Content is avaliable at SCOPUS

Meat Technology — Special Issue 66/3

www.meatcon.rs ▪ www.journalmeattechnology.com

UDK: 637.12:502.131.1

ID: 179484169

https://doi.org/10.18485/meattech.2025.66.3.37

Original Scientific Paper

Circular economy approaches in the dairy industry: strategies for waste utilisation and sustainable production

Jasna Lončina[1], Marija Kovandžić[1] and Tijana Ledina[1]*

[1] *University of Belgrade, Faculty of Veterinary Medicine, Bulevar oslobođenja 18, 11000 Belgrade, Serbia*

A R T I C L E I N F O

Keywords:
Dairy industry
Waste valorization
Sustainability
Whey
Bioplastic

A B S T R A C T

The dairy industry is a major part of the global agri-food system, associated with food production, but also with industrial waste and emissions. Significant amounts of whey, sludge, wastewater, and packaging are generated by the dairy chain. Effluents from dairy processing contain high loads of organic matter, suspended solids, fats, and nutrients. Circular economy principles offer the dairy sector an approach to transition from a linear to a regenerative model by transforming waste into value-added resources. Circular economy strategies applied in the dairy industry, including waste valorisation, energy recovery, nutrient recycling, and the use of biodegradable and recyclable packaging, can substantially improve the environmental performance of dairy systems, and contribute to sustainable development. The present work highlights the potential of circular economy access to transform dairy waste streams into valuable resources, contributing to environmental sustainability and economic resilience.

1. Introduction

The dairy sector plays an important role in ensuring food security by providing milk and dairy products. However, this comes with significant environmental challenges, such as greenhouse gas emissions, high water consumption, and large volumes of organic waste (*Milani et al.*, 2011; *Wang and Serventi*, 2019; *Olusegun*, 2024; *Mwirigi et al*., 2025).

The circular economy is a regenerative model designed to keep materials in use for as long as possible, extract maximum value from resources, and reduce impact on the environment (*Geissdoerfer et al*., 2017). In the context of the dairy industry, this involves optimising resource use, valorising waste and co-products, minimising waste, and designing processes that support closed-loop systems (*Adesra et al*., 2021). Given the growing regulatory, market and consumer pressures, the shift to sustainable production in the dairy sector has become essential. In this context, applying circular economy principles offers a valuable approach for transforming dairy industry waste into useful resources.

2. Dairy industry waste: sources and types

Dairy processing produces diverse by-products and waste. The volume, concentration and composition of dairy wastes varies depending on the scale and nature of operations, and it can be classified into two types: wastewater, i.e., effluent and solid waste (*Adesra et al*., 2021).

Wastewater in the dairy industry originates from different processing stages: from milk production on farm, milk receipt at the dairy, to processing

***Corresponding author:** Jasna Lončina, *jasna.djordjevic@vet.bg.ac.rs*

Paper received August 13rd 2025. Paper accepted August 14th 2025.
The paper was presented at the 63rd International Meat Industry Conference "Food for Thought: Innovations in Food and Nutrition" – Zlatibor, October 05th-08th 2025.
Published by Institute of Meat Hygiene and Technology – Belgrade, Serbia.

and product packaging (*Watkins and Nash*, 2014). Approximately one to three litres of wastewater are produced for every litre of milk produced (*Kushwaha et al.*, 2011). This effluent is often characterised by a high organic load. The organic load of the effluent is monitored by biological oxygen demand (BOD) and chemical oxygen demand (COD) in the range of 0.1-100 kg.m^{-3} with an index of biodegradability (BOD5/COD) typically in the range 0.4-0.8. Organic matter content is mainly due to the presence of carbohydrates (lactose) and proteins derived from milk. Additionally, fat content (0.1-10.6 kg.m^{-3}) suspended solids (0.1-22 kg.m^{-3}) and nutrients (N and P) also contribute to the contamination levels. Hygiene requirements in milk processing facilities and frequent cleaning result in effluents containing detergents and other cleaning agents (*Prazeres et al.*, 2012; *Slavov*, 2017). Without adequate treatment, the discharge of these effluents into natural water bodies can lead to eutrophication and degradation of aquatic ecosystems (*Prazeres et al.*, 2012). As such, effective wastewater management is a cornerstone of sustainable dairy operations (*Chokshi et al.*, 2016).

