



Determinants of goat milk composition and quality: Integrating genetic, nutritional, physiological, and management perspectives : A review

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Abstract

Goat milk is recognized as an important dairy product due to its nutritional value and the presence of bioactive compounds that may contribute to human health. The composition and quality of goat milk are influenced by a wide range of factors that interact throughout the production process, leading to considerable variation in its physicochemical, nutritional, and microbiological properties. This review provides a comprehensive overview of the major determinants affecting goat milk composition and quality by integrating genetic, nutritional, physiological, and management-related perspectives. Genetic factors, including breed characteristics and gene polymorphisms associated with milk synthesis, play a significant role in determining milk yield and the concentrations of fat, protein, lactose, and fatty acids. Nutritional factors influence milk composition through dietary nutrient supply, forage quality, feeding strategies, and supplementation practices, which can alter the nutritional and functional properties of milk. Physiological factors such as age, parity, stage of lactation, health status, and endocrine regulation also contribute to variations in milk composition and production performance. In addition, management practices, including housing conditions, hygiene standards, animal welfare, and milking procedures, are essential for maintaining milk quality and safety. The available evidence suggests that goat milk quality is shaped by the complex interaction of genetic potential, nutritional inputs, physiological status, and management conditions. Understanding these interrelated factors is essential for improving milk quality, enhancing production efficiency, and supporting the sustainable development of dairy goat production systems. This review highlights the importance of integrated management strategies to maximize the nutritional and technological value of goat milk under diverse production environments.

Keywords: Dairy goat, goat milk, milk composition, milk quality, production management

Introduction

Goat milk quality is influenced by a combination of nutritional, physicochemical, microbiological, technological, and sensory characteristics that collectively determine its value as a dairy product. These properties may vary considerably among breeds, production environments, and farming systems due to differences in genetic background, geographical conditions, feeding practices, and herd management. As a result, the composition and overall quality of goat milk are shaped by complex interactions among biological and environmental factors (Akshit *et al.*, 2024; Pereira *et al.*, 2025) ^[2, 34]. Genetic variation is one of the primary determinants of milk production and compositional traits in dairy goats. Differences among breeds can affect milk yield, fat and protein concentrations, fatty acid profiles, and the synthesis of several functional compounds. Recent progress in molecular genetics and genomic technologies has facilitated the identification of candidate genes associated with desirable milk characteristics, thereby supporting more effective breeding strategies for dairy goat improvement (Yang *et al.*, 2024) ^[28]. Alongside genetics, feeding management represents an important tool for modifying milk composition at the farm level. Factors such as forage quality, dietary nutrient balance, concentrate supplementation, and feeding systems have been reported to influence both milk production efficiency and the concentration of major milk constituents

(Nayik *et al.*, 2022; Khemiri *et al.*, 2023) ^[21]. Physiological factors also contribute substantially to variations in goat milk composition. Parameters including lactation stage, parity, age, and animal health status can alter milk yield and nutrient content throughout the production cycle. Moreover, management-related aspects such as housing conditions, milking hygiene, welfare practices, and environmental control play significant roles in maintaining milk quality and safety. These factors have become increasingly important as consumers demand dairy products that meet higher standards of quality, sustainability, traceability, and animal welfare (Saviard *et al.*, 2026) ^[27]. The growing recognition of goat milk as a valuable dairy product has encouraged greater scientific investigation into the factors affecting its quality and composition. This interest is driven by the expanding demand for nutritious, functional, and sustainably produced foods, as well as by the need to enhance the efficiency of dairy production systems under changing environmental conditions. Moreover, increasing concerns regarding resource utilization, product traceability, and consumer preferences have highlighted the importance of optimizing milk quality throughout the production chain. Therefore, identifying and understanding the determinants of goat milk characteristics represent important steps toward supporting sustainable development and long-term competitiveness within the dairy goat sector (AlKaisy *et al.*, 2023) ^[8]. This review summarizes current knowledge

regarding the major determinants influencing goat milk composition and quality, with emphasis on genetic, nutritional, physiological, environmental, and management-related factors. In addition, recent advances in dairy goat research and emerging opportunities for improving the sustainability and competitiveness of goat milk production systems are discussed.

