A2 Milk: physicochemical properties and technological processing characteristics

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Abstract

Introduction. The growing global demand for A2 milk is driven by increasing consumer awareness of its potential health benefits and improved digestibility, which, in turn, has stimulated scientific interest in its physicochemical properties and technological applications in dairy production.

Materials and methods. The study is based on an analysis of scientific publications addressing the composition, physicochemical characteristics, and technological features of A2 milk derived from different animal species. Relevant literature was selected from major scientific databases, including Scopus, Web of Science, PubMed, and ScienceDirect, as well as from peer-reviewed journals.

Results and discussion. The protein composition of A2 milk differs from A1 milk, with a higher content of whey proteins and specific casein fractions, which significantly affects its technological and sensory properties. A2 milk also contains higher levels of polyunsaturated fatty acids, including omega-3 and omega-6, while carbohydrate and vitamin composition remains largely similar; mineral content shows increased potassium, sodium, and phosphorus. The structural features of β-casein influence micelle stability, resulting in longer coagulation time, lower gel firmness, higher syneresis, and reduced cheese yield, although some studies report improved gel homogeneity, viscosity, and water-holding capacity under certain conditions, particularly with probiotic cultures. Thermal treatment demonstrates higher stability of whey proteins in A2 milk due to reduced aggregation. Fermentation may proceed more slowly, leading to weaker or more porous gel structures, although results vary depending on processing parameters and starter cultures. Products made from A2 milk often exhibit a softer texture and altered structural properties compared to conventional milk products. Despite these differences, the nutritional composition of final products remains largely comparable. Technological challenges include limited specialized research, variability of results, and difficulties in process optimization, while membrane and biotechnological approaches, along with microencapsulation and advanced processing techniques, offer potential for enhancing product functionality, stability, and the viability of bioactive components.

Conclusions. A2 milk exhibits distinct physicochemical and technological properties due to its specific protein structure, which influences coagulation behavior, thermal stability, and product yield. Further research and optimization of processing parameters are required to fully realize its potential in dairy production.

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Introduction

For millennia, since the Neolithic era, when humanity first domesticated and learned to breed livestock animals, milk has been an integral part of the human diet at various stages of life. Human evolution as a species often occurred with access to dairy products, which contributed to the preservation of the ability to digest milk in adulthood due to the persistence of lactase activity, thereby further increasing the popularity of milk and the demand for milk and dairy products (Gerbault et al., 2011).

According to the definition adopted by Codex Alimentarius (a collection of food standards developed under the supervision of the Food and Agriculture Organization (FAO) of the United Nations and the World Health Organization), milk is defined as "the normal secretion of the mammary gland of milking animals, obtained from one or more milkings without either addition thereto or extraction therefrom, intended for consumption as liquid milk or for further processing" (FAO, 2011). The consumption of milk and dairy products provides the body with calcium, magnesium, iodine, and other nutrients, which contributes to bone development in youth and their strength in adulthood (Givens, 2020).

In the most widespread animal milk in the world, cow's milk (Bekhit et al., 2022), caseins account for approximately 80% of all proteins. Four types of this class are distinguished: αs1-casein, αs2-casein, β-casein, and κ-casein. Each type has different genetic variants that may differ in amino acid sequence and properties. For example, β-casein, which constitutes the largest proportion of milk proteins, has 15 variants: A1, A2, A3, A4, B, C, D, E, F, G, H1, H2, I, J, and K. The main variants are A1 and A2 (Jeong et al., 2024), which have attracted considerable attention from researchers worldwide (Jiménez-Montenegro et al., 2022). The difference between them lies in the 67th amino acid residue of the β-casein polypeptide chain, which consists of 209 residues. The A1 variant has histidine at this position, whereas A2 has proline (Jeong et al., 2024). During digestion of A1 casein in the human body or as a result of its transformation under the influence of microbial enzymes (for example, during cheese ripening from the corresponding type of milk), the heptapeptide β-casomorphin-7 (BCM-7) is released (De Noni and Cattaneo, 2010). This compound has numerous biological properties, including due to its opioid activity. There is evidence of a correlational relationship between BCM-7 and the development of autism in children, ischemic heart disease, type 1 diabetes (Thiruvengadam et al., 2021), or even specific intolerance to the A1 variant of β-casein, which manifests as an allergy to milk containing these proteins (Jiménez-Montenegro et al., 2022). At the same time, giving preference exclusively to cattle that produce milk with the A2 variant of β-casein is not feasible, as this would lead to a reduction in genetic diversity, which would decrease fertility and productivity and could become a source of potential health problems (Scott et al., 2023).

One of the ways to solve this problem is the use of milk from other animal species, not only cow's milk; for example, horse and donkey milk are often given to children who cannot tolerate regular milk, due to their different composition and characteristics (Salimei and Fantuz, 2012). Although the milk of all mammals contains proteins, fats, carbohydrates, vitamins, and minerals, its qualitative and quantitative composition varies and largely depends on many factors, including whether the animal is a ruminant or non-ruminant, as well as genetic and physiological influences, feeding frequency and diet composition, environmental conditions, and others. However, one of the most important factors is the genetic factor, namely the animal species (Kalyankar et al., 2015; Sarode et al., 2016).

Recently, increasing attention has been paid to obtaining milk from animal species that are not traditional for the dairy industry. This is driven by both environmental constraints that limit further growth in cattle populations and the search for products with potential health

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benefits, including the absence of the A1 variant of β-casein. Milk from goats, sheep, camels, horses, and donkeys is most often considered in this context, as it is believed to be easier to digest, less allergenic, and more similar to human milk than cow's milk. In addition, this opens up broad opportunities for the development of niche, high-value products, ranging from cheeses and yogurts to ice cream, fermented beverages, infant formula, and others (Roy et al., 2020).

The relevance of this study lies in the growing global demand for A2 milk, driven by health concerns among consumers (Sharma and Dahal, 2024). This work aims to analyze the physicochemical properties of A2 milk from different animal species and the technological aspects of dairy product production based on it, in order to determine prospects for dairy industry development.

Materials and methods

This study was designed as a narrative review with a structured approach to the identification and analysis of scientific literature on the composition, physicochemical properties, and technological characteristics of A2 milk. Relevant publications were retrieved from major international scientific databases, including Scopus, Web of Science, PubMed, and ScienceDirect. Additional sources were identified through the reference lists of selected articles and recent review papers.

The materials comprised scientific publications addressing the composition, physicochemical properties, and technological aspects of A2 milk processing and dairy products derived from it. Particular attention was paid to studies on protein composition, casein fractions, mineral content, heat stability, coagulation properties, and the technological suitability of A2 milk for the production of fermented dairy products and cheese. Both review papers and original research articles were analyzed to obtain comprehensive and reliable information on the properties and processing characteristics of A2 milk.

The study employed methods of analysis, generalization, systematization, and comparative evaluation of scientific data on the composition, physicochemical properties, and technological applications of A2 milk from different animal species. The collected data were compared and synthesized to identify common patterns, differences, and technological features associated with A2 milk, as well as to assess its suitability for the production of various dairy products under different processing conditions and technological parameters.

Results and discussion

Protein and amino acid composition of A1 and A2 milk

Regardless of the type of milk, the total content of each protein fraction remains similar; however, there is still a statistically significant difference between them that affects its technological characteristics as a raw material and its sensory properties as a product (Bisutti et al., 2022). In particular, the content of whey proteins (α-lactalbumin (α-LA), β-lactoglobulin (β-LG)) is higher in A2 milk, while the content of most caseins (κ-CN, αS2-CN, β-CN) is higher in A1 milk (Figure 1). An exception is αS1-CN, which is more abundant in A2 milk (Vigolo et al., 2023).

