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Whey Valorization in the Dairy Industry: Emerging Technologies and Value-Added Applications

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Abstract

Whey is a major by-product of the dairy industry generated during the manufacture of cheese, casein, and other dairy products. Despite being traditionally considered a waste stream, whey contains valuable nutrients, particularly high-quality proteins, lactose, minerals, vitamins, and bioactive compounds, making it an important resource for sustainable food production. Improper disposal of untreated whey can create significant environmental concerns because of its high organic load. Whey valorization, therefore, provides an opportunity to transform this dairy by-product into useful ingredients, functional foods, nutraceuticals, and other value-added products while reducing environmental impacts. This review discusses the composition, nutritional characteristics, and environmental significance of whey and examines emerging technologies used for its efficient recovery and utilization. Membrane separation, drying, fermentation, enzymatic processing, and biotechnological approaches are highlighted for the recovery of valuable whey components. Applications of whey proteins, lactose, and bioactive peptides in beverages, fermented products, functional foods, sports nutrition, animal feed, pharmaceuticals, and other industrial sectors are also discussed. Particular emphasis is placed on the development of innovative whey-based products and the role of advanced processing technologies in improving their nutritional, functional, and economic value. The review further addresses major challenges, including processing costs, product stability, consumer acceptance, and industrial-scale implementation. Overall, effective whey valorization can support waste reduction, resource recovery, and the transition toward a more sustainable and circular dairy industry.

Keywords: Whey, whey valorization, dairy by-products, whey proteins, value-added products, functional foods, dairy processing, sustainable dairy industry

INTRODUCTION

The dairy industry is one of the major contributors to the global food sector, producing a wide range of products such as cheese, casein, yogurt, butter, and milk-based beverages. Along with these products, substantial quantities of by-products are generated during dairy processing. Whey is one of the most important liquid by-products, particularly from cheese and casein production. For many years, whey was primarily regarded as a waste material; however, its rich nutritional composition has increased interest in its recovery and utilization as a valuable resource [1].

Whey contains several important components, including high-quality proteins, lactose, minerals, vitamins, and other biologically active compounds. Whey proteins, in particular, possess desirable nutritional and functional properties and can be incorporated into a variety of food and nutritional products. The presence of these valuable components makes whey suitable for conversion into value-added ingredients rather than being discarded as an industrial waste stream [2].

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The disposal of untreated whey can also present environmental challenges because of its considerable organic content. Direct discharge into water bodies can increase the organic load and adversely affect water quality. Consequently, appropriate processing and utilization strategies are necessary to reduce the environmental burden associated with whey disposal while recovering its useful components [3].

Whey valorization refers to the conversion of whey and its individual components into products with greater nutritional, functional, technological, or economic value. Advances in dairy processing have enabled the separation and concentration of valuable whey components through technologies such as membrane filtration, drying, fermentation, and enzymatic processing. These approaches have expanded the potential applications of whey in food, nutrition, biotechnology, animal feed, pharmaceutical, and other industrial sectors [4].

The development of whey-based beverages, whey protein concentrates and isolates, fermented products, functional foods, and nutraceutical ingredients demonstrates the growing importance of whey valorization. In addition to creating new products, effective utilization of whey can contribute to resource recovery and more sustainable dairy processing practices.

Therefore, whey valorization represents an important approach for converting a dairy processing by-product into useful and commercially valuable resources. This review focuses on the composition and nutritional characteristics of whey, environmental concerns associated with its disposal, major processing and valorization technologies, applications in value-added products, emerging approaches, challenges, and prospects for sustainable utilization of whey in the dairy industry [5].

TYPES AND SOURCES OF WHEY

Whey is the liquid fraction separated from milk during the manufacture of certain dairy products, particularly cheese and casein. Depending on the method used for milk coagulation and the processing conditions, whey can differ in composition, acidity, mineral content, and suitability for further applications. The two principal categories are sweet whey and acid whey [6].

Sweet Whey

Sweet whey is mainly produced during the manufacture of rennet-coagulated cheeses. During this process, milk proteins are coagulated using rennet or related coagulating enzymes, resulting in the separation of the curd from the liquid whey fraction. Sweet whey generally has a relatively mild flavor and is an important source of whey proteins and lactose.

