WHEY VALORIZATION IN THE FOOD INDUSTRY: EMERGING SUSTAINABLE PATHWAYS FOR HIGH-VALUE FOOD APPLICATIONS: A REVIEW

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Abstract
The global dairy industry generates enormobus quantities of whey as a major by-product during the manufacture of cheese, Paneer, Chhana, casein, Shrikhand, Greek yogurt, and related dairy products. Historically regarded as an environmental pollutant because of its extremely high biochemical oxygen demand (BOD) and chemical oxygen demand (COD), whey has now emerged as one of the most valuable functional ingredients in the modern food industry. Whey retains nearly 50–55% of the nutrients originally present in milk, including high-quality proteins, lactose, minerals, vitamins, phospholipids, growth factors, and bioactive peptides. Rapid advances in dairy chemistry, membrane processing, enzymatic modification, fermentation technology, spray drying, and encapsulation have transformed whey from a low-value waste stream into a versatile ingredient for development of functional foods, nutraceuticals, sports nutrition products, and bioactive formulations. The present review critically examines the chemistry, composition, nutritional significance, techno-functional characteristics, biological activities, processing technologies, and multifarious applications of whey in beverages, fermented foods, bakery products, confectionery systems, dairy desserts, edible films, extruded snacks, infant foods, and therapeutic nutrition products. Particular emphasis has been placed on emerging technologies such as ultrafiltration, nanofiltration, electrodialysis, precision fermentation, bioactive peptide generation, microencapsulation, and AI-assisted process optimization. Recent developments in acid whey valorization, postbiotic production, whey-based sustainable packaging materials, and circular bioeconomy approaches are comprehensively discussed. Whey proteins exhibit exceptional nutritional quality and possess antioxidant, antihypertensive, antimicrobial, immunomodulatory, anti-inflammatory, antidiabetic, and muscle protein synthesis-promoting properties. Scientific evidence demonstrates that whey incorporation significantly enhances nutritional quality, texture, flavour, water-holding capacity, emulsification, probiotic viability, and consumer acceptability in diversified food systems(Luparelli et al., 2025). Furthermore, valorization of whey contributes substantially to reduction in environmental pollution, improved recovery of milk nutrients, enhancement of dairy plant profitability, and development of sustainable food processing systems. Future research should focus on advanced fractionation technologies, characterization of bioactive compounds, process intensification, shelf-life optimization, and commercial-scale development of innovative whey-derived ingredients. Whey valorization is expected to play a pivotal role in future sustainable dairy processing and circular bioeconomy strategies.
Keywords: *Whey valorization; Whey proteins; Bioactive peptides; Functional foods; Circular bioeconomy; Nutraceuticals; Membrane technology; Fermented foods; Functional beverages*

1. Introduction

The dairy industry occupies a central position in global food systems owing to its contribution toward nutritional security, rural economy, and food processing industries. During manufacture of cheese, paneer, chhana, casein, Greek yogurt, and related dairy products, substantial quantities of whey are generated as liquid by-products. It has been estimated that approximately 180–200 million tonnes of whey are produced annually worldwide, and the quantity continues to increase with expansion of cheese and fermented dairy industries (Smithers, 2008; Selmi et al., 2025).

For several decades, whey was regarded primarily as a troublesome waste stream because of its high organic load and disposal difficulties. Untreated whey possesses biochemical oxygen demand (BOD) values ranging between 30,000–50,000 mg/L and chemical oxygen demand (COD) values exceeding 60,000 mg/L, making indiscriminate disposal environmentally hazardous (Prazeres et al., 2012). Direct discharge of whey into water bodies causes oxygen depletion, eutrophication, microbial proliferation, and ecological imbalance. Consequently, sustainable management and utilization of whey have become major priorities for the dairy industry.

Scientific investigations have demonstrated that whey contains nearly half of the nutrients originally present in milk, including lactose, whey proteins, minerals, vitamins, and biologically active compounds. Whey proteins possess exceptionally high nutritional quality because of their balanced essential amino acid composition and high digestibility. In addition, whey proteins exhibit remarkable techno-functional properties such as emulsification, foaming, gelation, water-binding, and viscosity enhancement that support their incorporation into numerous food systems (de Wit, 1998). Recent advances in membrane processing, ultrafiltration, enzymatic hydrolysis, fermentation technology, and drying technologies have revolutionized whey utilization. Whey-derived ingredients such as whey protein concentrates (WPC), whey protein isolates (WPI), hydrolysates, bioactive peptides, lactose derivatives, and fermented whey products now occupy important positions in the global functional food and nutraceutical markets(Luparelli et al., 2025)..

