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Review: Genetic and protein variants of milk caseins in goats

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The milk casein genes in goats, are highly polymorphic genes with numerous synonymous and non-synonymous mutations. So far, 20 protein variants have been reported in goats for alpha-S1-casein, eight for beta-casein, 14 for alpha-S2-casein, and 24 for kappa-casein. This review provides a comprehensive overview on identified milk casein protein variants in goat and non-coding DNA sequence variants with some affecting the expression of the casein genes. The high frequency of some casein protein variants in different goat breeds and geographical regions might reflect specific breeding goals with respect to milk processing characteristics, properties for human nutrition and health, or adaptation to the environment. Because protein names, alongside the discovery of protein variants, go through a historical process, we linked old protein names with new ones that reveal more genetic variability. The haplotypes across the cluster of the four genetically linked casein genes are recommended as a valuable genetic tool for discrimination between breeds, managing genetic diversity within and between goat populations, and breeding strategies. The enormous variation in the casein proteins and genes is crucial for producing milk and dairy products with different properties for human health and nutrition, and for genetic improvement depending on local breeding goals.

KEYWORDS

milk protein, casein, goat, genetic variations, polymorphisms, nutrition, health

Introduction

Casein is the insoluble major protein component of milk comprising about 80% of the total milk protein fraction (Bhat et al., 2016). Milk caseins have a fundamental nutritional value since they provide calcium and phosphorus for bone formation and amino acid synthesis in offspring (Barth and Schlimme, 2012; Ghosh et al., 2016). Milk composition is a multifactorial complex trait. Besides genetic factors, the total protein and casein content is affected by various factors such as number of milking per day, stage of lactation, age of the animal, parity, rearing practices, seasonal components, and nutrition (Assan, 2014).

In goats, like in other mammals, four evolutionary conserved casein genes occur. The genes encoding alpha-S1-, beta-, alpha-S2-, and kappa-caseins are *CSN1S1*, *CSN2*, *CSN1S2*, and *CSN3*, respectively (Martin et al., 2002). All four genes are located in a

250 kb region between 85.978 and 86.211 Mb on *Capra hircus* chromosome 6 (Ferretti et al., 1990; Threadgill and Womack, 1990).

Caseins occur in milk in micelles which are large spherical colloidal particles. These micelles are buildup of several submicelles which are bound together by colloidal calcium phosphate (Fox and McSweeney, 1998). Alpha-S1-, α -S2-, and β -caseins, which are hydrophobic phosphate and calcium-sensitive caseins, are located inside the inner part of the micelle (Hui and Sherkat, 2005), which precipitate from raw milk upon acidification at pH 4.6 at 20°C (Park et al., 2017). Kappa-casein, the insensitive calcium protein, resides on the surface of the micelles where it stabilizes the micelles with a protruding hydrophobic chain (Guinee and O'Brien, 2010).

The most important economic effects of the milk casein proteins come from the relationship between protein quality, amount, coagulation, and techno-functional properties to produce yoghurts and cheese. Casein polymorphisms also affect the fat content, micellar size, mineralization, and sensory characteristic in milk. Therefore, casein polymorphisms play a significant role both in milk coagulation performance and cheese quality. Since the identification of the impact of milk protein polymorphisms on milk quality and its technological properties (Aschaffenburg and Drewry, 1955), milk protein variants have been intensively characterized in different species including goats (Marletta et al., 2007; Caroli et al., 2009; Giambra and Erhardt, 2012; Selvaggi et al., 2014; Ozdemir et al., 2018). As a side effect of the intensive work, simultaneous publications led to inconsistency in the naming and positioning of some sequence variants which were anchored in part to mature and in part to immature proteins and sometimes include mutations in non-coding regions. In addition, many studies have referred to the genetic and protein variants of caseins in goats with different nomenclature. This review gives a comprehensive overview on identified protein and DNA variants of the four casein genes in goats. One goal is to clarify names and nomenclatures, the positions of nucleotide and amino acid polymorphisms and provide a translation from DNA to protein variant. We focus on protein variants, but also describe linked nucleotide variants in non-coding regions of the gene, like the promoter, 5' and 3' untranslated regions, and introns, which could affect the transcription and translation and thereby production traits. Furthermore, we have derived haplotypes across all four linked genes and summarize the frequency of alleles in different breeds and the impact of milk protein variants on milk quality for cheese making, human health and human nutrition.

CSN1S1

At the functional level, alpha-S1-casein is required for the efficient export of other caseins from the endoplasmic reticulum to the Golgi compartment, the casein transport in the secretory pathway, and for the biogenesis of casein micelles in milk

(Chanat et al., 1999; Le Parc et al., 2010). Alpha-S1-casein has an important role in the capacity of milk to provide calcium phosphate for human nutrition (Kolb et al., 2011).

The percentage of α -S1-casein in goat milk varies from 0 to 25%. Alpha-S1-casein concentrations has been shown to be dependent on the existence of polymorphisms in the coding and regulatory sequences of the gene (Boulanger et al., 1984). In contrast, the α -S1-casein fraction in bovine milk constitutes up to 40% (Farrell et al., 2004). Strong, intermediate, low, and null expression levels of α -S1-casein in goat milk are distinguished (Moatsou et al., 2004; Caroli et al., 2007; Kupper et al., 2010). In the first group comprising *CSN1S1**A, *CSN1S1**A3, *CSN1S1**B1, *CSN1S1**B2, *CSN1S1**B3, *CSN1S1**B4, *CSN1S1**C, *CSN1S1**H, *CSN1S1**L, and *CSN1S1**M are "strong" variants, which are associated with a high content of α -S1-casein in milk. *CSN1S1**E and *CSN1S1**I are "intermediate" variants associated with a medium content. *CSN1S1**D, *CSN1S1**F, and *CSN1S1**G are "weak" variants associated with a low content, and *CSN1S1**N, *CSN1S1**01, and *CSN1S1**02 are "null" variants leading to the absence of α -S1-casein in the milk of animals homozygote for these alleles (Grosclaude et al., 1987; Brignon et al., 1990; Chianese et al., 1997; Grosclaude and Martin, 1997; Martin et al., 1999; Bevilacqua et al., 2002; Ramunno et al., 2005; Mestawet et al., 2013). The α -S1-casein strong variants produced around 3.6 g/L per allele, medium variants produced 1.1–1.6 g/L per allele, weak variants produced 0.45–0.6 g/L per allele, and null variants resulted in absence of the α -S1-casein in milk (Grosclaude et al., 1987; Grosclaude and Martin, 1997; Martin et al., 1999). Strong variants with high content of α -S1-casein are most desired in dairy production since they are associated with lower pH values, better coagulation properties, faster curdling rate and greater gel firmness, which contribute largely to high yield and quality of cheese, even if the rennet coagulation time was longer (Ambrosoli et al., 1988; Pirisi et al., 1994; Clark and Sherbon, 2000; Schmidely et al., 2002; Zullo et al., 2005; Caravaca et al., 2011; Devold et al., 2011; Cebo et al., 2012; Vacca et al., 2014; Johansson et al., 2015; Marković et al., 2018). Since the casein content in milk also affects the size of casein micelles and the amount and composition of milk fatty acids, cheese made from milk with strong α -S1-variants has a better structure and taste with less typical goat flavor than cheese produced from intermediate or weak variants (Delacroix Buchet et al., 1996). Generally, the lower α -S1-casein content in goat milk compared to bovine milk is associated with smaller casein micelles, with less hydrated pores (Park et al., 2007; Ingham et al., 2018; Nguyen et al., 2018). Hence, yoghurt (Miocinovic et al., 2016; Nguyen et al., 2018) and cheese (Park et al., 2007; Mestawet et al., 2014) made from goat milk have a lower dense gel structure and poor coagulation features compared to their counterparts made with cow milk.

The *CSN1S1* gene is located on chromosome 6 between 85.978 and 85.995 Mb and spans 16,808 bp. The DNA and protein reference sequences NC_030813 (goat genome

reference version LWLT01 (Bickhart et al., 2017)) and XP_017904616 (NCBI database), respectively, represent the CSN1SI*A protein variant (Boulanger et al., 1984; Brignon et al., 1989; Ramunno et al., 2004). The gene encodes 214 amino acids of α -S1-casein, the first 15 amino acids form the signal peptide sequence, followed by 199 amino acids long mature protein (Brignon et al., 1990). It consists of 19 exons ranging in size from 24 (exons 5, 6, 7, 8, 10, 13, 16) to 385 bp (exon 19) and 18 introns from 90 bp (intron 10) to 1,685 bp (intron 2) (Ramunno et al., 2004).

In the following, we briefly describe the 20 protein variants that have been identified so far (Supplementary Table S1).

The α -S1-casein CSN1SI*A is the reference protein. The sub variants CSN1SI*A' and CSN1SI*A2 represent the same reference protein, namely CSN1SI*A, though CSN1SI*A' carries a T/C transition in intron 9 (Kupper et al., 2010) and CSN1SI*A2 a G/A transition in the 5' flanking region (Ramunno et al., 2005). The same G/A transition is present also in variants CSN1SI*N and CSN1SI*01, which are null variants (Ramunno et al., 2005), which means absence of α -S1-casein in the milk of homozygous carriers. Hence, the G/A variation in the 5' flanking region is not responsible for the absence of α -S1-casein in milk. Different from the other CSN1SI*A proteins, CSN1SI*A3 carries a transversion from A to C at position CHR6:85987198 (exon 10) leading to the amino acid exchange from Gln₇₇ to Pro₇₇ (Mestawet et al., 2013). CSN1SI*A is the predominant protein variant in most Indian breeds (frequency >0.7) (Kumar et al., 2007; Rout et al., 2010) and in a few breeds from Spain, Italy and France (frequency >0.5, Supplementary Table S2) (Ramunno et al., 1991).