Genetic Determinants of Goat Milk Composition and Quality

Genetic factors constitute one of the principal sources of variation in goat milk production and quality. The genetic background of dairy goat's influences not only milk yield but also the concentration of major milk constituents, including fat, protein, lactose, minerals, and numerous bioactive compounds. Through long-term adaptation and selective breeding, substantial genetic diversity has developed among goat populations worldwide, resulting in marked differences in milk composition and technological properties. Consequently, genetic resources play a pivotal role in determining the nutritional value, processing performance, and commercial potential of goat milk (Mohseni Takalu *et al.*, 2026) ^[29]. The diversity observed among dairy goat breeds is reflected in their milk production characteristics and compositional profiles. Specialized dairy breeds are generally recognized for superior milk yield, whereas many indigenous and dual-purpose breeds often produce milk with greater concentrations of fat, protein, and total solids. In addition to differences in major nutrients, breed-specific variations have been reported in fatty acid composition, casein fractions, mineral content, and sensory properties. These characteristics are particularly important because they influence both consumer acceptance and the suitability of milk for the manufacture of value-added dairy products, including cheese, yogurt, and fermented milk products. Therefore, breed selection remains a fundamental strategy for optimizing milk quality and enhancing production efficiency under different farming conditions (Selvaggi *et al.*, 2018) ^[40].

Milk composition traits are controlled by complex biological mechanisms involving multiple genes and regulatory pathways. Significant genetic variation exists for economically important traits such as milk fat, protein, and lactose concentrations (Lopdell, 2023) ^[23]. Among these components, protein and casein contents are especially relevant to dairy processing because they directly affect coagulation properties, cheese yield, and product quality. Likewise, variations in milk fat composition contribute to differences in flavor, texture, and nutritional characteristics. The identification of genetic factors associated with these traits has therefore become a major focus of dairy goat research, as it provides opportunities to improve both milk quality and productivity through targeted breeding programs (Selionova *et al.*, 2021) ^[39]. Recent advances in molecular genetics and genomic technologies have accelerated the discovery of genes associated with milk production and compositional traits. Several candidate genes involved in protein synthesis, lipid metabolism, mammary gland development, and nutrient transport have been linked to variations in milk quality. In particular, polymorphisms within the casein gene cluster have received considerable attention because of their influence on protein content and cheese-making performance. The application of genome-wide association studies, high-throughput genotyping, and genomic prediction models has further improved the ability to identify genomic regions associated with desirable milk

characteristics, thereby increasing the accuracy and effectiveness of genetic selection programs (Massender *et al.*, 2022) ^[26].

The incorporation of molecular breeding approaches into dairy goat improvement programs has created new opportunities for accelerating genetic gain. Technologies such as marker-assisted selection and genomic selection enable the identification of superior animals at an early stage of life, reducing generation intervals and enhancing selection efficiency (Wadood *et al.*, 2026). Furthermore, transcriptomic and functional genomic analyses have expanded current understanding of the molecular mechanisms governing mammary gland function and milk synthesis. The integration of these advanced technologies with conventional breeding strategies is expected to contribute to sustained improvements in milk yield, compositional quality, and overall production efficiency, thereby supporting the long-term sustainability and competitiveness of the dairy goat sector (Sonea *et al.*, 2024) ^[28].

Nutritional Regulation of Milk Composition in Dairy Goats

Nutrition is a key determinant of milk composition and quality in dairy goats, as dietary nutrients directly influence mammary gland function and the synthesis of milk components. Feeding systems based on different forage-to-concentrate ratios can substantially affect milk yield and the concentration of major milk constituents (Goetsch *et al.*, 2026) ^[19]. High-quality forage promotes rumen health and fermentation efficiency, thereby supporting the synthesis of beneficial fatty acids and other milk components. In contrast, excessive concentrate inclusion may disrupt ruminal fermentation patterns and negatively affect milk fat synthesis. Furthermore, variations in forage species, botanical diversity, and feeding management practices have been associated with differences in the physicochemical and nutritional characteristics of goat milk. Previous studies have demonstrated that balanced forage-concentrate feeding strategies contribute to improved milk composition, animal performance, and production efficiency in dairy goat systems (Boudalia *et al.*, 2024) ^[28].

