

Current trends and future perspectives in dairy by-product valorisation

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Abstract: The increase in milk production and demand for dairy products worldwide has led to the emergence of a wide variety of products in the sector, whilst a high volume of solid (sludge) and liquid waste is also generated. Dairy industry wastes, due to their high organic load (biological oxygen demand, chemical oxygen demand), high moisture content and variable composition, can cause significant environmental and economic problems when disposed of directly. The aim of this research is to determine current methods and possible future trends for the valorisation of dairy industry by-products (whey, casein and lactose-containing wastes, wastewater and sewage sludge). Literature from 2010–2025 was systematically screened in databases such as Web of Science, ResearchGate, ScienceDirect, PubMed and Google Scholar in line with the PRISMA guide, and a total of 34 documents were examined. According to the results, various technologies aimed at conversion into valuable products (valorisation) and integration into the circular economy have come to the fore. Thermochemical methods such as hydrothermal carbonisation (HTC), hydrothermal liquefaction (HTL), pyrolysis and gasification increase energy and chemical substance recovery from wastes with high moisture content. Biological methods (anaerobic and aerobic digestion, composting, microbial fermentation) yield value-added products such as biogas, compost, bioplastic and single cell protein (SCP). The necessity of integrated systems combining both thermochemical and biological approaches is also established in the literature.

Keywords: valorisation; industry; milk; thermochemical methods; biological treatment

Milk is a staple food for more than six billion people worldwide, and it is an important food not only in developing countries but also in many geographies such as Europe, North and South America, Australia, New Zealand and parts of the Middle East. Global milk production has increased dramatically over the last three decades, from approximately 500 million tonnes in 1983 to 769 million tonnes in 2013 and close to 800 million tonnes in 2015. According to OECD/FAO (2016),

production is expected to increase by 23% compared to 2015, reaching 177 million tonnes by 2025, and international dairy trade is expected to expand in parallel with this increase. In addition, annual growth rates are expected to be 2.3% for butter, 2.1% for cheese, 2.2% for skimmed milk powder and 1.8% for whole milk powder (OECD-FAO 2016). The global dairy products market is expected to increase from USD 893 billion in 2022 to USD 1 243 billion in 2028 (IMARC Group 2023).

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Due to the risk of rapid spoilage of milk and seasonal production fluctuations, excess milk is usually converted into butter, ghee, fermented milk products, cheese and other dry products with longer shelf lives. The main product groups span a wide range: drinking milk (40%), cheese (35%), milk powders (15%), concentrated milks (2%), fermented milks (2%) and butter (30%); in addition, various products such as ice cream, baby food, cream-based products, high-protein products and lactose are also included in the sector (Augère-Granier 2018). Although many new products have been developed in the dairy industry today, butter, cheese, drinking milk and cream remain the main products of the sector.

Whilst dairy industry by-products were mostly used as animal feed or fertiliser in the past, technological advances have enabled milk to be separated into its basic components such as lactose, milk fat fractions, minerals and proteins. High functional and nutritional value by-products such as casein, caseinates, milk protein concentrates (MPC), milk casein concentrates (MCC), whey protein concentrates (WPC) and whey protein isolates (WPI) are now obtained. In addition to the commercial opportunities brought by these new by-product streams, an increase in the amount of wastewater (liquid waste) and solid waste (sludge) can also be observed. The high chemical oxygen demand (COD: 1–10 g·L⁻¹) and biological oxygen demand (BOD: 0.3–5.9 g·L⁻¹) values of industrial wastewater can cause environmental problems by reducing dissolved oxygen levels in aquatic ecosystems (Kothari et al. 2017; Adetunji and Olaniran 2021). Treatment and disposal of these wastes is often an expensive and complex process; the sustainability perspective considers these wastes as resources with potential for value gain (valorisation) rather than seeing them solely as a burden to be disposed of (Adesra et al. 2021; Capanoglu et al. 2022).

One of the biggest challenges in waste management is the efficient utilisation of industrial sludge and side streams. The contribution of dairy industry wastes to greenhouse gas emissions is one of the important factors that exacerbate global warming. In this context, biological methods such as anaerobic digestion and fermentation and thermochemical processes such as pyrolysis, gasification and liquefaction are the main strategies that aim to convert dairy wastes into valuable outputs (Okolie et al. 2022; Walsh et al. 2022). There are studies in the literature indicating that obtaining biofuel, biofertiliser and other bio-based products from dairy wastes with the help

of microbial processes is adopted as a sustainable and environmentally friendly approach (Adetunji and Olaniran 2021; Capanoglu et al. 2022). Most of the existing studies focus on the technical dimension of certain methods and a holistic view on the valorisation of dairy industry wastes has not yet been sufficiently addressed.

This study aims to move beyond the fragmented approaches in the existing literature, where thermochemical and biological methods are addressed separately, and to establish an integrated perspective on the valorisation of dairy industry by-products. A holistic framework encompassing all fractions of dairy industry wastes – such as whey, casein residues, lactose-rich streams, treatment sludge and effluents – and comparatively evaluating thermochemical and biological strategies for their valorisation has not yet been sufficiently established. This research aims to fill this gap through the analysis of 34 documents obtained from a systematic screening of the literature between 2010 and 2025, conducted in accordance with the PRISMA guidelines. The original findings derived from this screening can be summarised as follows: (i) HTC and HTL methods demonstrate a distinct superiority over conventional incineration or gasification in converting high-moisture-content wastes; (ii) no single method can be sufficient for all waste types and variable conditions, rendering the integration of thermochemical and biological processes a necessity; and (iii) the redesign of metabolic pathways through recombinant microorganisms enables the high-yield conversion of low-value by-products such as whey into target molecules, thereby establishing a commercially viable value chain within the framework of the circular bioeconomy.

