Journal of Agriculture, Biology and Applied Statistics
Vol. 5, Nos. 1-2, 2026, pp. 99-108
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URL: www.arfjournals.com
https://doi.org/10.47509/JABAS.2026.v05i01-02.09

Valorization of Dairy By-Products for Sustainable Food Systems: A Review

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To Cite this Article

Bhumendra Tripathi, Priyanka Yadav & Aparna Sharma (2026). Valorization of Dairy By-Products for Sustainable Food Systems: A Review. *Journal of Agriculture, Biology and Applied Statistics,* 5: 1-2, pp. 99-108.

Abstract: The dairy processing industry generates vast quantities of by-products principally whey, buttermilk, and processing sludge—that, if discharged untreated, impose a severe organic pollution load on receiving water bodies. Over the past two decades, the perception of these streams has shifted from "waste" to "resource," driven by advances in membrane separation, enzymatic biotechnology, and fermentation science. This review synthesizes current knowledge on the valorization of dairy by-products, with emphasis on whey protein recovery, lactose-derived prebiotics, bioethanol and bioenergy generation, buttermilk phospholipid utilization, and circular-economy frameworks for dairy waste management. Particular attention is given to the Indian context, where paneer and chhana whey represent an especially large and underexploited resource. The review concludes that integrated, multi-product biorefinery approaches offer the most viable pathway to convert dairy by-products from an environmental liability into an economically and nutritionally valuable resource, supporting the broader goals of sustainable and circular food systems.

Keywords*: Whey Valorization, Buttermilk, Circular Economy, Dairy by-products, Sustainable Food Systems, Lactose*

1. INTRODUCTION

Global dairy processing converts raw milk into a wide array of consumer products—cheese, paneer, butter, and fermented beverages—but a substantial fraction of the milk solids and water entering a plant leaves it again as by-product streams rather than as finished product. Cheese and paneer manufacture alone generates roughly nine to ten litres of whey for every kilogram of cheese produced, and this whey

Received : 18 July 2026 • **Revised :** 05 September 2026 • **Accepted :** 10 September 2026 • **Published :** 19 October 2026

retains most of the lactose, soluble whey proteins, minerals, and water-soluble vitamins originally present in the milk (Pires et al., 2021). For decades this stream was regarded as a low-value effluent, commonly discharged, spray-irrigated, or fed to livestock without further processing. This is no longer acceptable, either environmentally or economically. Untreated dairy effluent carries a very high organic load, and its uncontrolled disposal depletes dissolved oxygen in aquatic systems and damages downstream ecosystems.

Sustainability concerns, tightening environmental regulation, and the recognition that dairy by-products are biochemically rich rather than merely polluting have together driven a substantial body of research into "valorization" the deliberate conversion of a waste stream into a value-added product. This shift in perspective mirrors a broader movement within the food and agricultural sciences, in which agroecological and circular-economy thinking increasingly treats processing residues as embedded resources rather than terminal outputs. For the dairy sector specifically, this reframing carries particular weight because milk processing occurs at enormous global scale, and even modest improvements in by-product recovery translate into substantial aggregate reductions in organic pollution load, alongside meaningful gains in the nutritional and economic value extracted from a given volume of raw milk.

This review examines the principal by-product streams of the dairy industry, the technological routes available for their valorization, and the environmental and economic rationale for adopting them, situating the discussion within the broader theme of agroecology and sustainable food production that underpins current global conversations on food security and environmental stewardship. The discussion proceeds from the composition and environmental burden of dairy by-products, through the major whey- and buttermilk-valorization technologies, to circular-economy framings and the specific challenges and opportunities relevant to the Indian dairy processing context, before concluding with a synthesis of future research priorities.

2. DAIRY BY-PRODUCTS: GENERATION, COMPOSITION AND ENVIRONMENTAL BURDEN

The two principal liquid by-products of the dairy sector are cheese/paneer whey and buttermilk, alongside dairy processing sludge generated during wastewater treatment. Whey is compositionally dominated by lactose (approximately 4.5–

5% w/v), together with soluble whey proteins (β-lactoglobulin, α-lactalbumin, immunoglobulins), minerals, and residual fat (Czarniecka-Skubina et al., 2025). Because lactose is responsible for the majority of its organic load, whey exerts an extremely high biochemical and chemical oxygen demand; reported values for cheese whey commonly range from roughly 40 to 60 g/L BOD and 50 to 80 g/L COD, driven predominantly by lactose and residual fat content (Zou & Chang, 2022). Discharge of such effluent without treatment causes severe oxygen depletion in receiving waters, harming aquatic life and violating discharge norms in most jurisdictions.