The balance between dietary protein and energy is equally important for optimizing milk production and milk component synthesis. Adequate protein intake provides essential amino acids required for the synthesis of milk proteins, while sufficient dietary energy supports the metabolic demands of lactation. An imbalance between protein and energy supply may impair nutrient utilization efficiency and alter milk composition (Fu R., *et al.*, 2025) ^[34]. Although increased dietary protein levels may enhance milk yield and protein content, excessive protein supplementation can reduce feed efficiency and increase nitrogen losses to the environment. Likewise, inadequate energy intake during lactation may induce negative energy balance, which can affect milk fat metabolism and compromise milk quality. Therefore, nutritional strategies should focus on achieving an appropriate protein-to-energy ratio to maximize lactational performance and milk quality (AlKaisy *et al.*, 2023; Fernández *et al.*, 2025) ^[34, 44]. Mineral and vitamin supplementation also plays a critical role in maintaining milk quality and supporting physiological functions in dairy goats. Essential minerals, including calcium, phosphorus, magnesium, selenium, and zinc, are involved in milk secretion, immune responses, enzymatic activities, and metabolic regulation. Likewise, vitamins

contribute to antioxidant defense mechanisms, cellular metabolism, and mammary gland health. Deficiencies or imbalances in these nutrients may adversely affect milk production, animal health, and the nutritional value of milk. Several studies have reported that appropriate mineral and vitamin supplementation can improve nutrient utilization,

enhance animal performance, and support the production of high-quality milk. Consequently, maintaining adequate mineral and vitamin status is considered an important component of sustainable dairy goat nutrition programs (Saikia *et al.*, 2022; Agustín *et al.*, 2024) [28, 36].

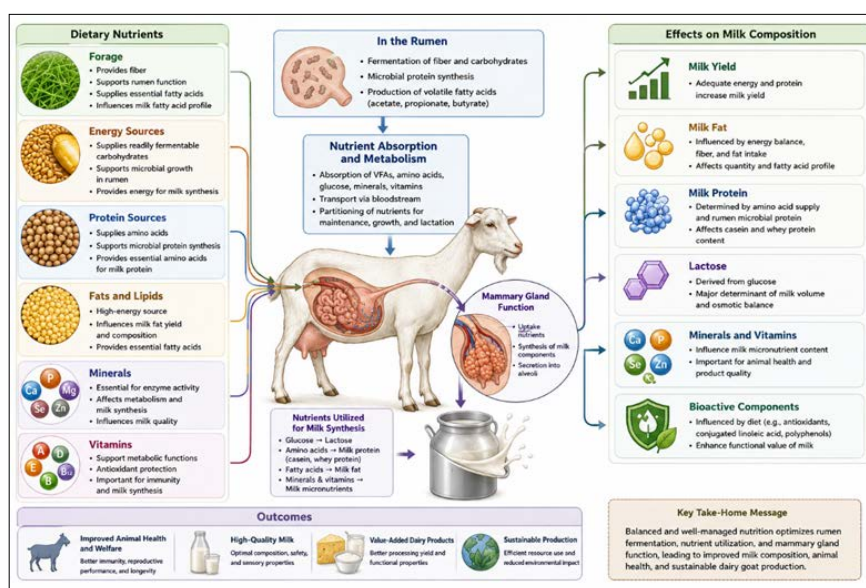


Fig 1: Effects of dietary nutrients on rumen metabolism, mammary gland function, and milk composition in dairy goats.

