because of the ability of the liver to store retinol in the regulation of its circulating concentrations (Nozière et al., 2006). Milk retinol enrichment observed in the FG group is likely related to higher β-carotene consumption with fresh grass than with hay, wet grass or corn silage (Nozière et al., 2006; Graulet et al., 2019).

Diet-related variations in vitamin B_2, pyridoxal and pyridoxamine concentrations in ruminant milk are highly original, especially in goats. The amounts of B vitamins available to ruminants from dietary sources (except vitamin B_{12}) and from synthesis by rumen microorganisms are dependent on the intensity of rumen fermentation, transit time, and microbiota composition, so the relationships between diet composition and B vitamin status and milk content in ruminants seem to be highly complex (Girard and Graulet, 2021). Their dietary intakes and rumen metabolism vary greatly, according to the literature data available to date (Girard and Graulet, 2021). Of the few studies, some have shown (whereas others have failed to do so) that the proportion and composition of the forage counterpart of the diet modulate milk concentrations of B vitamins (Girard and Graulet, 2021). In that respect, milk or milk-derived products of cows fed grass rather than corn silage or a total mixed ration are richer in vitamin B_2 (Poulsen et al., 2015a; Magan et al., 2020), and we observed the same in goat milk.

The yellow colour of milk being dependent on vitamin B_2 and carotenoid contents, it is likely that their enrichment in the milk of goats at pasture led to the secretion of yellower milk. However, this increase in the yellowness of milk is not really perceptible to the human eye. Indeed, milk yellowness variability is usually related to its level of β-carotene, which is lacking in goat milk, as we confirmed, even when animals are fed grazed grass. So, the indices illustrating yellowness (b^* and CI) are low in goat milk (comparable to values of milk of cows fed maize silage as main forage). Riboflavin concentration was 2 mg/L in the milk of the goats in our study, but being linked to the aqueous phase of milk part of this would be lost during butter- or cheese-making processes. In contrast, the lipophilic pigments β-carotene, lutein and zeaxanthin are concentrated in the milk fat and are recovered in butter and cheese, but their concentrations in goat milk likely remain too low to induce a human eye-visible increase in the yellow colour of goat cheeses.

Goat herds fed either hay or grass preserved by the wet method produced milk with equivalent colour, and carotenoid and vitamin composition, except for zeaxanthin concentration, which was greatly reduced in the milk of goats fed hay, whereas its level was equivalent between milk of goats fed either fresh grass or grass preserved by the wet method. The degradation of zeaxanthin in hay exposed to sun in the field and then to oxygen during storage could explain these differences (Zhang et al., 2011). A similar argument could be made for the lutein content of milk from hay-fed goats. However, it is intriguing that lutein concentration was lower, whereas zeaxanthin concentration was maintained in the milk of the WG group in comparison to the FG group.

Conclusion

The present study highlights, sometimes for the first time, variations in vitamin and carotenoid concentrations as well as in colour indices observed in the milk of goats reared in conventional systems used in France. These characteristics of milk vary mainly according to diet (and in particular the main forage in the diet), and additionally to the season and breed. In addition to the yellower milk, milk produced by goats fed fresh grass is enriched with nutritional compounds (vitamins A, E, B_2 and B_6 and carotenoids) in comparison to milk from goats fed conserved forages. Therefore, this study contributes to our knowledge of the effect of a fresh grass-based diet on the quality of goat dairy products that meet consumers' expectations. Moreover, it also shows that goat milk is really poor in folates and vitamin B_{12} compared to cow milk and lacks β-carotene whatever the goat breed, lactation stage or rank and diet provided to animals. To complete the present work, additional studies could aim to complement knowledge of the variation factors acting on concentrations of other vitamins (D, K and other B) in goat milk. Moreover, mechanisms implicated in the extremely low folate and vitamin B_{12} concentrations in goat milk should be studied and deciphered to provide means to mitigate them.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository. The data/models that support the study findings are available from the authors upon request.

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Conflicts of interest

None.

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