The CSN1SI*B protein is divided into four variants (CSN1SI*B1, CSN1SI*B2, CSN1SI*B3, CSN1SI*B4) (Grosclaude and Martin, 1997). All CSN1SI*B variants differ from the reference protein through the substitution of Gln₇₇ to Glu₇₇ (Brignon et al., 1989), a substitution that is associated with the presence of a phosphate group on Serine at position 75 (Brignon et al., 1989). Among all α -S1-casein variants, CSN1SI*B1 is considered the ancestor allele showing the closest homology to its bovine and ovine counterparts (Grosclaude and Martin, 1997). CSN1SI*B1 and CSN1SI*B' are identical proteins; the only difference is a synonymous SNP in the codon for Ser₆₆ in exon 9 in CSN1SI*B' (Caroli et al., 2007). The caseins CSN1SI*B2, CSN1SI*B3 and CSN1SI*B4 carry the additional T to C transition at position CHR6:85982615 (exon 4), leading to the substitution of Leu₁₆ to Pro₁₆ (Grosclaude and Martin, 1997; Cosenza et al., 2008). CSN1SI*B3 and CSN1SI*B4 carry the G to A transition at position CHR6:85988705 (exon 12) changing Arg₁₀₀ to Lys₁₀₀ (Grosclaude and Martin, 1997; Cosenza et al., 2008). CSN1SI*B4 differs from CSN1SI*B3 by the nucleotide substitution A to G at position CHR6:85993465 (exon 17) altering Thr₁₉₅ to Ala₁₉₅ (Grosclaude and Martin, 1997; Cosenza et al., 2008). With respect to names, it is necessary to

mention that firstly, CSN1SI*B2 was named simply CSN1SI*B in old papers (Boulanger et al., 1984; Brignon et al., 1989), and secondly, the variant CSN1SI*E had also been named CSN1SI*B⁻ (Grosclaude et al., 1987). CSN1SI*B protein variants can be found at high frequency (>0.5) in diverse breeds across the world (Supplementary Table S2).

CSN1SI*C and CSN1SI*C1 differ from the reference by five and four amino acid substitutions, respectively. The two variants carry the amino acid substitutions His₈ to Ile₈, Leu₁₆ to Pro₁₆, Gln₇₇ to Glu₇₇, and Arg₁₀₀ to Lys₁₀₀. The additional substitution Thr₁₉₅ to Ala₁₉₅ occurs only in CSN1SI*C (Leroux et al., 1990; Rahmatalla et al., 2021).

CSN1SI*D is characterized by a deletion of 11 amino acids at positions 59 to 69 which comprises the major phosphorylation site of the protein (Brignon et al., 1990). The deletion of the single nucleotide C at position CHR6:85986426 in exon 9 is a splice-site mutation which causes the exclusion of exon nine in the mature RNA assembly which also reduces the synthesis rate of the protein (Mahé and Grosclaude, 1989; Brignon et al., 1990). Besides the significant deletion, CSN1SI*D carries the substitutions Leu₁₆ to Pro₁₆ and Gln₇₇ to Glu₇₇, which also occur in most CSN1SI*B and CSN1SI*C protein variants (Mahé and Grosclaude, 1989; Brignon et al., 1990).

CSN1SI*E (formerly CSN1SI*B') has the same amino acid variant as CSN1SI*B4. Besides that, CSN1SI*E has an insertion of 457–458 bp in exon 19, which is expressed but untranslated (Jansàpérez et al., 1994). This insert is a truncated long interspersed repeated element (LINE), containing part of the ORF-2, the 3' UTR, and the original retrotransposon's poly (A) tail. The mutant 3' UTR likely controls the mRNA stability of transcripts and/or the translation rate which was seen as low casein content in goat milk of CSN1SI*E carriers (Jansàpérez et al., 1994). The CSN1SI*E allele is highly frequent (>0.5) in Saanen goats worldwide (Tadlaoui Ouafi et al., 2002; Maga et al., 2009), and in other breeds from Spain, France, and the United States (Supplementary Table S2) (Grosclaude et al., 1994; Jordana et al., 1996; Tadlaoui Ouafi et al., 2002; Caravaca et al., 2008; Maga et al., 2009).

CSN1SI*F contains the amino acid variants Pro₁₆ and Glu₇₇ as in CSN1SI*D (Grosclaude et al., 1987; Brignon et al., 1990). Most significant in CSN1SI*F is the lacks of 37 amino acids from position 59 to 95 as the consequence of a frameshift mutation due to a single nucleotide deletion in exon 9 (Grosclaude et al., 1987; Brignon et al., 1990). The deletion starts exactly at the same position and with the same mutation as in CSN1SI*D. Two additional insertions of 11 and 3 base pairs in intron nine are likely responsible for the skipping of exons 9, 10 and 11 in CSN1SI*F (Leroux et al., 1992). The content of this shortened α -S1-casein protein variant in milk is low, likely as a result of low efficiency and accuracy of the splicing machinery (Martin et al., 1999), which might result from either a reduced translation rate or intracellular degradation of the incomplete protein. Several breeds that originate from the Alpine region carry the CSN1SI*F

allele at a frequency above 0.40 (Grosclaude et al., 1987; Ramunno et al., 1991). A higher expression of *CSN1S1*F* compared to *CSN1S1*N* might be attributed to a mutation in the promotor region creating an extra putative activator protein 1 (AP-1) binding motif (Ramunno et al., 2005). However, experimental validation does not exist. Particular high frequency >0.90 of *CSN1S1*F* was found in Toggenburg goats from America and Orobica goats from Italy (Supplementary Table S2) (Caroli et al., 2006; Maga et al., 2009).

Protein variant *CSN1S1*G* is missing 13 amino acids from position 14 to 26. The G/A transition at position CHR6:85982647 in the 5' splice site at the beginning of intron 4 leads to the skipping of exon 4 (Martin and Leroux, 1994). The occurrence of the *CSN1S1*G* allele is associated with low α -S1-casein content in milk (Martin and Leroux, 1994).

*CSN1S1*H* differs from the reference variant *CSN1S1*A* by a single amino acid substitution at position 1, Arg₁ to Lys₁. This protein was classified as a strong variant (Chianese et al., 1997). For the Italian Garganica breed the frequency of 0.07 was reported (Sacchi et al., 2005).

For the protein variants *CSN1S1*G*, *CSN1S1*I*, *CSN1S1*J*, *CSN1S1*K*, *CSN1S1*L*, and *CSN1S1*M* there is information available for sequence variants only, but not for allele frequency in any breed. *CSN1S1*I* had the same amino acids sequence as variant *CSN1S1*A*. However, *CSN1S1*I* had only about half of the amount of casein in the milk than *CSN1S1*A* (Chianese et al., 1997), which led to the differentiation between *CSN1S1*I* and *CSN1S1*A*. The causal mutation is unidentified.

*CSN1S1*J* carries the combination of the amino acids substitutions Gln₇₇ to Glu₇₇ and Arg₁₀₀ to Lys₁₀₀, which are also found in other protein variants (Rahmatalla et al., 2021). *CSN1S1*J* detected in Bezoar ibex. This variant is similar to *CSN1S1*B1* which is consider the ancestor allele, but it contains the Arg₁₀₀ to Lys₁₀₀ substitution (Rahmatalla et al., 2021).

The *CSN1S1*K* protein variant differs from the reference by the unique amino acid substitution from Ile₄₄ to Val₄₄ as a results of a T to G transition at position CHR6:85984154 (exon 7) (Rahmatalla et al., 2021). The *CSN1S1*K* was found in wild Alpine ibex (Rahmatalla et al., 2021).

*CSN1S1*L* harbors the two amino acids Pro₁₆ and Glu₇₇ instead of Leu₁₆ and Gln₇₇ in the reference sequence and additionally the amino acid substitution from Arg₉₀ to His₉₀ (Chianese et al., 1997). The transition of G to A at CHR6:85987327 in exon 11 leads to the substitution of Arg₉₀ to His₉₀.

*CSN1S1*M* carries the Leu₁₆ to Pro₁₆ substitution, which occurs also in other protein variants. *CSN1S1*M* also contains the amino acid substitution of Ser₆₆ to Leu₆₆ which results from a C/T transition at CHR6:85986426 in exon 9 (Chianese et al., 1998; Bevilacqua et al., 2002).

*CSN1S1*N*, *CSN1S1*01* and *CSN1S1*02* are null variants resulting in truncated gene products and subsequently no casein in the milk. *CSN1S1*N* descends from protein variant *CSN1S1*M*, but contains also the nucleotide deletion of a single C

at CHR6:85986426 in exon 9 that also occurs in variants *CSN1S1*D* and *CSN1S1*F*, where it causes exon skipping. However, in *CSN1S1*N* the one-nucleotide deletion leads to a premature stop codon. The amount of the truncated transcript is reduced to one-third and the amount of α -S1-casein in milk in homozygous carriers is null (Ramunno et al., 2002; Ramunno et al., 2005). *CSN1S1*01* is a truncated protein where the last seven exons are missing. The truncation results from a deletion of about 8.5 kb starting from nucleotide 181 of intron 12. In homozygous carriers, α -S1-casein is absent in milk (Grosclaude et al., 1987; Leroux et al., 1990; Cosenza et al., 2003). *CSN1S1*02* is another null variant, leading to the absence of the respective protein in milk. Martin et al. (1999) proposed a large insertion that has not been identified so far. Albeit the goats carrying the null alleles homozygous do not have contain α -S1-casein in their milk, the Indian breeds Ganjam and Local MP have an allele frequencies of 0.40 and 0.45, respectively (Rout et al., 2010).

