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REVIEW

Recent advances in whey processing and valorisation: Technological and environmental perspectives

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Whey has several environmental risks if disposed of as waste in watercourses. However, there are numerous valorisation techniques to convert it into valuable and highly nutritious products. Techniques such as membrane filtration may be utilised, but these are not applicable to all categories of whey. Novel methodologies that are agile enough to deal with whey variability can produce valorised products. This review assesses the capability of whey processing techniques, applications and methodologies, discussing pertinent research that can innovate product development further. It focuses on environmental impacts of whey as a waste and ways of minimising it.

Keywords Whey, Cheese, Dairy effluent, Valorisation, Membrane processes, Pollution.

INTRODUCTION

The global dairy sector is under constant change following, for example, the new regional dairy policy (i.e. European Union (EU)) and the outcomes of ongoing negotiations in the World Trade Organization. Dairy market fluctuations and price volatility will be a constant challenge to the future dairy industry (Geary *et al*. 2010).

Whey, by-product generated during the manufacturing of cheese and casein-based dairy products, is rich in nutrients and has several commercial uses. However, whey is highly contaminated with a high organic load (Panghal *et al*. 2018). The waste generated in different dairy industries can be utilised in different value-added products (Figure 1) with the help of advanced technologies.

Approximately 80–90% of milk entering cheese manufacturing facilities becomes whey, with an estimated 180–190 million tonnes of waste whey produced globally each year, with 100-million tonnes of this cheese whey (Chandrapala *et al*. 2015; Flinois *et al*. 2019). This figure was first reported in 2018. Based on a 1–2% annual increase, this would now sit at around 187–206 million tonnes this year and 203–241 million tonnes come 2030 should the projected growth continue. Of this total, 40-million tonnes are produced within the EU alone, with 13-million tonnes of this annual surplus of cheese whey (Zotta *et al*. 2020). The high volumes of waste whey produced present environmental risks and effluent treatment is necessary because of these (Spalatelu 2012).

Due to consumer demand for coagulated milk products, such as Greek yoghurt, which has tripled in recent years, waste whey production volumes have increased. Consequently, the volume of whey generated has increased by 1–2% annually (Sharma *et al*. 2018; Mano *et al*. 2020).

Previously, waste whey was discharged via land applications, directly into receiving waters without pretreatment, stored in tanks or discharged in sewage (Prazeres *et al*. 2012). Alternative disposal methodologies involved the utilisation of cheese whey as a fertiliser, due to its available nutrient content. However, these routes have environmental risks because of the high biological oxygen demand (BOD) and chemical oxygen demand (COD). In water bodies, they are polluting water and have the potential to kill aquatic organisms (Pal and Nayak 2016; Lindsay *et al*. 2018). Waste regulations have restricted this disposal, with the resulting increased effluent treatment costs stimulating the development of the whey product

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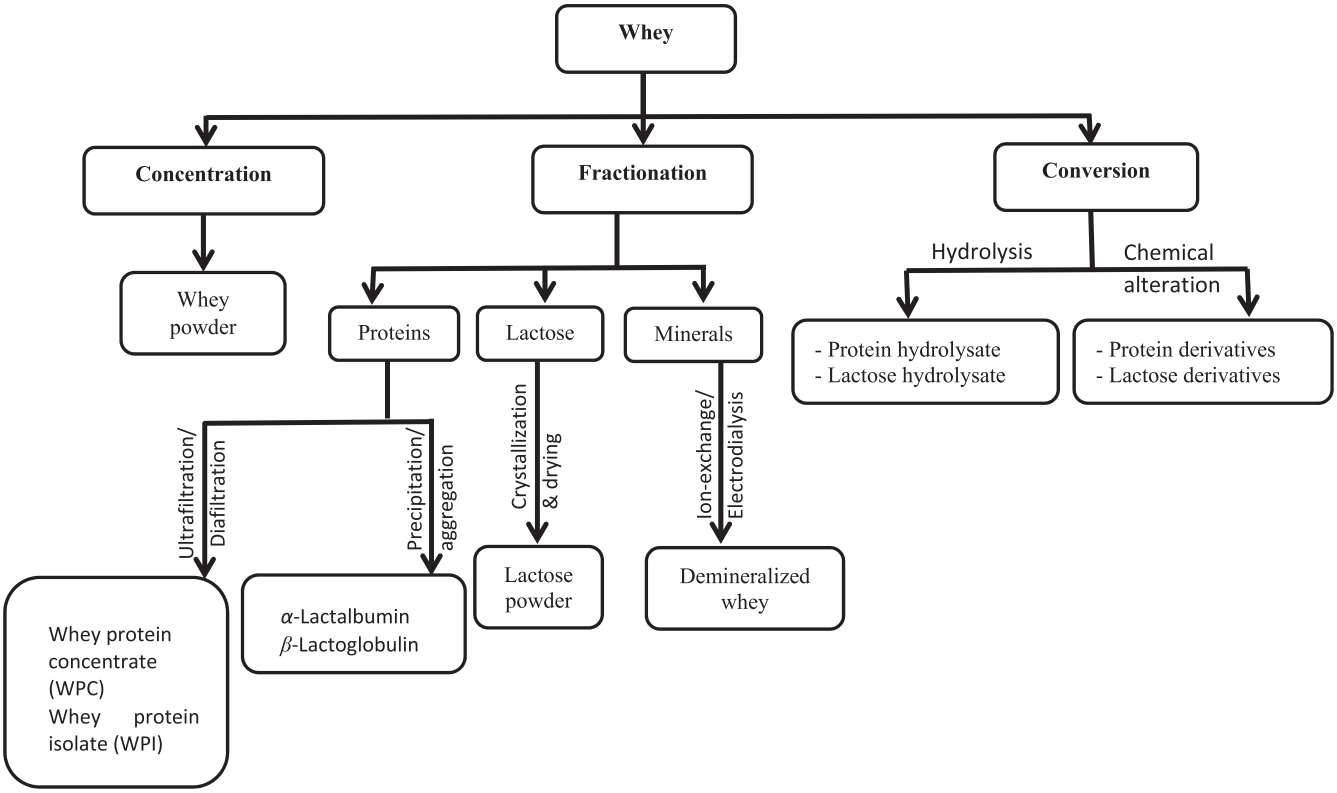

