

Extraction and Application of Defensive Proteins from Bovine Colostrum in Functional Beverages: A Review

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ABSTRACT

Bovine colostrum is a rich source of bioactive and defensive proteins, including immunoglobulins, lactoferrin, lysozyme, and lactoperoxidase, which contribute to immune defense, antimicrobial activity, and gastrointestinal health. Recent advances in membrane filtration, chromatography, freeze-drying, and spray-drying have improved the isolation, concentration, and preservation of these sensitive proteins for incorporation into functional food and beverage systems. This review examines the composition and biological functions of major defensive proteins in bovine colostrum, together with current approaches for their extraction, stabilization, and application in functional beverages. Attention is given to their potential roles in immune support, gastrointestinal health, and exercise recovery, as well as their possible applications for athletes, older adults, and other consumer groups. Key formulation challenges, including protein stability, heat sensitivity, sensory acceptability, processing costs, and product standardization, are also discussed. Although bovine colostrum-derived proteins show considerable potential as functional beverage ingredients, further well-designed clinical studies are required to establish their bioavailability, effective doses, long-term safety, and health benefits in different populations. Advances in separation technologies, encapsulation, and product formulation may support the development of more stable, acceptable, and evidence-based bovine colostrum functional beverages.



KEYWORDS: Bovine colostrum; defensive proteins; immunoglobulins; lactoferrin; functional beverages; bioactive proteins

1. INTRODUCTION

Foods contain a wide range of health-promoting components that can contribute to improving public health and overall well-being. Numerous studies have investigated the relationship between dietary patterns and health outcomes. Epidemiological evidence has demonstrated substantial health benefits associated with the consumption of fruits, vegetables, and whole grains (Gul et al., 2016). Beyond providing energy and essential nutrients, foods also contain biologically active compounds that may support cellular functions and provide protection against oxidative stress. In recent decades, considerable research attention has therefore focused on specialized food categories, including light, low-fat, diet, and functional foods (Granato et al., 2020).

The concept of functional foods emerged in Japan during the 1980s; however, a universally standardized statutory definition has not yet been established across regulatory systems worldwide (Ye et al., 2018). Functional foods can generally be described as natural or processed foods that, when consumed regularly as part of the normal diet and in appropriate amounts, provide beneficial physiological effects beyond basic nutritional requirements (Granato et al., 2017). Nevertheless, health-related claims for functional foods require appropriate scientific evidence of their efficacy and safety. Therefore, the development and evaluation of functional foods should consider both their physiological functionality and supporting safety and toxicological evidence.

Bovine colostrum is particularly rich in nutrients, including proteins, fats, vitamins, and minerals. It also contains numerous bioactive components, such as oligosaccharides, immunoglobulins, lactoferrin, and lysozyme, which contribute to passive immunity, antimicrobial defence, and gastrointestinal development in newborn calves. Although bovine colostrum primarily provides nutritional and immunological protection to calves, its bioactive constituents have also attracted considerable interest because of their potential benefits for human immune function and gastrointestinal health (Arslan et al., 2021).

Repeated investigations into the consumption of bovine colostrum and its relationship with human health have highlighted its potential immunological properties. Its use in therapeutic and healthcare-related applications has also been reported

(Dzik et al., 2017). Wong et al. (2014) reported that oral administration of bovine colostrum enhanced natural killer cell activity and intestinal immune responses. Immunoglobulin G (IgG), the predominant immunoglobulin in bovine colostrum, may contribute to innate and adaptive immune defence through pathogen binding and interactions with immune mechanisms associated with phagocytosis and host defence.

2. Composition of Bovine Colostrum

Milk composition varies considerably throughout lactation, and bovine colostrum has a distinct nutritional composition compared with mature milk (Lago et al., 2018). In particular, colostrum contains substantially higher concentrations of proteins, moderately higher levels of fat, and considerably lower concentrations of lactose than mature milk (Table 1). This unique composition is physiologically important for newborn calves, which depend on the passive transfer of immunoglobulins from colostrum for early immune protection.

As shown in Table 1, the concentrations of several milk components and minerals change as lactation progresses and milk production increases. Compared with mature milk, colostrum provides a protein-rich and relatively low-carbohydrate nutritional matrix. From a processing perspective, its composition also provides opportunities to modify fat content and energy density according to specific nutritional and product-development requirements. Furthermore, milk proteins, particularly whey proteins, are recognized for their complete amino acid profiles and high digestibility (Kontkanen et al., 2011). Bovine colostrum is distinguished by its substantially higher concentration of immunoglobulins and other bioactive components compared with mature milk (Table 1).

Table 1. Selected components of bovine colostrum compared with mature milk

Component	Unit	Bovine colostrum	Mature milk
Fat	mg/mL	64.00	39.00
Protein	mg/mL	140.00	36.00
Casein	mg/mL	43.00	25.00
Whey	mg/mL	120.00	5.10
Lactose	mg/mL	27.00	49.00
Dry matter	mg/mL	276.40	125.00
IgG	mg/mL	55.00	0.257
IgA	mg/mL	1.66	0.04–0.06
IgM	mg/mL	4.32	0.03–0.06
Lactoferrin	mg/mL	0.82	0.10–0.30
Calcium (Ca)	mg/kg	4,716.10	1,220.00
Phosphorus (P)	mg/kg	4,452.10	1,520.00
Magnesium (Mg)	mg/kg	733.24	120.00
Sodium (Na)	mg/kg	1,058.93	580.00
Potassium (K)	mg/kg	2,845.89	1,520.00
Zinc (Zn)	mg/kg	38.10	5.30
Iron (Fe)	mg/kg	5.33	0.80

2.1. Nutritional Components

The recommended dietary allowance for protein in healthy adults with minimal physical activity is approximately 0.8 g/kg body weight per day (Richter et al., 2019; Yu et al., 2020). However, evidence suggests that higher protein intakes, approximately 1.2–1.6 g/kg body weight per day, may be beneficial under certain physiological conditions and should ideally be distributed across meals to support skeletal muscle protein synthesis (Wu, 2016; Burd et al., 2019). In older adults, inadequate protein intake may contribute to age-related loss of skeletal muscle mass and function, an issue that may be further influenced by age-associated changes in protein digestion and metabolism (Deer & Volpi, 2015).

In this context, bovine colostrum may provide a nutrient-dense source of high-quality protein that can be incorporated into a balanced diet. In addition to its macronutrients, bovine colostrum contains vitamins, minerals, and a diverse range of protein-derived bioactive components that may contribute additional nutritional and functional properties. Its relatively high concentrations of proteins and bioactive constituents compared with mature milk have contributed to increasing interest in bovine colostrum as an ingredient for functional foods and beverages.

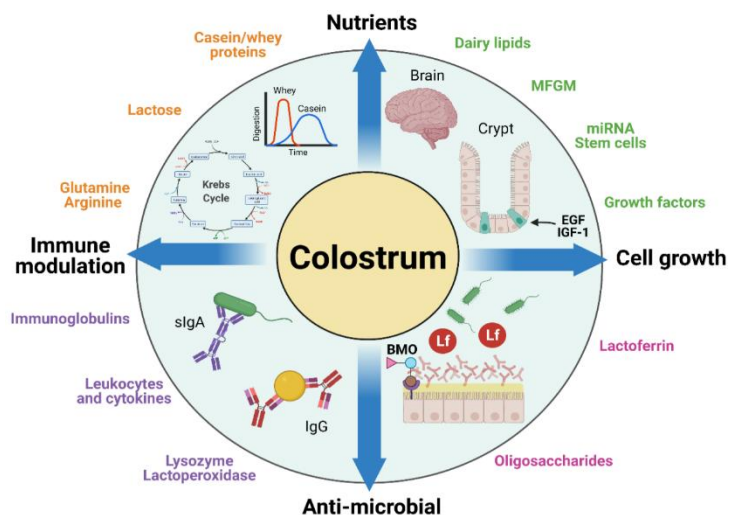


Figure 1. Nutritional and present in bovine biological functions, immunomodulatory, antimicrobial, and cell-growth activities. Reproduced from Sangild et al. (2021)

bioactive components are colostrum and their key including nutritional,

The manuscript then introduces several classes of bioactive components relevant to the nutritional and functional properties of bovine colostrum, including lactoferrin, lysozyme, α -lactalbumin, milk-fat-globule-membrane proteins, oligosaccharides, microRNAs, and other milk-derived cellular components (Figure 1).