OVERVIEW OF DAIRY BY-PRODUCTS

Whey. Whey, an important by-product of cheese production, has a yellow-green colour due to its riboflavin content and contains approximately 65 g of solids per litre. It constitutes 85–95% of the initial volume of milk, and contains approximately 55% of the nutrients in the original milk and approximately 20% of the total protein (Okolie et al. 2022). Its exact composition varies depending on a variety of factors, including the source of the milk, the cheese production method (enzymatic or acidic coagulation), animal breed, seasonal changes, feeding conditions and stage of lactation. Whey is generally divided into two main categories, 'sweet whey' and 'acidic whey', based on the processing techniques applied (Walsh et al. 2022).

Whey is traditionally processed into dried products – whey powder, whey protein concentrates (WPC), whey protein isolates (WPI) or powdered lactose – by evaporation, ultrafiltration (UF), nanofiltration (NF) or reverse osmosis (RO) prior to drying (spray or freeze drying) (Chen et al. 2019). Whey proteins separated by these methods attract attention in the food industry with their emulsifier, gelling, water binding and foaming functions due to their physicochemical and nutritional properties. They are used in a wide variety of food products including soups, salad dressings, processed meat products, dairy products, bakery products or specific cheese varieties such as ricotta, and fermented whey beverages (Pereira et al. 2015; Piskorz et al. 2019). They are of nutritional, biological and functional importance due to their minor components such as bioactive peptides with antihypertensive, antioxidant and antimicrobial effects and indigestible oligosaccharides with prebiotic effects (Chaudhary et al. 2023). Since processes such as ultrafiltration and multistage evaporation require high capital and large facilities, adoption of these technologies by small and medium-sized enterprises is generally limited, restricting the commercial utilisation of whey for human consumption (Ryan and Walsh 2016). In some regions of Europe, only a small amount of whey is used in the production of cheese varieties in which the whey proteins are thermally coagulated (Pires et al. 2021).

The nutritionally beneficial composition of whey, which has a high production volume and environmental impact, has recently increased the interest in the valorisation of this by-product. In particular, the protein and mineral content of secondary whey obtained from sheep's milk is higher than that obtained from cow's milk, making it necessary to determine efficient methods of use. In the past, dairy companies disposed of secondary whey by spreading it on land or discharging it into rivers, lakes and seas (Pereira et al. 2015). Today, although the majority of this by-product is used as animal feed, it has the potential to be used as a raw material in biotechnological processes where high-value compounds are produced, as it contains many important elements such as denatured proteins, soluble peptides, oligosaccharides, lactose, non-protein-bound nitrogen components, water-soluble vitamins, minerals and free amino acids (Minhalma et al. 2007; Monti et al. 2018).

Secondary whey contains about half the dry matter of the original whey and consists mostly of lactose and minerals; it may also contain some residual fat and nitrogenous components that do not precipitate with

heat treatment. It is considered important to recover some of these solid components before final disposal (Cassano et al. 2019). Secondary whey from cow's milk generally contains 0.15–0.22% protein, 1.0–1.13% salt and 4.8–5.0% lactose, whilst the protein level of the one obtained from sheep's milk is higher. Secondary cheese whey of sheep origin has been reported to contain approximately 6.71% dry matter, 0.49% protein, 0.53% fat and 2.08% minerals (Pereira et al. 2002; Secchi et al. 2012). Considering these compositions, secondary whey can be evaluated in a wide range of applications including food product formulations, nutraceuticals and biofuel production (Piskorz et al. 2019).

One of the critical components of whey is lactose, which is especially prominent in baby foods and various food processing applications (Minhalma et al. 2007). Commercial separation of lactose is mostly achieved by increasing the solids content of the permeate obtained after UF containing 4–8% lactose and 0.5% salt to 60% using multistage evaporators. The resulting concentrate is subjected to crystallisation, then separated and dried to lactose powder. In order to increase yield and purity, some facilities also apply nanofiltration (NF) to remove some of the salt and increase the lactose concentration before crystallisation (Minhalma et al. 2007).

Whey, as a high-organic-load by-product of the dairy industry, not only poses an environmental problem but is also regarded as a valuable feedstock source for biosurfactant production. Semproli et al. (2022) synthesised an alkyl galactoside library from lactose-rich whey via a two-step enzymatic approach and demonstrated that these compounds serve as effective polar headgroups for non-ionic biosurfactants. In that study, alkyl β -D-galactopyranosides obtained through enzymatic transglycosylation of lactose were esterified with palmitic acid to produce *n*-butyl 6-O-palmitoyl-galactosides, and it was determined that galactopyranoside derivatives exhibited superior interfacial tension and emulsifying performance compared with galactofuranosides. Udourioh et al. (2025), in their comprehensive review on the valorisation of dairy industry wastes, also reported that bacterial strains such as *Lactococcus lactis* and *Streptococcus thermophilus* have been successfully used for biosurfactant production in whey-based media. Panesar and Kennedy (2012) showed that whey can be converted, via microbial fermentation, into value-added bioproducts such as lactic acid, ethanol, citric acid, single-cell protein and enzymes, and that these processes provide notable reductions in BOD. The same study emphasised that innovative

products such as exopolysaccharides, biofuels, biosurfactants and bacteriocins can also be obtained from whey, and stated that immobilisation technology improves production economics by enabling repeated cell use, higher cell densities and easier purification. Pescuma et al. (2015) likewise emphasised that whey can be converted by microbial fermentation into biofuels, biodegradable plastics and various metabolites, that fermentation processes are more economical than chemical synthesis, and that they do not generate toxic by-products.