Buttermilk, generated during the churning of cream into butter, differs qualitatively from whey: it retains the milk fat globule membrane (MFGM), a phospholipid- and sphingolipid-rich structure that is largely absent from other dairy fractions (Barukčić et al., 2019). Although buttermilk is less polluting on a volume basis than whey, it remains an underused stream in most processing facilities, frequently sold at low value as animal feed or a minor beverage ingredient rather than being fractionated for its bioactive components.

At the systems level, dairy waste streams collectively represent a large, distributed source of recoverable proteins, lactose, lipids, and minerals, and their improper management constitutes both an environmental risk and a loss of nutritional and economic value (Obayomi et al., 2026). This dual framing—pollutant versus resource—is the conceptual foundation for the valorization strategies discussed in the sections that follow.

3. WHEY VALORIZATION STRATEGIES

3.1. Recovery and Application of Whey Proteins

Whey proteins possess a biological value higher than most other dietary proteins, including egg albumin, owing to their favourable essential amino acid profile, and they have documented physiological activity extending to antihypertensive, immunomodulatory, and antimicrobial effects (Barukčić et al., 2019). Their recovery is achieved primarily through membrane separation technologies ultrafiltration, microfiltration, and diafiltration—which concentrate whey protein while allowing lactose, minerals, and water to pass into the permeate fraction. These membrane-based routes have increasingly displaced thermal precipitation methods because heat treatment tends to denature whey proteins and compromise their functional properties, whereas non-thermal approaches such as membrane

filtration and high-pressure processing better preserve solubility, gelation, and foaming behaviour (Czarniecka-Skubina et al., 2025). Concentrated whey protein fractions are subsequently spray-dried to yield whey protein concentrate (WPC) or whey protein isolate (WPI) powders that are incorporated into functional foods, sports nutrition products, and infant formula. Notably, whey protein has also been explored as a carrier for micronutrient fortification: work conducted at the National Dairy Research Institute, Karnal, demonstrated that whey protein concentrate can be complexed with iron to produce a spray-dried WPC–iron complex with improved in vitro bioaccessibility relative to conventional iron sulphate fortificants, illustrating how a dairy by-product can be engineered into a functional ingredient with public-health relevance (Banjare et al., 2019).

3.2. Valorization of Lactose: Prebiotics and High-Value Derivatives

Lactose is the single largest organic component of whey by mass, yet it possesses comparatively low sweetness and limited direct commercial value, which has historically made it the most difficult whey constituent to valorize profitably (Rocha & Guerra, 2020). Contemporary biotechnological routes address this limitation by converting lactose into higher-value derivatives. Enzymatic transgalactosylation using β-galactosidases derived from organisms such as Aspergillus oryzae and Kluyveromyces lactis converts lactose into galacto-oligosaccharides (GOS), which function as prebiotic ingredients that selectively stimulate beneficial gut microbiota. Reported GOS yields vary considerably with substrate concentration and enzyme source, but sweet whey with a high initial lactose content has been shown to support substantially greater GOS conversion than dilute acid whey. Beyond GOS, lactose serves as the starting material for a range of other value-added compounds, including lactulose, lactobionic acid, and lactitol, each with established or emerging applications in the food, nutraceutical, and pharmaceutical sectors (Rocha & Guerra, 2020). Despite this technological promise, the industrial implementation of lactose recovery and derivatization continues to face practical barriers related to logistics, capital investment, and the fragmented, small-scale structure of much of the dairy processing sector, particularly in developing economies.

3.3. Whey as a Feedstock for Bioethanol and Bioenergy

Because whey is lactose-rich, inexpensive, and generated in stable, large quantities worldwide, it has attracted sustained interest as a fermentation feedstock for bioethanol

production (Zou & Chang, 2022). Conventional ethanol-producing yeasts such as Saccharomyces cerevisiae lack the metabolic pathway to ferment lactose directly, so whey-to-ethanol processes typically rely on naturally lactose-fermenting yeasts of the genus Kluyveromyces, on co-culture strategies that pair lactose-hydrolysing organisms with efficient ethanol producers, or on pre-hydrolysis of lactose using β-galactosidase prior to fermentation (Tesfaw, 2023). This bioconversion route offers a dual benefit: it generates a marketable fuel or beverage-grade ethanol while simultaneously reducing the organic load, and therefore the chemical oxygen demand, of the residual effluent, which lowers subsequent wastewater treatment costs. Beyond ethanol, whey and its permeate fraction have also been investigated as substrates for biogas generation through anaerobic co-digestion with other organic residues such as cattle manure, offering a further route to convert an otherwise polluting stream into recoverable thermal or electrical energy within an integrated dairy biorefinery framework (Obayomi et al., 2026).