2.2. Fats and Lipids

Bovine colostrum contains a relatively high concentration of fat compared with mature milk, with lipids occurring predominantly as milk fat globules surrounded by the milk fat globule membrane (MFGM). The lipid fraction contains several nutritionally and biologically important components, including saturated and unsaturated fatty acids, phospholipids, sphingolipids, gangliosides, and cholesterol. These components contribute not only to the energy value of colostrum but also to its structural and functional properties.

The fatty acid composition of bovine colostrum differs from that of mature milk and changes considerably during the transition from colostrum to mature milk (O'Callaghan et al., 2020). In particular, the lipid fraction contains bioactive polar lipids associated with the MFGM, which have attracted increasing interest because of their potential physiological and technological functions.

The MFGM is a complex structure composed primarily of polar lipids and membrane-associated proteins. In addition to protecting the triglyceride-rich core of milk fat globules, MFGM components may contribute to the nutritional and functional characteristics of bovine colostrum. Their amphiphilic properties are also relevant to food formulation because they can influence emulsification, stability, and interactions with other components in functional beverage systems.

From a product-development perspective, the fat content of bovine colostrum requires careful consideration because it can influence energy density, sensory characteristics, oxidative stability, and the physicochemical properties of functional beverages. Consequently, the extent to which the lipid fraction is retained or removed should depend on the intended nutritional profile and formulation requirements of the final product.

2.3. Bioactive and Defensive Proteins

Bovine colostrum is a rich source of bioactive and defensive proteins that contribute to its immunological, antimicrobial, and nutritional properties (Arslan et al., 2021; McGrath et al., 2016). Major defensive proteins include immunoglobulins (IgG, IgA, and IgM), lactoferrin, lysozyme, and lactoperoxidase. These components play important roles in providing passive immune protection to newborn calves and have attracted considerable interest because of their potential applications in human nutrition and functional foods.

Immunoglobulins constitute a major group of immune-active proteins in bovine colostrum, with IgG being the predominant immunoglobulin, followed by IgA and IgM (Arslan et al., 2021). These proteins contribute to immune defence through the recognition and neutralization of pathogens. Other bioactive proteins, particularly lactoferrin, lysozyme, and lactoperoxidase, possess antimicrobial and immunomodulatory properties and may act individually or synergistically with other immune components.

The high concentrations and diverse biological activities of these proteins make bovine colostrum a promising source of functional ingredients. However, their successful incorporation into functional foods and beverages requires appropriate extraction, purification, and stabilization techniques to preserve their structural integrity and biological activity during processing and storage.

2.3.1. Immunoglobulins

Immunoglobulins (Igs), also known as antibodies, are among the most important defensive proteins present in bovine colostrum. The three major immunoglobulin isotypes are immunoglobulin G (IgG), including the subclasses IgG1 and IgG2, immunoglobulin A (IgA), and immunoglobulin M (IgM). Among these, IgG is the predominant immunoglobulin in bovine colostrum and accounts for approximately 85–90% of the total immunoglobulin content. IgG1 constitutes the largest proportion of total IgG, followed by IgM, IgA, and IgG2. The substantially higher concentration of immunoglobulins in colostrum compared with mature milk is one of the major compositional characteristics that distinguishes the two secretions (Arslan et al., 2021).

Immunoglobulins play a fundamental role in providing passive immune protection to newborn calves. Because the bovine placenta restricts the prenatal transfer of maternal immunoglobulins, calves are born with very low circulating antibody concentrations and therefore depend heavily on the timely consumption of colostrum for passive immunity. Following ingestion, colostral immunoglobulins provide protection against a variety of enteric pathogens, including pathogenic bacteria and viruses, through antigen recognition, neutralization, and other antibody-mediated immune mechanisms. IgG is particularly important in systemic immune protection, whereas IgA contributes predominantly to mucosal defence, especially within the gastrointestinal tract. IgM also contributes to early immune responses through its ability to recognize and bind antigens.

A major difference between bovine colostrum and mature milk is the markedly higher concentration of IgG in colostrum. During the first days after parturition, IgG concentrations may reach approximately 50–100 mg/mL, although considerable variation occurs depending on factors such as breed, parity, time after calving, health status, and colostrum management (Arslan et al., 2021). The concentration decreases rapidly during the transition from colostrum to mature milk, emphasizing the importance of early colostrum collection when immunoglobulin-rich fractions are intended for nutritional or functional applications.

The high immunoglobulin content of bovine colostrum has also generated considerable interest in its potential application beyond neonatal calf nutrition. Bovine colostrum has been investigated as a source of antibody-rich preparations for functional foods, nutraceuticals, and other health-related products. In particular, the ability of bovine immunoglobulins to recognize and bind microbial antigens has encouraged investigation of their potential role in supporting gastrointestinal and immune functions. Nevertheless, their biological effects following human consumption depend on several factors, including resistance to gastrointestinal digestion, the amount consumed, processing conditions, and the formulation of the final product.

The preservation of immunoglobulin structure and biological activity is therefore particularly important when bovine colostrum is processed for functional beverage applications. Immunoglobulins are sensitive to processing conditions, especially excessive heat, and inappropriate processing may result in protein denaturation and reduced biological activity. Consequently, extraction and processing strategies intended for immunoglobulin-rich functional ingredients should minimize conditions that adversely affect protein structure while achieving the required microbiological safety and product stability. From a functional beverage perspective, the relatively high abundance of IgG in bovine colostrum makes it an attractive target for separation and concentration. However, successful utilization requires consideration of not only extraction efficiency but also protein stability during purification, preservation, beverage formulation, storage, and gastrointestinal digestion. These factors ultimately determine whether the immunoglobulins retain sufficient biological activity in the final product.

2.3.2. Lactoferrin

Lactoferrin is an iron-binding glycoprotein and one of the major bioactive proteins present in bovine colostrum. It is widely recognized for its antimicrobial, immunomodulatory, anti-inflammatory, and iron-binding properties. The concentration of lactoferrin is substantially higher in bovine colostrum than in mature milk, highlighting its importance during the early stages of lactation (Arslan et al., 2021). Lactoferrin is therefore considered an important component contributing to the protective and functional properties of bovine colostrum.

One of the principal biological functions of lactoferrin is its ability to bind iron with high affinity. By sequestering free iron, lactoferrin can restrict the availability of this essential nutrient to microorganisms and thereby inhibit the growth of certain pathogenic bacteria. Its antimicrobial activity is not limited to iron deprivation, as lactoferrin may also interact directly with microbial surfaces and influence host defence mechanisms. These properties contribute to its broad antibacterial activity and its potential role in maintaining gastrointestinal microbial balance (Superti, 2020).

In addition to its antibacterial properties, lactoferrin has been associated with antiviral activity. Its antiviral effects may involve interactions with viral particles or host-cell surface molecules, thereby interfering with viral attachment or entry into susceptible cells. Lactoferrin has consequently been investigated for its activity against several viral pathogens (Wakabayashi et al., 2014). Nevertheless, the extent of these effects depends on the virus, experimental model, lactoferrin concentration, and route of administration; therefore, findings from *in vitro* studies should not be interpreted directly as evidence of clinical efficacy.

Lactoferrin also contributes to the regulation of immune and inflammatory responses. It can interact with several immune-cell populations and participate in both innate and adaptive immune responses. Lactoferrin receptors have been identified

on intestinal tissues and various immune cells, including monocytes, macrophages, neutrophils, and lymphocytes. Through these interactions, lactoferrin may influence immune-cell activation, inflammatory signalling, and host responses to microbial challenges (Siqueiros-Cendón et al., 2014).

Another important function of lactoferrin is its involvement in iron homeostasis. In addition to limiting iron availability to microorganisms, lactoferrin can participate in intestinal iron uptake and cellular iron regulation. Its iron-binding capacity may also contribute to antioxidant protection by reducing the availability of free iron capable of participating in reactions that generate reactive oxygen species. These combined antimicrobial, immunological, and iron-regulatory functions have contributed to considerable interest in lactoferrin as a functional food and nutraceutical ingredient.

The gastrointestinal tract represents an important site for the potential biological activity of orally consumed lactoferrin. Lactoferrin and its digestion-derived peptides may interact with intestinal epithelial cells, microorganisms, and immune components within the gastrointestinal environment. Previous studies have therefore investigated lactoferrin in relation to intestinal barrier function, microbial defence, and gastrointestinal health (Superti, 2020). However, its biological effectiveness following oral consumption depends strongly on protein stability, gastrointestinal digestion, dose, and the food matrix in which it is delivered.