From the perspective of biopolymer production, whey and lactose function as low-cost carbon sources in microbial and algal fermentation processes. Wu et al. (2011) reported that the green alga *Neochloris oleoabundans*, under mixotrophic cultivation conditions, used lactose as the sole carbon source to produce a high-viscosity exopolysaccharide at concentrations of up to $5 \text{ g}\cdot\text{L}^{-1}$, and that the weight-average molecular weight of this biopolymer was approximately 505 kDa. The biopolymer exhibited pseudoplastic rheological behaviour, its viscosity increased markedly with NaCl addition, and, with properties comparable to xanthan gum, it was shown to have application potential in industrial fields such as food, cosmetics and enhanced oil recovery. Zikmanis et al. (2020) demonstrated that whey and its derivatives can be used as renewable carbon and nitrogen sources in the production of biodegradable microbial polymers such as exopolysaccharides (EPS) and polyhydroxyalkanoates (PHA), and that high productivity can be achieved in fed-batch cultivation. The same review stated that, in cases where producer cultures cannot directly hydrolyse lactose, applying enzymatic hydrolysis with β -galactosidase as a pre-treatment, and optimising the carbon-to-nitrogen ratio through the use of whey permeate, supports biopolymer biosynthesis. Udourioh et al. (2025) systematically documented that biodegradable polymers such as polyhydroxyalkanoates (PHA) and poly-3-hydroxybutyric acid (PHB) can be produced from dairy industry wastes via bacterial strains such as *Thermus thermophilus*, *Ralstonia eutropha* and *Pseudomonas hydrogenovora*. Fancello et al. (2024) reported that second cheese whey (SCW), with a lactose content of up to 6%, is a cost-effective substrate for the production of biodegradable bioplastics, lactic acid, bioethanol and single-cell protein. Taken together, all these findings confirm that whey and lactose are technically and economically viable feedstocks for biosurfactant and biopolymer production.

Casein residues. Casein is a complex consisting of four basic proteins, α_{s1} -, α_{s2} -, β - and κ -casein, which constitute approximately 80% of the total protein in cattle, buffalo, goat or sheep milk. These proteins are found in the form of micelles or large aggregates in milk and can be separated by different techniques such as isoelectric precipitation (\sim pH 4.6), limited proteolysis, ultracentrifugation, ultrafiltration (UF) or microfiltration (MF). Depending on the applied processing method, the three basic products obtained – isoelectric (acid) casein, rennet casein and micellar casein – show different technological and functional properties (O'Sullivan et al. 2001; Mulvihill et al. 2003).

Casein is separated from whey proteins during the coagulation and sedimentation stages; it constitutes approximately 80% of milk protein. When precipitation is carried out by means of acid or enzyme (rennet), whey proteins in milk are denatured (for example, by heat treatment at $90 \text{ }^\circ\text{C}$ for 10 min); they are then precipitated together with casein micelles by adding acid at pH 4.6 or by using CaCl_2 . The commercial value of the casein precipitate obtained by this method is considered to be more limited compared to other types of casein (Monti et al. 2018).

Rennet casein is obtained by drying the water-insoluble casein fraction after coagulation with rennet. Although its solubility is low, it is especially preferred in the production of analogue cheese because it provides homogeneous distribution at high temperatures and in the presence of calcium-binding salts and forms a strong protein matrix during cooling (Monti et al. 2018). Acid casein is usually precipitated by lowering the pH value of skim milk to 4.6 (often using hydrochloric acid) and reaching the isoelectric point. This precipitated casein fraction is separated by mechanical methods such as centrifugation or filtration, then dried and turned into a commercial product. Since acid casein is not completely soluble in water, it is reported to be used mostly in applications that do not require solubility, such as protein bars or breakfast cereals (Monti et al. 2018).

Acid casein can be converted to water-soluble caseinate forms by adjusting the pH value to approximately 6.7. The most common approach is to produce sodium caseinate by adding sodium hydroxide (NaOH); potassium caseinate can also be produced using potassium hydroxide (KOH), ammonium caseinate with ammonium hydroxide (NH_4OH), and calcium caseinate with calcium hydroxide [$\text{Ca}(\text{OH})_2$] (Pereira et al. 2007). Although caseinate production is mostly carried out by freeze drying in laboratory environ-

ments, spray drying is widely used in industry; cylinder drying is a relatively less preferred method. The area of use of casein and caseinates is quite wide: they are found in many sectors from the food and beverage industry to industrial applications, from pharmaceuticals to cosmetics. The food and beverage sector covers more than 70% of the casein and caseinate market worldwide; this market is stated to grow by an average of 5% annually (Pereira et al. 2002). Due to their contributions in terms of structure, function and nutrition, caseins and caseinates can take on various roles such as emulsifier, stabiliser, gelling agent and nutritional supplement.

Casein and caseinates, which offer a versatile area of use as well as high nutritional value, are increasingly attracting attention. Different production processes such as acid, rennet or micellar casein have significant effects on the quality and commercial value of the final product. Production scale and process optimisation are therefore critical factors. The development of advanced process technologies and dissemination of cost-effective methods is expected to further expand the areas of use of casein and caseinates by contributing to innovative applications in the food, pharmaceutical and cosmetic sectors (Secchi et al. 2012).

Lactose-rich streams. By 2022, lactose demand is expected to exceed 1.3 million tonnes, driven primarily by the growing interest in nutritional products. The main reason why whey continues to be an important source of lactose is its widespread availability. The production process usually involves concentrating liquid whey or UF permeate under vacuum, then forming lactose crystals from the concentrate, which are

subsequently collected, washed and dried after being freed from impurities (Chen et al. 2019).