Because of its favorable composition and relatively mild characteristics, sweet whey is widely considered suitable to produce whey protein ingredients, beverages, nutritional formulations, and other value-added products. Processing technologies can be used to concentrate its protein fraction and recover other useful components.

Acid Whey

Acid whey is generated during the production of acid-coagulated dairy products, including certain types of cheese and fermented dairy products. In this process, milk proteins are precipitated through acidification, resulting in a whey fraction with a lower pH than sweet whey.

Acid whey contains valuable nutrients but may present greater processing challenges because of its higher mineral content and acidic characteristics. Nevertheless, advances in separation, concentration, fermentation, and formulation technologies have created opportunities for its utilization in beverages, functional foods, animal nutrition, and other applications [7].

Major Sources of Whey

The principal sources of whey include:

- Cheese manufacturing.
- Casein production.
- Acid-coagulated dairy products.
- Fermented dairy processing.
- Other processes involving separation or precipitation of milk proteins.

The quantity and characteristics of whey obtained depend on the type of dairy product manufactured and the processing conditions employed. Understanding these differences is important for selecting suitable valorization strategies [8].

Importance of Whey Classification for Valorization

Classification of whey according to its source and characteristics is important when selecting an appropriate processing and utilization method. Sweet and acid whey differ in their physicochemical properties and, therefore, may require different separation, concentration, stabilization, or formulation approaches.

The identification of suitable applications for each type of whey can improve the recovery of valuable components and support the development of commercially useful products. Consequently, characterization and classification of whey form an important foundation for efficient whey valorization in the dairy industry [9].

CHEMICAL COMPOSITION AND NUTRITIONAL PROPERTIES OF WHEY

Whey is a nutritionally valuable dairy fraction containing a combination of proteins, lactose, minerals, vitamins, and other bioactive components. Its composition varies depending on the type of whey, the characteristics of the milk used, the method of coagulation, and the processing conditions. The presence of these components makes whey an important raw material for the development of value-added food and nutritional products.

Whey Proteins

Whey proteins represent one of the most important components of whey because of their high nutritional quality and functional characteristics. Major whey proteins include β-lactoglobulin, α-lactalbumin, serum albumin, immunoglobulins, and lactoferrin. These proteins contain essential amino acids and can contribute to the nutritional value of foods and dietary formulations.

In addition to their nutritional importance, whey proteins possess functional properties such as emulsification, foaming, water binding, and gel formation. These characteristics allow whey protein ingredients to be incorporated into beverages, bakery products, dairy formulations, sports nutrition products, and functional foods. Concentration and purification technologies can further enhance their usefulness in specialized food applications [10].

Lactose

Lactose is the principal carbohydrate present in whey and represents an important component for valorization. It can be recovered and utilized in food formulations and other industrial applications. Advances in separation and concentration technologies have made it possible to recover lactose from whey while simultaneously concentrating other valuable components.

Lactose can also serve as a substrate for microbial fermentation, providing opportunities to produce compounds such as organic acids and other bioproducts. Therefore, effective lactose recovery and utilization can contribute to the overall efficiency of whey processing [11].

Minerals

Whey contains several minerals that contribute to its nutritional characteristics. Calcium, phosphorus, potassium, sodium, and magnesium are among the important mineral constituents associated with whey. The concentration and distribution of minerals can vary between sweet and acid whey.

Mineral recovery can be integrated with other whey-processing operations, allowing the production of ingredients with specific nutritional or technological characteristics. However, the mineral composition of whey should be considered when designing separation and formulation processes [12].

Vitamins

Whey contains vitamins in relatively smaller quantities compared with its major components. The presence of vitamins, together with proteins, lactose, and minerals, contributes to the overall nutritional value of whey. Depending on the processing conditions, some components may be retained, concentrated, or reduced during different stages of whey processing.

Bioactive Components

Whey contains several components that have attracted interest because of their potential biological and functional properties. Whey proteins and their derived peptides have been investigated for activities such as antioxidant and other physiological effects. Components including lactoferrin and immunoglobulins have also contributed to interest in whey as a source of functional ingredients.