These characteristics are particularly relevant when lactoferrin is incorporated into functional beverages. Processing conditions such as temperature, pH, ionic strength, and storage conditions can affect protein conformation and biological activity. Excessive thermal treatment may cause denaturation or aggregation, whereas appropriate separation and stabilization strategies can help preserve lactoferrin functionality. Therefore, processing methods used for colostrum-derived functional beverages should be optimized to maintain lactoferrin stability while ensuring microbiological safety and acceptable product quality.

From a product-development perspective, lactoferrin is particularly attractive because it combines nutritional functionality with antimicrobial and immunomodulatory properties. Its relatively high concentration in bovine colostrum and its broad spectrum of reported biological activities make it an important target for extraction and purification. However, the translation of these properties into functional beverage applications requires careful consideration of extraction efficiency, processing stability, bioavailability, effective dosage, sensory properties, and clinical evidence.

Overall, lactoferrin represents one of the most promising defensive proteins in bovine colostrum for functional food and beverage development. Nevertheless, claims regarding specific human-health benefits should be supported by appropriately designed clinical studies, as evidence from mechanistic, *in vitro*, or animal studies does not necessarily establish equivalent effects in humans.

2.3.3. Lysozyme and Lactoperoxidase

Lysozyme and lactoperoxidase are important components of the natural antimicrobial defence system of bovine colostrum. Although they are present at considerably lower concentrations than major colostrum proteins such as immunoglobulins, both enzymes contribute to the antimicrobial and protective properties of colostrum and have potential relevance to functional food and beverage applications (Arslan et al., 2021; Klimesova et al., 2025).

Lysozyme is an antimicrobial enzyme involved in innate immune defence. Its principal antibacterial mechanism involves hydrolysis of the β -(1 $\rightarrow$ 4) glycosidic linkage between *N*-acetylmuramic acid and *N*-acetylglucosamine in bacterial peptidoglycan. Disruption of the peptidoglycan structure compromises bacterial cell-wall integrity and may ultimately lead to cell lysis. The antimicrobial effectiveness of lysozyme varies among microorganisms because of differences in cell-wall structure and accessibility of the peptidoglycan layer.

In addition to its direct antimicrobial activity, lysozyme may function synergistically with other defensive components of bovine colostrum, particularly lactoferrin and immunoglobulins. Such interactions suggest that the protective activity of bovine colostrum results from the combined effects of several bioactive components rather than the activity of an individual protein (Klimesova et al., 2025). Recent literature continues to identify lysozyme, together with lactoferrin and lactoperoxidase, as an important endogenous antimicrobial component of bovine milk and colostrum.

Lactoperoxidase is a heme-containing glycoprotein enzyme that contributes to the antimicrobial defence system of bovine colostrum. In the presence of hydrogen peroxide, lactoperoxidase catalyses the oxidation of thiocyanate, generating reactive products with antimicrobial activity. These products can interfere with essential microbial metabolic processes, particularly through oxidation of sulfhydryl groups in microbial proteins, thereby inhibiting microbial growth and activity (Arslan et al., 2021).

The lactoperoxidase system exhibits activity against several Gram-positive and Gram-negative microorganisms. Its antimicrobial properties, together with those of lactoferrin, lysozyme and immunoglobulins, contribute to the broader protective characteristics of bovine colostrum. Recent evidence continues to recognize lactoperoxidase as an important bioactive protein in bovine colostrum with potential applications related to antimicrobial defence and functional food development (Klimesova et al., 2025; Riaz et al., 2026).

The concentration and activity of lactoperoxidase vary during the transition from colostrum to mature milk. Concentrations of approximately 11–45 mg/L have been reported in bovine colostrum compared with approximately 13–30 mg/L in mature bovine milk, with concentrations changing during the first several days following parturition (Arslan et al., 2021).

From a technological perspective, lysozyme and lactoperoxidase are also relevant because endogenous antimicrobial proteins can influence microbial growth, processing behaviour and potentially the shelf life of dairy products (Klimesova et al., 2025). Their biological activity, however, can be affected by processing conditions such as temperature, pH, ionic strength and interactions with other food-matrix components. Consequently, appropriate extraction and stabilization strategies are necessary when these proteins are intended for incorporation into functional beverages.

The utilization of lysozyme and lactoperoxidase in bovine-colostrum-based functional beverages therefore requires consideration of both biological activity and technological stability. Although their antimicrobial properties are well documented, further studies are needed to determine how processing, gastrointestinal digestion, dosage and the beverage matrix influence their bioavailability and functionality in humans.

2.3.4. Cytokines and Growth Factors

Bovine colostrum contains a diverse range of cytokines and growth factors that contribute to immune regulation, tissue development, cellular proliferation, differentiation, and gastrointestinal maturation. Important growth factors identified in bovine colostrum include epidermal growth factor (EGF), transforming growth factor-beta (TGF- β), insulin-like growth factors (IGF-1 and IGF-2), and vascular endothelial growth factor (VEGF). In addition, colostrum contains several cytokines involved in the regulation of inflammatory and immune responses (Duan et al., 2024; Riaz et al., 2026). Recent evidence continues to recognize these secondary bioactive components as important contributors to the physiological functions of bovine colostrum.

EGF is a small peptide growth factor involved in the regulation of cell proliferation, differentiation, survival, and tissue repair. It consists of 53 amino acid residues stabilized by three intramolecular disulfide bonds. Within the gastrointestinal tract, EGF contributes to epithelial growth and may support the maintenance and repair of the intestinal mucosa. This activity is particularly relevant during early development, when the gastrointestinal epithelium undergoes rapid structural and functional maturation. Growth factors present in colostrum are therefore increasingly recognized as biologically important components beyond its basic nutritional value (Duan et al., 2024; Riaz et al., 2026).

TGF- β is another important regulatory growth factor present in bovine colostrum. It has a central role in immune homeostasis through regulation of lymphocyte proliferation, differentiation, activation, and survival. TGF- β contributes to maintaining immune tolerance while also participating in the initiation and resolution of inflammatory responses (Sanjabi et al., 2017). Its effects involve interactions with several immune-cell populations, including lymphocytes, natural killer cells, macrophages, dendritic cells, mast cells, and granulocytes. Through these mechanisms, TGF- β contributes to the broader immunomodulatory properties associated with bovine colostrum.

TGF- β may also influence gastrointestinal development and epithelial integrity. Together with other colostrum growth factors, it participates in cellular signalling pathways associated with intestinal-cell proliferation, differentiation, tissue repair, and inflammatory regulation. These properties are particularly relevant to the potential application of bovine colostrum in products designed to support gastrointestinal health (Duan et al., 2024; Riaz et al., 2026).

Insulin-like growth factors, particularly IGF-1, are present at relatively high concentrations in bovine colostrum compared with mature milk. IGF-1 participates in cellular growth, differentiation, protein metabolism and tissue development. Its concentration is highest during the early postpartum period and decreases substantially during subsequent milkings. The presence of IGF-1 and related growth factors has therefore contributed to interest in bovine colostrum as a source of biologically active ingredients (Riaz et al., 2026).

Importantly, the presence of IGF-1 in commercial bovine-colostrum products remains an active research topic. A 2025 study specifically developed an ultrasensitive analytical method for quantifying IGF-1 in bovine colostrum powders, further demonstrating the relevance of monitoring this growth factor in processed colostrum products.

VEGF is primarily involved in angiogenesis and vascular development and represents another growth-related signalling molecule identified in colostrum. Together with EGF, TGF- β and IGFs, these molecules form part of a complex bioactive system that may contribute to tissue growth and maturation. Their effects, however, depend on concentration, stability, receptor availability, and the physiological context in which they are delivered.

For functional beverage development, the presence of cytokines and growth factors is potentially important but also presents technological challenges. These biologically active molecules may be susceptible to degradation or structural changes during thermal processing, storage, and gastrointestinal digestion. Processing strategies should therefore aim to preserve their biological integrity while ensuring microbiological safety and acceptable product stability. Growth factors appear to possess some thermal tolerance, although stability varies considerably among individual compounds and processing conditions.

Although cytokines and growth factors contribute to the biological rationale for bovine-colostrum-based functional products, their presence alone should not be interpreted as evidence of a clinical health benefit in humans. Bioavailability following oral consumption, effective dose, interactions with the food matrix, gastrointestinal stability, and long-term safety require further investigation. This distinction is especially important when developing functional beverages that may ultimately carry health-related claims.