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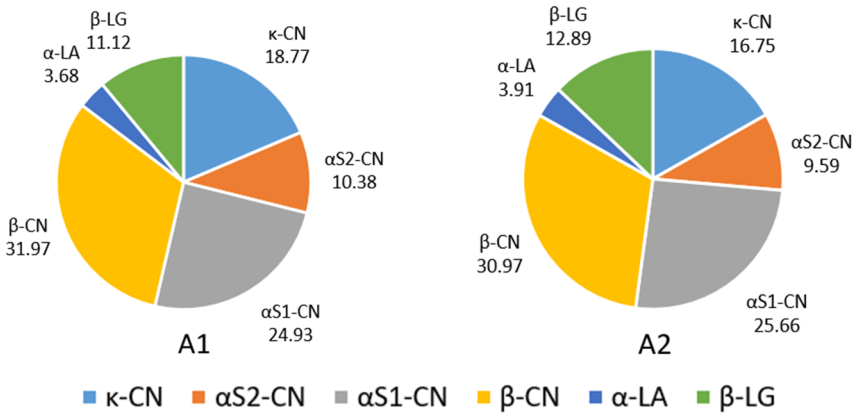


Figure 1. Comparison of protein composition (as % of total proteins) of A1 and A2 milk (according to Vigolo et al., 2023)

Whey proteins usually have a barely noticeable sweetish taste; however, as their concentration increases, undesirable notes may develop, including astringency, wet cardboard flavor, and sulfur-like notes (Vogel et al., 2021; Whetstine et al., 2005). A higher content of whey proteins in raw milk may improve the texture of fermented dairy products but can negatively affect their sensory qualities (Isleten and Karagul-Yuceer, 2006). In addition, whey proteins exhibit a high affinity for a number of aromatic compounds (e.g., hexanal, isovaleric acid, γ-nonalactone, methyl palmitate, and phenol). Upon binding with these compounds, milk may lose part of its flavor and aroma, including characteristic "grassy" notes, which is especially noticeable during heating (Zhang et al., 2025). In contrast, caseins are more likely to soften astringent and bitter flavors in milk and fermented dairy products, providing a rich creamy taste and a full, uniform aroma. This occurs due to the formation of gel-like aggregates and the binding of aromatic compounds, especially hydrophobic ones, which contributes to their slower and more balanced release during consumption (Balivo et al., 2024).

There are significant differences in the amino acid composition of A1 and A2 milk. A1 milk is characterized by a higher content of most amino acids, including aspartic acid, histidine, lysine, isoleucine, methionine, and valine. The only exception is leucine, the level of which is significantly higher in A2 milk. There are no differences between the two types of milk in the content of proline, serine, and tyrosine. Therefore, A1 milk contains most amino acids in higher amounts, whereas A2 milk is distinguished only by an increased leucine content (de Vitte et al., 2022).

The higher content of most amino acids in A1 milk (including essential amino acids) may positively affect the nutritional value of finished dairy products and the availability of amino acids after digestion. In contrast, A2 milk, which is rich in leucine, may be more attractive for athletes (leucine is a stimulator of muscle protein synthesis activation at various levels of physical activity) (Anthony et al., 2000; Garlick, 2005) or for elderly people (it helps maintain muscle function) (Xu et al., 2015).

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Fatty acid composition

A1 milk contains 0.58% more monounsaturated fatty acids (MUFA) than A2 milk (Table 1).

Table 1

Fatty acid composition of A1 and A2 milk*

Fatty acid	A1 milk (%)	A2 milk (%)
Monounsaturated fatty acids	**23.62**	**23.04**
Myristoleic acid (14C)	1.74	1.47
Pentadecanoic acid (15C)	0.012	0.012
Palmitoleic acid (16C)	0.170	0.286
Heptadecanoic acid (17C)	0.256	0.360
Oleic acid (18C)	18.06	17.19
Elaidic acid (18C)	3.23	3.58
Polyunsaturated fatty acids	**4.97**	**5.49**
Conjugated linoleic acid (18C)	0.234	0.217
Linoleic acid (18C)	3.26	3.64
α-Linolenic acid (18C)	1.15	1.19
Eicosatetraenoic acid (20C)	0.112	0.174
Eicosapentaenoic acid (20C)	0,052	0.092
Docosadienoic acid (22C)	0,250	0.088
Docosahexaenoic acid (22C)	0.014	0.011
Omega-3 fatty acids	*1.22*	*1.29*
Omega-6 fatty acids	*3.52*	*3.98*
ω-6/ω-3	*2.88*	*3.09*
Saturated fatty acids	**71.41**	**71.47**
Butyric acid (4C)	3.71	2.99
Caproic acid (6C)	3.23	2.90
Undecylic acid (11C)	0.049	0.067
Lauric acid (12C)	3.95	4.32
Tridecanoic acid (13C)	0.120	0.117
Myristic acid (14C)	11.93	12.04
Pentadecanoic acid (15C)	1.47	1.41
Palmitic acid (16C)	27.94	27.89
Margaric acid (17C)	0.663	0.865
Stearic acid (18C)	12.43	13.04
Behenic acid (22C)	0.033	0.028
Lignoceric acid (24C)	0.061	0.047

*Adapted from de Vitte et al., 2022

At the same time, the content of oleic acid in A1 milk is significantly higher than in A2 milk, whereas the levels of palmitoleic, heptadecanoic, and elaidic acids are higher in A2 milk compared to A1 milk (de Vitte et al., 2022). Oleic acid has antioxidant properties and is considered beneficial for the cardiovascular system (Haug et al., 2007), while palmitoleic acid reduces the risk of type 2 diabetes but increases low-density lipoproteins (LDL), which

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negatively affects cardiovascular health (Mozaffarian et al., 2013). Heptadecanoic and elaidic acids have mixed effects on the human body (Haug et al., 2007; De Oliveira et al., 2018). All fatty acids can impart undesirable flavors to milk and fermented dairy products, but only in excess; under normal conditions, they do not have a significant impact on the taste of A1 or A2 milk (Haug et al., 2007).

The content of polyunsaturated fatty acids (PUFA) in A2 milk is significantly higher than in A1 milk (see Table 1). The levels of omega-3 and omega-6 fatty acids, linoleic and α-linolenic acids, eicosatetraenoic and eicosapentaenoic acids are higher in A2 milk, whereas docosadienoic acid is higher in A1 milk (de Vitte et al., 2022). PUFA may contribute to improved cardiovascular health, reduction of LDL levels, and other health benefits (Al-Musa and Ethafa, 2023). However, the ratio of omega-6 to omega-3 fatty acids is within the recommended range (Stabnikova and Paredes-López, 2024) for both types of milk.

A comparison of the saturated fatty acid (SFA) content in A1 and A2 milk shows no statistically significant difference between these values. However, the content of butanoic, caproic, and lignoceric acids in A1 milk is significantly higher than in A2 milk, whereas the content of lauric, margaric, and stearic acids is higher in A1 milk (de Vitte et al., 2022). Butanoic and caproic acids, due to their short chain length, are mainly located in the primary positions of triacylglycerols, and therefore are easily released by lipases and are among the main acids that influence the taste and aroma of fermented dairy products (Jensen, 2002). Lignoceric, lauric, margaric, and stearic acids do not play such a significant role in organoleptic properties, but they may have positive effects on human health, such as strengthening the immune system and reducing the likelihood of cardiovascular diseases (Haug et al., 2007; Jenkins et al., 2015; Korat et al., 2020).

Carbohydrate composition

The carbohydrate composition of A1 and A2 cow's milk is identical; carbohydrates account for 5% of milk mass, of which approximately 4.8% is lactose (Jianqin et al., 2016).