Increasing consumer demand for high-protein foods, functional beverages, sports nutrition products, probiotic formulations, and sustainable ingredients has further stimulated industrial interest in whey valorization. Moreover, circular bioeconomy concepts emphasize maximum recovery and utilization of food processing by-products, thereby positioning whey as a strategic resource rather than waste material. The present review critically examines the composition, chemistry, functional properties, nutritional significance, processing technologies, industrial applications, environmental implications, and future prospects of whey valorization in the food industry.

2. Classification and Composition of Whey

2.1 Types of whey: Whey may be broadly classified into sweet whey and acid whey depending upon the coagulation method employed during dairy processing.

2.1.1 Sweet whey: Sweet whey is generated during enzymatic coagulation of milk in cheese manufacture. It generally possesses pH values between 6.0 and 6.5 and contains comparatively lower mineral content.

2.1.2 Acid whey: Acid whey is obtained during acid coagulation processes such as paneer, chhana, cottage cheese, Greek yogurt, and acid casein manufacture. Acid whey possesses lower pH (4.2–4.8) and relatively higher concentrations of soluble calcium and phosphate.

Table 1. Typical Composition of Sweet and Acid Whey

Component	Sweet Whey (%)	Acid Whey (%)
Moisture	93.0–94.0	93.5–94.5
Lactose	4.5–5.0	4.0–4.5
Protein	0.6–0.8	0.7–0.9
Fat	0.05–0.5	0.02–0.5
Ash	0.5–0.7	0.7–0.9
pH	6.0–6.5	4.2–4.8

2.2 Whey proteins: Whey proteins represent one of the most nutritionally valuable protein fractions in milk. The major whey proteins include β-lactoglobulin, α-lactalbumin, Immunoglobulins, Bovine serum albumin, Lactoferrin and Lactoperoxidase. These proteins possess excellent digestibility and balanced amino acid composition.

Table 2. Major whey proteins and its biological functions

Protein Fraction	Approximate Proportion (%)	Functional/Biological Role
β-lactoglobulin	50–55	Gelation, emulsification
α-lactalbumin	20–25	Nutritional enhancement
Immunoglobulins	10–15	Immune protection
Bovine serum albumin	5–10	Ligand binding
Lactoferrin	1–2	Antimicrobial activity
Lactoperoxidase	<1	Oxidative defense

3. Functional and technological properties of whey proteins: Whey proteins possess outstanding techno-functional properties that contribute significantly to food quality and processing performance.

3.1 Solubility: Whey proteins exhibit excellent solubility over a broad pH range, facilitating incorporation into beverages and liquid foods.

3.2 Emulsification Properties: The amphiphilic nature of whey proteins allows stabilization of oil-water emulsions. Whey proteins rapidly adsorb at interfaces and reduce interfacial tension.

3.3 Foaming Properties: Whey proteins improve foam formation and stability in bakery products, whipped toppings, and aerated desserts.

3.4 Gelation: Heat-induced denaturation promotes protein aggregation and gel formation useful in yogurt, desserts, and processed foods.

3.5 Water-Holding Capacity: Protein hydration improves moisture retention and texture stability.

Table 3. Functional Properties and Industrial Applications of Whey Proteins

Functional Property	Mechanism	Major Food Applications
Solubility	Protein hydration	Beverages
Emulsification	Interfacial adsorption	Sauces and dressings
Foaming	Air incorporation	Bakery products
Gelation	Heat-induced aggregation	Desserts and yogurt
Water binding	Hydration interactions	Meat products
Film formation	Protein network formation	Edible packaging

4. Nutritional and Health Significance

4.1 Protein Quality: Whey proteins possess exceptionally high biological value and protein digestibility-corrected amino acid score (PDCAAS). Branched-chain amino acids, particularly leucine, stimulate muscle protein synthesis and recovery.

4.2 Bioactive Peptides: Enzymatic hydrolysis of whey proteins generates peptides exhibiting Antioxidant activity, Antihypertensive properties, Antimicrobial effects, Immunomodulatory activity and Anti-inflammatory potential

4.3 Antioxidant Activity: Sulfur-containing amino acids promote glutathione synthesis, thereby enhancing antioxidant defense systems.

4.4 Sports Nutrition and Clinical Applications: Whey proteins are extensively utilized in sports nutrition products because of rapid digestibility and anabolic effects (Czarniecka-Skubina E, et al., 2025).