Beyond the basic process, lactose can be converted into a variety of derivative products by chemical reactions, fermentation or hydrolysis (Chen et al. 2019). Today, more than 70% of lactose is used in the food and beverage sector. In the food sector, the largest share is processed foods (including meat products) at 30%, followed by baby foods at 18% and confectionery products at 16%. Since lactose is not broken down by yeast in bakery products, it contributes to the Maillard reaction and forms the desired golden brown crust. In some confectionery products, lactose is also preferred to obtain high-quality caramel. According to Paterson (2011), approximately 780 thousand tonnes of lactose are used in this area annually (Chen et al. 2019).

Another important area of use of lactose in the food sector is the production of baby foods based on cow's milk, which has a lactose content of approximately 4.8%. Manufacturers can use edible or pharmaceutical quality crystalline lactose or demineralised whey. The pharmaceutical industry is also an important market for lactose: here lactose must be of high purity and is used as an excipient in tablet production and as a carrier in dry powder inhalers. Lactose is also used in bioplastic production, demonstrating its versatility across different sectors (Secchi et al. 2012).

Dairy sludge and effluents. The dairy industry, one of the largest agricultural sectors in the EU (O'Sullivan et al. 2001), is currently considered to be the largest producer of industrial food wastewater worldwide and a leading source of phosphorus-rich wastewater (Kolev Slavov 2017; Erkan et al. 2018). In order to meet

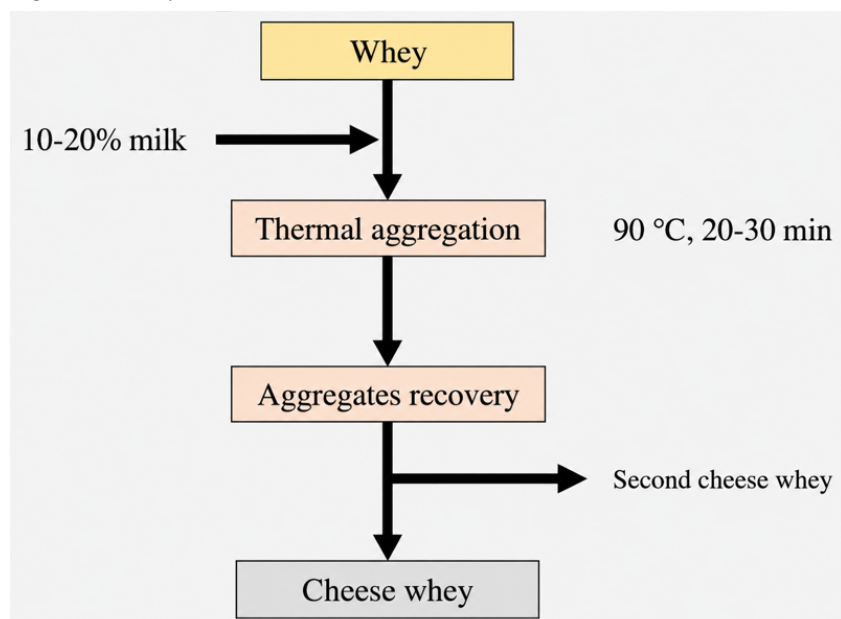


Figure 1. Whey cheese manufacturing and second cheese whey production (Walsh et al. 2022)

discharge standards, dairy wastewater is either sent to municipal wastewater treatment plants or treated on-site in factories with their own treatment plants. When conventional treatment methods are used, a significant amount of solid organic waste is generated, including dairy processing sludge (DPS); this sludge is treated on-site (Oliveira et al. 2019). According to EU legislation, DPS can be used in agricultural lands such as fields and pastures, as it contains many macro and micro nutrients necessary for healthy plant and animal growth (Pankakoski et al. 2000; Ryan and Walsh 2016). In addition to land application, DPS can also be evaluated as a compost additive, animal feed, biofuel or a material to be dried and burned (Ryan and Walsh 2016; Kwapinska et al. 2018). Since studies on DPS are limited, there is no comprehensive data on its fertiliser value and environmental risks. This lack of information makes it difficult to accept DPS as a sustainable commercial product.

DPS formed in cheese production facilities may contain approximately 50% more phosphorus compared to facilities processing fresh milk (Kolev Slavov 2017). Although heavy metal levels in DPS are reported to be low (Pankakoski et al. 2000; Kwapinska et al. 2018), some emerging organic pollutants can be found and transferred to plants due to their lipophilic properties (Ashekuzzaman et al. 2019). This situation leads to safety concerns about products grown in DPS-applied lands (Pankakoski et al. 2000).

Other concerns regarding land application of DPS include its high fat and suspended solids content, rapid

decomposition and strong odours (Shete and Shinkar 2013; Atallah et al. 2020). Therefore, DPS is difficult to store for long periods, has high transportation costs and is usually applied to lands close to dairy facilities. When there is insufficient agricultural land in the vicinity, excess DPS may occur, posing a risk of nutrient accumulation that could harm the aquatic ecosystem in the region (Kwapinska et al. 2018).

MATERIAL AND METHODS

Research materials. The material of this study consisted of scientific articles and documents accessed using certain keywords as a result of the literature search. In this context, the research material consists of documents obtained as a result of a detailed literature search conducted with the determined keywords such as 'evaluation of milk by-products', 'whey and its industrial use' and 'functional properties of dairy product sub-fractions'. International academic databases such as Web of Science, ResearchGate, ScienceDirect, PubMed and Google Scholar were used for literature compilation. The sources in the form of articles and reviews examined within the scope of the research were compiled to cover studies from the last decade (2010–2025). The publications obtained as a result of the search were evaluated in terms of valorisation strategies, functional properties, health and food industry applications, and their future perspectives, and the obtained data were systematically classified and presented.