4. BUTTERMILK: AN UNDERUTILIZED RESERVOIR OF BIOACTIVE LIPIDS

Although whey has received the greater share of research attention, buttermilk represents a comparatively underexploited by-product with distinctive nutritional value. Its defining feature is the milk fat globule membrane, a tri-layered structure rich in phospholipids and sphingomyelin that is largely lost from cream during the churning process and concentrates instead in the buttermilk fraction (Barukčić et al., 2019). MFGM-associated compounds have been linked in the literature to cholesterol-lowering, anti-inflammatory, and antimicrobial activity, including inhibitory effects against Helicobacter pylori, positioning buttermilk-derived phospholipid concentrates as candidate ingredients for cardiovascular- and gastrointestinal-health-oriented functional foods. Technologically, ultrafiltration can be used to concentrate buttermilk proteins and phospholipids while simultaneously improving its coagulation behaviour for downstream applications such as cheese manufacture, and the production of fermented or flavoured buttermilk-based beverages has repeatedly been identified as the most economically and technologically feasible route for buttermilk valorization at present (Barukčić et al., 2019). Nevertheless, both buttermilk and whey remain, in the assessment of several reviewers, insufficiently exploited relative to their compositional potential, largely because functional-beverage formulations based on these by-products can

be deficient in dietary fibre and require additional formulation work to achieve consumer-acceptable sensory quality.

5. CIRCULAR ECONOMY APPROACHES IN DAIRY BY-PRODUCT MANAGEMENT

A circular economy framing reconceptualizes dairy by-products not as terminal waste but as inputs to subsequent value chains, whether within the food sector or in adjacent sectors such as agriculture and energy (Obayomi et al., 2026). Under this framing, whey, buttermilk, and dairy processing sludge are treated as recoverable sources of protein, lactose, lipids, and minerals such as calcium and phosphorus, rather than as streams requiring only treatment and disposal. Dairy plants that actively recover or valorize whey rather than discharging it have been shown to markedly reduce key pollution indicators; recovery-oriented processing has been associated with substantial reductions in biochemical oxygen demand, chemical oxygen demand, fat content, and total nitrogen load relative to plants that do not recover whey (Czarniecka-Skubina et al., 2025), illustrating that valorization and pollution abatement are complementary rather than competing objectives.

Beyond direct food and beverage applications, circular-economy strategies extend dairy by-product use into agricultural and environmental domains. Treated dairy wastewater and residual nutrient streams have been applied in irrigation and soil-amendment contexts, and microbial and enzymatic bioprocessing routes allow high-value product recovery including organic acids, biopolymers, and pigments—directly from whey and dairy wastewater (Obayomi et al., 2026). Taken together, these approaches point toward an integrated dairy biorefinery model, in which a single processing facility recovers protein, lactose derivatives, bioenergy, and agricultural nutrients from what was formerly a single undifferentiated waste stream, thereby maximizing resource efficiency and minimizing net environmental burden across the value chain.

6. INDIAN PERSPECTIVE: PANEER AND CHHANA WHEY VALORIZATION

The valorization imperative is particularly acute in India, where paneer and chhana—rather than rennet-coagulated cheese constitute the dominant source of whey generation, owing to the scale of indigenous dairy product manufacture (Banjare et al., 2019). Paneer and chhana whey is typically acid-coagulated, and

its disposal is complicated by the fact that much of India's dairy processing occurs in small and medium-scale units that lack the capital and technical infrastructure required for whey recovery, meaning that a large proportion of this resource continues to be discharged or used only as low-value animal feed. This is a significant lost opportunity given that paneer/chhana whey carries an extremely high organic load, with reported biological oxygen demand and chemical oxygen demand values considerably exceeding permissible discharge limits.