Recent advances in dairy goat nutrition have increasingly emphasized the use of functional feed additives and targeted feeding strategies to enhance the concentration of bioactive compounds in milk. Feed additives such as phytochemicals, plant extracts, probiotics, prebiotics, agro-industrial by-products, and antioxidant-rich ingredients have shown promising effects on milk quality and functionality (Ertürkmen *et al.*, 2024^[17]). These dietary interventions may improve the fatty acid profile, increase antioxidant capacity, and enhance the overall nutritional value of goat milk. Moreover, several studies have demonstrated that natural feed additives can increase the proportion of beneficial unsaturated fatty acids while reducing oxidative deterioration of milk lipids. Such approaches not only improve production performance but also enhance the health-promoting properties of goat milk, thereby increasing its value as a functional dairy product. Therefore, nutritional strategies aimed at enriching bioactive compounds represent a promising approach for improving both the biological quality and market competitiveness of goat milk (Contò *et al.*, 2026; Ansori *et al.*, 2024) [4, 9].

Table 1: Effect of Lactation Stage on Milk Yield, Composition, and Physicochemical Characteristics in Dairy Goats

Parameters	Early Lactation	Mid Lactation	Late Lactation	References
Fat (%)	3.27	3.26	3.30	El-Tarabany <i>et al.</i> , 2018 [13] Dosseh <i>et al.</i> , 2025 [12]
	6.4-8.2	6.5-7.8	7.6-8.78	
Protein (%)	3.60	3.62	3.65	El-Tarabany <i>et al.</i> , 2018 [13] Dosseh <i>et al.</i> , 2025 [12]
	3.5-3.7	3.3-3.4	3.4-3.7	
Lactose (%)	4.09	4.06	3.85	El-Tarabany <i>et al.</i> , 2018 [13]
	5.3-5.6	4.9-5.1	5.1-5.5	

Physiological Factors Affecting Goat Milk Characteristics

Physiological status represents one of the major sources of variation in milk yield and composition in dairy goats, affecting both the quantity and quality of milk throughout the lactation period. Among physiological determinants, the stage of lactation has a particularly significant influence on milk characteristics (Barłowska *et al.*, 2020) [6]. Milk composition changes dynamically from early to late lactation due to alterations in nutrient partitioning, metabolic activity, and mammary gland function. Early lactation is generally characterized by high milk production accompanied by fluctuations in fat and protein concentrations, whereas late lactation is often associated with increased concentrations of milk solids as milk volume gradually declines. Several studies have reported that lactation stage significantly affects the concentrations of fat, protein, lactose, total solids, and other physicochemical properties of goat milk, thereby influencing its nutritional and technological quality (El-Tarabany *et al.*, 2018) [13].

				Dosseh <i>et al.</i> , 2025 [12]
Total Solids (%)	10.99	11.18	11.29	El-Tarabany <i>et al.</i> , 2018 [13]
Solid non Fat (%)	7.74	7.80	7.76	El-Tarabany <i>et al.</i> , 2018 [13] Dosseh <i>et al.</i> , 2025 [12]
	9.8-10.1	8.8-9.3	9-10.2	
Density (g/cm ³)	31-32.7	28.6-29.5	28.5-31.4	Dosseh <i>et al.</i> , 2025 [12]
Milk yield (kg/day)	1.63	1.33	1.11	El-Tarabany <i>et al.</i> , 2018 [13] Dosseh <i>et al.</i> , 2025 [12]
	0.088-0.278	0.059-0.158	0.028-0.089	

Parity and age also contribute substantially to variation in milk production performance and milk composition. Milk yield generally increases during successive lactations as goats reach physiological maturity and achieve greater mammary gland development. Multiparous animals often produce higher milk yields than primiparous goats because of increased secretory tissue capacity and improved adaptation to lactation demands. However, advancing age may eventually reduce productive efficiency due to physiological decline and changes in metabolic function. In addition, parity and age have been associated with variations in milk fat, protein, lactose, and total solids, reflecting differences in nutrient utilization and endocrine regulation. Previous studies demonstrated that age, parity, and lactation stage collectively influence milk yield and compositional traits in dairy goats under different production systems (Urbańska *et al.*, 2023; Vacca *et al.*, 2018) ^[44, 45].