In addition to effluents, the dairy industry generates substantial amounts of solid waste, such as treatment sludge, residual solids from milk processing, and non-biodegradable packaging. Sludge is generally classified into two categories: chemical sludge and biological sludge. It contains both biodegradable organic matter and non-biodegradable solids (*Kwapinska et al.*, 2019), and such, can be valuable but also potentially hazardous when improperly managed (*Frąc et al.*, 2017). Sludge properties depend on the specific treatment technology applied (aerobic or anaerobic) and on the chemicals used in physicochemical processes. The quantity of sludge produced is directly proportional to wastewater volume (*Adesra et al.*, 2021). Packaging waste, mainly plastics, contributes to marine and terrestrial pollution unless recycled (*Esposito et al.*, 2020). Untreated disposal of dairy processing wastes through landfilling or incineration can lead to long-term environmental hazards, such as methane emissions and leachate pollution. Implementing proper segregation and recycling mechanisms, such as diverting organic waste, can significantly mitigate these impacts (*La Pera et al.*, 2023; *Scharff et al.*, 2023; *U.S. Environmental Protection Agency*, 2025).

3. By-products of dairy industry

The main by-products of the dairy industry, whey and buttermilk, were traditionally considered as waste, but are now being recognised for their rich nutritional composition and potential applications. Whey, by-product of cheese production, is rich in lactose, proteins, and minerals. For every kilogram of cheese produced, up to 9 litres of whey is generated (*Barukčić et al.*, 2019; *Lappa et al.*, 2019). Buttermilk is a by-product obtained during the churning of cream into butter, and it contains lactose, proteins, vitamins, and minerals, as well as bioactive compounds, such as probiotics and peptides. Due its rich nutritional content and functional properties, buttermilk is increasingly being valued not only as beverage but also as an ingredient in food formulations for improving texture, flavour, and shelf life (*Shah*, 2000; *Hameed et al.*, 2023). These by-products offer opportunities for value addition when appropriately processed and integrated into food, feed, or other industrial applications (*Prazeres et al.*, 2012).

4. Circular economy strategies in the dairy industry and waste valorisation pathways

Circular economy implementation in the dairy industry involves a range of strategies which aim to convert waste into valuable resources. Valorisation is a core principle of the circular economy, focusing on closing material loops, minimising environmental impact, and maximising resource efficiency (*Olusegun*, 2024; *Udourioh et al.*, 2025).

Whey and buttermilk, once considered low-value by-products, have been successfully transformed into valuable ingredients in the dairy industry. Whey proteins, rich in essential amino acids and bioactive peptides, are isolated using membrane filtration technologies and incorporated into high-value products, such as sports nutrition supplements, infant formulas, and functional foods, due to their excellent nutritional and functional properties. This valorisation not only improves economic returns but also supports sustainability by reducing waste (*Smithers*, 2008). Buttermilk, containing milk fat globule membrane components, proteins, and bioactive lipids, has gained attention for its emulsifying properties and potential health benefits. It is increasingly used in beverages, bakery products, and nutritional formulations, contributing to product innovation and enhanced nutritional profiles. Together, these examples illustrate the dairy industry's shift towards circular economy principles by converting traditional low-value streams into high-value functional ingredients (*Smithers*, 2008).

Dairy sludge can be treated through anaerobic digestion to produce biogas (typically CH_4 and CO_2). This renewable energy source can fulfil the facility's energy demand, while the nutrient-rich digestate can be used as an organic, nutrient-rich biofertiliser (*Scott and Blanchard*, 2021; *Duan et al.*, 2025). Anaerobic digestion contributes not only to waste reduction but also to lessening climate change stimulation (*Massé and Massé*, 2010).

Membrane-based separations, such as microfiltration, ultrafiltration, nanofiltration and reverse osmosis, are effective for selectively separating and concentrating valuable molecules while enabling the treatment and reuse of dairy process water. These techniques facilitate the recovery of components like proteins and lactose, contribute to reducing waste volumes, and enhance resource efficiency by closing production loops within the dairy industry (*Luo et al.*, 2011; *Reig et al.*, 2021; *Ahmad et al.*, 2022).

An emerging valorisation pathway involves converting lactose-rich streams, such as those from cheese whey, into bioplastics. Through microbial fermentation processes, lactose-containing residues can produce polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), which are biodegradable and suitable for use in food packaging. For example, *Bacillus megaterium* has been shown to produce polyhydroxybutyrate (PHB), a type of PHA, from whey (*Obruca et al*., 2011). Biorefinery approaches also propose the use of whey for PHA production, providing a more environmentally acceptable alternative to conventional plastics (*Asunis et al*., 2020). Microbial processes converting deproteinised dairy streams into biohydrogen and PHAs demonstrated high yields of biopolymer (~62%) illustrating both sustainability and circular economy potential (*Colombo et al*., 2019).