Vitamins and minerals

There is no significant difference in the vitamin content of A1 and A2 milk (Xiao et al., 2022). However, among minerals, only Ca predominates in A1 milk, whereas K, Na, and P predominate in A2 milk. No difference in Mg content is observed between A1 and A2 milk (Table 2) (Daniloski et al., 2022).

Table 2

Comparison of mineral content of A1 and A2 milk

Minerals	Content (mmol/L)	
	A1 milk	A2 milk
Ca	34.27 ± 0.63	30.19 ± 0.00
K	20.22 ± 0.193	64.11 ± 0.59
Mg	5.02 ± 0.00	4.96 ± 0.02
Na	15.53 ± 0.08	26.94 ± 0.05
P	26.26 ± 0.26	30.75 ± 0.16

*Adapted from Daniloski et al., 2022

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Calcium in milk plays a significant role, as its increased content contributes to curd formation and moisture retention in the curd during cheese production. Phosphorus is an important component, as it is associated with the accumulation of solids in the curd and improved retention of nutrients, although excessive amounts may reduce fat retention. Sodium in milk has a relatively weak effect on coagulation properties; however, high concentrations are associated with a reduced retention of proteins in the curd. Potassium appears to have no significant role in the coagulation process (Stocco et al., 2021).

Considering the described features of the mineral composition, A1 milk may be characterized by better coagulation properties and higher technological suitability for cheese production, particularly due to the formation of a denser and more stable curd with a higher moisture retention capacity. In contrast, under such conditions, A2 milk may form a curd with different structural characteristics, which could potentially affect the distribution of solids and fat and lead to differences in yield and texture of the final product. Thus, differences in the mineral profile between A1 and A2 milk may be manifested primarily in their functional and technological properties during processing rather than in nutritional value as such.

Physicochemical properties of A2 milk

Fresh A1 and A2 milk do not differ in pH (pH = 6.49) (de Vitte et al., 2022).The color of A1 and A2 milk shows slight differences – in terms of lightness and yellowness they are the same; however, A2 milk has a more pronounced green tint than A1 milk. However, this did not affect the expert evaluation of its appearance, which was also the same for milk containing both types of β-casein (de Vitte et al., 2022).

During heat treatment of milk, whey proteins undergo the main changes, particularly β-lactoglobulin and α-lactalbumin, which begin to denature at temperatures above 70 °C. In A1 milk, β-casein tends to actively form aggregates, particularly through interaction with κ-casein of the micelles. As a result, during pasteurization, a larger portion of proteins transitions into an insoluble state, whereas in A2 milk, a significant proportion of whey proteins remains soluble. This is associated with the ability of the A2 variant of β-casein to act similarly to a "chaperone," meaning it binds partially unfolded proteins and prevents their aggregation.

In A1 milk, after heating, more ordered β-sheet structures are formed, which easily stick together into large aggregates. In contrast, in A2 milk after heating, a higher proportion of random structures and β-turns is observed, as well as a more stable α-helical conformation, which makes the proteins more resistant to thermal effects.

During sterilization (121 °C) and especially during ultra-high-temperature treatment (140 °C), these differences become even more noticeable. In A1 milk, the amount of κ-casein decreases intensively, large stable aggregates are formed that do not break down even under reducing conditions, and such denaturation is considered an indicator of thermal damage to milk. In A2 milk, despite the high temperatures, proteins retain a larger proportion of soluble forms, aggregate less, and their structure remains more flexible. In addition, A1 milk has a stronger negative charge and smaller casein micelles, whereas A2 milk has larger micelles but with a lower content of κ-casein. This also affects the different responses of these types of milk to heating.

Thus, it can be said that A2 milk exhibits higher thermal stability, better preserves whey proteins, and is less prone to the formation of large aggregates, whereas A1 milk undergoes protein denaturation and aggregation more rapidly during pasteurization, sterilization, and ultra-high-temperature processing (Daniloski et al., 2022).

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A1 and A2 β-caseins behave differently in emulsions. A2 more easily forms emulsions and produces smaller fat droplets, meaning that at the initial stage it acts as a better emulsifier. However, over time such emulsions are less stable. In contrast, the A1 variant of β-casein forms droplets of larger diameter but is able to stabilize the emulsion more reliably, preventing its breakdown. This is because it better covers the surface of fat particles and, during adsorption, acquires a more ordered structure due to an increase in the proportion of α-helices, whereas the A2 variant of β-casein retains a less compact conformation, which reduces its ability to keep droplets stable. Thus, A2 is better for rapid emulsion formation, while A1 is better for long-term emulsion stability (Darewicz and Dziuba, 2007).

Species-specific features of A2 milk composition

Recently, the dairy market, especially in Europe, has been unstable and has experienced a number of crises associated with rising prices, unpredictable fluctuations in demand, and a complex economic and political-regulatory situation. As one of the current ways to reduce the impact of external factors and maintain stability in the industry, the idea of increased implementation of A2 milk in production capacities is being considered more frequently (Fernández-Rico et al., 2022). Among other approaches, the option of expanding the raw material base by including milk from various animals – goats, buffaloes, sheep, etc. – is being consistently studied (Jiménez-Montenegro et al., 2022).

In Northern European cattle breeds, particularly Friesian, Ayrshire, British Shorthorn, and Holstein, A1 β-casein predominates. In contrast, A2 milk is characteristic of Guernsey and Jersey breeds, animals from the Channel Islands, as well as southern French breeds. In addition, A2 milk is produced by Zebu cattle of African and Asian origin, as well as by certain European breeds such as Charolais and Limousin. On a global scale, both Holstein-Friesian and Jersey cows can produce milk of both types (A1 and A2); however, the percentage of animals producing A2 milk is lower in the Holstein breed than in the Jersey breed. Therefore, the distribution of cows producing A1 or A2 milk depends more on the region than on the breed itself: for example, in Germany about 90% of Holstein-Friesian cows produce A2 milk, whereas in North America this figure ranges between 50-65% (Trivedi et al., 2025).

It is obvious that the breed of cow from which the milk is obtained will influence its composition. For example, milk from Jersey cows has a higher protein content than milk from Friesian cows and therefore contains a higher amount of β-casein (Mckenzie et al., 1984), which will affect its functional and technological characteristics. A comprehensive review comparing the composition and properties of A2 milk from different cow breeds could not be found at present, and therefore this may be one of the promising directions for future research in this field.

The composition of milk differs between animal species (Table 3).

Buffalo milk ranks second in the world in terms of production volume after cow's milk, accounting for approximately 15% of global production (Mejares, et al., 2022). It is distinguished by health-beneficial properties, primarily due to the significant amount of biologically active compounds, including δ-valerobetaine and acetyl-L-carnitine, which exhibit antioxidant and anti-inflammatory effects and are capable of inhibiting the proliferation of cancer cells (Liao et al., 2025). Another important factor that distinguishes buffalo milk is the absence of the A1 variant of β-casein – all buffalo species produce exclusively A2 milk, and even individuals with a mixed genotype (producing both β-casein variants simultaneously) have not been identified (Sodhi et al., 2012; Sridharan and Chidananda, 2020).