The health status of dairy goats, particularly the physiological integrity of the mammary gland, plays a crucial role in determining milk quality and production efficiency. Mammary gland disorders, including subclinical and clinical mastitis, can impair milk synthesis, alter milk composition, and negatively affect milk safety. These responses are closely linked to hormonal and physiological mechanisms regulating lactation. Hormones such as prolactin, growth hormone, oxytocin, insulin, and corticosteroids coordinate mammary gland development, nutrient allocation, and milk secretion throughout the lactation cycle (Mukherjee *et al.*, 2023) ^[30]. Disturbances in hormonal balance caused by disease, physiological stress, or environmental challenges may adversely affect milk yield and compositional stability. Consequently, the physiological variation observed in goat milk characteristics results from the complex interaction among lactation stage, parity, age, mammary gland health, and endocrine regulation, all of which collectively determine the productive performance and quality of milk in dairy goat production systems (Castro *et al.*, 2023; Tibebu *et al.*, 2025) ^[8, 34].

Environmental and Management Influences on Milk Quality

Environmental conditions and management practices are among the most important external factors influencing milk quality in dairy goats. Seasonal variation and climatic conditions can directly affect feed availability, water intake, metabolic activity, and animal comfort, thereby influencing milk yield and composition (Erduran, 2022) ^[14]. Changes in ambient temperature, humidity, and photoperiod have been associated with fluctuations in milk fat, protein, lactose, and total solids concentrations. Seasonal differences may also alter the fatty acid profile and physicochemical characteristics of milk due to variations in forage quality and feeding conditions throughout the year. Consequently, environmental fluctuations represent a significant source of variation in milk quality and production performance across dairy goat production systems (Meza-Herrera *et al.*, 2024) ^[28]. Housing systems and animal welfare are closely linked to the productive performance and health status of dairy goats. Appropriate housing conditions provide protection from adverse weather, improve animal comfort, and reduce exposure to environmental stressors that may negatively affect milk production. Well-designed housing systems with adequate ventilation, bedding quality, stocking density, and sanitation contribute to improved welfare and reduced

disease incidence. Animal welfare has become an increasingly important consideration in modern dairy production because physiological stress can alter endocrine responses, impair immune function, and ultimately affect milk composition and quality. Therefore, management practices that promote animal comfort and welfare are essential for maintaining consistent milk production and ensuring the production of high-quality milk (Kotsampasi *et al.*, 2024) ^[22]. Milking procedures and hygiene management play a fundamental role in preserving milk quality and safety. Proper milking practices, including udder preparation, equipment sanitation, and post-milking hygiene, help minimize microbial contamination and reduce the incidence of mastitis. Poor hygiene standards can increase somatic cell counts and bacterial loads, leading to deterioration in milk quality and shelf life (Deshapriya *et al.*, 2019) ^[11]. In addition, environmental challenges such as heat stress have emerged as major concerns in dairy goat production, particularly in regions characterized by high temperatures and humidity. Heat stress can disrupt metabolic and endocrine functions, reduce feed intake, compromise immune competence, and decrease milk yield. These physiological responses may also alter milk composition and technological properties. As a result, the implementation of effective heat mitigation measures, including shade provision, cooling systems, and adequate water availability, is essential for maintaining animal performance and milk quality under challenging environmental conditions (Toledo *et al.*, 2022; Oliveira *et al.*, 2025) ^[34, 43].

Effective farm management strategies integrate environmental control, animal welfare, nutrition, health monitoring, and hygienic milking practices to optimize milk quality and production efficiency. A comprehensive management approach can reduce the negative effects of environmental stressors while enhancing animal health and productive performance. Regular monitoring of housing conditions, implementation of biosecurity measures, maintenance of milking hygiene, and adoption of welfare-oriented management practices contribute significantly to the production of safe and high-quality goat milk. Consequently, sustainable improvements in milk quality require a holistic management framework that considers the complex interactions among environmental conditions, animal welfare, health status, and farm management practices (Fiorillo & Amico, 2024; Niloofar *et al.*, 2023) ^[16, 32].