Biodegradable packaging films composed of proteins, polysaccharides and microbial cellulose represent a promising shift towards sustainable materials with decreased environmental impact. Whey protein-based films have excellent oxygen barrier and good mechanical properties, degrade naturally, and can be formulated to include active compounds, such as antimicrobial and antioxidant agents. Recent advancement includes multilayer structures integrating whey-based layers designed for strength and shelf life without compromising environmental performance (*Potrč et al*., 2020; *Reichert et al*., 2020; *Bugnicourt et al*., 2021; *Kandasamy et al*., 2021; *Singh et al*., 2025). Despite these benefits, biodegradable and compostable packaging materials face challenges, such as higher production costs than their fossil fuel-based counterparts, limited shelf-life stability, and consumer adaption (*Peelman et al*., 2013).

The application of circular economy principles in the dairy industry has unlocked new revenue streams by converting low-value or waste materials into marketable products. Whey valorisation, for instance, contributes to economic growth by enabling the recovery of functional ingredients and supporting sustainability within dairy operations (*Ţiţa et al*., 2024). Investments in renewable energy technologies, such as anaerobic digestion of whey, which generates biogas to provide energy and reduces carbon emissions, offer long-term cost savings and energy autonomy for dairy facilities (*Pires et al.,* 2021).

5. Conclusion

The Circular economy is a more sustainable pathway for dairy industry, aligning economic profitability with positive environmental impact. By implementing circular economy principles, dairy producers can reduce their ecological footprints, enhance resource sustainability, and build more resilient supply chains. Realising the full potential of these principles in the dairy sector will require investment in advanced technologies, as well as strong stakeholder engagement and policy support.

Disclosure Statement: No potential conflict of interest was reported by the authors.

Acknowledgements: The study was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract number 451-03-136/2025-03/200143).

References

Adesra, A., Srivastava, V. K., & Varjani, S. (2021). Valorization of dairy wastes: Integrative approaches for value added products. *Indian Journal of Microbiology*, 61(3), 270–278. https://doi.org/10.1007/s12088-021-00943-5

Ahmad, N. N. R., Ang, L. W., Teow, Y. H., Mohammad, A. W., & Hilal, N. (2022). Nanofiltration membrane processes for water recycling, reuse and product recovery within various industries: A review. *Journal of Water Processing Engineering*, 45, 102478. https://doi.org/10.1016/j.jwpe.2022.102478

Asunis, F., De Gioannis, G., Dessi, P., Isipato, M., Lens, P. N. L., Muntoni, A., Polettini, A., Pomi, R., Rossi, A., & Spiga, D. (2020). The dairy biorefinery: Integrating treatment processes for cheese whey valorisation. *Journal of Environmental Management*, 276, 111240. https://doi.org/10.1016/j.jenvman.2020.111240

Barukčić, I., Lisak Jakopović, K., & Božanić, R. (2019). Valorisation of whey and buttermilk for production of functional beverages – An overview of current possibilities. *Food Technology and Biotechnology*, 57(4), 448–460. https://doi.org/10.17113/ftb.57.04.19.6460

Bugnicourt E, Coltelli MB, Cinelli P, Lazzeri A, Canesi I, Braca F, Martínez BM, Alonso R, Agostinis L, Verstichel, S., Six, L., Mets, S., Gómez, E. C., Ißbrücker, C., Geerinck, R., Nettleton, D. F., Campos, I., Pieczyk, P., & Schmid, M. (2021). Bio-based packaging: Materials, modifications, industrial applications and sustainability. *Polymers*, 12(7), E1558. https://doi.org/10.3390/polym12071558

Chokshi, K., Pancha, I., Ghosh, A., & Mishra, S. (2016). Microalgal biomass generation by phycoremediation of dairy industry wastewater: An integrated approach towards sustainable biofuel production. *Bioresource Technology*, 221, 455–460. https://doi.org/10.1016/j.biortech.2016.09.070

Colombo, B., Calvo, M. V., Sciarria, T. P., Scaglia, F., Kizito, S. S., D'Imporzano, G., & Adani, F. (2019). Biohydrogen and polyhydroxyalkanoates (PHA) as products of a two-steps bioprocess from deproteinized dairy wastes. *Waste Management*, 95, 22–31. https://doi.org/10.1016/j.wasman.2019.06.028