3. Biological Role of Defensive Proteins

3.1. Immune Effects of Bovine Colostrum in Healthy and Physically Active Individuals

The immunological effects of bovine colostrum (BC) have received considerable attention, particularly in the context of sports nutrition and physically active populations. Prolonged and strenuous exercise can transiently alter several aspects of immune function and may be associated with an increased incidence of upper respiratory symptoms in athletes. Consequently, BC supplementation has been investigated as a nutritional strategy to support immune function and gastrointestinal integrity during periods of intensive exercise (Davison, 2021).

Several studies have examined the effects of BC supplementation on innate and mucosal immune responses. Changes in neutrophil function, including phagocytic activity, have been investigated following the consumption of different BC preparations. However, the available evidence is not entirely consistent, and responses appear to depend on the dose, duration of supplementation, characteristics of the BC preparation, exercise protocol, and immune markers assessed (Davison et al., 2020; Davison, 2021).

Secretory immunoglobulin A (sIgA) is an important component of mucosal immunity and represents one of the most frequently investigated immune markers in studies involving athletes. Some studies have reported increased salivary sIgA concentrations following several weeks of BC supplementation, suggesting a potential role in supporting mucosal immune defence. In contrast, other investigations have found little or no significant change in resting sIgA concentrations. Therefore, the effects of BC supplementation on mucosal immunity should be interpreted cautiously rather than regarded as consistently established (Jones et al., 2014; Davison, 2021).

The potential effects of BC on immune function may extend beyond immunoglobulin responses. Colostrum contains several biologically active constituents, including immunoglobulins, lactoferrin, lysozyme, lactoperoxidase, cytokines, growth factors, and bioactive peptides, which may interact with intestinal epithelial and immune systems. These components may influence innate immune responses, microbial interactions, inflammatory signalling, and intestinal barrier function. Nevertheless, it remains difficult to attribute an observed physiological response to a single colostrum component because BC represents a complex biological matrix containing multiple potentially interacting compounds.

Another important area of investigation concerns the effects of BC supplementation on exercise-induced gastrointestinal permeability. Strenuous and prolonged exercise can compromise intestinal barrier integrity, potentially increasing gastrointestinal permeability. Previous human studies have reported that BC, either alone or in combination with other interventions, may attenuate exercise-associated increases in intestinal permeability (Davison et al., 2016). Maintenance of intestinal barrier integrity may be relevant to immune function because disruption of the gastrointestinal barrier can increase exposure to luminal microbial products and potentially contribute to systemic inflammatory responses.

More recent evidence continues to investigate the relationship between BC supplementation, exercise, and immunity. A recent study evaluated acute BC supplementation in physically active adults undergoing prolonged cycling exercise. The study reported modulation of selected innate immune responses, including changes in neutrophil oxidative burst and salivary lysozyme responses, although not all measured immune markers were significantly affected. These findings provide contemporary human evidence that BC may influence specific aspects of exercise-associated immune function while also demonstrating that its effects are not uniform across all immune outcomes.

This distinction is important when interpreting the broader literature. BC should not be described simply as an “immune booster,” because immune function involves numerous interacting cellular, humoral, and mucosal mechanisms. Instead, current evidence suggests that BC supplementation may modulate selected immune responses, particularly under physiological stress such as prolonged exercise. The magnitude and clinical relevance of these effects require further investigation using standardized BC preparations, adequately powered trials, and clearly defined immune outcomes.

Overall, evidence from physically active populations suggests potential benefits of BC supplementation for selected aspects of mucosal immunity, innate immune responses, and gastrointestinal barrier integrity. However, inconsistencies among studies prevent definitive conclusions regarding its ability to reduce infection risk or produce broad enhancement of immune function. Future studies should therefore distinguish changes in laboratory immune biomarkers from clinically meaningful outcomes such as infection incidence, symptom severity, recovery, and overall health status.

3.2. Colostrum for Immune Nutrition in Older Adults

Ageing is associated with progressive changes in both innate and adaptive immune function, a process commonly referred to as immunosenescence. These changes can include alterations in T-lymphocyte function, natural killer (NK) cell activity, inflammatory regulation, and the overall capacity to respond effectively to infectious challenges. Consequently, older adults may become increasingly susceptible to infections and other age-associated disorders involving immune dysregulation (Salvioli et al., 2013).

Bovine colostrum has attracted interest in this context because it contains several immunologically active components, including immunoglobulins, lactoferrin, antimicrobial proteins, cytokines, growth factors, and bioactive peptides. Collectively, these constituents may interact with the gastrointestinal and immune systems and could potentially contribute to the maintenance of immune function in older populations. However, direct clinical evidence specifically demonstrating immune benefits of BC in older adults remains limited, and findings from studies of individual colostrum components should not automatically be interpreted as effects of whole bovine colostrum.

The original manuscript refers to a study involving sedentary, non-smoking older adults with relatively low NK-cell activity. In that study, participants consumed a symbiotic preparation containing *Saccharomyces boulardii* lysate together with cranberry and colostrum-derived lactoferrin, and an increase in NK-cell activity was observed after approximately two months compared with placebo (Naito et al., 2014). Importantly, because the intervention contained several biologically active ingredients, the observed response cannot be attributed specifically to bovine colostrum or lactoferrin.

This limitation is particularly important when interpreting the potential immunological effects of colostrum in older adults. Lactoferrin itself has antimicrobial, immunomodulatory, and anti-inflammatory properties, but the biological response to a multi-component supplement may result from additive or synergistic effects among its constituents. Therefore, the Naito et al. (2014) findings provide supportive evidence for the potential of colostrum-derived components in immune-oriented nutritional formulations rather than definitive evidence that BC supplementation alone increases NK-cell activity.

In addition to immune function, the high-quality proteins and bioactive components present in BC may be relevant to age-related changes in nutritional status, skeletal muscle maintenance, gastrointestinal function, and recovery. Older adults frequently experience reduced dietary protein intake and an attenuated anabolic response to protein consumption, increasing the importance of adequate intake of high-quality dietary protein (Deer & Volpi, 2015). Nevertheless, these nutritional characteristics should be distinguished from specific immunological effects, which require direct clinical evaluation.

Recent reviews continue to identify older adults as a potentially relevant population for BC-based nutritional interventions because of the combined nutritional, antimicrobial, immunological, and gastrointestinal properties of colostrum. However, contemporary literature also emphasizes substantial variability in BC composition and the need for standardized preparations and stronger clinical evidence before specific health benefits can be established (Riaz et al., 2026).

Overall, bovine colostrum and its isolated bioactive components represent promising candidates for the development of functional nutritional products targeting older populations. Nevertheless, current evidence is insufficient to conclude that BC supplementation broadly enhances immune function or reduces infection risk in older adults. Future randomized controlled trials should investigate standardized BC preparations, clinically relevant doses, treatment duration, immune biomarkers, gastrointestinal outcomes, infection incidence, and potential interactions with age-related nutritional status.

4. Clinical Applications of Bovine Colostrum

Bovine colostrum (BC) has been investigated for a range of potential clinical and nutritional applications because of its high concentrations of proteins, immunoglobulins, growth factors, antimicrobial proteins, and other bioactive constituents. Particular research attention has focused on sports performance and recovery, gastrointestinal health, immune function, and maintenance of musculoskeletal health. However, the strength of evidence varies considerably among these applications, and differences in BC composition, supplementation dose, intervention duration, participant characteristics, and study design make direct comparisons challenging (Davison, 2021; Riaz et al., 2026).

One of the earliest areas of human research involved the use of BC supplementation in sports and exercise. Studies beginning in the late 1990s investigated whether BC could improve exercise performance, body composition, recovery, and immune responses. Subsequent research has examined a variety of outcomes, including strength, lean body mass, endurance performance, gastrointestinal permeability, inflammatory responses, and recovery following strenuous exercise (Davison, 2021). Nevertheless, the available evidence is heterogeneous, and improvements have not been consistently demonstrated across all populations or performance outcomes.

BC supplementation may be particularly relevant during prolonged or intensive exercise because strenuous physical activity can transiently influence immune function and compromise gastrointestinal barrier integrity. Previous studies have reported that BC supplementation may attenuate exercise-induced increases in intestinal permeability, suggesting a potential protective effect on gastrointestinal barrier function (Davison et al., 2016). Such effects may be important for athletes undertaking prolonged endurance exercise, during which gastrointestinal disturbances and increased intestinal permeability can occur.