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Table 3

Composition of A2 milk from different animal species (g/L)

Characteristics	Milk's origin						
	Cow	**Buffalo**	**Goat**	**Sheep**	**Camel**	**Mare**	**Donkey**
Proteins	30–39	27–47	30–52	45–70	24–42	14–32	14–20
α_{S1}-CN	8–10.7	8.9	0–13.0	2.4–22.1	4.9–5.7	2.4	–
α_{S2}-CN	2.8–3.4	5.1	2.3–11.6	6.0	2,1–2,5	0,2	–
β-CN	8.6–9.3	12.6–20.9	0–29.6	15.6–39.6	14.4–16.9	10.66	–
κ-CN	2.3–3.3	4.1–5.4	2.8–13.4	3.2–12.23	0.8–0.9	0,24	–
α-LA	1.2–1.3	1.4	0.7–2.3	1–1.9	0.8–3.5	2.37	1,9
β-LG	3.2–3.3	3,9	1.5–5.0	6.5–13.5	Absent	2.55	3,3
Fats	33–54	53–90	30–72	50–90	20–60	3–42	3–18
MUFA	22.7–30.3	24.0–29.4	21.8–35.9	23.0–39.1	28.1–31.1	18.9–36.2	15.31–35.0
PUFA	2.4–6.3	2.3–3.9	2.6–5.6	2.5–7.3	1.8–11.1	12.8–51.3	14.17–30.5
SFA	55.7–72.8	62.1–74	59.9–73.7	57.5–74.6	47–69.9	37.5–55.8	46.7–67.7
Lactose	44–56	32–49	32–50	41–59	35–51	56–72	58–74
Oligosaccharides	0.03–0.06	–	0.25–0.30	0.02–0.04	–	–	–

*Adapted from Roy et al., 2020

Compared to cow's milk, buffalo milk is characterized by a higher content of casein proteins, particularly αS2-, β-, and κ-casein. At the same time, the concentrations of αS2- and κ-casein are approximately twice as high as those in cow's milk. The levels of whey proteins and lactose in buffalo and cow milk are approximately the same. In addition, the fat content of buffalo milk is almost twice that of cow's milk. Both types of milk have a similar distribution of SFA, MUFA, and PUFA, with SFA constituting the largest proportion. In buffalo milk, the PUFA level is somewhat lower than in cow's milk, which may indicate a reduced positive effect on human health. At the same time, the levels of MUFA and SFA in both types of milk are practically the same.

Buffalo milk is characterized by a significantly higher content of Ca, Mg, P, and Na than cow's milk. At the same time, cow's milk contains more K compared to buffalo milk (Liao et al., 2025). Similar to buffalo milk, goat milk does not contain the A1 variant of β-casein – almost all milk obtained from goats belongs to the A2 type. This milk also has smaller fat globules than cow's milk, which contributes to its better digestibility in the human body (Jung et al., 2017).

In goat milk, the lactose content is approximately 10% lower than in cow's milk. In contrast, the concentration of oligosaccharides may exceed the levels found in cow's milk several times. The concentration of αS1-casein in goat milk is closely related to the genetic

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characteristics of the animals. In goats that have alleles A, B, or C, this protein may account for up to a quarter of the total protein composition of milk. At the same time, in goats with alleles O or N, αS1-casein is completely absent. For cow's milk, the situation is different: the content of αS1-casein is relatively stable and constitutes approximately the same proportion of total protein regardless of genetic variations (Prosser, 2021).

Like the milk from the animal species mentioned above, sheep milk is also A2 milk, as it completely lacks the A1 variant of β-casein (Ravenwood et al., 2023). Sheep milk is distinguished by the highest casein content among the main types of milk (76–83% of total protein), while the whey protein fraction is mainly represented by β-lactoglobulin and α-lactalbumin and accounts for up to 17–22%. In addition, sheep milk contains more conjugated linoleic acid, butanoic acid, and omega-3 fatty acids than other types of milk. It is also characterized by higher levels of most vitamins, except for vitamin D, biotin, and folic acid, whose levels are similar to those in cow's milk (Ahmad et al., 2025).

Camel milk contains exclusively the A2 variant of β-casein (Singh S. et al., 2024) and has a characteristic composition: the average protein content is 24–42 g/L, fat 20–60 g/L, and lactose 35–51 g/L. It is rich in Ca, K, Mg, and vitamin C, the concentration of which is significantly higher than in cow's milk, making it an important source of antioxidants in arid regions. Unlike the milk of most other mammals, camel milk contains a higher proportion of β-casein and lacks β-lactoglobulin, the main allergen in cow's milk (Alhaj et al., 2022). It has lower levels of SFA but higher levels of MUFA and PUFA compared to cow's milk. Long-chain and unsaturated fatty acids predominate in camel milk, which may reduce the risk of cardiovascular diseases associated with excessive fat intake. Its fat is also characterized by a high content of conjugated linoleic acid, which contributes to the normalization of blood glucose levels, improves lipid metabolism, supports immune function, and may help prevent osteoporosis and certain types of cancer (Bakry et al., 2021).

Mare and donkey milk differ in their lower content of total solids, fat, and protein but contain more lactose. In terms of composition, they are closer to human milk than to cow's milk, reflecting species differences in the chemical composition of milk (Faccia et al., 2020). Donkey milk is a good source of vitamins A, B2, and C, as well as macroelements (calcium, phosphorus, magnesium, potassium, sodium) and microelements (iron, zinc, copper) (Singh M. et al., 2024).

Comparative analysis of A2 milk from different species

Functional and nutritional properties of milk from different animal species. Buffalo milk has a lower level of PUFA compared to cow's milk, which may lead to a reduced potential anti-inflammatory and cardioprotective effect provided by some PUFA (Pegolo et al., 2017).

Due to the low content of proteins capable of causing allergic reactions, goat milk is considered hypoallergenic, and its protein composition is similar to that of human breast milk (Jung et al., 2017). As a result, it is often considered a possible basis for the production of high-quality goat milk-based infant formula. Milk characterized by a lower αS1-casein content forms a softer and more delicate curd, which alters the physicochemical properties of casein gels formed in the stomach during the digestion of formulas based on it. As a result, such gels are digested more easily and are emptied from the stomach faster compared to standard infant formulas (Muñoz-Salinas et al., 2022).

Sheep milk contains the highest concentration of conjugated linoleic acid and α-linolenic acid among all major types of milk. These compounds are associated with antitumor activity, prevention of coronary heart disease and atherosclerosis, protection against

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osteoporosis, and increased immune system activity. Due to its high fat and mineral content, sheep milk and products made from it are considered a beneficial alternative to cow's milk, especially for people with specific dietary needs. In addition, they are used in dermatological and anti-aging products, particularly in soaps with emollient effects for chronic skin conditions such as psoriasis and eczema (Mohapatra et al., 2019).

The average size of fat globules in camel milk is smaller than that in cow, buffalo, and goat milk, which contributes to faster digestion and absorption in the human body (Bakry et al., 2021). Camel milk is considered a promising functional food with pronounced health benefits. Its unique composition – characterized by a high content of β-casein, the absence of allergenic β-lactoglobulin, and a fat profile similar to that of human milk – makes it suitable even for individuals sensitive to cow's milk. Compared to cow's milk, it contains higher amounts of vitamin C, iron, calcium, magnesium, and lactoferrin, which contribute to strengthening immune defense and maintaining metabolic balance. The generally lower fat and lactose content facilitates digestion and allows its consumption by people with mild lactose intolerance. Camel milk has also been associated with improved glucose control due to protection of pancreatic β-cells and regulation of insulin and glucagon secretion. In addition, biologically active compounds present in the milk may exert immunomodulatory and antitumor effects, further highlighting its potential in maintaining and improving human health (Singh S. et al., 2024).

It is known that mare's milk can be used to alleviate symptoms of hepatitis, chronic ulcers, and tuberculosis. Donkey milk promotes the release of anti-inflammatory interleukins, enhances immune response in old age, prevents atherosclerosis, and exhibits antiproliferative and antitumor properties (Faccia et al., 2020).

Structural, functional, and technological properties of milk from different animal species. Milk viscosity is primarily determined by fat and protein content; due to the higher levels of these components, buffalo milk is thicker than cow's milk. In addition to physical parameters, buffalo milk also differs from cow's milk in functional characteristics. It has lower heat stability, which is manifested by faster coagulation during heating, whereas in cow's milk this process occurs more slowly. This difference is due to the higher protein content in buffalo milk, whose proteins aggregate more intensively during heat treatment. At the same time, this milk demonstrates higher buffering capacity: during acidification, its pH decreases more slowly, which is associated with a greater number of casein micelles in its composition (Liao et al., 2025).