Goat milk that lacks α -S1-casein has a higher pH value and a low content of chemical components like total solids, protein, casein, Nitrogen, fat, and Phosphorus compared to milk with strong α -S1-casein variants (Ambrosoli et al., 1988; Pirisi et al., 1994; Clark and Sherbon, 2000; Devold et al., 2011; Johansson et al., 2015; Marković et al., 2018). In addition, milk containing α -S1-casein null variants is characterized by large casein micelles with weak gel firmness and long coagulation time (Devold et al., 2011; Johansson et al., 2015). The gross yield of cheese and the content of fat and non-fat solids as well as the fat to dry matter ratio and the total solids recovery rate from milk that lacks α -S1-casein is low (Pirisi et al., 1994). Furthermore, textural parameters of cheese such as hardness and plasticity were low in cheese that is produced from goat milk lacking α -S1-casein (Pirisi et al., 1994). In contrast, milk containing strong α -S1-casein variants produce firmer curd that is associated with high gross yield of cheese with a better composition (Devold et al., 2011; Johansson et al., 2015).

CSN2

Beta-casein is the most hydrophobic casein as a result of a highly charged N-terminal domain and an anionic phosphoserine cluster (Swaisgood, 2003). Beta-casein is the major protein in goat milk (Clark and Mora Garcia, 2017) comprising up to 50% of the total casein content. In comparison, human milk casein contains 60%–70% and bovine milk casein 36% β -casein (Guo, 2009; Elagamy, 2016). Beta-casein is a primary source of essential amino acids and facilitates the mineral transport for infants (Sadler and Smith, 2013). The peptides derived from β -casein during digestion have antihypertensive and immune-stimulating properties (Silva et al., 2006; Lamothe et al., 2007).

TABLE 1 Nucleotide and amino acid variants within the gene and mature protein of the CSN2.

Encoded protein variant	Protein/DNA variant name	Position on chr 6 (bp) ^a	86,008,407	86,008,401	86,008,103	86,008,049	86,008,047	86,008,016	86,007,341/ 86,007,342	86,006,394	References	
			Position on the gene	Exon 7	Exon 7	Exon 7	Exon 7	Exon 7	Exon 7	Exon 8		Exon 9 (3' UTR)
			Amino acid position ^b	47	58	148	166	167	177	207		
CSN2 [*] C	CSN2 [*] C	NC_030813 XP_005681778	C Asp	T Leu	G Pro	G Ser	G Q	A Val	AC Val	G	Wang et al. (2001); Neveu et al. (2002); Bickhart et al. (2017)	
CSN2 [*] A	CSN2 [*] A	CSN2 [*] A_Gen. CSN2 [*] A_Prot.						G Ala			Roberts et al. (1992), Rando (1998)	
CSN2 [*] A	CSN2 [*] A1	CSN2 [*] A1_Gen. CSN2 [*] A1_Prot.								A	Cosenza et al. (2005)	
CSN2 [*] B	CSN2 [*] B [*]	CSN2 [*] B_Gen. CSN2 [*] B_Prot.									NCD; Mahé and Grosclaude (1993)	
CSN2 [*] C	CSN2 [*] C1	CSN2 [*] C1_Gen. CSN2 [*] C1_Prot.								A	Chessa et al. (2008)	
CSN2 [*] C	CSN2 [*] C2 ^{**}	CSN2 [*] C2_Gen. CSN2 [*] C2_Prot.								A	Nicolai et al. (2021)	
CSN2 [*] D	CSN2 [*] D	CSN2 [*] D_Gen. CSN2 [*] D_Prot.							TT Asn		NCD; Galliano et al. (2004)	
CSN2 [*] E	CSN2 [*] E	CSN2 [*] E_Gen. CSN2 [*] E_Prot.				T Tyr					Caroli et al. (2006)	
CSN2 [*] F	CSN2 [*] F (CSN2 [*] E)	CSN2 [*] F_Gen. CSN2 [*] F_Prot.	A Thr								NCD; Chianese et al. (2007); Moatsou et al. (2007)	
CSN2 [*] F	CSN2 [*] F1	CSN2 [*] F1_Gen. CSN2 [*] F1_Prot.	A Thr							A	Nicolai et al. (2021)	
CSN2 [*] G	CSN2 [*] G (CSN2 [*] F)	CSN2 [*] G_Gen. CSN2 [*] G_Prot.			A Leu						Rahmatalla et al. (2021)	
CSN2 [*] 0	CSN2 [*] 0	CSN2 [*] 0_Gen. CSN2 [*] 0_Prot.		Del_T Stop codon	NT	NT	NT	NT	NT	NT	Persuy et al. (1999)	
CSN2 [*] 0	CSN2 [*] 0	CSN2 [*] 0_Gen. CSN2 [*] 0_Prot.					A Stop codon ^c	NT	NT		Rando et al. (1996), Boulanger et al. (1984)	

^aChromosomal position in base pairs (bp) in the positive strand according to the goat genome reference version LWLT01, which represent CSN2^{*}C.

^bAmino acids position according to the reference protein sequence XP_005681778. The whole sequence of 257 amino acids comprises 207 of the mature protein. All the amino acid position based on the mature protein.

^{*}: Variant CSN2^{*}B migrates faster under alkaline pH and slower in acid pH and there is difference in mobility compared to variant CSN2^{*}A

^{**}: CSN2^{*}C2 coding for the same amino acid sequence as variant CSN2^{*}C1, but it was lower the amount of the expressed protein.

^cThe nucleotide mutation generates a stop codon.

Mutations in the 3'UTR are shown in italics and bold and non-synonymous mutations are shown in normal font.

Del= deletion, NCD = Not characterized at the DNA level.

NT: Not translated after stop codon.

The name of the old variant are given in parentheses.

The *CSN2* gene is located on chromosome 6 between 86.006 and 86.015 Mb (NC_030813, goat genome reference version LWLT01) (Bickhart et al., 2017). The 9,072 bp long gene consists of nine exons ranging in size from 24 (exon 5) to 492 bp (exon 7) (Roberts et al., 1992; Hayes and Petit, 1993). The protein contains 222 amino acids, which comprise 207 functional amino acids and 15 amino acids of a signal peptide (XP_005681778 (NCBI database).

So far, eight protein variants have been identified (Table 1). Variants *CSN2**A, *CSN2**B, *CSN2**C, *CSN2**D, and *CSN2**E are “strong” variants associated with high β -casein content in milk (5 g/L per allele) (Roberts et al., 1992; Mahé and Grosclaude, 1993; Neveu et al., 2002; Galliano et al., 2004; Cosenza et al., 2005; Caroli et al., 2006). The variants *CSN2**C2 and *CSN2**F1 were associated with intermediate β -casein content (3.3 and 2.7 g/L per allele, respectively) (Nicolai et al., 2021). The two null alleles *CSN2**0 and *CSN2**0' are associated with a lack of β -casein in milk (Persuy et al., 1999). In the *CSN2* gene, the existence of the strong variants were associated with the highest milk protein content and yield in Sarda goats from Italy (Vacca et al., 2014).

The reference protein is variant *CSN2**C (Wang et al., 2001; Neveu et al., 2002). *CSN2**A differs from the reference by the amino acid substitution of Val₁₇₇ to Ala₁₇₇ (Neveu et al., 2002) as a result of an A/G transition at position CHR6:86008016 in exon 7 (Roberts et al., 1992). *CSN2**A is considered the ancestral allele in goats because the amino acid alanine at position 177 is also found in sheep, cattle and buffalo (Chessa et al., 2005). The variant *CSN2**A1 differs from *CSN2**A by an additional G/A SNP in exon 9, which belongs to the 3' untranslated region (Cosenza et al., 2005). *CSN2**A was predominant with a frequency above 0.90 in Girgentana and Argentata dell'Etna from Italy, and in most Indian goats (Supplementary Table S3) (Marletta et al., 2005; Rout et al., 2010). A high frequency above 0.70 was evident in French Creole goats, West African breeds, and Buren goat from Germany (Supplementary Table S3) (Mahé and Grosclaude, 1993; Caroli et al., 2007; Kupper et al., 2010).

The *CSN2**B variant was characterized *via* isoelectric protein electrophoresis, where *CSN2**B migrates faster than *CSN2**A (Mahé and Grosclaude, 1993). The mobility differences between *CSN2**A and *CSN2**B might be due to an extra phosphate group in *CSN2**B (Mahé and Grosclaude, 1993).

*CSN2**C1 and *CSN2**C2 encode the same protein *CSN2**C, the reference protein sequence. The protein variant *CSN2**C is predominant with a frequency of ≥ 0.70 in most Italian goats, Angora and Hair goats from Turkey, Rajasthan and South goats from India as well as Banat White goats from Romania (Supplementary Table S3) (Chessa et al., 2005; Caroli et al., 2006; Chessa et al., 2007; Kusza et al., 2016). The two subtypes differ in a synonymous transition of G to A in the 3' untranslated region of exon 9 in *CSN2**C (Chessa et al., 2008; Nicolai et al., 2021). This single nucleotide polymorphism likely leads to lower amount of β -casein if the animals is homozygous for the *CSN2**C2 subtype compared to *CSN2**C1. An impact on the

mRNA stability and or translation rate might be causal for the low amount of the protein (Nicolai et al., 2021). The variant *CSN2**C1 was found with a frequency of more than 0.10 in Bunte Deutsche Edelziege and Weiße Deutsche Edelziege goats from Germany and Italian Girgentana goats (Kupper et al., 2010; Tortorici et al., 2014).