Studies have also investigated BC supplementation in relation to body composition and muscular performance. Improvements in lean body mass and selected measures of exercise performance have been reported in some intervention studies, although responses vary according to supplementation protocols and participant characteristics. In trained athletes, BC has additionally been investigated for its potential effects on inflammatory responses and recovery following intensive exercise (Kotsis et al., 2018; Davison, 2021).

The manuscript also discusses BC supplementation in older adults undertaking resistance training. In this context, supplementation has been associated with improvements in selected measures of muscular strength and bone metabolism compared with whey-protein supplementation. Both BC- and whey-supplemented groups have also demonstrated improvements in outcomes such as upper-body strength, muscle thickness, and lean tissue mass, indicating that some benefits may reflect increased high-quality protein intake rather than effects unique to BC. This distinction is important when evaluating the specific functional value of colostrum.

The mechanisms responsible for the reported effects of BC supplementation remain incompletely understood. BC contains high-quality proteins and amino acids in addition to immunoglobulins, lactoferrin, growth factors, cytokines, oligosaccharides, and other biologically active compounds. Consequently, observed physiological responses may result

from interactions among multiple components rather than from a single bioactive constituent. Furthermore, because many intervention studies compare BC with protein-rich control products such as whey protein, differences between treatments cannot necessarily be explained solely by total protein or amino-acid intake (Główka et al., 2020; Jones et al., 2015).

The gastrointestinal tract is another important area of potential clinical application. BC-derived immunoglobulins, lactoferrin, growth factors, and other bioactive components may interact with intestinal epithelial and immune systems. Experimental and clinical studies have therefore investigated BC in relation to intestinal permeability, mucosal integrity, inflammatory responses, and gastrointestinal disorders. Recent literature continues to identify gastrointestinal health as a promising area for BC application, although the available clinical evidence differs substantially according to the condition investigated and should not be generalized across patient populations.

Similarly, the immunological properties of BC have stimulated interest in its use as a functional ingredient for populations experiencing physiological stress or altered immune responses. However, evidence of changes in immune biomarkers should be distinguished from clinically demonstrated reductions in infection incidence or disease severity. The potential clinical value of BC therefore requires evaluation using clinically meaningful outcomes rather than relying exclusively on laboratory markers of immune activity.

An additional consideration is the bioavailability of colostral proteins and peptides following oral consumption. Unlike intravenous or locally administered therapeutic agents, orally consumed BC components are exposed to acidic gastric conditions, digestive enzymes, and interactions with other dietary constituents. Some proteins or their bioactive fragments may retain biological activity within the gastrointestinal tract, whereas others may undergo substantial digestion. Therefore, the presence of a biologically active compound in BC does not necessarily indicate that it will reach systemic circulation in an intact and physiologically active form.

5. Extraction and Purification of Defensive Proteins

The extraction and purification of defensive proteins from bovine colostrum are critical steps in the development of high-value functional ingredients. Bovine colostrum contains a complex mixture of proteins, lipids, carbohydrates, minerals, and other bioactive constituents; therefore, selective separation of immunoglobulins, lactoferrin, lysozyme, lactoperoxidase, and related proteins requires processing techniques capable of achieving adequate recovery and purity while preserving biological activity. This is particularly important because many colostral proteins are sensitive to heat, extreme pH conditions, and other processing stresses (Costa et al., 2023; Riaz et al., 2026).

Before protein fractionation, bovine colostrum generally requires preliminary processing to reduce fat, casein, cellular material, and other components that may interfere with subsequent separation. Centrifugation, clarification, pH adjustment, and membrane-based processes can be employed depending on the target protein and intended final product. The selection of an extraction strategy should consider not only protein yield and purity but also processing cost, scalability, microbiological safety, environmental impact, and retention of biological activity.

Among the available technologies, membrane filtration and chromatography are particularly important for the recovery and purification of colostral proteins. Membrane processes provide a relatively mild, predominantly non-thermal approach for concentrating and fractionating proteins according to molecular size and other physicochemical characteristics, whereas chromatographic techniques provide greater selectivity and can achieve substantially higher purity. These methods may also be used sequentially, with membrane filtration serving as a concentration or pre-purification step followed by chromatographic purification of specific target proteins.

Recent developments in colostrum processing increasingly emphasize the use of mild processing conditions to preserve thermolabile immunoglobulins and other bioactive components. This consideration is especially relevant when purified proteins are intended for incorporation into functional beverages, where biological functionality must be maintained throughout extraction, formulation, preservation, storage, and consumption (Riaz et al., 2026).

5.1. Membrane Filtration

Membrane filtration is one of the most widely investigated approaches for the concentration and fractionation of proteins from bovine colostrum and other dairy streams. Compared with conventional thermal separation processes, membrane filtration can generally be performed under relatively mild temperature conditions and does not necessarily require a phase change or extensive chemical treatment. These characteristics make membrane technology particularly attractive for the recovery of heat-sensitive bioactive proteins.

The principal membrane-based processes relevant to bovine colostrum include microfiltration (MF) and ultrafiltration (UF). These processes differ primarily in membrane pore size or molecular-weight cut-off and consequently in the types of components that are retained or transmitted through the membrane. The selection of membrane characteristics depends on the composition of the starting material, the target protein, the desired degree of purification, and subsequent processing requirements.

Microfiltration generally employs membranes with larger pore sizes than ultrafiltration and can be used to reduce bacterial contamination and remove suspended material or cellular debris. In colostrum processing, MF can therefore function as an initial clarification or microbial-reduction step while limiting exposure of heat-sensitive proteins to severe thermal

conditions. Recent reviews continue to identify microfiltration as a promising non-thermal approach for maintaining bioactive constituents during colostrum processing.

However, microfiltration of bovine colostrum is technologically challenging because of its high solids content and complex protein composition. Casein micelles and other macromolecular components can accumulate at the membrane surface, resulting in concentration polarization and membrane fouling. Fouling reduces permeate flux, alters separation selectivity, and can increase processing time, water consumption, cleaning requirements, and operational costs. Consequently, pretreatments such as fat removal and casein reduction may improve membrane performance.

Ultrafiltration uses membranes characterized by molecular-weight cut-offs that enable selective concentration of proteins while allowing smaller components to pass into the permeate. Depending on the membrane selected, UF can therefore be employed to concentrate immunoglobulins, lactoferrin, and other higher-molecular-weight proteins while reducing the concentrations of lactose, salts, and other lower-molecular-weight constituents.

Membrane molecular-weight cut-offs must nevertheless be selected carefully because the separation of individual colostrum proteins cannot be explained solely by their nominal molecular masses. Protein conformation, aggregation, membrane-protein interactions, ionic strength, pH, temperature, transmembrane pressure, and concentration polarization can all affect retention and transmission. Optimization of these parameters is therefore necessary to maximize protein recovery and maintain membrane performance.

Membrane filtration has previously been combined successfully with downstream chromatographic purification for lactoferrin recovery from bovine colostrum. In one production-scale approach, sequential ultrafiltration followed by strong cation-exchange chromatography produced lactoferrin with a final reported purity of approximately 94.2% and recovery of approximately 82.5%, demonstrating the potential of integrated membrane–chromatography systems for high-value protein recovery.

The original manuscript also discusses advanced membrane modifications such as charged ultrafiltration membranes and electro-ultrafiltration (EUF). Charged membranes can potentially improve selectivity by combining size-based separation with electrostatic interactions, which may assist in separating proteins with similar molecular sizes but different surface charges or isoelectric points. EUF incorporates an external electric field to influence protein transport and may help reduce concentration polarization or fouling under appropriately controlled conditions. However, the practical effectiveness of these technologies depends strongly on protein characteristics and operating conditions.

Several processing variables influence membrane separation efficiency, including pH, ionic strength, transmembrane pressure, temperature, feed concentration, cross-flow velocity, membrane material, pore size, and molecular-weight cut-off. Adjusting pH relative to the isoelectric point of the target protein can alter protein charge and membrane interactions, while inappropriate pressure or concentration conditions can accelerate fouling without producing proportional increases in permeate flux.

For industrial applications, membrane filtration offers several advantages, including relatively mild processing conditions, the possibility of continuous operation, reduced reliance on chemical separation agents, and compatibility with subsequent purification technologies. Nevertheless, membrane fouling, incomplete selectivity among proteins of similar size, cleaning requirements, protein losses, and capital costs remain important limitations.