Duan, Y., Wang, Z., Ganeshan, P., Sar, T., Xu, S., Rajendran, K., Sindhu, R., Binod, P., Pandey, A., Zhang, Z., Taherzadeh, M. J., & Awasthi, M. K. (2025). Anaerobic digestion in global bio-energy production for sustainable bioeconomy: Potential and research challenges. *Renewable and Sustainable Energy Reviews*, 208, 114985. https://doi.org/10.1016/j.rser.2024.114985

Esposito, B., Sessa, M. R., Sica, D., & Malandrino, O. (2020). Towards circular economy in the agri-food sector: A systematic literature review. *Sustainability*, 12(18), 7401. https://doi.org/10.3390/su12187401

Frąc, M., Jezierska-Tys, S., Oszust, A., Gryta, A., & Pastor, M. (2017). Assessment of microbiological and biochemical properties of dairy sewage sludge. *International Journal of Environmental Science and Technology*, 14, 679–688. https://doi.org/10.1007/s13762-016-1179-9

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Hameed, A., Anwar, M. J., Perveen, S., Amir, M., Naeem, I., Imran, M., Hussain, M., Ahmad, I., Afzal, M. I., Inayat, S., & Awuchi, C. G. (2023). Functional, industrial and therapeutic applications of dairy waste materials. *International Journal of Food Properties*, 26(1), 1470–1496. https://doi.org/10.1080/10942912.2023.2213854

Kandasamy, S., Yoo, J., Yun, J., Kang, H.-B., Seol, K.-H., Kim, H.-W., & Ham, J.-S. (2021). Application of whey protein-based edible films and coatings in food industries: An updated overview. *Coatings*, 11(9), 1056. https://doi.org/10.3390/coatings11091056

Kushwaha, J. P., Srivastava, V. C., & Mall, I. D. (2011). An overview of various technologies for the treatment of dairy wastewaters. *Critical Reviews in Food Science and Nutrition*, 51, 442–452. https://doi.org/10.1080/10408391003663879

Kwapinska, M., Horvat, A., Liu, Y., & Leahy, J. J. (2019). Pilot scale pyrolysis of activated sludge waste from milk processing factory. *Waste and Biomass Valorization*, 11, 2887–2903. https://doi.org/10.1007/s12649-019-00596-y

Lappa, I. K., Papadaki, A., Kachrimanidou, V., Terpou, A., Koulougliotis, D., Eriotou, E., & Kopsahelis, N. (2019). Cheese whey processing: Integrated biorefinery concepts and emerging food applications. *Foods*, 8(8), 347. https://doi.org/10.3390/foods8080347

Le Pera, A., Sellaro, M., Sicilia, F., Ciccoli, R., Sceberras, B., Freda, C., Fanelli, E., & Cornacchia, G. (2023). Environmental and economic impacts of improper materials in the recycling of separated collected food waste through anaerobic digestion and composting. *Science of the Total Environment*, 880, 163240. https://doi.org/10.1016/j.scitotenv.2023.163240

Luo, J., Ding, L., Qi, B., Jaffrin, M. Y., & Wan, Y. (2011). A two-stage ultrafiltration and nanofiltration process for recycling dairy wastewater. *Bioresource Technology*, 102(16), 7437–7442. https://doi.org/10.1016/j.biortech.2011.05.012

Massé, D. I., & Massé, L. (2010). Characterization of wastewater from hog slaughterhouses in eastern Canada and evaluation of their in-plant wastewater treatment systems. *Canadian Biosystems Engineering*, 52(6), 49–56.

Milani, F. X., Nutter, D., & Thoma, G. (2011). Invited review: Environmental impacts of dairy processing and products: a review. *Journal of Dairy Science*, 94(9), 4243–4254. https://doi.org/10.3168/jds.2010-3955

Mwirigi, D., Fekete-Farkas, M., & Borbély, C. (2025). From cow to climate – Tracing the path of dairy sustainability: Unveiling the impact on sustainable development goals through bibliometric and literature analyses. *Animals*, 17(7), 931. https://doi.org/10.3390/ani15070931

Obruca, S., Marova, I., Melusova, S., & Mravcova, L. (2011). Production of polyhydroxyalkanoates from cheese whey employing *Bacillus megaterium* CCM 2037. *Annals of Microbiology*, 61, 947–953.