Research conducted within Indian dairy science institutions has sought to close this gap. Concentration technologies such as single-effect evaporation have been used to reduce the volume of paneer whey prior to its incorporation into fermented products such as dahi, improving the nutritional density of the final product while simultaneously reducing the volume of effluent requiring disposal. Ultrasound-assisted ultrafiltration and spray-drying process intensification have similarly been investigated as means of improving whey protein concentrate recovery specifically from paneer and chhana whey, addressing the particular processing challenges posed by its acidic pH and higher mineral content relative to sweet cheese whey. Institutional work at the National Dairy Research Institute has further demonstrated that whey protein concentrate recovered from Indian dairy by-products can be functionalized for public-health applications, such as iron fortification, underscoring that valorization research in the Indian context is oriented not only toward pollution abatement but also toward nutritional security (Banjare et al., 2019). Scaling these approaches to the cooperative and small-processor level, where the bulk of Indian paneer and chhana production actually occurs, remains an important applied research priority.

7. CHALLENGES IN LARGE-SCALE VALORIZATION

Despite substantial technological progress, several barriers continue to constrain the widespread industrial adoption of dairy by-product valorization. First, capital cost remains a significant obstacle: membrane filtration, spray-drying, and enzymatic processing infrastructure require investment levels that are often beyond the reach of small and medium-sized dairy processors, particularly in regions where whey and buttermilk generation is most dispersed (Rocha & Guerra, 2020). Second, the logistics of whey collection and transport are complicated by its high water content and rapid microbial spoilage, which limit the geographic radius over which centralized valorization facilities can economically operate. Third, product-quality

and functional variability arising from seasonal, breed-related, and processing-related differences in raw milk composition can complicate the standardization of whey- and buttermilk-derived ingredients for food industry use. Finally, consumer acceptance of by-product-derived functional foods and beverages is not guaranteed, and sensory limitations—such as the reported dietary-fibre deficiency and flavour profile of buttermilk-based beverages—require targeted product development rather than direct substitution (Barukčić et al., 2019).

There is also a market-development dimension to these challenges. Ingredients such as whey protein concentrate, galacto-oligosaccharides, and MFGM-enriched buttermilk fractions compete in international markets against established plant-derived and synthetic alternatives, and their commercial viability depends on achieving cost parity or a demonstrable functional advantage. For smaller processors in particular, the absence of readily accessible technical extension services, quality-testing infrastructure, and access to export-grade certification can further limit the ability to convert laboratory-proven valorization methods into commercially viable product lines, even where the underlying science is well established (Pires et al., 2021). Addressing these barriers is therefore as much a matter of institutional and market infrastructure as it is one of process technology.

8. FUTURE PERSPECTIVES

Future research and industrial development in this field are likely to converge on integrated, multi-product biorefinery models rather than single-output valorization strategies. Coupling protein recovery, prebiotic oligosaccharide synthesis, and bioethanol or biogas generation within a single processing sequence would allow near-complete utilization of the lactose, protein, and mineral fractions of whey, while simultaneously minimizing the volume and organic strength of any residual effluent requiring conventional treatment (Zou & Chang, 2022; Obayomi et al., 2026). For buttermilk, continued advances in membrane concentration and lipid fractionation are likely to support a wider range of MFGM-enriched functional food and nutraceutical formulations beyond simple beverages. In the Indian context specifically, there is a clear need for decentralized, low-capital valorization technologies suited to the scale of cooperative and small-processor paneer and chhana production, alongside policy and extension support to help these units adopt even basic recovery practices such as whey protein concentration. Finally, integrating dairy by-product valorization within broader agroecological and food-

security frameworks—linking whey-derived nutrients back into fortified foods, animal feed, or agricultural soil amendments—would strengthen the alignment between dairy sector sustainability and wider circular-economy and sustainable-development goals.

9. CONCLUSION

Dairy by-products, historically treated as an environmental liability, are increasingly recognized as a biochemically rich resource whose valorization can simultaneously address pollution control, resource efficiency, and functional food development. Whey protein recovery, lactose-derived prebiotic synthesis, whey-to-bioethanol conversion, and buttermilk phospholipid utilization each represent technologically mature or maturing pathways for converting these streams into value-added products. Circular-economy and biorefinery frameworks offer the most promising route to realizing this potential at scale, but capital cost, logistical constraints, and the small-scale, dispersed structure of much of the global—and particularly the Indian—dairy processing sector remain significant barriers. Continued research attention to low-cost, decentralized valorization technologies, coupled with supportive policy frameworks, will be essential to fully translate the scientific promise of dairy by-product valorization into practical contributions to sustainable food systems.

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