*CSN2**D differs from the reference protein in the amino acid substitution from Val₂₀₇ to Asn₂₀₇ (Galliano et al., 2004). DNA sequence comparisons show a AC/TT substitution at positions CHR6:86007341 and CHR6:86007342 in exon 8 that is responsible for the amino acid change.

*CSN2**E is characterized by the amino acid exchange from Ser₁₆₆ to Thr₁₆₆ which results from the G/T transversion at position CHR6:86008049 in exon 7 (Caroli et al., 2006). *CSN2**E was found at a low frequency (0.08) only in Italian Frisa goats (Caroli et al., 2006).

The protein variant *CSN2**F differs from the reference by the substitution of Asp₄₇ to Thr₄₇ (Chianese et al., 2007; Moatsou et al., 2007). The underlying SNP is a C/A transversion at position CHR6:86008407 in exon 7. By mistake, this protein variant had been named *CSN2**E by Caroli et al. (2006) although *CSN2**E already existed. It was correctly renamed as *CSN2**F by Martin et al. (2013). *CSN2**F1 and *CSN2**F represent the same β -casein protein. *CSN2**F1 differs from *CSN2**F by a synonymous transition G/A in the 3' untranslated region in exon 9 (Nicolai et al., 2021).

*CSN2**G (previously *CSN2**F) is characterized by the amino acid substitution from Pro₁₄₈ to Leu₁₄₈ and found in Wild Alpine ibex (Rahmatalla et al., 2021). The nucleotide mutation is a G/A substitution at position CHR6:86008103 in exon 7 (Rahmatalla et al., 2021).

Observations of milk lacking β -casein led to the conclusion that at least two null alleles exist (Dall'Olio et al., 1989; Mahé and Grosclaude, 1989). Variant *CSN2**0 has one nucleotide deletion (T/-) at position CHR6:86008401 in exon 7 which introduces a premature stop codon at position 58 in the mature protein (Persuy et al., 1999). The *CSN2**0 null variant was detected in a frequency below 0.10 in Creole goats from France and some Italian and Indian goats (Supplementary Table S3) (Mahé and Grosclaude, 1993; Marletta et al., 2005; Sacchi et al., 2005; Rout et al., 2010; Vacca et al., 2014). However, the frequency was 0.19 in Italian Garganica goats (Albenzio et al., 2009). *CSN2**0' carries the single nucleotide substitution C to T at position CHR6:86008047 in exon 7, which introduces a premature stop codon at position 167 of the mature protein (Rando et al., 1996). The *CSN2**0' null variant was found at a frequency below 0.10 in some Italian breeds and in Arbi goats from Tunis (Supplementary Table S3) (Chessa et al., 2005; Gigli et al., 2008; Vacca et al., 2009a; Tortorici et al., 2014). In *CSN2**0', another SNP in the promoter region was detected which negatively affects the transcriptional activity of the gene (Cosenza et al., 2007; Cosenza et al., 2016).

No information was available for the allele frequency of *CSN2**C2, *CSN2**D, *CSN2**F, *CSN2**F1, and *CSN2**G.

The β -caseins in milk are primarily classified into the two types A1 and A2. A1 and A2 differ in the generation of β -casomorphin-7 (BCM-7) peptides during digestion (Jianqin et al., 2016). The peptide β -casomorphin-7 gained attention because it was associated with gastrointestinal disturbances, ischemic heart disease, arteriosclerosis, type 1 diabetes, and sudden infant death syndrome in humans (Birgisdottir et al., 2002; Tailford et al., 2003; Ho et al., 2014). The peptide β -casomorphin-7 is uniquely derived from the digestion of β -casein type A1, but not from A2. Different from cow milk, goat milk mainly contains the β -casein type A2 (Cieslinska et al., 2012). Therefore, β -casein of the type A2 contributes to the healthy properties of goat milk because it does not produce the peptide β -casomorphin-7 during digestion (De Noni and Cattaneo, 2010).

It is worth noting that with the increasing awareness of consumers' behavior and their interest in healthy eating and functional food, different companies launched β -casein type A2 milk from cattle on the market. Costs are associated with the separate handling of this type of milk during processing. Since goat milk naturally contains β -casein type A2, this milk plays a crucial role in providing functional milk and milk products to the food market. A positive benefit for human health is realized here without additional marketing costs.

CSN1S2

The alpha-S2-casein protein plays an important role in the transport of calcium phosphate. The alpha-S2-casein content in goat milk is relatively high comprising about 19%, while it constitutes up to 10% in bovine milk (McMahon and Brown, 1984). The antimicrobial peptide cathelicidin-1 which derives from the digestion of alpha-S2-casein has the activity to inhibit the growth of Gram-positive and Gram-negative bacteria (Zucht et al., 1995; López-Expósito et al., 2008; Gigli, 2016).

The *CSN1S2* gene resides on chromosome 6 between 86.077 and 86.094 Mb, which is about 16,695 bp long and consists of 18 exons (NCBI, accession no. NC_030813). The gene encodes 223 amino acids comprising 208 functional amino acids and 15 amino acids of a signal peptide (<https://www.uniprot.org/uniprot/P33049>).

The DNA [NC_030813, goat genome reference version LWLT01 (Bickhart et al., 2017)] and protein reference sequence (XP_013820127.2, NCBI database) represent the *CSN1S2**A variant (Boulanger et al., 1984; Bouniol et al., 1993; Bickhart et al., 2017). *CSN1S2**A is considered the ancestor variant for goat according to the evolutionary path from sheep and cattle (Sacchi et al., 2005). This variant is common with a frequency of ≥ 0.70 in distinct Saanen goats, most Italian, German and Indian goats, Dwarf goats from Nigeria, and Nubian goats from Sudan (Supplementary Table S4) (Boulanger et al.,

1984; Bouniol et al., 1994; Ramunno et al., 2001b; Erhardt et al., 2002; Marletta et al., 2004; Chiatti et al., 2005; Marletta et al., 2005; Caroli et al., 2007; Chessa et al., 2007; Kupper et al., 2010; Rout et al., 2010; Yue et al., 2013).

So far, 14 alpha-S2-casein protein variants have been identified (*CSN1S2**A, *CSN1S2**B, *CSN1S2**C, *CSN1S2**D, *CSN1S2**E, *CSN1S2**F, *CSN1S2**G, *CSN1S2**H, *CSN1S2**I, *CSN1S2**J, *CSN1S2**K, *CSN1S2**0, truncated sub-variant A, and truncated sub-variant E) (Table 2) (Boulanger et al., 1984; Bouniol, 1993; Bouniol et al., 1994; Veltri et al., 2000; Ramunno et al., 2001a; Ramunno et al., 2001b; Lagonigro et al., 2001; Erhardt et al., 2002; Cunsolo et al., 2006; Rahmatalla et al., 2021). While the protein variants *CSN1S2**A, *CSN1S2**B, *CSN1S2**C, *CSN1S2**E, *CSN1S2**F, and *CSN1S2**G are associated with normal amounts of α -S2-casein of about 2.5 g/L per allele (Boulanger et al., 1984; Grosclaude et al., 1987; Bouniol et al., 1994; Ramunno et al., 2001a), *CSN1S2**D is associated with a reduced amount of about 1.5 g/L per allele (Ramunno et al., 2001a). In *CSN1S2**0 homozygous goats, alpha-S2-casein was not detectable (Ramunno et al., 2001b).

*CSN1S2**B differs from the reference (*CSN1S2**A) by a G/A substitution at CHR6:86084638 in exon 9, which is responsible for the amino acid substitution Glu₆₄ to Lys₆₄ that affects a phosphorylation site (Boulanger et al., 1984; Bouniol et al., 1994). *CSN1S2**B occurs at a frequency above 0.40 in Egyptian and Lithuanian Native goats (Othman and Ahmed, 2006; Baltrėnaitė et al., 2009).

*CSN1S2**C distinguishes from the reference by the transversion A/T at CHR6:86089401 in exon 16 which changing Lys₁₆₇ to Ile₁₆₇ (Bouniol et al., 1994). This variant occurs at a frequency ≥ 0.40 in Vallesana and Roccaverano Italian goats, Dwarf Cameroon goats, Borno goats from Nigeria, Hair goats from Turkey, as well as Maharashtra and Rajasthan from India (Supplementary Table S4) (Sacchi et al., 2005; Caroli et al., 2007; Chessa et al., 2007).

*CSN1S2**D contains a 106 bp deletion comprising the last 11 bp of exon 11 and the first 95 bp of the following intron (Ramunno et al., 2001a). This deletion is responsible for the lack of the three codons Pro₁₂₂, Thr₁₂₃, and Val₁₂₄. Furthermore, the last undeleted nucleotide (A) of exon 11 together with the two nucleotides (AT) of the following intron generate a codon for the amino acid Asn₁₂₁ instead of Thr₁₂₁. which is followed by a new GT dinucleotide splicing donor site. The rare *CSN1S2**D variant was found in Italian Argentata dell'Etna and Girgentana goats and Hungarian goats with a frequency of 0.01 (Kusza et al., 2007; Gigli et al., 2008).