Buffalo milk contains significantly more fat than cow's milk, while the ratio of saturated fatty acids is similar in both types of milk. Due to its higher fat content, buffalo milk is a valuable raw material for the production of dairy products, especially soft cheeses with a stretched texture, such as mozzarella (Mollica et al., 2021).

The mentioned differences in mineral composition (Liao et al., 2025) indicate potentially better coagulation and structure-forming properties of buffalo milk, making it more suitable for the production of cheeses with a firm curd and high product yield, unlike cow's milk, which may form a less firm curd but remains more versatile for various processing applications.

The low level of αS1-casein in goat milk affects the structure of casein micelles. They are formed larger in size and have more hydrated pores than those in cow milk. This structure of the micelles determines differences in the properties of products made from goat milk. In particular, yogurts and cheeses produced from it form a gel matrix that is less dense compared to similar products made from cow milk.

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In addition, at low content or complete absence of αS1-casein, the process of formation and secretion of casein micelles in goat milk is disrupted, which further affects its physicochemical properties and technological characteristics (Prosser, 2021).

Significant differences in κ-casein content are observed between goat and cow milk: goat milk contains more, while cow milk contains less. This protein influences curd formation and firmness; therefore, interspecies differences in its quantity affect the technological properties of milk during cheese production (Muñoz-Salinas et al., 2022). Since κ-casein is located on the surface of casein micelles and performs a stabilizing function by preventing their aggregation, its content significantly affects the stability and behavior of protein structures during coagulation (Rahmatalla et al., 2022).

Fresh sheep milk is rarely consumed in its natural form due to its high fat and total solids content; most of it is processed into cheese and yogurt. Compared to cow milk (2.8% w/w), sheep milk contains more casein (4.4% w/w) and has larger casein micelles, which affects the rate of coagulation and the properties of rennet coagulation.

Studies show that the size of fat globules in sheep milk is the smallest among the main types of milk; even in goat milk, the globules are slightly larger. Due to their smaller size, sheep milk is easier to digest and assimilate than milk from other species, such as cow milk (Ahmad et al., 2025).

The increased content of butanoic acid and short-chain fatty acids in sheep milk significantly influences the flavor profile of the final product: this acid adds buttery and slightly salty-sour notes and often determines the characteristic aroma of many aged cheeses, which can be both a desirable characteristic (for cheese itself) and a factor that should be controlled in other products (Jo et al., 2018; Zheng, et al., 2021).

The smaller size of fat globules and the distinct lipid composition of sheep milk facilitate digestion and may alter the texture and viscosity of the final product – this makes it possible to position products as easier to digest; moreover, these physicochemical properties affect processing operations (homogenization, emulsification) and the final stability of products (Pan et al., 2021, 2024).

From a technological and storage perspective, the increased content of PUFA, particularly omega-3, makes products more susceptible to lipid oxidative degradation; this increases the risk of off-flavors and shortens the shelf life of products. Therefore, packaging barriers, antioxidant additives, or microencapsulation of fatty oils should be used to preserve sensory and nutritional properties (Clarke et al., 2021; Rahim et al., 2022).

For cheese and other fermented dairy product manufacturers, the increased fat content and short-chain fatty acids mean better raw material and potentially higher cheese yield, a more intense flavor, and faster aroma development during ripening (Mollica et al., 2021).

Processing of camel milk is associated with certain technological difficulties due to its specific composition and physicochemical properties. In particular, the higher proportion of SFA in camel milk requires a higher churning temperature in butter production compared to cow milk. This affects the rheological properties and melting temperature of butter produced from such milk (Bakry et al., 2021).

During yogurt production, weak curd formation, unstable consistency, and slow acid development are observed due to the natural antimicrobial properties of camel milk. To improve structural characteristics, probiotic cultures, exopolysaccharide-producing microorganisms, and additives such as gelatin, calcium salts, or cow milk protein concentrates are usually used. These technological approaches help increase viscosity, reduce syneresis, and form a denser protein network. Partial mixing of camel milk with cow milk also improves the texture and sensory properties of the final product.

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The production of ice cream based on camel milk is simpler than the production of yogurt or cheese. Optimization of the formulation by adjusting fat and total solids content and using natural stabilizers ensures acceptable texture, storage stability, and pleasant sensory properties. The addition of date paste, fruit pieces, or syrup not only improves flavor and viscosity but also enriches the product with natural sugars and antioxidants, creating a healthier alternative to traditional ice cream.

The production of camel milk powder is possible by both freeze-drying and spray-drying. The selection of the temperature regime significantly affects the preservation of nutrients and biologically active compounds, solubility, fat oxidation, and storage stability. Optimized drying parameters provide a shelf life of up to 9-10 months and make it possible to produce functional ingredients for the food industry.

In addition, camel milk is used in chocolate production, which is similar in composition and technology to chocolate made from cow milk but contains more proteins, minerals, and biologically active substances. Such chocolate is considered a potentially beneficial substitute for conventional chocolate, especially for children and people with impaired glucose tolerance, although further studies are needed to confirm these properties (Singh S. et al., 2024).

The low total solids content in mare and donkey milk reduces their milk's ability to form gels, and the composition of the protein fraction creates additional technological difficulties. Coagulation of mare milk using enzymes is practically impossible, which complicates cheese production. Donkey milk may be suitable for cheesemaking when special technological approaches are used, in particular certain coagulating agents, increased coagulation intensity, enrichment with milk from other species, or the addition of transglutaminase to improve protein network formation (Faccia et al., 2020).

Processing characteristics of A2 milk. β-casein plays an important role in the formation and stabilization of milk colloidal systems. Due to its surface-active nature, it participates in emulsion formation and determines the distribution and stability of fat droplets. This affects the consistency and texture of various dairy products, both liquid, such as kefir, and solid, such as hard cheese. Emulsion stability and the ability of β-casein to adsorb at the fat-water interface are important in the production of yogurts, ice cream, and other products where phase separation must be prevented and homogeneity ensured. In addition, the behavior of β-casein determines the nature of gel formation during fermentation, which is important for the structure of cheeses and other fermented dairy products, and also affects the solubility and stability of protein systems during heat treatment, for example in sterilized milk or milk powder. Thus, the colloidal properties of β-casein are directly related to the quality, stability, and sensory characteristics of final products (Modler, 1985).

Differences in protein composition between A1 and A2 milk (Table 4) have direct technological significance for the dairy industry. Since the A2 variant of β-casein has better emulsifying properties (Darewicz and Dziuba, 2007), products based on it may have a more delicate, light, and creamy consistency; therefore, it is advisable to use it for the production of desserts or infant foods. However, the stability of such emulsions is lower, so during storage they tend to break down more quickly. In contrast, the A1 variant of β-casein provides a stronger and more durable structure due to better fat particle coverage and the ability to form an ordered protein network; therefore, it is more suitable for the production of cheeses, yogurts, and products that require long-term storage or resistance to technological stresses, such as heating or freezing. Thus, A2 is advantageous where a delicate texture and rapid emulsion formation are required, whereas A1 has an advantage in cases where the stability and structural density of the final product are critical.