The recovery of these components can increase the value obtained from whey and provide opportunities for developing specialized nutritional and functional products [13].

Nutritional Significance of Whey

The combination of high-quality proteins, lactose, minerals, and other valuable constituents makes whey more than a conventional dairy waste stream. Its nutritional composition provides a basis for its use in food, dietary, functional, and nutraceutical applications.

However, the nutritional composition of whey alone does not determine its suitability for a particular product. Processing conditions, stability, sensory characteristics, microbiological quality, and the intended application must also be considered. Consequently, characterization of whey is an essential step in selecting appropriate valorization technologies and developing safe, stable, and commercially useful products [14, 15].

ENVIRONMENTAL CONCERNS ASSOCIATED WITH WHEY DISPOSAL

Whey is a valuable dairy by-product; however, its improper disposal can create significant environmental concerns because of its high organic content, particularly lactose and proteins. The decomposition of these organic constituents can result in high biological oxygen demand (BOD) and chemical oxygen demand (COD), and untreated discharge into aquatic environments may reduce dissolved oxygen levels and adversely affect water quality and aquatic organisms. The large volume of whey generated during dairy processing also creates challenges related to its storage, transportation, treatment, and disposal, while its high moisture content can make conventional waste-management practices less economical. Consequently, increasing attention has been given to whey valorization as an alternative approach to disposal. Recovery of valuable components – such as proteins, lactose, minerals, and bioactive compounds through technologies including membrane separation, concentration, drying, fermentation, and enzymatic processing – can reduce the environmental burden associated with whey while generating useful ingredients and value-added products. Effective whey utilization, therefore, supports sustainable dairy processing by promoting resource recovery, reducing waste, and improving the economic value of dairy production streams. An integrated approach that considers environmental protection, processing costs, product quality, and market potential is essential for developing efficient and sustainable whey management strategies [16].

TECHNOLOGIES FOR WHEY PROCESSING AND VALORIZATION

The valorization of whey depends on efficient processing technologies that enable the recovery, concentration, and transformation of its valuable components into useful products. Among the important approaches, membrane-based separation technologies – such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis – are widely used for selectively separating whey

constituents and concentrating proteins, lactose, and minerals. Ultrafiltration is particularly useful for concentrating whey proteins and producing whey protein concentrates, while nanofiltration and reverse osmosis can assist in the concentration and partial separation of lactose and mineral fractions. Drying technologies, particularly spray drying, are employed to convert concentrated whey and whey-derived ingredients into stable powders with improved storage and transportation characteristics. Freeze drying can also be used when preservation of sensitive components is important, although its higher processing cost may limit large-scale applications. Fermentation provides another important route for whey valorization, in which microorganisms utilize lactose as a substrate for producing useful compounds such as organic acids and other fermentation products. Enzymatic processing can further improve whey utilization through the hydrolysis of lactose and whey proteins, producing lactose-reduced ingredients and bioactive peptides with potential functional applications. The selection of a particular technology depends on the composition of whey, desired product characteristics, processing cost, energy requirements, and intended application. Integration of multiple technologies can improve the recovery of different whey components and facilitate the development of food, nutritional, functional, and industrial products. Thus, modern processing technologies play an important role in transforming whey from a dairy processing by-product into a valuable source of ingredients and value-added products [17, 18].

WHEY PROTEIN-BASED VALUE-ADDED PRODUCTS

Whey proteins are among the most valuable components recovered from whey because of their high nutritional quality and useful functional properties. Processing technologies – such as ultrafiltration, diafiltration, and drying – allow whey proteins to be concentrated and converted into commercially useful ingredients, including whey protein concentrates (WPC), whey protein isolates (WPI), and whey protein hydrolysates. Whey protein concentrates contain varying levels of protein along with other whey constituents, whereas whey protein isolates undergo further processing to obtain a higher protein content and reduced levels of lactose and minerals [19]. Whey protein hydrolysates are produced through enzymatic breakdown of proteins into smaller peptides, which can provide specific nutritional and functional advantages. These whey protein ingredients are widely incorporated into beverages, dairy formulations, bakery products, nutritional supplements, sports nutrition products, and functional foods. Their ability to form emulsions, foams, and gels also makes them useful in improving the texture, stability, and overall quality of food products. Whey proteins can additionally be used as carriers for bioactive compounds and in specialized nutritional formulations. The development of protein-enriched foods and beverages from whey demonstrates how dairy processing by-products can be transformed into products with greater nutritional and economic value. However, factors – such as processing conditions, protein stability, sensory characteristics, cost, and consumer acceptance – must be considered when developing whey protein-based products. Efficient recovery and appropriate formulation of whey proteins, therefore, provide important opportunities for increasing the value of whey while supporting sustainable utilization of dairy processing resources [19].