*CSN1S2**E is characterized by a C/G mutation at CHR6: 86089479 in exon 16, leading to the amino acid exchange Pro₁₉₇ to Arg₁₉₇ (Chianese et al., 1998; Veltri et al., 2000; Lagonigro et al., 2001). Additionally, the of A/T transversion of *CSN1S2**C changing Lys₁₆₇ to Ile₁₆₇ is present also in *CSN1S2**E. Furthermore, a deletion of 4 bp (AAAT) was identified in intron 4 (Lagonigro et al., 2001). *CSN1S2**E was found at low

frequency (below 0.11) in some Italian goats, Hair goats from Turkey, and South goats from India (Sacchi et al., 2005; Caroli et al., 2006; Chessa et al., 2007; Gigli et al., 2008; Albenzio et al., 2009; Vacca et al., 2009b; Palmeri et al., 2014; Vacca et al., 2014). In addition to the full-length protein variants CSNIS2*A and CSNIS2*E, two truncated sub-variants were identified, which lack the C-terminal tetrapeptide (Gln₁₉₉, Pro₂₀₀, Leu₂₀₁, Gln₂₀₂, Pro₂₀₃, Leu₂₀₄). These truncated variants likely originate from differential splicing of pre-messenger RNA during the translation process of CSNIS2*A and CSNIS2*E variants (Cunsolo et al., 2006).

CSNIS2*F differs from the reference by a G/A transition at CHR6:86080969 in exon 3 substituting Val₇ to Ile₇ (Ramunno et al., 2001a). CSNIS2*F is common (frequency ≥ 0.40) in Italian Garganica, Orobica, Frisa, Sarda goats, and Weiße Deutsche Edelziege (Sacchi et al., 2005; Caroli et al., 2006; Vacca et al., 2009b; Kupper et al., 2010).

There is not much known about the nucleotide and protein sequence of the variant CSNIS2*G. This protein has an isoelectric point between CSNIS2*A and CSNIS2*C (Erhardt et al., 2002).

CSNIS2*H differs from CSNIS2*A by a G/C substitution at CHR6:86085160 in exon 11 leading to the substitution of Ala₁₁₉ by Pro₁₁₉ (Rahmatalla et al., 2021). This variant is predominant in Sudanese goats (Supplementary Table S4) (Rahmatalla et al., 2021).

CSNIS2*I contains the same mutations that distinguish CSNIS2*G from the reference and additionally a G/A substitution at CHR6:86085714 in exon 12 that is responsible for the change of Glu₁₂₇ to Lys₁₂₇ (Rahmatalla et al., 2021). So far, CSNIS2*I has been detected in Nubian and Desert goats only at a frequency of 0.21 and 0.10, respectively (Rahmatalla et al., 2021).

CSNIS2*J diverges from the reference by a T/C substitution at CHR6:86081887 in exon 5 and G/A substitution at CHR6:86089407 in exon 16 that account for the substitutions Ile₂₀ to Thr₂₀ and Ser₁₆₉ to Asn₁₆₉, respectively (Rahmatalla et al., 2021). In addition, the mutation which distinguishes CSNIS2*H from CSNIS2*A is present also in CSNIS2*J (Rahmatalla et al., 2021).

CSNIS2*K carries the same three amino acid substitution that occur in CSNIS2*J (Rahmatalla et al., 2021) and additionally the amino acid substitutions Phe₁₇ to Ser₁₇ and Glu₁₂₇ to Lys₁₂₇ as a result of the nucleotide substitutions of T to C at CHR6:86081790 in exon 4 and G to A at CHR6:86085714 in exon 12, respectively (Rahmatalla et al., 2021). The CSNIS2*J and CSNIS2*K were identified in wild Nubian ibex (Rahmatalla et al., 2021).

CSNIS2*0 carries a stop codon at the amino acid position 110 as a result of a G to A transition at CHR6:86085134 in exon 11, which disrupts the codon for Try₁₁₀ (Ramunno et al., 2001b). As a consequence, a truncated non-functional protein of 109 instead of 208 amino acids is generated. Homozygous CSNIS2*0 carriers do not have α -S2-casein in milk. Nevertheless, the allele frequency in the Indian breeds Ganjam and Local MP is 0.55 and 0.48, respectively (Rout et al., 2010).

No information was available for the allele frequency of CSNIS2*J, CSNIS2*K, and the truncated sub-variants of CSNIS2*A and CSNIS2*E.

CSNIS2 variants affected the milk protein content and milk yield in Sarda goats from Italy (Vacca et al., 2014). In Sarda goats, CSNIS2*AC genotyped animals produce the highest fat and protein yield, which affect the technological properties for cheese processing, while animals carrying the CSNIS2*CF genotype have the highest daily milk yield (Vacca et al., 2014). Interestingly, the variants CSNIS2*A, CSNIS2*C, and CSNIS2*F were associated with a high amount of α -S2-casein in milk and produced 2.5 g/l per allele (Boulanger et al., 1984; Bouniol et al., 1994; Ramunno et al., 2001a). In Chinese dairy goats, animals carrying the CSNIS2*FF genotype have higher milk fat and total solids content than CSNIS2*AA and CSNIS2*AF genotypes, but do not have lower milk yield (Yue et al., 2013). However, Lan et al. (2005) found significant lower milk yield of Xinong Saanen goats carrying the CSNIS2*FF genotypes compared to other genotypes. The contradictory effects of CSNIS2*FF genotyped animals might be attributed to the small sample size in the study of Lan et al. (2005). The variation in the α -S2-casein level in milk is associated with the unique physicochemical characteristic of milk. Thereby, α -S2-casein levels affect the cheese-making properties (Selvaggi and Tufarelli, 2011).

CSN3

Kappa-casein (k-casein) is a calcium insensitive protein that forms a protective layer around the calcium-sensitive caseins α -S1, α -S2, and β , resulting in stable casein micelles (Quaglia and Gennaro, 2003). The formation, stabilization, and aggregation of casein micelles affect the physical characteristics and technological properties of milk (Alexander et al., 1988; Glantz et al., 2010). Kappa-casein is the only casein that is highly glycosylated (Haratifar and Guri, 2017). The mature kappa-casein protein has a labile peptide bond whose cleavage by chymosin or rennin produces a soluble hydrophilic glycopeptide called caseino-macropeptide (amino acids 106–171) and an insoluble peptide or para-k-casein (amino acids 1–105) (Yahyaoui et al., 2003). The caseino-macropeptide is important for milk coagulation.

Kappa-casein comprises about 20% in goat and sheep milk, in comparison, only 12–14% in cow milk (Fox and Brodtkorb, 2008; Molik et al., 2012). Kappa-casein is essential for lactation. For example, mice lacking this gene (CSN3^{-/-}) fail to lactate because of destabilization of the micelles in the lumen of the mammary gland (Shekar et al., 2006). Kappa-casein contributes to the nutritional properties of milk. The protein has beneficial effects on oral health (Vacca-Smith and Bowen, 1995; Johansson and Lif Holgersson, 2011) and the digestion of k-casein generates an antimicrobial peptide (Malkoski et al., 2001).

TABLE 2 Nucleotide and amino acid variants within the gene and mature protein of the *CSN1S2*.

Encoded protein variant	Protein/DNA variant name	Position on chr 6 (bp) ^a	86,080,969	86,081,790	86,081,847	86,081,887	86,084,638	86,085,134	86,085,160	86,085,167	86,085,714	86,089,401	86,089,407	86,089,479	References	
			Position on the gene	E-3	E-4	I-4	E-5	E-9	E-11	E-11	E-11 & I-12	E-12	E-16	E-16		E-16
			Amino acid position ^b	7	17		20	64	110	119		127	167	169		197
CSN1S2*A	CSN1S2*A	NC_030813 XP_013820127.2	G Val	T Phe		T Ile	G Glu	G W	G Ala		G Glu	A Lys	G Ser	C Pro	Boulanger et al. (1984); Bouniol et al. (1993); Bickhart et al., 2017	
CSN1S2*B	CSN1S2*B	CSN1S2*B_Gen. CSN1S2*B_Prot.					A Lys								Boulanger et al. (1984); Bouniol et al. (1993)	
CSN1S2*C	CSN1S2*C	CSN1S2*C_Gen. CSN1S2*C_Prot.										T Ile			Bouniol et al. (1994)	
CSN1S2*D	CSN1S2*D	CSN1S2*D_Gen. CSN1S2*D_Prot.								Del-1 Asn-Del-2-Del-3-Del-4					Ramunno et al. (2001a)	
CSN1S2*E	CSN1S2*E	CSN1S2*E_Gen. CSN1S2*E_Prot.			Del-5							T Ile		G Arg	Veltri et al. (2000); Lagonigro et al. (2001)	
CSN1S2*F	CSN1S2*F	CSN1S2*F_Gen. CSN1S2*F_Prot.	A Ile												Ramunno et al. (2001a)	
CSN1S2*G	CSN1S2*G*	CSN1S2*G_Gen. CSN1S2*G_Prot.													NCD; Erhardt et al. (2002)	
CSN1S2*H	CSN1S2*H	CSN1S2*H_Gen. CSN1S2*H_Prot.							C Pro						Rahmatalla et al. (2021)	
CSN1S2*I	CSN1S2*I	CSN1S2*I_Gen. CSN1S2*I_Prot.							C Pro		A Lys				Rahmatalla et al. (2021)	
CSN1S2*J	CSN1S2*J	CSN1S2*J_Gen. CSN1S2*J_Prot.				C Thr			C Pro				A Asn		Rahmatalla et al. (2021)	
CSN1S2*K	CSN1S2*K	CSN1S2*K_Gen. CSN1S2*K_Prot.		C Ser		C Thr			C Pro		A Lys		A Asn		Rahmatalla et al. (2021)	
CSN1S2*0	CSN1S2*0	CSN1S2*0_Gen. CSN1S2*0_Prot.						A Pre mature Stop codon	NT	NT	NT	NT	NT	NT	Ramunno et al. (2001b)	
Truncated sub variant A	Truncated sub variant A ^c	Truncated sub variant A_Gen. Truncated sub variant A_Prot.													NCD; Cunsolo et al., 2006	

(Continued on following page)

TABLE 2 (Continued) Nucleotide and amino acid variants within the gene and mature protein of the *CSN1S2*.