Table 4. Bioactive Activities of Whey-Derived Peptides

Bioactivity	Mechanism	Potential Health Benefit
Antioxidant	Radical scavenging	Reduced oxidative stress
ACE inhibitory	Blood pressure regulation	Cardiovascular protection
Antimicrobial	Membrane disruption	Improved immunity
Immunomodulatory	Cytokine regulation	Enhanced immune response
Antidiabetic	Enzyme inhibition	Glycemic control

5. Emerging Technologies for Whey Valorization

5.1 Membrane Processing Technologies: Membrane technologies represent the cornerstone of modern whey processing.

Major Technologies include Ultrafiltration, Nanofiltration, Reverse osmosis, Electrodialysis and Diafiltration. These technologies enable production of WPC, WPI, lactose concentrates, and mineral fractions (Czarniecka-Skubina E, et al.,2025).

5.2 Spray Drying: Spray drying converts liquid whey into stable powder suitable for transportation and storage.

5.3 Fermentation Technologies: Microbial fermentation improves sensory quality, nutritional characteristics, and probiotic functionality.

5.4 Enzymatic Hydrolysis: Hydrolysis enhances digestibility and produces bioactive peptides.

5.5 Microencapsulation: Encapsulation technologies improve stability of whey-derived bioactives and probiotics.

6. Whey Utilization in Food Products

6.1 Functional and Nutritional Beverages: Fruit whey beverages represent one of the fastest-growing whey application sectors.

Advantages includes refreshing flavor, high nutritional value, good mineral content and improved consumer acceptability

Table 5. Sensory Evaluation of Whey-Based Beverages

Beverage Type	Overall Acceptability Score
Plain whey beverage	7.2
Mango whey beverage	8.6
Pineapple whey beverage	8.4
Probiotic whey beverage	8.7

6.2 Bakery Products: Whey proteins improve the dough rheology, crust colour, moisture retention and nutritional quality. Lactose contributes desirable Maillard browning reactions during baking.

6.3 Fermented Foods: Whey serves as an excellent substrate for probiotic cultures.

6.4 Confectionery Products: Whey solids are successfully utilized in the toffees, caramels, dairy sweets and chocolate fillings

6.5 Dairy Desserts and Ice Cream: Whey proteins improve whipping properties, body, texture, and melting resistance.

6.6 Extruded Snacks and Energy Bars: Whey proteins enhance protein enrichment and textural quality.

7. Whey in Circular Bioeconomy and Sustainability

7.1 Environmental Benefits: Valorization of whey significantly reduces environmental pollution associated with dairy waste disposal.

Table 6. Environmental and Economic Benefits of Whey Valorization

Parameter	Untreated Disposal	Whey Valorization
BOD load	Very high	Significantly reduced
Resource recovery	Minimal	Excellent
Economic return	Negligible	High
Sustainability	Poor	Strong

7.2 Circular Dairy Economy: Whey utilization supports waste minimization, resource efficiency, sustainable processing and circular bioeconomy approaches

8. Emerging Research Trends (2021–2026)

Current research areas include whey-derived bioactive peptides, precision fermentation, synbiotic whey beverages, edible films and biodegradable packaging, AI-assisted dairy processing, personalized nutrition, postbiotic production and nanotechnology applications (Czarniecka-Skubina E, et al. (2025)

9. Challenges and Industrial Constraints: Despite extensive potential, several challenges remain, eg. high processing cost, storage instability, lactose intolerance concerns, consumer perception, regulatory constraints and transportation cost of liquid whey. The advanced stabilization and fractionation technologies are expected to address many of these limitations (Luparelli et al., 2025).

10. Future Prospects: Future developments are expected to focus on Bioactive peptide isolation, Functional and therapeutic foods, Clinical nutrition products, High-protein beverages, Sustainable packaging materials, Green processing technologies and Integrated whey biorefineries.The integration of biotechnology, membrane processing, artificial intelligence, and food engineering will further expand the industrial significance of whey.

Conclusion

Whey has evolved from an environmentally problematic dairy by-product into one of the most valuable functional ingredients in the global food industry. Advances in dairy chemistry, membrane processing, fermentation technologies, enzymatic modification, and drying technologies have transformed whey into a versatile platform for development of functional foods, nutraceuticals, sports nutrition products, and sustainable food systems. Whey proteins exhibit excellent nutritional quality and techno-functional characteristics that significantly improve texture, flavour, stability, and nutritional profile of food products.

Scientific evidence demonstrates that whey valorization contributes simultaneously to environmental protection, economic sustainability, resource recovery, and product innovation. Emerging applications involving bioactive peptides, personalized nutrition, edible films, postbiotics, and circular bioeconomy strategies further highlight the future industrial significance of whey. Continued research on advanced processing technologies, bioactive compound characterization, process optimization, and commercial-scale implementation will strengthen the role of whey valorization in sustainable dairy processing systems.

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