Recent literature continues to emphasize preservation of immunoglobulins and other thermolabile bioactive constituents during bovine-colostrum processing. A recent study similarly identifies processing conditions and stabilization technologies as critical determinants of the structural and biological integrity of colostrum proteins (Riaz et al., 2026).

5.2. Chromatography

Chromatography is a highly selective technique for the separation and purification of defensive proteins from bovine colostrum. Because colostrum contains a complex mixture of immunoglobulins (IgG, IgA, and IgM), lactoferrin, enzymes, growth factors, and other proteins, chromatographic methods can provide higher-resolution separation than membrane filtration alone. Separation can be achieved according to physicochemical characteristics such as charge, molecular size, hydrophobicity, and specific ligand-binding affinity (Owczarek et al., 2019).

Among the available chromatographic techniques, ion-exchange chromatography (IEC) is particularly relevant for the recovery of colostrum proteins. IEC separates proteins according to differences in their net surface charge at a specified pH. The charge of a protein is strongly influenced by the relationship between the operating pH and its isoelectric point (pI); consequently, careful control of pH and ionic strength is essential for achieving selective binding and elution.

Cation-exchange chromatography is commonly used for lactoferrin purification because lactoferrin has a relatively high isoelectric point and therefore carries a net positive charge under many processing conditions used for dairy-protein separation. Under appropriately selected conditions, lactoferrin can bind to negatively charged cation-exchange resins while other proteins are removed during washing. The bound lactoferrin can subsequently be recovered by modifying the ionic strength or pH of the mobile phase. Ion-exchange approaches have been widely investigated for the fractionation of lactoferrin and other whey-derived proteins (Santos et al., 2012).

Affinity chromatography provides an even higher degree of molecular selectivity by exploiting specific interactions between a target protein and an immobilized ligand. This approach is particularly useful for the purification of immunoglobulins,

where affinity ligands can selectively recognize and bind antibody molecules. Protein A-based affinity chromatography, for example, is widely used for immunoglobulin purification because of the specific interaction between Protein A and the Fc region of certain immunoglobulins (Ramos-de-la-Peña et al., 2019).

Despite its high selectivity, affinity chromatography has several limitations for large-scale food applications. Affinity ligands and chromatographic resins can be expensive, and repeated regeneration, cleaning, and validation may increase processing costs. Furthermore, the suitability of a particular ligand depends on the immunoglobulin class, species, binding characteristics, and intended purity of the recovered product. These considerations are especially important when the final ingredient is intended for a functional beverage rather than a high-value pharmaceutical application.

Size-exclusion chromatography (SEC) separates proteins primarily according to their hydrodynamic size. Larger molecules pass more rapidly through the column because they have limited access to the pores of the stationary phase, whereas smaller molecules enter the pores and consequently have longer retention times. SEC can therefore be useful as a polishing step to remove aggregates, degradation products, or contaminants from previously concentrated protein fractions (Owczarek et al., 2019).

However, SEC generally has relatively low sample-loading capacity and requires substantial solvent volumes, which can limit its economic feasibility for large-scale recovery of food proteins. For this reason, it is more appropriately considered a final purification or analytical step than a primary industrial fractionation technology for bovine colostrum.

Chromatographic techniques are frequently most effective when integrated with membrane filtration. In such systems, microfiltration or ultrafiltration can initially remove unwanted components and concentrate the protein-rich fraction, thereby reducing the volume that subsequently requires chromatographic purification. Chromatography can then provide the additional selectivity required to isolate individual proteins such as lactoferrin or immunoglobulins. This combination can improve overall process efficiency while reducing the burden placed on expensive chromatographic media.

Recent developments in chromatographic processing also include membrane chromatography, monolithic stationary phases, and other high-throughput separation systems. These approaches aim to reduce limitations associated with conventional packed-bed columns, particularly slow mass transfer, high pressure drops, and long processing times. Such improvements may increase the scalability of chromatographic protein purification, although economic feasibility remains an important consideration for food-grade applications.

The selection of an appropriate chromatographic technique ultimately depends on the characteristics of the target protein, including its molecular weight, isoelectric point, surface charge, stability, and required final purity (Ramos-de-la-Peña et al., 2019). Processing conditions must also be sufficiently mild to minimize denaturation and loss of biological activity, particularly when purified proteins are intended for functional foods and beverages.

For functional beverage development, complete purification of individual proteins may not always be necessary. Highly purified proteins can substantially increase production costs, whereas partially purified fractions containing several complementary bioactive proteins may provide a more economically feasible approach. The required degree of purification should therefore be determined by the intended product, safety requirements, biological functionality, regulatory considerations, and the health claims associated with the final formulation.

6. Stability and Preservation of Extracted Proteins

Maintaining the structural integrity and biological activity of proteins extracted from bovine colostrum is essential for their successful incorporation into functional beverages (Kandasamy & Naveen, 2022). Immunoglobulins, lactoferrin, and growth factors are sensitive to environmental conditions such as high temperature, pH changes, enzymatic degradation, and microbial contamination. Therefore, appropriate preservation techniques are required to maintain their stability during processing and storage.

Freeze-drying (lyophilization) removes water from frozen protein-rich colostrum under vacuum and generally causes less thermal damage, thereby helping to preserve protein structure and biological activity (Bjelošević et al., 2020). However, freeze-drying is relatively expensive and time-consuming, which can limit its application at an industrial scale.

Spray-drying, in contrast, is faster and more economical and is widely applicable to large-scale powder production. Nevertheless, exposure to elevated temperatures may partially denature heat-sensitive colostrum proteins and reduce their biological activity (Oyinloye & Yoon, 2020). Optimization of inlet and outlet temperatures and the use of suitable protective agents can help minimize these effects.

Both technologies can extend product shelf life, improve microbiological stability, and facilitate the incorporation of colostrum-derived proteins into powdered or ready-to-drink functional products. Selection of an appropriate drying method should therefore balance protein stability, processing cost, production scale, and the intended application of the final product. Recent literature similarly emphasizes mild and optimized processing conditions to preserve the functional properties of bovine colostrum components (Riaz et al., 2026).

7. Formulation of Functional Beverages

Bovine colostrum-derived defensive proteins can be incorporated into functional beverages to provide nutritional value together with potentially beneficial bioactive properties. Suitable product formats may include dairy-based beverages,

protein drinks, and other functional formulations. However, successful product development requires careful consideration of protein stability, solubility, sensory quality, and interactions with other beverage components.

Processing conditions are particularly important because changes in temperature, pH, and ionic strength can influence protein structure, solubility, aggregation, and biological activity. Excessive thermal treatment should therefore be avoided where possible, particularly for thermolabile proteins such as immunoglobulins and lactoferrin.

Sensory acceptability is another major consideration. Colostrum-derived ingredients may influence the taste, aroma, colour, viscosity, and overall mouthfeel of the final beverage. Appropriate formulation strategies are therefore required to achieve a balance between the desired concentration of bioactive proteins and consumer acceptability.

Stabilization approaches, including encapsulation and appropriate drying technologies, may further protect sensitive bioactive components during processing and storage (Ye et al., 2018). Ultimately, the development of colostrum-based functional beverages should integrate nutritional functionality, protein stability, microbiological safety, sensory acceptability, and shelf-life requirements.

8. Health Benefits of Colostrum-Based Functional Beverages

Functional beverages containing bovine colostrum or its bioactive proteins have attracted interest because of their potential nutritional, immunological, and gastrointestinal benefits. These effects are mainly associated with immunoglobulins, lactoferrin, antimicrobial proteins, growth factors, and other bioactive constituents naturally present in colostrum (Davison, 2021; Riaz et al., 2026).

Colostrum-derived immunoglobulins and lactoferrin may contribute to mucosal defence and interactions with gastrointestinal microorganisms, while lactoferrin, lysozyme, and lactoperoxidase exhibit antimicrobial and immunomodulatory properties. However, the biological activity of these proteins after incorporation into beverages depends on their stability during processing, storage, and gastrointestinal digestion.

In physically active individuals, BC supplementation has been investigated for its effects on immune responses, gastrointestinal permeability, exercise recovery, and performance. Some studies have reported beneficial effects on selected immune and inflammatory markers, although findings remain inconsistent across different supplementation protocols (Kotsis et al., 2018; Davison, 2021). Recent evidence also indicates that BC may modulate selected exercise-associated innate immune responses, but these effects should not be interpreted as a general enhancement of immunity.