Encoded protein variant	Protein/DNA variant name	Position on chr 6 (bp) ^a	86,080,969	86,081,790	86,081,847	86,081,887	86,084,638	86,085,134	86,085,160	86,085,167	86,085,714	86,089,401	86,089,407	86,089,479	References
		Position on the gene	E-3	E-4	I-4	E-5	E-9	E-11	E-11	E-11 & I-12	E-12	E-16	E-16	E-16	
		Amino acid position ^b	7	17		20	64	110	119	121-122-123-124	127	167	169	197	
Truncated sub variant E	Truncated sub variant E ^c	Truncated sub variant E_Gen. Truncated sub variant E_Prot.													NCD; Cansolo et al., 2006

^aChromosomal position in base pairs (bp) in the positive strand according to the goat genome reference version LWLT01, which represent *CSN1S2**A.

^bAmino acids position according to the reference protein sequence XP_013820127.2. The whole sequence of 223 amino acids comprises 208 of the mature protein. All the amino acid position based on the mature protein.

*: *CSN1S2**G variant has an isoelectric point between *CSN1S2**A and *CSN1S2**C.

Del-1: Deletion of 106 bp (CTCCCACCGTGGTGAGTGCTTTTTTATATGTGTTTCTTGTTTATTTTTTTTTTCTTCTGTTTTTGGTGAAGGATGAGTTCAGGATAAAGATTTGTAATAATG)

^cDeletion of the C-terminal tetra peptide.

Del-2: Deletion of the amino acid Proline (Pro).

Del-3: Deletion of the amino acid Threonine (Thr).

Del-4: Deletion of the amino acid Valine (Val).

Del-5: Deletion of 4 bp (AAAT).

Del.: Deletion.

NCD: Not characterize at the DNA level.

NT: Not translated after stop codon.

The *CSN3* gene is located on chromosome 6 between 86.197 and 86.211 Mb [NC_030813, goat genome reference version LWLT01 (Bickhart et al., 2017)]. The gene spans 14,114 bp and comprises five exons (Martin et al., 2002). The protein contains 192 amino acids which include 21 amino acids of the signal peptide and 171 amino acids of the mature protein (Mercier et al., 1976; Coll et al., 1993). The mature protein is encoded in only two exons, exons 3 (9 amino acids) and exon 4 (162 amino acids) (Yahyaoui et al., 2003).

The *CSN3* gene in goats is highly polymorphic. To date, 35 variants are known that yield 24 protein variants and 11 synonymous mutations which are detectable only at the DNA level (Supplementary Table S5). In this review we follow the new nomenclatures of the k-casein variants recently described by Gautam et al. (2019). The DNA (NC_030813, goat genome reference version LWLT01 (Bickhart et al., 2017)) and protein reference sequences of *CSN3* (NP_001272516, NCBI database) represent the protein variant *CSN3*B* as the reference (Yahyaoui et al., 2001; Jann et al., 2004). We supplement the information with nucleotide positions in the coding sequence that is given in the reference X60763 (NCBI database) (Supplementary Table S5) (Coll et al., 1993) to facilitate the comparison between the position in the new goat reference genome of k-casein variants with previous studies that used the position in the coding sequence to name variants.

The reference protein *CSN3*B* is the predominant k-casein variant that occurs at a frequency >0.70 in most Italian and East Africa goats, Toggenberg and Buren goats from Germany, and Polish Saanen, fawn and white improved goats (Supplementary Table S6) (Chessa et al., 2003; Yahyaoui et al., 2003; Sacchi et al., 2005; Caroli et al., 2006; Kiplagat et al., 2010; Kupper et al., 2010; Strzelec and Niżnikowski, 2011; Rahmatalla et al., 2021).

The difference between *CSN3*A* and *CSN3*B* is the amino acid substitution Ile₁₁₉ to Val₁₁₉ which is the result of the transition of A to G at CHR6:86209184 in exon 4 (Coll et al., 1993; Yahyaoui et al., 2001). *CSN3*A* occurs also at a frequency ≥0.7 in Ionica and Montefalcone from Italy, Bunte and Weise Deutsche Edelziege, and Thueringer Waldziege from Germany as well as Ardi and Syrian goats from Saudi Arabia (Supplementary Table S6) (Caroli et al., 2001; Angiolillo et al., 2002; Kumar et al., 2009; El-Shazly et al., 2017). *CSN3*A'* and *CSN3*A''* encode the same protein variant *CSN3*A*, but, carry the synonymous mutations T to C at CHR6:86209207 and C to T at CHR6:86209258 in exon 4, respectively (Kiplagat et al., 2010; Gautam et al., 2019). *CSN3*A''* was found at low frequency in goats from Kenya and Maasai from Ethiopia. In that study, *CSN3*A''* was named *CSN3*O* (Kiplagat et al., 2010).

*CSN3*B'*, *CSN3*B''*, *CSN3*B'''* have the equivalent *CSN3*B* protein variant. In addition to the transition of G to A at CHR6:86209184 that alters the amino acid Val₁₁₉ to Ile₁₁₉, *CSN3*B'*, *CSN3*B''*, *CSN3*B'''* carry the synonymous mutations C to T at CHR6:86208883, C to T at CHR6:86209003, and A to G at CHR6:86209297 in exon 4, respectively (Supplementary Table S5)

(Chessa and Bolla, 2003; Yahyaoui et al., 2003; Jann et al., 2004; Prinzenberg et al., 2005; Kiplagat et al., 2010). Previously, *CSN3*B*, *CSN3*B'*, *CSN3*B''*, and *CSN3*B'''* had the names *CSN3*D*, *CSN3*D'*, *CSN3*D''*, and *CSN3*P*, respectively (Jann et al., 2004; Kiplagat et al., 2010). The homozygous *CSN3*B* genotype was associated with a higher milk protein content in Saanen goats (Catota-Gómez et al., 2017) and longer milk coagulation time in Spanish Murciano-Granadina goats compared to *CSN3*A* carriers (Caravaca et al., 2011).

*CSN3*C* differs from the reference variant *CSN3*B* in the three amino acid substitutions Val₆₅ to Ile₆₅, Ala₁₅₆ to Val₁₅₆, and Ser₁₅₉ to Pro₁₅₉ (Yahyaoui et al., 2001). The amino acid substitutions occurred as a result of a G to A, C to T, and T to C transitions at position CHR6:86209022, CHR6:86209296, and CHR6:86209304 in exon 4 (Yahyaoui et al., 2001), respectively. *CSN3*C* occurs at a frequency below 0.20 in some breeds from Italy, Canaria Spanish goats, goats from Germany and Turkey, Saanen goats worldwide, and Lithuania goats (Supplementary Table S6) (Chessa et al., 2003; Yahyaoui et al., 2003; Prinzenberg et al., 2005; Sacchi et al., 2005; Caroli et al., 2006; Gigli et al., 2008; Baltrėnaitė et al., 2009; Vacca et al., 2014; Catota-Gómez et al., 2017). *CSN3*C'* differs from *CSN3*C* through a synonymous mutation in codon 131 (Prinzenberg et al., 2005).

In the *CSN3*D* (previously named *CSN3*B*), the amino acid substitutions Val₆₅ to Ile₆₅ and Ser₁₅₉ to Pro₁₅₉ that exist in *CSN3*C* were also found. In addition, *CSN3*D* carries the Gln₄₄ to Arg₄₄ substitution because of an A to G transition at CHR6:86208960 in exon 4 (Caroli et al., 2001; Yahyaoui et al., 2001). This variant occurs at a frequency of less than 0.40 in Italian and German goats and Ardi goats from Saudi Arabia (Supplementary Table S6).

*CSN3*D'* differs from *CSN3*D* by a synonymous mutation in codon 56 and occurs at a frequency of 0.01 in Girgentana goats from Italy (Gerlando et al., 2015).

The *CSN3*E* protein variant differs from the reference by the amino acid substitution of Asp₉₀ by Gly₉₀ as the results of an A to G transition at position CHR6:86209098 in exon 4 (Angiolillo et al., 2002). *CSN3*E* occurs in Montefalcone goats from Italy at a frequency up to 0.45 (Angiolillo et al., 2002; Yahyaoui et al., 2003).

*CSN3*F* differs from the reference protein in the amino acid substitution of Ser₁₅₉ by Pro₁₅₉ which occurred due to the T to C transition at CHR6:86209304 in exon 4 (Yahyaoui et al., 2003). This variant was detected in breeds from Italy at a frequency below 0.15 and in Wild Spanish at a frequency of 0.98 (Yahyaoui et al., 2003). The variants *CSN3*F'* and *CSN3*F''* encode the same *CSN3*F* protein. *CSN3*F* differs from *CSN3*F'* by a synonymous mutation in codon 77. *CSN3*F'* occurs at a low frequency (0.01) in Raigarh goats from India (Gautam et al., 2019).