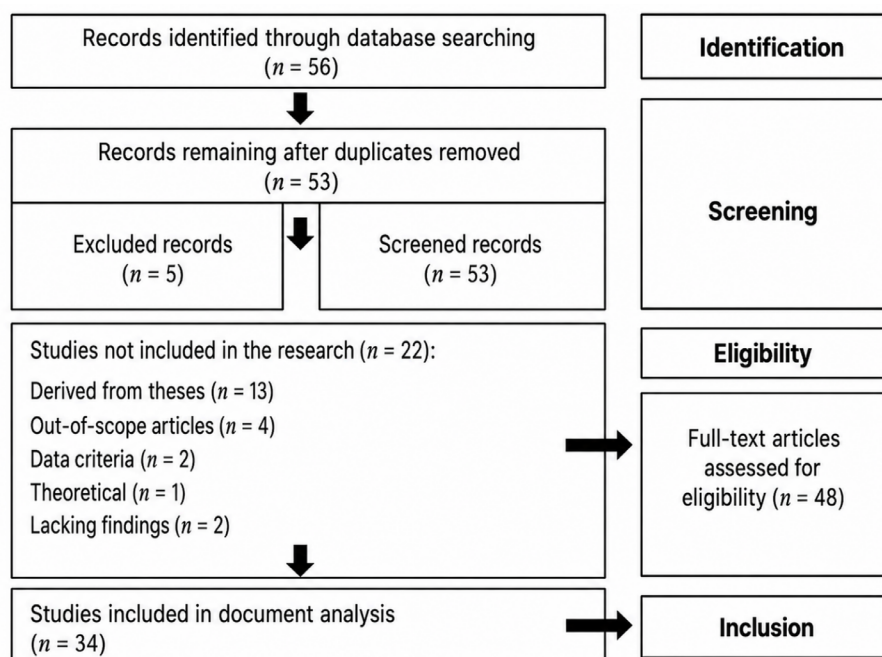


Figure 2. PRISMA diagram

Data analysis. The research started with the identification phase, in which a total of 56 documents were accessed; 53 documents were evaluated in the screening phase after duplicate records were removed. In the eligibility phase, 48 full texts that could be accessed were evaluated for eligibility and 22 of them were not included in the research. Among the studies not included, there are 13 documents produced from theses, 4 documents that are out of the field, 2 documents that are out of the date criterion, 1 document that is theoretical and 2 documents that do not contain findings. The remaining 34 documents were included in the study. In this study, a flow diagram was prepared in line with the PRISMA guide (Navarro et al. 2017) and presented in Figure 2.

As shown in Figure 2, the sources included in the study were examined using document analysis and secondary data analysis techniques. The advantages (e.g. reduced costs, resource utilisation efficiency, environmental sustainability) and challenges (e.g. legal regulations, technical infrastructure deficiencies, consumer acceptance) related to the evaluation of milk by-products were systematically classified and addressed through document analysis. Document analysis was used to qualitatively evaluate the effects of milk by-products on production, food safety and sustainability in the dairy and food sector. Secondary data analysis of data obtained from previous studies was applied to reveal the effects of milk by-products on the economy, sectoral efficiency and sustainability.

RESULTS AND DISCUSSION

The dairy industry produces high amounts of solid (sludge) and liquid (effluent) waste due to the wide variety of production and cleaning stages (Kolev Slavov

2017). Whilst chemical and biological sludges are included among solid wastes, liquid wastes are generally considered important due to their high organic load. A facility processing an average of 500 000 L of milk per day can produce 200–350 kg of sludge, demonstrating that sludge disposal in particular can cause high operating costs (60% of the total cost) (Perkins 2019). Since liquid wastes (DWW) contain milk-derived components such as carbohydrates, proteins and fat, they rapidly lead to oxygen depletion and disrupt the environmental balance when discharged without treatment (Atallah et al. 2020). In addition, the high moisture content of dairy industry wastes makes it difficult to process these wastes by traditional thermochemical methods such as direct incineration or gasification (Horvat et al. 2019; Kwapinska et al. 2020). Both HTC and HTL are approaches that aim to obtain carbon-rich products by using water as solvent, catalyst and/or reaction medium under special conditions (subcritical or supercritical) (Healy et al. 2016). HTL can provide higher efficiency in the dissolution of biomass and conversion to bio-oil due to the use of supercritical water (280–370 °C, 221 bar) (Lachos-Perez et al. 2021, 2022). It has been stated that the calorific value of bio-oil obtained from dairy industry waste increases and this method offers disposal opportunity by reducing the chemical oxygen demand (COD) of wastewater (Jayashree et al. 2014; Settanni et al. 2020). Pyrolysis is another thermochemical method carried out in an oxygen-free environment in the temperature range of 300–600 °C, yielding tar (bio-oil), gas and solid product (biochar) (Horvat et al. 2019).