BC-derived ingredients may also have potential applications in older adults and populations requiring nutritional support because of their high-quality proteins and bioactive components. Nevertheless, evidence for specific clinical benefits remains limited, particularly for long-term consumption and disease-related outcomes. Therefore, well-designed human intervention studies are required before definitive health claims can be established.

9. Regulatory and Safety Considerations

The development of bovine-colostrum-based functional beverages requires careful consideration of microbiological safety, product standardization, processing conditions, allergenicity, and regulatory requirements. Because bovine colostrum is a biological material, its composition can vary according to breed, parity, health status, time after parturition, and collection conditions. Appropriate standardization is therefore important to ensure consistent quality and bioactive composition of the final product (Fasse et al., 2021).

Microbiological safety is a major concern because raw bovine colostrum can contain pathogenic and spoilage microorganisms introduced during collection, handling, transportation, or storage. Suitable processing treatments are therefore required before human consumption. However, excessive heat treatment may reduce the activity of heat-sensitive components such as immunoglobulins, creating a need to balance microbial safety with preservation of bioactivity (Fasse et al., 2021).

Potential allergenicity must also be considered because bovine colostrum contains milk proteins such as caseins and β -lactoglobulin. Individuals with cow's milk protein allergy may therefore require particular caution. Lactose content and gastrointestinal tolerance should also be considered when products are intended for lactose-sensitive consumers. Recent clinical literature generally describes bovine colostrum as well tolerated, although mild gastrointestinal effects such as abdominal discomfort, gas, or transient diarrhoea have occasionally been reported (Karakulah et al., 2025).

Health claims should be supported by appropriate scientific evidence. The presence of immunoglobulins, lactoferrin, growth factors, or other bioactive compounds does not by itself demonstrate a clinical benefit. Therefore, claims for functional beverages should distinguish between nutritional composition, experimentally demonstrated biological activity, and clinically established health effects.

10. Challenges and Future Perspectives

Despite its potential as a functional ingredient, the utilization of bovine colostrum (BC) in functional beverages presents several challenges. Variability in colostrum composition, particularly in the concentrations of immunoglobulins and other bioactive components, can complicate product standardization. Moreover, many colostrum proteins are sensitive to processing conditions, requiring a careful balance between microbiological safety and preservation of biological activity (Costa et al., 2023).

Further improvements in mild extraction, purification, and stabilization technologies are needed to enhance the recovery and stability of defensive proteins. Encapsulation and related delivery approaches may also protect sensitive bioactive components during processing, storage, and gastrointestinal digestion (Ye et al., 2018). In addition, sensory acceptability, production cost, scalability, and shelf stability remain important considerations for commercial beverage development.

Future research should prioritize standardized BC preparations and well-designed human clinical trials to establish effective doses, bioavailability, long-term safety, and clinically meaningful health benefits. Such evidence, together with advances in processing and formulation, will be essential for translating bovine colostrum-derived defensive proteins into commercially viable functional beverages.

Conclusion

Bovine colostrum is a valuable source of defensive and bioactive proteins, particularly immunoglobulins, lactoferrin, lysozyme, and lactoperoxidase, with potential applications in functional food and beverage development. Advances in membrane filtration, chromatography, and preservation technologies provide opportunities to recover and stabilize these proteins while maintaining their biological activity. The incorporation of colostrum-derived proteins into functional beverages offers promising possibilities for delivering bioactive components in convenient dietary products. However, protein stability, processing conditions, sensory acceptability, product standardization, and production costs remain important considerations for successful commercialization. Although available evidence indicates potential immunological, gastrointestinal, and nutritional benefits, stronger clinical evidence is required before definitive health claims can be established. Future research integrating optimized extraction and formulation technologies with well-designed human studies will be important for developing safe, stable, and evidence-based bovine colostrum functional beverages.

References

- Arslan, A., Kaplan, M., Duman, H., Bayraktar, A., Ertürk, M., Henrick, B. M., Frese, S. A., & Karav, S. (2021). Bovine colostrum and its potential for human health and nutrition. *Frontiers in Nutrition*, 8, 651721. <https://doi.org/10.3389/fnut.2021.651721>
- Bjelošević, M., Zvonar Pobirk, A., Planinšek, O., & Ahlin Grabnar, P. (2020). Excipients in freeze-dried biopharmaceuticals: Contributions toward formulation stability and lyophilisation cycle optimisation. *International Journal of Pharmaceutics*, 576, 119029. <https://doi.org/10.1016/j.ijpharm.2020.119029>
- Burd, N. A., Beals, J. W., Martinez, I. G., Salvador, A. F., & Skinner, S. K. (2019). Food-first approach to enhance the regulation of post-exercise skeletal muscle protein synthesis and remodeling. *Sports Medicine*, 49(Suppl 1), 59–68. <https://doi.org/10.1007/s40279-018-1009-y>
- Costa, A., Sneddon, N. W., Goi, A., Visentin, G., Mammi, L. M. E., Savarino, E. V., Zingone, F., Formigoni, A., Penasa, M., & De Marchi, M. (2023). Invited review: Bovine colostrum, a promising ingredient for humans and animals—Properties, processing technologies, and uses. *Journal of Dairy Science*, 106(8), 5197–5217. <https://doi.org/10.3168/jds.2022-23013>
- Davison, G. (2021). The use of bovine colostrum in sport and exercise. *Nutrients*, 13(6), 1789. <https://doi.org/10.3390/nu13061789>
- Davison, G., Jones, A. W., Marchbank, T., & Playford, R. J. (2020). Oral bovine colostrum supplementation does not increase circulating insulin-like growth factor-1 concentration in healthy adults: Results from short- and long-term administration studies. *European Journal of Nutrition*, 59(4), 1473–1479. <https://doi.org/10.1007/s00394-019-02004-6>
- Davison, G., Marchbank, T., March, D. S., Thatcher, R., & Playford, R. J. (2016). Zinc carnosine works with bovine colostrum in truncating heavy exercise-induced increase in gut permeability in healthy volunteers. *The American Journal of Clinical Nutrition*, 104(2), 526–536. <https://doi.org/10.3945/ajcn.116.134403>
- Davison, G. (2021). The use of bovine colostrum in sport and exercise. *Nutrients*, 13(6), 1789. <https://doi.org/10.3390/nu13061789>
- Deer, R. R., & Volpi, E. (2015). Protein intake and muscle function in older adults. *Current Opinion in Clinical Nutrition and Metabolic Care*, 18(3), 248–253. <https://doi.org/10.1097/MCO.0000000000000162>
- Duan, H., Sun, Q., Chen, C., Wang, R., & Yan, W. (2024). A review: The effect of bovine colostrum on immunity in people of all ages. *Nutrients*, 16(13), 2007. <https://doi.org/10.3390/nu16132007>
- Dzik, S., Miciński, B., Aitzhanova, I., Miciński, J., Pogorzelska, J., Beisenov, A., & Kowalski, I. M. (2017). Properties of bovine colostrum and the possibilities of use. *Polish Annals of Medicine*, 24(2), 295–299. <https://doi.org/10.1016/j.poamed.2017.03.004>
- Fasse, S., Alarinta, J., Frahm, B., & Wirtanen, G. (2021). Bovine colostrum for human consumption—Improving microbial quality and maintaining bioactive characteristics through processing. *Dairy*, 2(4), 556–575. <https://doi.org/10.3390/dairy2040044>
- Główska, N., Durkalec-Michalski, K., & Woźniewicz, M. (2020). Immunological outcomes of bovine colostrum supplementation in trained and physically active people: A systematic review and meta-analysis. *Nutrients*, 12(4), 1023. <https://doi.org/10.3390/nu12041023>
- Granato, D., Barba, F. J., Bursać Kovačević, D., Lorenzo, J. M., Cruz, A. G., & Putnik, P. (2020). Functional foods: Product development, technological trends, efficacy testing, and safety. *Annual Review of Food Science and Technology*, 11, 93–118. <https://doi.org/10.1146/annurev-food-032519-051708>