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Table 4

Comparative technological properties of β-casein variants A1 and A2 (Darewicz and Dziuba, 2007; Faggion et al., 2025)

Indicator	β-casein A1	β-casein A2	Advantage
Emulsifying capacity (mean droplet size d_{32} immediately after homogenization, μm)	1.82	**1.73** (smaller droplets)	A2 ↑
Emulsion stability (residual turbidity after 24 h, % of initial)	**98%**	**90%** (faster breakdown)	A1 ↑
Surface load (on hydrophobic surface, mg/m^2)	**3.14**	**3.08** (lower)	A1 ↑
Change in secondary structure after adsorption on a hydrophobic surface	α-helix increases to 20%	α-helix increases only to 17%	A1 ↑
Adsorption rate at the oil/water interface	slower	faster (due to higher solubility at pH 6.7)	A2 ↑
Suitability for products with delicate creamy texture (desserts, infant formula, cream, ice cream)	good	excellent (rapid formation of small droplets, delicate texture)	A2 ↑
Suitability for products requiring high stability during storage and mechanical stress (long shelf-life yogurts, cream cheeses, beverages)	excellent (high emulsion stability)	lower (emulsion separates quickly)	A1 ↑
Suitability for hard cheeses	higher hardness; better syneresis (lower losses in whey)	lower hardness; poorer syneresis (higher losses; REC reduced by 3–5%).	A1 ↑
Gel hardness / syneresis	excellent (yield higher by 0.36-1.15%; firmer texture)	lower (yield lower by 0.36-1.15%; softer texture)	A1 ↑

The protein profile of A2 milk determines distinct physicochemical properties during gel and curd formation. Despite the absence of significant differences in coagulation time, the structure of the acid curd in A2 milk is characterized by increased density. This feature is explained by the interaction between β- and κ-casein fractions, where the combination of allelic variants of proteins in A2 milk promotes the formation of more rigid and stable structures compared to the protein combination in A1 milk. The results of recent studies on the parameters of rennet and acid coagulation of milk with different contents of β-casein A1 and A2 are summarized in Table 5.

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Table 5

Comparison of rennet and acid coagulation parameters of A1 and A2 milk

Parameter	Rennet coagulation (A2 relative to A1)	Acid coagulation (A2 relative to A1)
Time to coagulation onset	+2.8 min (Faggion et al., 2025), up to +3 min (Bisutti et al., 2022; Hallén et al., 2007) (longer for A2)	+ (longer for A2) (Daniloski et al., 2022; Nguyen et al., 2018)
Time to reach maximum firmness	+ (related to shorter rennet coagulation time in A1 (Bittanteetal., 2012)	+ (longer for A2) (Juan and Trujillo, 2022)
Curd firmness	-2.7 mm (lower for A2) (Faggion et al., 2025; Gustavsson et al., 2014; Hallén et al., 2007)	Lower (lower gel density and elastic modulus for A2) (Daniloski et al., 2022; Juan and Trujillo, 2022)
Syneresis	Higher for A2 (more whey formed (Juan and Trujillo, 2022), associated with porous structure (Nguyen et al., 2018)	Lower water-holding capacity (lower for A2), porous gel structure (Daniloski et al., 2022; Juan and Trujillo, 2022)
Cheese yield (%)	-0.36% (lower for A2) (Faggion et al., 2025; Marziali and Ng-Kwai-Hang, 1986; Vigolo et al., 2023;)	- (lower for acid gels of A2 due to weaker structure) (Daniloski et al., 2022)

The processes of acid coagulation and fermentation occur at a similar rate in both types of milk. The maximum and average acidification rates, as well as the time to reach peak acidity, remain at the same level, indicating similar fermentative potential. Despite similar fermentation times to reach pH 4.6, A2 milk has a longer lag phase, which indicates a slowdown in the initial stages of acid production. After process stabilization, the rate of pH decrease becomes similar, and the structural characteristics of the final gel do not show significant differences in water-holding capacity.

During rennet coagulation, the protein composition of A2 milk promotes faster curd firming and increased curd firmness. The ability to form a denser coagulation structure is associated with a more favorable genetic combination of β- and κ-casein, where the presence of the κ-casein B allele improves gel formation, whereas the κ-casein E allele has the opposite effect. In milk containing β-casein A2 together with the κ-casein B variant, the curd forms with greater mechanical stability, whereas the combination with κ-casein E is associated with reduced coagulation ability.

The formation of a denser protein network in A2 milk is accompanied by increased syneresis and potentially higher cheese yield. This effect is explained by the higher density of protein aggregates, which are able to retain a greater proportion of total solids and form a more compact gel network. From a technological perspective, this determines the advantage of A2-type milk in the production of fermented products and cheeses, where high curd firmness and stability are required while maintaining normal fermentation dynamics (Juan and Trujillo, 2022).

Heat treatment is a key stage in the production of drinking milk, as it ensures microbiological safety, stability, and storage suitability of the product. Depending on the

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purpose, pasteurization or sterilization is used, which differ in temperature regimes and their effects on protein composition and the structure of milk components.

Pasteurization is carried out at a temperature of about 72 °C for 15 s, which ensures the destruction of pathogenic microorganisms and minimal structural changes in proteins. Sterilization is carried out at 121 °C for 2.6 min or at 140 °C for 3 s (UHT treatment), which allows a long shelf life to be achieved but has a more significant effect on the structure of protein molecules and mineral balance.

When heated above 70 °C, noticeable changes in the secondary structure of proteins occur in milk with different β-casein phenotypes. In A1/A1 and A1/A2 samples, more intensive formation of aggregated β-sheets and a decrease in the number of intramolecular β-structures are observed, whereas in A2/A2 milk this effect is less pronounced. A2 milk is characterized by greater thermal stability of protein fractions due to the presence of proline at position 67 of β-casein, which stabilizes the polypeptide chain and reduces the tendency toward aggregation.

During pasteurization (72 °C), a larger proportion of native whey proteins is preserved in A2/A2 milk, whereas in A1/A1 and A1/A2 samples β-lactoglobulin denatures more rapidly and interacts with κ-casein, forming protein-protein complexes. During sterilization (121-140 °C), these processes intensify, leading to the formation of dense aggregates and a decrease in the amount of soluble proteins. In A1 milk, a higher tendency toward aggregate formation is observed even after treatment at 121 °C, whereas in A2 milk most protein bonds remain stable.

An increase in processing temperature leads to a decrease in pH (from 6.83 to 6.69 in A2/A2 samples) and causes a shift in the calcium-phosphate equilibrium toward the precipitation of colloidal calcium phosphate. A2 milk is characterized by larger casein micelles (up to 238 nm at 140 °C) and a less pronounced negative charge compared to A1 milk, which indicates reduced electrostatic stabilization of the system, but at the same time a lower tendency of protein particles to aggregate.

Thus, A2 milk responds more mildly to heat treatment than A1 milk: its protein structures are less prone to denaturation and aggregation, and conformational changes are partially reversible. The optimal pasteurization regime (72 °C/15 s) ensures microbiological safety with minimal impact on the protein–mineral complex, whereas sterilization, which is necessary for long-term storage, may cause deeper structural changes, especially in A1-type milk (Daniloski et al., 2022).

The production of skimmed or concentrated A2 milk does not differ technologically from A1 milk, since the methods used for their production do not alter the native structure of milk proteins, including β-casein (Fernández-Rico et al., 2022; Kumar et al., 2013).

Although specialized publications evaluating the effects of fortification or fermentation of drinking products made from A2 milk are limited (Fernández-Rico et al., 2022), general reviews on beverage development note technological barriers, in particular the lack of kinetic data for predicting the stability of components under industrial conditions, whereas encapsulation and emulsion-based approaches are considered promising methods for delivering bioactive components to improve their stability and availability (Vieira and Souza, 2022). At the same time, the scientific basis for practical recommendations on the use of A2 milk in industry is still incomplete, which further complicates their development and implementation (Fernández-Rico et al., 2022).