Whilst fast pyrolysis (Figure 3) is generally preferred due to its high bio-oil yield, bio-oil yield is lower in slow pyrolysis; on the other hand, biochar yield can be higher (Lachos-Perez et al. 2021). Although the high moisture

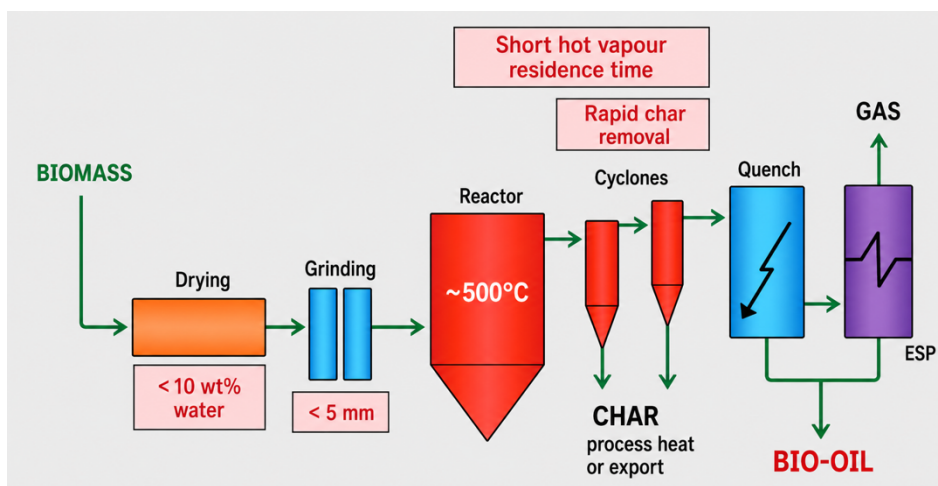


Figure 3. Typical scheme for production of bio-oil via fast pyrolysis (Lachos-Perez et al. 2022)

and nitrogen content of dairy sludge complicates the pyrolysis process, small-capacity pyrolysis units at the local scale offer a sustainable recycling opportunity by obtaining biochar (Theegala and Midgett 2012). The quality and potential usage areas of the products (biochar and bio-oil) obtained by this method are determined by the nutrients (N, P, K) and pollutants (heavy metals, volatile compounds) they contain (Kolev Slavov 2017).

The processing of dairy industry wastes by thermochemical methods (gasification, hydrothermal gasification etc., Figure 4) enables the production of syngas and other value-added products, depending on the use of high temperatures (800–1 000 °C and above) and appropriate oxidising agents (air, steam, supercritical water etc.) (Chen et al. 2018). The CO and H₂-rich syngas generated during the gasification process can be used directly as fuel or converted into various compounds such as methanol, ethanol, dimethyl ether (DME) (Perera et al. 2021). Studies have shown that the lower heating value and gasification efficiency of the produced gases increase with the increase in operating temperature, but the moisture content of the waste and elements such as salt and heavy metals in its chemical composition can negatively affect the process (Bridgwater 2018). Hydrothermal gasification (supercritical water gasification) offers an important alternative for biomasses with high moisture content such as dairy industry waste. This method stands out with its lower solid residue (char) formation and rapid conversion compared to traditional gasification processes (Zhang et al. 2021a).

In the physicochemical examination of wastewater originating from the dairy industry, there is a wide range of changes observed in parameters such as pH, BOD, COD and suspended solids (SS) (Maroušek 2014). Detergents and similar chemicals used in cleaning processes mix with wastewater; factors such as leak-

age, overflow and production control deficiencies increase the amount of waste (Adetunji and Olaniran 2021). Dairy industry wastes are produced in different compositions depending on seasonal changes and this may affect the treatment processes (Oliveira et al. 2019). Traditional disposal methods such as landfilling and incineration are insufficient in terms of increasing waste amount and environmental sustainability (Kuo et al. 2014). Reusing wastes and converting them into valuable products (valorisation) offers both economic and ecological advantages (Chang et al. 2023). Dairy wastes, especially those with high moisture content, can be converted into fuel, fertiliser or other value-added products by evaluating them in an integrated manner with thermochemical methods (pyrolysis, gasification, hydrothermal treatment etc.) and biological processes (anaerobic digestion, composting etc.) (Bhaskar et al. 2011). The hydrothermal carbonisation (HTC) process has the potential to obtain both a high carbon solid product called 'hydrochar' and various valuable components in liquid and gas phases by processing dairy industry wastes at high pressure and temperature range of 100–374 °C (Gómez et al. 2020; Khalaf et al. 2023). Hydrochar obtained by HTC can be hydrophobic and have high calorific value comparable to lignite coal in terms of fuel properties; on the other hand, the retention of nutrients such as nitrogen or phosphorus in the fuel can lead to NO_x emissions during combustion, thus requiring pretreatment or nutrient recovery strategies depending on the application (Assamoi and Lawryshyn 2012). In addition, parameters such as temperature, pH, retention time and character of the waste significantly affect hydrochar yield and nutrient distribution (Audu et al. 2020). The balanced selection of these parameters is of critical importance both in terms of energy efficiency and the use of the liquid phase obtained as a by-product as a fer-

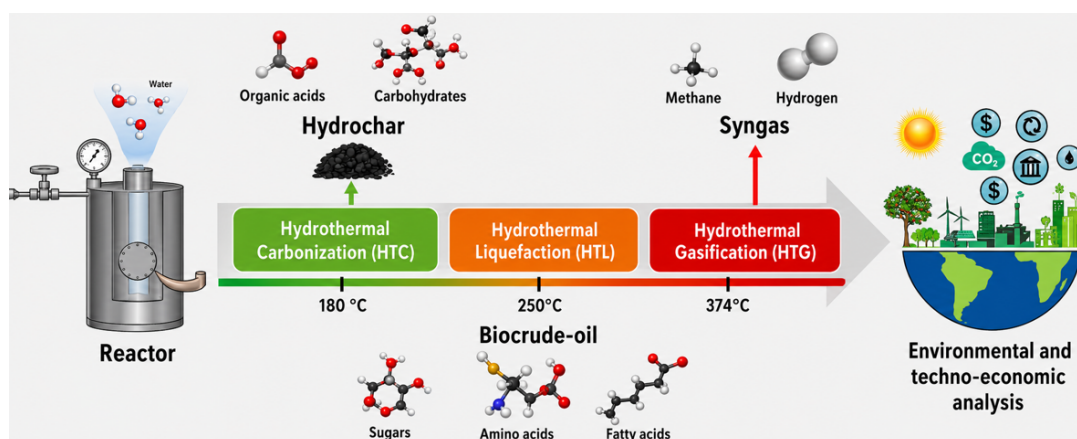


Figure 4. Hydrothermal carbonisation, liquefaction and gasification (Healy et al. 2016)

tiliser or chemical precursor (Lachos-Perez et al. 2022). HTC and similar innovative technologies should therefore be considered together with process optimisation and nutrient recovery approaches in order to obtain high value-added products from dairy industry wastes.