- Granato, D., Nunes, D. S., & Barba, F. J. (2017). An integrated strategy between food chemistry, biology, nutrition, pharmacology, and statistics in the development of functional foods: A proposal. *Trends in Food Science & Technology*, 62, 13–22. <https://doi.org/10.1016/j.tifs.2016.12.010>
- Gul, K., Singh, A. K., & Jabeen, R. (2016). Nutraceuticals and functional foods: The foods for the future world. *Critical Reviews in Food Science and Nutrition*, 56(16), 2617–2627. <https://doi.org/10.1080/10408398.2014.903384>
- Jones, A. W., Cameron, S. J. S., Thatcher, R., Beecroft, M. S., Mur, L. A. J., & Davison, G. (2014). Effects of bovine colostrum supplementation on upper respiratory illness in active males. *Brain, Behavior, and Immunity*, 39, 194–203. <https://doi.org/10.1016/j.bbi.2013.10.032>
- Jones, A. W., Thatcher, R., March, D. S., & Davison, G. (2015). Influence of 4 weeks of bovine colostrum supplementation on neutrophil and mucosal immune responses to prolonged cycling. *Scandinavian Journal of Medicine & Science in Sports*, 25(6), 788–796. <https://doi.org/10.1111/sms.12433>
- Karakülah, Y. S., Yalçıntaş, Y. M., Bechelany, M., & Karav, S. (2025). Clinical applications of bovine colostrum in gastrointestinal disorders: Mechanisms, evidence, and therapeutic potential. *International Journal of Molecular Sciences*, 26(21), 10673. <https://doi.org/10.3390/ijms262110673>
- Klimesova, M., Krizova, L., Nejeschlebova, H., Hanus, O., & Vorlova, L. (2025). Endogenous inhibitory compounds in bovine milk, their significance and methods of detection. *Czech Journal of Animal Science*, 70(12), 499–517. <https://doi.org/10.17221/146/2025-CJAS>
- Kotsis, Y., Mikellidi, A., Aresti, C., Persia, E., Sotiropoulos, A., Panagiotakos, D. B., Antonopoulou, S., & Nomikos, T. (2018). A low-dose, 6-week bovine colostrum supplementation maintains performance and attenuates inflammatory indices following a Loughborough Intermittent Shuttle Test in soccer players. *European Journal of Nutrition*, 57(3), 1181–1195. <https://doi.org/10.1007/s00394-017-1401-7>
- Lago, A., Socha, M., Geiger, A., Cook, D., Silva-del-Río, N., Blanc, C., Quesnell, R., & Leonardi, C. (2018). Efficacy of colostrum replacer versus maternal colostrum on immunological status, health, and growth of preweaned dairy calves. *Journal of Dairy Science*, 101(2), 1344–1354. <https://doi.org/10.3168/jds.2017-13032>
- McGrath, B. A., Fox, P. F., McSweeney, P. L. H., & Kelly, A. L. (2016). Composition and properties of bovine colostrum: A review. *Dairy Science & Technology*, 96(2), 133–158. <https://doi.org/10.1007/s13594-015-0258-x>
- Naito, Y., Marotta, F., Kantah, M. K., Zerbini, N., Kushugulova, A., Zhumadilov, Z., Illuzzi, N., Sapienza, C., Takadanohara, H., Kobayashi, R., & Catanzaro, R. (2014). Gut-targeted immunonutrition boosting natural killer cell activity using *Saccharomyces boulardii* lysates in immuno-compromised healthy elderly subjects. *Rejuvenation Research*, 17(2), 184–187. <https://doi.org/10.1089/rej.2013.1500>
- O'Callaghan, T. F., O'Donovan, M., Murphy, J. P., Sugrue, K., Mannion, D., McCarthy, W. P., Timlin, M., Kilcawley, K. N., Hickey, R. M., & Tobin, J. T. (2020). Evolution of the bovine milk fatty acid profile—from colostrum to milk five days post parturition. *International Dairy Journal*, 104, 104655. <https://doi.org/10.1016/j.idairyj.2020.104655>
- Owczarek, B., Gerszberg, A., & Hnatuszko-Konka, K. (2019). A brief reminder of systems of production and chromatography-based recovery of recombinant protein biopharmaceuticals. *BioMed Research International*, 2019, 4216060. <https://doi.org/10.1155/2019/4216060>
- Ramos-de-la-Peña, A. M., González-Valdez, J., & Aguilar, O. (2019). Protein A chromatography: Challenges and progress in the purification of monoclonal antibodies. *Journal of Separation Science*, 42(9), 1816–1827. <https://doi.org/10.1002/jssc.201800963>
- Riaz, S., Imran, A., Rasheed, M., Amjad, A., Shankar, A., Chauhan, G., Basharat, Z., Islam, F., Naeem, U., & Ndagire, C. T. (2026). Health benefits and value addition of bovine colostrum (BC): A comprehensive review of its nutritional and functional potential. *Food Science of Animal Resources*, 46(1), 55. <https://doi.org/10.1007/s44463-026-00057-w>
- Richter, M., Baerlocher, K., Bauer, J. M., Elmadfa, I., Heseker, H., Leschik-Bonnet, E., Stangl, G., Volkert, D., Stehle, P., & German Nutrition Society (DGE). (2019). Revised reference values for the intake of protein. *Annals of Nutrition and Metabolism*, 74(3), 242–250. <https://doi.org/10.1159/000499374>
- Salvioli, S., Monti, D., Lanzarini, C., Conte, M., Pirazzini, C., Bacalini, M. G., Garagnani, P., Giuliani, C., Fontanesi, E., Ostan, R., Lunzi, L., Sevini, F., Yari, S. L., Barbieri, A., Lomartire, L., Borelli, V., Vianello, D., Bellavista, E., Martucci, M., Cevenini, E., Pini, E., Scurti, M., Biondi, F., Santoro, A., Capri, M., & Franceschi, C. (2013). Immune system, cell senescence, aging and longevity—Inflamm-aging reappraised. *Current Pharmaceutical Design*, 19(9), 1675–1679. <https://doi.org/10.2174/1381612811319090015>
- Sangild, P. T., Vonderohe, C., Melendez Hebib, V., & Burrin, D. G. (2021). Potential benefits of bovine colostrum in pediatric nutrition and health. *Nutrients*, 13(8), 2551. <https://doi.org/10.3390/nu13082551>
- Sanjabi, S., Oh, S. A., & Li, M. O. (2017). Regulation of the immune response by TGF- β : From conception to autoimmunity and infection. *Cold Spring Harbor Perspectives in Biology*, 9(6), a022236. <https://doi.org/10.1101/cshperspect.a022236>
- Santos, M. J., Teixeira, J. A., & Rodrigues, L. R. (2012). Fractionation of the major whey proteins and isolation of β -lactoglobulin variants by anion exchange chromatography. *Separation and Purification Technology*, 90, 133–139. <https://doi.org/10.1016/j.seppur.2012.02.030>
- Siqueiros-Cendón, T., Arévalo-Gallegos, S., Iglesias-Figueroa, B. F., García-Montoya, I. A., Salazar-Martínez, J., & Rascón-Cruz, Q. (2014). Immunomodulatory effects of lactoferrin. *Acta Pharmacologica Sinica*, 35(5), 557–566. <https://doi.org/10.1038/aps.2013.200>
- Superti, F. (2020). Lactoferrin from bovine milk: A protective companion for life. *Nutrients*, 12(9), 2562. <https://doi.org/10.3390/nu12092562>

- Wakabayashi, H., Oda, H., Yamauchi, K., & Abe, F. (2014). Lactoferrin for prevention of common viral infections. *Journal of Infection and Chemotherapy*, 20(11), 666–671. <https://doi.org/10.1016/j.jiac.2014.08.003>
- Wong, E. B., Mallet, J.-F., Duarte, J., Matar, C., & Ritz, B. W. (2014). Bovine colostrum enhances natural killer cell activity and immune response in a mouse model of influenza infection and mediates intestinal immunity through Toll-like receptors 2 and 4. *Nutrition Research*, 34(4), 318–325. <https://doi.org/10.1016/j.nutres.2014.02.007>
- Wu, G. (2016). Dietary protein intake and human health. *Food & Function*, 7(3), 1251–1265. <https://doi.org/10.1039/C5FO01530H>
- Ye, Q., Georges, N., & Selomulya, C. (2018). Microencapsulation of active ingredients in functional foods: From research stage to commercial food products. *Trends in Food Science & Technology*, 78, 167–179. <https://doi.org/10.1016/j.tifs.2018.05.025>
- Yu, Z., Nan, F., Wang, L. Y., Jiang, H., Chen, W., & Jiang, Y. (2020). Effects of high-protein diet on glycemic control, insulin resistance and blood pressure in type 2 diabetes: A systematic review and meta-analysis of randomized controlled trials. *Clinical Nutrition*, 39(6), 1724–1734. <https://doi.org/10.1016/j.clnu.2019.08.008>