*CSN3*G* is characterized by G to A and T to C mutations at CHR6:86209022, and CHR6:86209304 in exon 4, respectively, in

comparison to the reference variant CSN3*B. The mutations cause the amino acid exchange Val₆₅ to Ile₆₅ and Ser₁₅₉ to Pro₁₅₉, respectively (Yahyaoui et al., 2003). An addition synonymous mutation is present in codon 43 (Yahyaoui et al., 2003). CSN3*G was found at a frequency of less than 0.15 in a few breeds from Italy and Hair and Angora goats from Turkey (Yahyaoui et al., 2003; Prinzenberg et al., 2005; Gigli et al., 2008; Gerlando et al., 2015). Variant CSN3*G' has the same amino acid substitutions as variant CSN3*G, but does not contain the synonymous mutation in codon 43 (Supplementary Table S5). The name CSN3*G' was introduced by Gautam et al. (2019); before that this variant had been named CSN3*F or CSN3*L (Jann et al., 2004; Kiplagat et al., 2010). CSN3*G'' contains the same amino acid substitution as variant CSN3*G and in addition two synonymous mutations in codon 43 and 56 (Vacca et al., 2014; Gerlando et al., 2015; Gautam et al., 2019). The name CSN3*G'' was also introduced by Gautam et al. (2019) before this variant had been named CSN3*N and CSN3*S (Vacca et al., 2014; Gerlando et al., 2015).

CSN3*H differs from CSN3*B in the amino acid substitution from Asn₅₃ to Ser₅₃ due to the transition of A to G in exon 4 at CHR6:86208987 (Jann et al., 2004).

CSN3*I varies from the reference in the amino acid substitution Val₆₅ to Ile₆₅ as a result of a G to A transition at CHR6:86209022 in exon 4 (Jann et al., 2004).

CSN3*J varies from the reference CSN3*B in the substitution of the amino acid Tyr₆₁ to Cys₆₁ because of the transition of A to G in exon 4 at CHR6:86209011. (Jann et al., 2004).

CSN3*K distinguishes from the reference variant by the amino acid substitution Gln₄₄ to Arg₄₄ that is caused by an A to G transition at CHR6:86208960 in exon 4 (Jann et al., 2004). CSN3*K and CSN3*I were found at a frequency ≤ 0.10 in Bunte and Weise Deutsche Edeldziege, and Buren goats from Germany (Kupper et al., 2010). In addition, CSN3*K was detected in Taggar and Saanen goats from Sudan (Rahmatalla et al., 2021).

CSN3*L contains the same amino acid substitution Gln₄₄ to Arg₄₄ that occurs in CSN3*K. The additional substitution of Ser₁₅₉ by Pro₁₅₉ differentiate CSN3*L from the reference. This substitution to Pro₁₅₉ has been detected before in the other protein variants CSN3*C, CSN3*D, CSN3*F, and CSN3*G (Kiplagat et al., 2010; Gautam et al., 2019). CSN3*L had been named before as CSN3*D (Kiplagat et al., 2010). This protein variant was found in Afar goats from Ethiopia only at a frequency of 0.05 (Kiplagat et al., 2010).

CSN3*M (provisionally named CSN3*Y) differs from the reference protein by three non-synonymous mutations. CSN3*M is characterized by a G to A transition at CHR6:86209097 resulting in the amino acid exchange of Asp₉₀ to Asn₉₀, a T to C transition at CHR6:86209263 resulting in a Val₁₄₅ to Ala₁₄₅ substitution, and a T to C transition at CHR6:86209304 resulting in the amino acid change from Ser₁₅₉ to Pro₁₅₉ (Chessa et al., 2003; Prinzenberg et al., 2005). CSN3*M occurs at a frequency of ≤ 0.05 in few Italian goats and Red Sokoto goats from Cameroon and Nigeria (Supplementary Table S6) (Chessa et al., 2003; Prinzenberg et al.,

2005; Sacchi et al., 2005; Caroli et al., 2007; Gigli et al., 2008; Vacca et al., 2014). CSN3*M' (previously named CSN3*N) differs from the variant CSN3*M by a synonymous mutation in codon 156 (Kiplagat et al., 2010; Gautam et al., 2019). CSN3*M' occurs at a frequency of 0.01 in Short Eared goats from Somalia (Kiplagat et al., 2010).

CSN3*N, named before as CSN3*M, carries the two amino acid substitutions Asp₉₀ to Asn₉₀ and Val₁₄₅ to Ala₁₄₅ (Kiplagat et al., 2010; Gautam et al., 2019).

The CSN3*O protein variant (previously CSN3*Q) carries the substitutions of Val₆₅ to Ile₆₅, Ile₁₁₉ to Val₁₁₉ and Ser₁₅₉ to Pro₁₅₉ compared to the reference (Kiplagat et al., 2010; Gautam et al., 2019). CSN3*O and CSN3*N found in a few goats from Africa at a frequency of less than 0.05 and 0.15, respectively (Kiplagat et al., 2010; Rahmatalla et al., 2021).

The replacements of Gln₄₄ to Arg₄₄ and Val₆₅ to Ile₆₅ lead to the variant CSN3*P (Gautam et al., 2019).

CSN3*Q carries the substitutions Gln₄₄ to Arg₄₄, Ile₁₁₉ to Val₁₁₉ and Ser₁₅₉ to Pro₁₅₉, that had been detected and described before in other k-casein variants. Furthermore, CSN3*Q has the amino acid substitution Thr₈₂ to Ala₈₂ which is the result of an A to G transition at CHR6:86209073 in exon 4 (Gautam et al., 2019). CSN3*Q and CSN3*P were found at a frequency of 0.01 in Blank Bengal Indian goats (Gautam et al., 2019).

CSN3*R distinguishes from the reference in the amino acids Pro₈₀ to Leu₈₀ and Ile₁₁₉ to Val₁₁₉. The exchanges from Pro₈₀ to Leu₈₀ and Ile₁₁₉ to Val₁₁₉ result from a transition of C to T and A to G in exon 4 at CHR6:86,209,068 and CHR6:86209184, respectively (Gautam et al., 2019).

CSN3*S is distinguished from the reference by the amino acid substitutions Val₆₇ to Ala₆₇ and Ile₁₁₉ to Val₁₁₉. The substitution of Val₆₇ to Ala₆₇ is a result of a T to C transition at CHR6:86209029 in exon 4 (Gautam et al., 2019). The frequency of CSN3*S and CSN3*R is about 0.01 in Siroh goats from India (Gautam et al., 2019).

CSN3*T carries also the Ile₁₁₉ to Val₁₁₉ substitution. In addition, the substitution Ser₃₇ to Arg₃₇ is present which results from an A to C transversion at CHR6:86208938 in exon 4 (Gautam et al., 2019).

CSN3*U varies from the reference by two amino acid substitutions, Val₇₈ to Ala₇₈ and Asn₁₄₃ to His₁₄₃. The substitution of Val₇₈ to Ala₇₈ results from the mutation TT to CA at CHR6:86209062 and CHR6:86209063; the substitution of Asn₁₄₃ to His₁₄₃ occurs due to an A to C transversion at CHR6:86209256 in exon 4 (Gautam et al., 2019).

CSN3*V variant carries the Asn₅₃ to Ser₅₃ substitution that occurs also in variant CSN3*H, but variant CSN3*V contains also the amino acid change from Ser₁₅₉ to Pro₁₅₉ that can be found also in other k-casein variants (Gautam et al., 2019).

In CSN3*W, the amino acid substitution Asn₅₃ to Ser₅₃ is found as in CSN3*H and CSN3*V. In addition, the amino acid substitution Thr₁₃₈ to Ala₁₃₈ as a result of an A to G transition at CHR6:86209241 occurs in CSN3*W (Gautam et al., 2019). The protein variants CSN3*H, CSN3*T, CSN3*U, CSN3*V, and

CSN3*W are rare. They were found at a frequency of 0.01 in Rajgarh Indian breed (Gautam et al., 2019).

CSN3*X differs from the reference by the amino acid substitutions Ser₃₃ to Asn₃₃ and Ser₃₇ to Thr₃₇ which are the result of G to A transitions at CHR6:86208927 and CHR6:86208939, respectively. CSN3*X was identified in Alpine ibex (Rahmatalla et al., 2021).

No information is available for the allele frequency of CSN3*A', CSN3*B'', CSN3*J, and CSN3*X.

The CSN3 protein variants are classified into two groups based on the isoelectric focusing point (IEP). CSN3*A, CSN3*B, CSN3*B', CSN3*B'', CSN3*C, CSN3*C', CSN3*F, CSN3*G, CSN3*H, CSN3*I, CSN3*J, CSN3*L have an isoelectric focusing point of 5.29 and belong to group A^{IEF}. CSN3*D, CSN3*E, CSN3*K, CSN3*M have an isoelectric focusing point of 5.66 and belong to group B^{IEF} (Prinzenberg et al., 2005). The IEF pattern of CSN3*D' and CSN3*N were not experimentally tested, but estimated using the ExpASY tool (Gasteiger et al., 2003). The D' variant was classified to group B^{IEF} and the N variant (new name G'') was classified to group A^{IEF} (Gerlando et al., 2015). The k-casein variants in group B^{IEF} were significantly associated with higher milk casein and protein content, which was shown in different goat breeds (Chiatti et al., 2005; Chiatti et al., 2007; Caravaca et al., 2009).