Thermochemical methods (HTC, HTL, pyrolysis etc.) have a remarkable potential in reducing the problems caused by the high moisture content and organic load of dairy wastes. HTC and HTL stand out with their ability to convert especially high-moisture wastes into fuel or valuable chemical precursors (Healy et al. 2016), and the pyrolysis process has also been considered important in terms of being easier to scale and obtaining a product with versatile uses such as biochar (Theegala and Midgett 2012). The process parameters of each method (temperature, pressure, residence time, pH, catalyst, etc.) have a great impact on product yield and product distribution (Suman et al. 2017).

In HTL, the high catalytic properties of supercritical water increase bio-oil formation whilst at the same time there is potential to increase the energy efficiency of the process. Low solids content may limit bio-oil yield, and issues such as product viscosity or stability may require additional treatment/purification steps (Minhalma et al. 2007). The possibilities of using biochar as a fertiliser, fuel additive or adsorbent should be investigated with appropriate process optimisation and additional treatment approaches (e.g. gas cleaning, tar removal) (Audu et al. 2020). For a successful application, the specific parameters and product properties of each method must be carefully evaluated, and process optimisation and treatment/development steps must be designed according to the final use of the product.

Gasification has the potential to produce energy and chemical products from dairy industry sludge and wastewater. The success of the process depends on the management of basic parameters such as temperature, pressure, oxidising agent and reactor design (Lampi 2001). In traditional gasification (with oxidants such as air, steam etc.), the process operating under conditions below the stoichiometric air/fuel ratio can increase the calorific value of the produced gas, while very high moisture content increases energy consumption and reduces efficiency (Parashar et al. 2016). Hydrothermal gasification, with high pressure and temperatures ranging from 400 °C to 700 °C, enables the conversion of dairy waste into gas to a large extent in a short time and reduces tar formation compared to traditional gasification (Zhang et al. 2021b). Extensive pilot and scale-up studies are still needed for the continuity and energy efficiency of the process.

The utilisation of dairy industry wastes by biological methods offers significant advantages in terms of both reducing environmental pollution and obtaining high value-added products [e.g. biogas, compost, enzymes, single-cell protein (SCP), bioplastics] (Khalaf et al. 2023). Anaerobic and aerobic processes are the most widely used technologies in this field, and products such as energy (biogas, hydrogen) or organic fertiliser are produced through the microbial conversion of organic components such as carbohydrates, proteins and fats in milk waste (Joshiba et al. 2019; Adesra et al. 2021). In the anaerobic digestion (AD) process, biogas, mainly consisting of CO₂ and methane (CH₄), is obtained by the decomposition of organic matter in an oxygen-free environment, whilst the remaining digestate can be used as fertiliser in agricultural areas (Kwapinska et al. 2023). Among the aerobic processes, methods such as activated sludge process (ASP), rotational biological contactors (RBC), batch reactor (SBR) and aerobic composting are used (Oliveira et al. 2019). Microbial-based transformations such as lactic acid fermentation, SCP production and polyhydroxyalkanoate (PHA) synthesis have the potential to evaluate dairy wastes on an industrial scale (Raziq et al. 2020; Koukoumaki et al. 2024). The digested sludge produced in biological processes is rich in nutrients (nitrogen, phosphorus etc.) and is used directly as fertiliser or soil conditioner (Kwapinska et al. 2023). Aerobic processes are effective in reducing odour and pathogens through biological oxidation, and the resulting compost or stabilised waste can be used in agriculture (Joshiba et al. 2019). Since a single biological method cannot always efficiently process all waste types and variable conditions alone, it has been stated that anaerobic and aerobic processes or biological and thermochemical methods should be used in an integrated manner (OECD/FAO 2016). Integrated systems make it possible to obtain high levels of bioenergy (biogas, hydrogen etc.) and value-added by-products (such as compost, hydrochar, SCP) by evaluating both wet and dry dairy wastes.

Recombinant microorganisms and metabolic engineering strategies play a decisive role in increasing the production of bioactive compounds from dairy industry wastes. Keasling (2010) demonstrated that metabolic engineering can produce a broad spectrum of chemicals from inexpensive starting materials and that microbial production of natural products can be enabled by transferring specific enzymes or entire metabolic pathways into engineered microorganisms. Boumaiza et al. (2018) achieved the recombinant production of the sweet protein

MNEI by cultivating *Lactococcus lactis* on cheese whey using the nisin-controlled gene expression (NICE) system, and revealed the decisive effect of codon optimisation on protein yield. Nadal et al. (2009) achieved the production of 1 400 mg·L⁻¹ diacetyl and acetoin at pH 5.5 from whey permeate by transferring the *ilvBN* genes from *Lactococcus lactis* into *Lactobacillus casei* and introducing mutations in the lactate dehydrogenase and pyruvate dehydrogenase genes. Meng et al. (2020) produced 65.5 g·L⁻¹ 2,3-butanediol from whey powder at a yield of 0.44 g·g⁻¹ by deleting by-product pathways in *Klebsiella oxytoca*. Ma et al. (2024) introduced heterologous metabolic pathways into *Clostridium saccharoperbutylacetonicum* and obtained 15.1 g·L⁻¹ butanol and 2.7 g·L⁻¹ butyl acetate from acid whey. Chaudhary et al. (2023) emphasised that different microbial cell factories are effectively used to convert dairy wastes into environmentally friendly products such as biofuels, biopolymers and single-cell protein through aerobic and anaerobic processing.