Olusegun, O. (2024). Exploring the role of circular economy principles in minimizing dairy waste and maximizing resource efficiency. *ResearchGate*. https://www.researchgate.net/publication/387559061_Exploring_the_Role_of_Circular_Economy_Principles_in_Minimizing_Dairy_Waste_and_Maximizing_Resource_Efficiency

Peelman, N., Ragaert, P., De Meulenaer, B., Adons, D., Peeters, R., Cardon, L., Van Impe, F., & Devlieghere, F. (2013). Application of bioplastics for food packaging. *Trends in Food Science & Technology*, 32(2), 128–141.

Pires, A., García Marnotes, M., Díaz, O., Cobos, A., & Pereira, C. D. (2021). Dairy by-products: A review on the valorization of whey and second cheese whey. *Preprints*. https://doi.org/10.20944/preprints202104.0545.v1

Potrč, S., Zemljič, L., Sterniša, M., Možina, S. S., & Plohl, O. (2020). Development of biodegradable whey-based laminate functionalised by chitosan-natural extract formulations. *International Journal of Molecular Sciences*, 21(10), 3668. https://doi.org/10.3390/ijms21103668

Prazeres, A. R., Carvalho, F., & Rivas, J. (2012). Cheese whey management: A review. *Journal of Environmental Management*, 110, 48–68.

Reichert, C. L., Bugnicourt, E., Coltelli, M. B., et al. (2020). Bio-based packaging: Materials, modifications, industrial applications and sustainability. *Polymers*, 12(7), E1558. https://doi.org/10.3390/polym12071558

Reig, M., Vecino, X., & Cortina, J. L. (2021). Use of membrane technologies in dairy industry: An overview. *Foods*, 10(11), 2768. https://doi.org/10.3390/foods10112768

Scharff, H., Soon, H.-Y., Taremwa, S. R., Zegers, D., Dick, B., Zanon, T. V. B., & Shamrock, J. (2023). The impact of landfill management approaches on methane emissions. *Waste Management & Research*, 42(11), 1052–1064. https://doi.org/10.1177/0734242X231200742

Scott, A., & Blanchard, R. (2021). The role of anaerobic digestion in reducing dairy farm greenhouse gas emissions. *Sustainability*, 13(5), 2612. https://doi.org/10.3390/su13052612

Shah, N. P. (2000). Effects of milk-derived bioactives: An overview. *British Journal of Nutrition*, 84(S1), S3–S10. https://doi.org/10.1017/S000711450000218X

Singh, S., Habib, M., Rao, E. S., Kumar, Y., Bashir, K., Jan, S., & Jan, K. (2025). A comprehensive overview of biodegradable packaging films: Part I - source, additives, and preparation methods. *Discover Food*, 5, 41. https://doi.org/10.1007/s44187-025-00303-y

Slavov, A. K. (2017). General characteristics and treatment possibilities of dairy wastewater – a review. *Food Technology and Biotechnology*, 55(1), 14–28. https://doi.org/10.17113/ftb.55.01.17.4520

Smithers, G. W. (2008). Whey and whey proteins—From 'gutter-to-gold'. *International Dairy Journal*, 18(7), 695–704.

Tița, M. A., Moga, V.-M., Constantinescu, M. A., Bătușaru, C. M., & Tița, O. (2024). Harnessing the potential of whey in the creation of innovative food products: Contributions to the circular economy. *Recycling*, 9(5), 79. https://doi.org/10.3390/recycling9050079

U.S. Environmental Protection Agency, (2025). Quantifying methane emissions from landfilled food waste. EPA-600-R-23-064.

Udourioh, G. A., Solomon, M. M., & Okolie, J. A. (2025). A review of the valorization of dairy industry wastes through thermochemical, biological, and integrated processes for value-added products. *Food Science and Animal Resources*, 45(2), 375–408. https://doi.org/10.5851/kosfa.2025.e2

Wang, Y., & Serventi, L. (2019). Sustainability of dairy and soy processing: A review on wastewater recycling. *Journal of Cleaner Production*, 237, 117821. https://doi.org/10.1016/j.jclepro.2019.117821

Watkins, M., & Nash, D. (2014). Dairy factory wastewaters, their use on land and possible environmental impacts—a mini review. *Open Agriculture Journal*, 4, 1–9. https://doi.org/10.2174/1874331501004010001

Authors info

Jasna Lončina, https://orcid.org/0000-0001-5198-5549
Marija Kovandžić, https://orcid.org/0000-0003-3853-8546
Tijana Ledina, https://orcid.org/0000-0002-9903-1477