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Production of fermented dairy products from A2 milk

Fermentation of products based on A2 milk is accompanied by differences in the rate of pH decrease and the properties of the formed curd; however, different studies show varying results (Table 6). Some studies indicate that A2 milk is characterized by a longer fermentation time (approximately 176 min compared to 146-148 min for A1 milk), slower gel formation, and the formation of a weaker and more porous gel, which is associated with the characteristics of the protein structure: larger casein micelles, lower κ-casein content, and a higher level of β-lactoglobulin in the whey phase (Daniloski et al., 2024).

Table 6

Comparison of physicochemical and structural properties of fermented A2 and A1 milk

A2 fermentation time	A2 gel firmness	Whey separation in A2 milk	Viscosity of A2	Author's conclusion	Reference
Longer (176 min vs. 146-148 min)	Lower (1.63 N vs. 1.91 N)	Higher (23% vs. 16%)	Lower (-5.7 N·s vs. -7.2 N·s)	Using A2 milk leads to prolonged gelation time, with altered digestive properties compared to yogurts containing β-casein A1; A2 exhibits weaker gel structure and higher porosity	Daniloski et al., 2024
- (same: 10 h)	Higher without probiotics (66.13 g vs. 59.86 g), lower with them (94.59 g vs. 120.58 g)	Lower (higher water-holding capacity, less whey)	Higher	A2 fermented milk shows better viscosity and a more stable structure than conventional fermented milk; differences in casein micelle structure between regular and A2 milk are confirmed	Wang et al., 2022

Other data indicate that fermented A2 milk forms a denser and more stable curd with a uniform microstructure without flake-like aggregates, and the coagulation process occurs without whey separation, which indicates improved gel-forming ability compared to regular milk. As a result, fermented products based on it, particularly yogurts, have a more homogeneous consistency, higher viscosity, and greater resistance to mechanical stress (Wang et al., 2022).

During digestion, yogurts made from A2 milk form a denser curd that breaks down more slowly than in products containing β-casein A1. While in A1/A1 and A1/A2 samples the breakdown of the protein matrix occurs more rapidly, A2/A2 products are characterized by the preservation of a more stable structure under the action of digestive enzymes (Daniloski et al., 2024).

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Starter cultures and their interaction with A2 milk proteins. For the fermentation of A2 milk, symbiotic cultures of *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus* are traditionally used. According to some data, the characteristics of the A2 protein fraction – larger casein micelles, lower κ-casein content, and a higher level of β-lactoglobulin in the whey – reduce protein-protein interactions and decrease the ability of proteins to interact during pH reduction. The larger size of casein micelles limits the number of surface contacts and, consequently, reduces the number of bonds between proteins that usually form during fermentation. This leads to a less dense product texture and a longer fermentation period (Daniloski et al., 2024).

At the same time, other results demonstrate that the casein complex in A2 milk leads to improved protein hydrolysis and the formation of smaller peptides compared to conventional milk. It is known that the addition of probiotic strains *Lactiplantibacillus plantarum* MWLp-12 and *Limosilactobacillus fermentum* MWLf-4 enhances this process by promoting more active protein breakdown and increasing titratable acidity. These strains produce significant amounts of exopolysaccharides (350-460 mg/L), which form a more interconnected protein matrix and improve the water-holding capacity of the product. As a result, the curd of fermented milk becomes thicker, and its structure becomes denser and more homogeneous (Wang et al., 2022).

Formation of structure and consistency of fermented products. The textural properties of products made from A2 milk differ depending on the study. In some cases, a softer consistency, lower elasticity, viscosity, and cohesiveness, higher gel porosity, and increased whey separation have been reported, which is associated with a reduced number of structural contacts in the protein matrix and a lower content of aggregated β-sheets (Daniloski et al., 2024).

In other studies, increased homogeneity, higher viscosity, resistance to mechanical stress, and the formation of a denser curd without whey separation have been reported, indicating a more stable gel microstructure in fermented products based on A2 milk. Their fermentation increases gel strength, consistency, viscosity index, and the connectivity of the protein network. Such products have greater density, resistance to phase separation, and a pleasant creamy texture (Wang et al., 2022).

During digestion, products made from A2 milk form a denser curd that is broken down more slowly by digestive enzymes compared to products containing β-casein A1 (Daniloski et al., 2024).

Data on the properties of fermented products made from A2 milk are contradictory and depend on the source. Some studies indicate slower gel formation, lower modulus strength, higher porosity, reduced cohesiveness, and a softer consistency of A2 milk yogurts, while others report the formation of a denser, more stable, and more homogeneous curd without whey separation, as well as increased viscosity and resistance to mechanical stress. Such divergence suggests that the properties of fermented products from A2 milk strongly depend on processing conditions, technological parameters, and microstructural characteristics of the protein fraction in specific experimental models. Despite these discrepancies, both types of results indicate that β-casein A2 forms structures that differ from those typical of products made from A1 milk. This highlights the need for further investigation of the influence of technological factors on the development of final textural and rheological properties of fermented products based on A2 milk, as well as the development of protocols and standardization of future research in this area.

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Production of cheeses from A2 milk. Cheeses are classified by texture (very hard, hard, semi-hard, semi-soft, soft), which is mainly related to the moisture content in the cheese. The classification also considers the type of milk, the moisture-to-protein ratio, the coagulation method, cooking temperature, and microbiota. Most cheeses are produced by rennet coagulation (about 75% of global production), whereas acid cheeses are formed through lactic acid production. The production of rennet cheeses is divided into two phases: curd production and ripening. Acid and acid-heat cheeses, as well as some rennet cheeses, are consumed fresh without a ripening period.

Hard cheeses are characterized by low moisture content, which is achieved through intensive whey drainage, pressing, and salting. The main coagulation method is rennet coagulation, using enzymes (chymosin and pepsin) to coagulate milk caseins at a pH of about 6. Milk is heated to a certain temperature, and rennet is added (from the stomachs of lambs or calves, or plant coagulants such as fig sap or thistle extract). After coagulation, a curd forms, which is cut to accelerate whey separation using baskets or molds with weight pressing. The whey drains quickly, and the curd mass is placed in a cool shaded place. Dry salting is carried out on the surface repeatedly over 9 days, followed by washing with water to form a rind. The cheese is pressed with weights for additional moisture removal, placed on shelves in an enclosed room for ripening, where it becomes more delicate. Such cheeses can be stored for a long time and exported. Examples include Cheddar (first mentioned in 1500), Gouda (1697), Parmesan (1579), and Grana (1200). Hard cheeses ripen for months or years, developing an intense flavor due to biochemical changes.

Soft cheeses have a high moisture content, which makes them less stable and therefore they require rapid consumption. Coagulation may be rennet or acid-based, with less intensive whey drainage and without strong pressing. For rennet soft cheeses, milk is coagulated with rennet, the curd is cut, but whey drains more slowly, without significant heating or pressing, which preserves moisture. Salting is carried out either dry or in brine for hardening. Ripening takes place in a closed room, where the cheese becomes softer. Plant coagulants (thistle, saffron) are used for some varieties, but they are not suitable for long ripening due to excessive proteolytic activity, which leads to bitterness. Examples include Camembert (1791), Brie, Port du Salut, or Saint Paulin (1816). Soft cheeses often have a rind or a mold surface and are common in monasteries and farm production, with regional variations.

Fresh cheeses are produced mainly by acid coagulation and are consumed immediately after curd formation without ripening. Milk is inoculated with lactic acid bacteria that ferment lactose, producing lactic acid. At pH 4.6, caseins coagulate, forming a gel with entrapped fat. The gel is cut to separate whey, and the curd mass is drained without strong pressing. The curd may form accidentally due to natural microbiota or intentionally with the addition of starter cultures. For some varieties, salt is added or dehydration is carried out to extend shelf life. Examples include cottage cheese, cream cheese, and quark. These cheeses originate from acid cheeses similar to those produced in Ancient Rome or the Middle East, with rapid consumption due to instability. Some fresh cheeses are produced using hot water for shaping (manual pressing), similar to pasta filata cheeses (McSweeney et al., 2025).