The economic justification of these approaches is shaped by the reduction of waste disposal costs and the conversion of low-value by-products into high value-added chemicals. Panesar and Kennedy (2012) stated that whey, as a rich growth medium, can be converted into bioproducts such as lactic acid, ethanol and enzymes, and that immobilisation technology strengthens economic feasibility by enabling continuous production. Wang et al. (2023) demonstrated the biosynthesis of (S)-equol from soy whey using recombinant *Escherichia coli*, achieving a substrate yield of 0.96 mol·mol⁻¹ and a concentration of 91.5 mg·L⁻¹, thereby proving that a waste by-product can be converted into a valuable bioactive compound. Liu et al. (2020) showed that a naturally occurring (non-engineered) *L. lactis* isolate could produce acetoin from low-value dairy side streams at a titre of 41 g·L⁻¹ and at a level exceeding 90% of the theoretical yield. Volk et al. (2022) documented that metabolic engineering advances systematically within the design-build-test-learn framework and provides the foundation for molecule production at industrial scale. Taken together, these findings confirm that redesigning metabolic pathways through recombinant microorganisms enables the high-yield conversion of organic components in dairy wastes into target molecules, and that this transformation both alleviates environmental burden and establishes a commercially viable value chain.

CONCLUSION

The study has shown that the difficulties encountered in the disposal of dairy by-products due to their high moisture content and organic load can be overcome by both thermochemical and biological methods. Methods such as HTC, HTL and hydrothermal gasification, where water is used as a solvent or catalyst under high temperature and pressure, increase the energy recovery potential by enabling the conversion of wastes with high moisture content into fuel or valuable chemical precursors. Other thermochemical methods such as pyrolysis and traditional gasification can be used for waste streams with lower moisture content, and thus various products such as bio-oil, biogas and biochar can be obtained. Since the efficiency of these methods depends on parameters such as operating temperature, pressure, pH, residence time and presence of catalyst, process optimisation and additional treatment/adaptation applications are of great importance.

The transformation of dairy industry wastes with the help of microbial and enzymatic processes (e.g. anaerobic and aerobic digestion, composting, single cell protein or bioplastic production) offers advantages both in reducing waste volume and in obtaining high value-added products. Considering that a single method cannot always be sufficient for all waste types and variable conditions, thermochemical and biological methods should be used in an integrated manner. The conversion of whey, sludge and wastewater into high value-added bioproducts under the biorefinery concept represents one of the most promising approaches from the perspective of circular bioeconomy principles. Udourioh et al. (2025) showed that dairy industry wastes can be converted into value-added products such as biogas, biofertiliser, biopolymers and biosurfactants through thermochemical, biological and integrated processes, and that the integration of hydrothermal carbonisation with pyrolysis, or anaerobic digestion with thermochemical processes, offers advantages in the valorisation of both wet and dry wastes. Chaudhary et al. (2023) emphasised that different microbial cell factories convert dairy wastes into environmentally friendly products such as biofuels, biopolymers and single-cell protein, and that this transformation is directly aligned with the Sustainable Development Goals. Within this biorefinery vision, polyhydroxyalkanoate (PHA)-based bioplastic production occupies a privileged position. Zikmanis et al. (2020) showed that whey

and its derivatives are used as renewable carbon and nitrogen sources in the production of biodegradable microbial polymers such as PHA, and Fancello et al. (2024) reported that second cheese whey is a cost-effective substrate for biodegradable bioplastics.

The future contribution of genetically engineered microbe-assisted microbial processes to these integrated biorefinery systems is shaped by increasing production yields and expanding substrate utilisation capacity. Meng et al. (2020) achieved 2,3-butanediol production from whey powder at a yield of $0.44 \text{ g}\cdot\text{g}^{-1}$ by deleting by-product pathways in *Klebsiella oxytoca*, and Ma et al. (2024) enabled the utilisation of all carbon sources in acid whey by introducing heterologous pathways for lactose, galactose and lactate metabolism into *Clostridium saccharoperbutylacetonicum*. Boumaiza et al. (2018) demonstrated that *Lactococcus lactis* can be used effectively for recombinant protein production on cheese whey with minimal pre-treatment. Volk et al. (2022) emphasised that metabolic engineering progresses systematically within the design-build-test-learn framework and provides the foundation for molecule production at industrial scale. Keasling (2010) predicted that cells specifically designed for the desired chemical and production process will be used in the future, and that metabolic engineering will become competitive with synthetic organic chemistry. Udourioh et al. (2025) further stated that investigating genetically engineered microbes to increase bioactive compound production should be a focus of future studies, and that data-driven approaches should be used in the optimisation of dairy waste valorisation processes. When these evaluations are considered as a whole, it becomes clear that genetic engineering tools increase substrate flexibility, enhance product selectivity and strengthen economic feasibility in integrated biorefinery systems; therefore, the integration of these technologies with biological and thermochemical processes has become essential for the full valorisation of dairy wastes within the framework of the circular bioeconomy. Both economic and ecological benefits will thus be provided in waste management processes, and dairy industry by-products will be utilised in accordance with sustainability principles.

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