WHEY-BASED DAIRY AND FUNCTIONAL FOODS

Whey can be utilized as a valuable ingredient in the development of a wide range of dairy and functional food products because of its nutritional composition and functional properties. Whey-based beverages are one of the important applications, where processed whey can be formulated into refreshing and nutritionally enriched drinks. Fermentation of whey using suitable microorganisms can further improve its utilization and provide opportunities for developing fermented beverages with desirable sensory and functional characteristics. Whey can also be incorporated into dairy formulations, desserts, bakery products, and other food products to enhance their nutritional value and improve functional properties. The addition of whey proteins can contribute to desirable characteristics, such as emulsification, foaming, water binding, and gel formation, depending on the formulation and processing conditions. Whey proteins and their derived components have also attracted attention in the development of functional foods and nutraceutical products because of their nutritional quality and potential biological properties [20]. Probiotic whey-based products represent another area of interest, in which whey can serve as a suitable medium for incorporating beneficial microorganisms into food

formulations. The development of such products provides an opportunity to utilize whey efficiently while creating foods with additional nutritional and functional value. However, factors – such as flavor, acidity, stability, microbial safety, processing conditions, and consumer acceptance – need to be considered during product development. Appropriate formulation and processing can, therefore, help transform whey into diverse dairy and functional food products while contributing to sustainable utilization of dairy industry by-products [21].

UTILIZATION OF WHEY COMPONENTS

The individual components present in whey can be recovered and utilized for the development of a variety of value-added products and industrial applications. Whey proteins are particularly important because of their nutritional quality and functional properties, and they can be incorporated into beverages, nutritional formulations, functional foods, bakery products, and other food systems. Lactose, which is a major carbohydrate component of whey, can be recovered through suitable separation and concentration processes and subsequently utilized in food formulations or as a substrate for fermentation processes [22]. Fermentation of lactose-containing whey can provide opportunities for producing useful bioproducts, including organic acids and other compounds of industrial interest. Whey proteins can also be enzymatically hydrolyzed to produce peptides with potential functional and biological properties, creating opportunities for their incorporation into specialized food and nutraceutical formulations. Minerals present in whey, including calcium, phosphorus, potassium, sodium, and magnesium, can also be recovered or concentrated depending on the processing method and may contribute to the nutritional value of whey-derived ingredients. Other components, including lactoferrin and immunoglobulins, have attracted interest because of their functional and biological characteristics and their potential applications in specialized products. The selective recovery of individual whey components can, therefore, improve the overall efficiency and economic value of whey utilization. An integrated processing approach in which proteins, lactose, minerals, and other valuable constituents are recovered through appropriate technologies can minimize waste while maximizing resource utilization. Thus, component-wise valorization represents an important strategy for converting whey into a range of nutritionally valuable, functional, and commercially useful products [23].

APPLICATIONS BEYOND THE FOOD INDUSTRY

Whey and its recovered components have potential applications beyond conventional food products because of their nutritional, functional, and biochemical characteristics. Whey proteins and their fractions can be utilized in animal feed formulations as sources of high-quality nutrients, while selected protein components may also be explored for specialized pharmaceutical and nutraceutical applications. Bioactive whey-derived peptides and proteins have attracted interest for their potential use in products requiring specific functional properties. Whey components can also serve as raw materials in biotechnology-based processes, where lactose and other nutrients may be utilized by microorganisms to produce useful metabolites and bioproducts. In addition, whey-derived ingredients may have applications in cosmetic formulations where proteins and other functional components can contribute to product characteristics. The use of whey as a substrate for biotechnological production also provides opportunities for converting dairy processing streams into higher-value materials rather than treating them solely as waste. Such applications can diversify the economic utilization of whey and increase the overall value recovered from dairy processing. However, applications outside the food sector require appropriate purification, quality control, safety assessment, regulatory compliance, and economic evaluation. Continued research into the functional properties and processing of whey components may, therefore, expand their use in pharmaceutical, cosmetic, animal nutrition, and biotechnology-related industries while supporting more efficient and sustainable utilization of dairy resources [24].