Future Perspectives for Sustainable Improvement of Goat Milk Quality

The sustainable improvement of goat milk quality will increasingly depend on the adoption of innovative technologies and data-driven management approaches. Precision livestock farming (PLF) has emerged as a promising strategy for enhancing production efficiency, animal health, and milk quality through the continuous monitoring of physiological, behavioral, and environmental parameters (Losacco *et al.*, 2025) ^[24]. The integration of sensor technologies, wearable devices, automated milking systems, and digital decision-support tools enables farmers to identify health disorders, optimize feeding practices, and improve reproductive and productive performance in real time. Such technologies facilitate timely management interventions, reduce production losses, and support the

consistent production of high-quality milk. As digital innovations continue to advance, their implementation in dairy goat systems is expected to improve resource-use efficiency and strengthen the sustainability of milk production (Arsenos *et al.*, 2021; Mata, 2026) ^[5, 27]. Future advancements in dairy goat production will also require a more integrated approach that combines genetic improvement, nutritional management, animal welfare, and environmental stewardship (Lu, 2023) ^[8]. Recent developments in genomics and breeding technologies provide opportunities to select animals with superior milk quality traits, improved disease resistance, and greater adaptability to environmental stressors. Nevertheless, genetic potential can only be fully expressed when supported by appropriate nutritional and management practices. Consequently, multidisciplinary strategies that integrate genetics, nutrition, health management, and welfare-oriented production systems are essential for improving milk quality and production efficiency. In addition, climate change has intensified the need for climate-resilient dairy goat systems capable of maintaining productivity under increasingly variable environmental conditions. Strategies aimed at enhancing heat tolerance, improving feed efficiency, optimizing water utilization, and reducing greenhouse gas emissions are expected to play a crucial role in ensuring the long-term sustainability of dairy goat farming (Rahimi *et al.*, 2024; Sejian *et al.*, 2021) ^[28, 38]. Consumer preferences are also shaping the future direction of the dairy goat industry. Growing awareness of nutrition, food safety, environmental sustainability, and human health has increased demand for functional dairy products with added nutritional and bioactive value (Granato *et al.*, 2022) ^[20]. Goat milk naturally contains several health-promoting compounds, including bioactive peptides, beneficial fatty acids, and antioxidant components, which may be further enhanced through targeted breeding, nutritional interventions, and advanced processing technologies. Future research should therefore focus not only on improving conventional production traits but also on enhancing the functional and nutraceutical properties of goat milk (Nayik *et al.*, 2021) ^[31]. Despite considerable progress in dairy goat research, important knowledge gaps remain regarding the complex interactions among genetics, nutrition, physiology, management, and environmental factors affecting milk quality. Future studies incorporating omics technologies, precision farming tools, and sustainability assessment frameworks will be essential for developing comprehensive strategies that support resilient production systems and maximize the nutritional, functional, and economic value of goat milk (Day *et al.*, 2025; AlKaisy *et al.*, 2023) ^[34, 44].

Conclusion

Goat milk composition and quality are influenced by a multifactorial network involving genetic, nutritional, physiological, environmental, and management-related determinants. Genetic factors provide the foundation for milk production potential and compositional characteristics, whereas nutritional management regulates the supply of nutrients necessary for milk synthesis and the expression of desirable milk traits. Physiological factors, including lactation stage, parity, age, health status, and endocrine activity, contribute substantially to variations in milk yield and composition throughout the lactation cycle. Moreover, environmental conditions and management practices play a

pivotal role in shaping milk quality through their effects on animal welfare, mammary gland health, hygienic status, and overall production performance. The available evidence indicates that these determinants operate in a highly interconnected manner, emphasizing the need to evaluate goat milk quality within an integrated production framework. Sustainable improvement of goat milk quality requires the implementation of comprehensive strategies that simultaneously address genetic selection, nutritional optimization, herd health management, and environmental stewardship. Advances in genomic technologies, precision livestock farming, and functional feeding approaches offer promising opportunities to enhance milk quality while improving production efficiency and sustainability. In parallel, increasing consumer interest in safe, nutritious, and value-added dairy products highlights the importance of producing goat milk with superior nutritional and functional attributes. Future research should prioritize multidisciplinary approaches that explore the interactions among biological, nutritional, and environmental factors, thereby supporting the development of resilient dairy goat production systems capable of meeting evolving industry demands and maximizing the nutritional, technological, and economic value of goat milk.

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