Compared with A1 milk, A2 milk is characterized by slower rennet coagulation and the formation of weaker gels. For A2 milk, the following have been reported: (1) a longer time to the onset of coagulation – the time to the beginning of coagulation increases by 2.8 min (Faggion et al., 2025; Vigolo et al., 2023); (2) lower curd firmness; (3) slower increase in curd firmness.This is associated with structural features of casein micelles in the A2 variant.

A2 milk is characterized by a larger diameter of casein micelles. Enlarged micelles have a less dense internal structure, greater internal free space, and lower stability. This results in fewer bonds between micelles, leading to the formation of a weaker casein spatial network,

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which manifests in an overall deterioration of coagulation properties, slower gel strength development, and reduced efficiency of rennet coagulation (Vigolo et al., 2023).

Structural features of β-casein A2 (the presence of an additional proline) may enhance the molecular "chaperone" activity of the protein and hinder protein aggregation, which also reduces the efficiency of rennet gel formation. In acid coagulation, A2 milk forms a weaker acid gel compared with A1 milk. Its curd structure at different stages of acid coagulation is the weakest, and the rate of gel firming is minimal. The coagulum formed from A2 milk is more porous and softer, which is consistent with the smaller average size of fat globules in this type of milk, which reduce the rigidity of acid gels (Gai et al., 2023).

Studies on the effect of different milk types on cheese yield confirm that an increased proportion of A2 protein in milk is accompanied by some deterioration in technological properties, but only at the initial stages of coagulation. When the proportion of A2 milk exceeds 50%, a decrease in the efficiency of coagulation and the transfer of protein and fat into the curd is observed, which is reflected in reduced cheese yield. In the whey of samples obtained from 100% A1 milk, lower losses of protein and fat are recorded, whereas in A2 milk these losses increase, indicating less efficient curd formation and firming.

These differences are explained by the structural features of β-casein A2, which increase the hydrophilicity of protein micelles, enlarge their average size, and reduce the content of calcium and phosphorus. At the same time, the reduced concentration of κ-casein characteristic of milk containing β-casein A2 increases micelle size variability and negatively affects coagulation properties. As a result, A2 milk is characterized by larger, less compact micelles that aggregate less efficiently during the initial phase of coagulation.

Considering that these differences are mainly manifested at the early stages of the renneting process, further ripening of cheese made from A1 and A2 milk does not show significant differences in chemical composition or final sensory characteristics. This indicates that the genetic variant of β-casein mainly affects the initial stages of curd formation, whereas the final parameters of the mature product become similar after ripening (Vigolo et al., 2023).

Despite this, some studies still conclude that A1 milk may be considered more suitable for cheesemaking than A2 milk due to slower rennet and acid coagulation and a weaker curd structure of the last one (Gai et al., 2023).

A2 milk produces a lower cheese mass yield at all stages, and losses may reach up to 1.15% of the final mass. There is also a tendency toward lower yields of solids and water, although the differences are not always statistically significant.

The composition of cheeses made from A2 milk practically does not differ in terms of protein, fat, total solids, and mineral content. However, color parameters change, as the color of the resulting product shifts toward green.

Cheeses made from A2 milk have a softer texture: they are characterized by lower hardness, elasticity, chewiness, and adhesiveness; therefore, they require less effort to chew and recover their shape to a lesser extent after compression (Faggion et al., 2025).

Problems and prospects for development. Despite the active implementation of membrane and biotechnological methods in the dairy industry, one of the key problems is the insufficient number of specialized studies specifically devoted to A1 and A2 milk. Most of the available scientific data on ultrafiltration, nanofiltration, and biotechnological approaches have been obtained using regular cow's milk without differentiation by β-casein type; therefore, possible differences in process behavior, membrane separation efficiency, or properties of final products remain insufficiently studied and require further experimental research (Reig et al., 2021).

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A significant technological problem of membrane processes is the formation of deposits on the membrane surface, which reduces plant productivity, worsens separation selectivity, and requires regular equipment cleaning. In addition, during membrane processing, partial damage to casein micelles or fat globules may occur, which can affect the rheological properties of concentrates and the technological characteristics of raw materials in cheese and protein product manufacturing (Chen et al., 2018). At the same time, the efficiency of ultrafiltration and nanofiltration largely depends on process conditions, membrane type, and membrane module design, which complicates technology standardization and requires optimization for each type of dairy raw material (Reig et al., 2021).

In the field of biotechnological methods, the main challenges remain ensuring stable viability of probiotic cultures during technological processing and product storage, as well as uniform distribution of cells within the product. Although microencapsulation significantly increases probiotic survival, the implementation of this technology on an industrial scale may be associated with additional costs, increased process complexity, and the need to select optimal encapsulating materials for each type of product (D'Amico et al., 2025; Kamalesh et al., 2025).

At the same time, the prospects for the development of this field are considerable. Membrane technologies make it possible to purposefully modify milk composition, produce products with increased protein content, reduced lactose content, or modified mineral composition, which creates the prerequisites for the production of specialized and functional dairy products (Reig et al., 2021). The combination of membrane processes with biotechnological methods, in particular the use of microencapsulated probiotics, makes it possible to develop new types of dairy products with enhanced functionality, stable microflora, and improved nutritional properties (Chen et al., 2018; D'Amico et al., 2025).

An important promising direction is also the development of the market for A2 milk and products based on it. Increasing consumer awareness of the differences between β-casein A1 and A2, as well as the association of A2 milk with better digestibility, contributes to the formation of stable demand for such products. Consumers show a willingness to pay a higher price for A2 milk, which creates economic incentives for producers despite the lower productivity of cows with the A2 genotype and the additional costs associated with breeding and the separation of raw material streams (Żbik et al., 2024).

Thus, the main challenges in the development of A2 milk processing technologies include the lack of specialized research, technological limitations of membrane processes, and the complexity of implementing biotechnological methods under industrial conditions. At the same time, the prospects for development are associated with the creation of functional and specialized dairy products, the improvement of membrane and biotechnological processes, and the expansion of the A2 milk product market, making this area one of the most promising in the modern dairy industry.

Conclusions

A2 milk from different animal species is characterized by significant variability in physicochemical properties, which is due to genetic characteristics of the species and breed, feeding conditions, stage of lactation, and climatic and regional factors. The key structural feature of A2 milk is the presence of proline at position 67 of β-casein, which affects the stability of casein micelles, coagulation processes, heat stability, and digestibility of protein fractions. Differences in the ratio of proteins, fats, and lactose in the milk of different animal

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species determine its nutritional value, biological value, and technological suitability for the production of various dairy products.

A2 milk is characterized by higher heat stability of protein fractions and specific colloidal and gel-forming properties; however, it may demonstrate poorer coagulation characteristics, including slower rennet and acid coagulation, formation of a weaker or more porous curd structure, higher syneresis, and in some cases reduced product yield, which is particularly important for cheese technology and concentrated dairy products. Overall, data on fermented and coagulated products made from A2 milk remain somewhat inconsistent, suggesting a strong influence of factors such as mineral composition of milk, heat treatment conditions, starter culture composition, fermentation temperature, and duration of fermentation on the structural and mechanical properties of the final products.

Further development of the use of A2 milk in the dairy industry should be associated with the optimization of technological parameters of coagulation, heat treatment, and fermentation, adjustment of the mineral composition of milk, as well as the application of membrane and biotechnological methods that would improve the stability of protein systems, product yield, and the reproducibility of technological processes.

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