CHALLENGES AND LIMITATIONS

Despite the considerable potential of whey valorization, several challenges can affect its efficient utilization on an industrial scale. The high moisture content and relatively short storage stability of untreated whey can create difficulties in handling, transportation, and storage, making rapid processing or suitable preservation necessary. The cost of advanced separation, concentration, drying, and

purification technologies can also influence the economic feasibility of whey-based products, particularly for small and medium-sized dairy processing units. Variations in the composition of whey according to its source and processing conditions may further affect the consistency and quality of recovered ingredients [8]. Product development can also be influenced by sensory characteristics, including taste, aroma, acidity, and texture, which may affect consumer acceptance of whey-based foods and beverages. Maintaining microbiological quality and ensuring adequate control during processing are essential because whey is a nutrient-rich medium that can support microbial growth if improperly handled. In addition, the recovery of specific components may require multiple processing stages, increasing energy consumption and operational complexity. Large-scale implementation may, therefore, require optimization of processing conditions, improved equipment efficiency, and integration of different technologies. Regulatory requirements, quality standards, market demand, and consumer awareness must also be considered when commercializing whey-derived products. Addressing these technological, economic, safety, and consumer-related challenges is essential for achieving efficient and commercially sustainable whey valorization [12].

SUSTAINABILITY AND CIRCULAR ECONOMY PERSPECTIVE

Whey valorization has an important role in promoting sustainability within the dairy industry by converting a nutrient-rich processing by-product into useful resources and value-added products. Instead of treating whey solely as a waste stream requiring disposal, its proteins, lactose, minerals, and other components can be recovered and utilized through suitable processing technologies. This approach can help reduce the environmental burden associated with the discharge of untreated whey while improving the utilization of resources already present within the dairy processing system [6]. The recovery of whey components can also create additional economic opportunities through the production of food ingredients, functional products, nutritional formulations, animal feed, and biotechnology-derived products. From a circular economy perspective, integrated whey processing can promote resource efficiency by maximizing the recovery of useful components and minimizing material losses. Combining separation, concentration, fermentation, enzymatic processing, and drying technologies can further improve the overall utilization of whey and support the development of multiple products from a single processing stream. Sustainable whey management should, however, consider energy consumption, water requirements, processing costs, product safety, and the economic feasibility of recovery systems. The adoption of efficient and environmentally responsible technologies can, therefore, help dairy industries move toward more sustainable production models in which by-products are increasingly regarded as valuable secondary resources. Thus, whey valorization represents a practical approach for linking environmental protection, resource recovery, economic value creation, and sustainable development within the modern dairy industry [16].

CONCLUSION

Whey valorization represents an important approach for converting a traditionally underutilized dairy by-product into valuable resources and value-added products. The presence of high-quality proteins, lactose, minerals, vitamins, and bioactive compounds makes whey a promising raw material for applications in functional foods, nutritional beverages, fermented products, nutraceuticals, animal feed, pharmaceuticals, cosmetics, and biotechnology. Modern processing technologies – such as membrane separation, drying, fermentation, enzymatic hydrolysis, and integrated recovery systems – have improved the efficient utilization of individual whey components while reducing the environmental burden associated with untreated whey disposal. However, challenges related to processing costs, compositional variation, microbial stability, sensory characteristics, energy requirements, regulatory compliance, and large-scale implementation continue to influence the commercial potential of whey-based products. Future development should, therefore, focus on economical, energy-efficient, scalable, and sustainable processing systems capable of recovering multiple valuable components from whey. Overall, effective whey valorization can contribute to waste reduction, resource recovery, economic diversification, and the development of a circular and sustainable dairy industry.

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