Casein haplotypes

Due to the strong genetic linkage of the four casein genes within a cluster of 250 kb, the haplotype approach has been a suitable tool instead of evaluating a single gene for accessing the variability within and among populations in diversity studies (Sacchi et al., 2005; Finocchiaro et al., 2008; Gigli et al., 2008; Kupper et al., 2010; Criscione et al., 2019), for breeding strategies (Haplotype Assisted Selection) (Caroli et al., 2006; Hayes et al., 2006), and for prediction of individual milk composition and suitability for milk processing. However, the full definition of the casein haplotypes would require genomic sequence data and is also complicated because of the large number of genetic variations found at the four casein loci. One of the major problems in comparing the different research when considering haplotypes is the different mutations used for deriving casein haplotypes. Furthermore, the number of genotyped animals per population or breeds, and the availability of pedigree and parent information affect the reconstructing and thereby the accuracy of the exact haplotypes carried by each animal.

The evaluation of the haplotype variability in five Italian goat breeds from Northern and Southern Italy identified 18 common haplotypes (Sacchi et al., 2005). However, the study failed to genotype CSN2*C which, therefore, could not be considered in the haplotype construction. The haplotype CSN1S1*F-CSN1S2*F-CSN3*D occurred in all breeds and was the most common haplotype in the Southern Italian breeds. In the Northern Italian breed, the haplotypes CSN1S1*E-CSN1S2*C-CSN3*D and

CSN1S1*F-CSN1S2*C-CSN3*D were most prevalent. A high frequency of the CSN1S1*0-CSN1S2*C-CSN3*A haplotype, containing the null variant CSN1S1*0, was detected in Vallesana Italian goats. Interestingly, the haplotype CSN1S1*F-CSN2*0, which was found in Maltese goats, was associated with a very low casein level of around 2.5 g/L, even if it was linked to a strong variant of CSN1S2. Eventually, the "Maltese" haplotype is the result of selection for milk with specific nutritional properties rather than for cheese-making (Sacchi et al., 2005).

In a study of Caroli et al. (2006) in four goat breeds from Northern Italy, 13 haplotypes were identified that occurred at a frequency >0.05 in at least one breed. Based on the evolution model, CSN1S1*B-CSN2*A-CSN1S2*A-CSN3*B was suggested to be the ancestral haplotype (Caroli et al., 2006).

Fifty four haplotypes were detected by using 30 SNPs within the casein genes in the analysis of six Southern Italian breeds and Norwegian dairy goat which highlighted the significant diversity among the breed (Criscione et al., 2019).

The haplotype structure within each casein gene was constructed in Norwegian goats based on 39 SNPs (Hayes et al., 2006). The unique number of haplotypes were 10, 6, 4, and 8 for CSN1S1, CSN2, CSN1S2, and CSN3, respectively. Since CSN1S1 haplotypes significantly affected the protein percentage and fat yield, and CSN3 haplotypes the protein and fat percentage, the authors suggest the use of a haplotype-assisted selection approach in Norwegian dairy goats, which are used specifically for cheese production (Hayes et al., 2006).

The haplotype structure was based on 22 SNPs and one deletion within the four casein genes in two geographically distant populations, the Sicilian Girgentana breed that likely originated from Afghanistan and the Himalaya area and the Norwegian goat breed (Finocchiaro et al., 2008). The number of haplotypes were 10, 8, 3, and 11 for CSN1S1, CSN2, CSN1S2, and CSN3, respectively. Although considerably geographically distant and phenotypically divergent, casein haplotypes were identical between both breeds.

In five Italian Sicilian goat breeds, 27 haplotypes were observed at a frequency >0.03. The most frequent haplotype in Derivata di Siria and Maltese was CSN1S1*F-CSN2*C-CSN1S2*F-CSN3*B. This haplotype is associated with low milk casein content, and therefore superior for the production of hypoallergenic goat milk (Gigli et al., 2008). In Argentata dell'Etna, Girgentana and Messinese the most frequent haplotype was CSN1S1*A-CSN2*C-CSN1S2*A-CSN3*B which is also most favorable for cheese production (Gigli et al., 2008).

In Bunte Deutsche Edeldziege and Weiße Deutsche Edeldziege dairy goats from Germany, 30 haplotypes with a frequency higher than 0.01 were detected, only four haplotypes were found in Buren meat goats (Kupper et al., 2010). The ancestral haplotype CSN1S1*B-CSN2*A-CSN1S2*A-CSN3*B was evident in all three breeds with the highest frequency in Buren goats (Kupper et al., 2010). The CSN1S1*E-CSN2*A-CSN1S2*A-CSN3*B haplotype was most frequent in both dairy

breeds followed by *CSN1S1*F-CSN2*C-CSN1S2*F-CSN3*B* in Bunte Deutsche Edelziege and *CSN1S1*F-CSN2*C1-CSN1S2*F-CSN3*B* in Weiße Deutsche Edelziege, which might be attributed to the selection of milk quantity. The deep divergence in the casein gene haplotypes in dairy goat breeds was attributed to different selection aims among breeds.

Application of casein variants for genetic selection programs

The selection for favorable alleles of major genes within a breed is cost-effective if it can be implemented in an existing selection system. Major genes affecting milk protein content, particularly caseins, are well known. The prevalence of specific casein variants in different goat breeds is probably the result of breeding goals but could be also due to random fixation. Currently, there are several kits on the market for testing milk protein variants in goats (Simões and Gutiérrez, 2018). Genotyping *CSN1S1* is of particular interest for breeders and the milk industry since genetic variation in the *CSN1S1* gene is one of the primary factors affecting milk protein content and technological properties, such as cheese yield and cheese curd formation. Selection schemes in Alpine and Saanen goats currently use *CSN1S1* variants for the pre-selection of young males undergoing the progeny test (Manfredi et al., 2000).

It is also conceivable to select goats carrying casein gene variants with anti-allergenic properties to produce healthy milk as functional food for human nutrition (Robinson, 2001).

Impact of casein variants in goat milk on human health and nutrition

Goat milk proteins possess unique biologically active components that affect the milk properties and have an impact on numerous aspects of human nutrition. Goat milk contains less lactose and higher alkalinity compared to cow milk (Robinson, 2011). Goat milk is highly digestible and has been approved repeatedly as an alternative milk source for people, who suffer from lactose intolerance and cow milk protein allergies (Park and Haenlein, 2017). Therefore, goat milk has a therapeutic value in human medicine and nutrition (Park, 2009).

Many people who are allergic and have gastrointestinal disorders to cow milk can tolerate goat milk because of considerable variation in goat milk protein sequences (Park and Haenlein, 2017). Numerous cow milk proteins have been identified as allergens (Wal, 2002). Alpha-S1-casein, α -S2-casein, and beta-lactoglobulin are among the most crucial milk protein allergens (Wal, 1998; Crittenden and Bennett, 2005). Beta-lactoglobulin does not occur in human milk (O'Mahony et al., 2014). For example, α -S1-casein from cow milk forms hard curds in the stomach which

can cause digestion problems. Therefore, the advantage of goat milk is the low concentration or even null content of α -S1-casein and other allergic casein protein variants (Bernacka, 2011; Yangilar, 2013).

For instance, the association of the casein protein variants with the null or low content of those proteins might affect the production of goat milk with hypoallergenic characteristics and selecting milk with null or reduced content of the particular protein. In this concern, some variants in goat α -S1-casein, β -casein, and α -S2-casein in different goat breeds are associated with null or reduced expression of the encoded protein (Persuy et al., 1999; Rando et al., 2000; Ramunno et al., 2001a; Ramunno et al., 2001b; Ramunno et al., 2005; Caroli et al., 2006).

Through the digestion of goat milk proteins and milk products, several interesting peptides have been identified with bioactive properties. The beneficial health effects of these peptides include antihypertensive, anti-diabetic, antithrombotic, immunomodulatory, antibacterial, antifungal, antiviral, antioxidant, binding and transporting metals, preventing amnesia, and causing smooth muscle contractions properties (Ebringer et al., 2008; Atanasova and Ivanova, 2010; Zhang et al., 2015; Gong et al., 2020).

Conclusion

In this review, we provide a comprehensive overview on the genetic variation of the four casein proteins in different goat breeds. We provide a translation of genetic DNA variants to the corresponding amino acid changes, as well as the protein variants. In addition, we also updated the names of different protein variants according to the information we found in a literature search on reported protein and genetic variants in casein to summarize more than 30 years of research. The effect of different casein gene variants on the casein content, milk composition, and cheese-making properties is discussed. The wide variation occurring in the milk caseins has impact on the nutritional value for humans and on technological properties in milk processing. The different characteristics of goat milk likely affected breeding goals and adaptation, which led to high frequency of some casein variants in various goat breeds and country. The casein genomic and proteomic variations as well as the casein haplotypes approach might be useful in selection of the animals according to the specific breeding goals.

Author contributions

SAR, DA, and GAB substantially contributed to the conception and design of the article and interpreting the relevant literature. SAR drafted the manuscript. DA and GAB critical revision of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fgene.2022.995349/full#supplementary-material>

SUPPLEMENTARY TABLE S1

Nucleotide and amino acid variants within the gene and mature protein of the *CSN1S1*.

SUPPLEMENTARY TABLE S2

Frequency of *CSN1S1* variants in different goat breeds and countries.

SUPPLEMENTARY TABLE S3

Frequency of *CSN2* variants in different goat breeds and countries.

SUPPLEMENTARY TABLE S4

Frequency of *CSN1S2* variants in different goat breeds and countries.

SUPPLEMENTARY TABLE S5

Nucleotide and amino acid variants within the gene and mature protein of the *CSN3*.

SUPPLEMENTARY TABLE S6

Frequency of *CSN3* variants in different goat breeds and countries.

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