Figure 1 Application opportunities for whey processing.

marketplace. Increased consumer awareness of the environmental impact of the dairy industry has meant the industry has focussed on waste treatments for whey more efficiently prior to disposal (Rivas *et al*. 2011). This has stimulated valorisation and innovative techniques for processing whey (Risner *et al*. 2019).

Disposal of whey via waste treatment facilities can be a costly endeavour for creameries which can be the difference between business success and failure in a category with low profit margins and high volume. Processing and disposal of acid whey (AW) is typically problematic due to compositional differences, compared to sweet whey (SW). Generally, AW is lower in pH, protein and lactose contents, but higher in calcium, phosphorus and lactic acid (Schmidt *et al*. 1984), resulting in a different behaviour of AW components during concentration, rendering the stream very hard to process (Dec and Chojnowski 2006). Hence, alternative techniques for processing, valorisation and reduction of potent pollutants have been developed (Risner *et al*. 2019).

In addition, whey is utilised to produce some types of cheese of acid–heat-induced coagulation pattern, including ricotta. However, this is a high-wastage process, yielding only 5 kg of ricotta from a 105-kg formulation containing 100 kg whey and 5 kg milk (Farkye 2017); hence, additional effluent treatments are crucial. On average, 85–95% of milk volume in cheesemaking is accounted for by whey, which retains around 55% of the milk nutrients (Geiger *et al*. 2016).

The aim of this review is to report the environmental impacts of whey as a waste and the recent advances and limitations related to whey treatments and processing techniques. In addition, this review's purpose is to highlight the potential whey products and valorisation strategies and its future trends, which contribute substantially to establish a foundation for the dairy industry to develop innovative products with feasible sustainability approaches. Current environment and social governance (ESG) initiatives across the dairy sector are focussed on reducing greenhouse gas (GHG) emissions associated with whole milk production and processing. Reducing GHG emissions and decarbonising the dairy product supply chain can be stimulated by reducing wastes directly and valorising co-products such as whey to achieve this.

WHEY WASTE MANAGEMENT

Whey categories (applications and challenges)

Based on milk coagulation pattern, whey is categorised into sweet whey 'SW' and acid whey 'AW', with different nutritional composition and production means (Table 1; Mulcahy 2017; Guo and Wang 2019; Stout and Drake 2019; Tallapragada and Rayavarapu 2019). The applications and challenges concerning SW and AW are shown in Table 2 (Farkye 2004; Shon *et al*. 2007; Huffman and de Barros Ferreira 2011; Božanić *et al*. 2014; Chandrapala *et al*. 2015; Zargar *et al*. 2015; Bansal and Bhandari 2016; Bolwig *et al*. 2019; Risner *et al*. 2019; Tallapragada and Rayavarapu 2019).

Demand for acid-coagulated products tripled in recent years, producing >1.6 billion litres of AW (Chandrapala *et al*. 2015). To mitigate drying challenges of acid whey, magnesium hydroxide or calcium hydroxide may be added to neutralise acidity, thus preventing lump formation. Free-flowing agents such as sodium silicate or magnesium silicate may be added to aid drying (Huffman and de Barros Ferreira 2011).

Environmental impact (energy demand and carbon footprint)

Cheese consumption has increased by 5% over the past 5 years (Masotti *et al*. 2018), with Cheddar cheese classified as the most popular type. Cheese production is the second largest consumer of energy in the United Kingdom (317 kt oil equivalents per year) after the baked goods industry (318 kt oil equivalents per year) (UK National Statistics 2020). Several life cycle assessment (LCA) studies identified milk production as the main hotspot (van Middelaar *et al*. 2011; Kim *et al*. 2013; González-García *et al*. 2013; Broekema and Kramer 2014). The LCA provides an environmental impact profile of a functional unit in a system such as a litre of whole milk. It conforms to a cradle to grave approach for products and processes being defined by ISO14040. The LCA provides a carbon footprint of GHG emissions for the functional unit, and it is represented as a global warming potential (GWP).

The high biological oxygen demand (BOD) and chemical oxygen demand (COD) of waste whey render it a potent environmental pollutant, if it is disposed, which are summarised in Table 3. However, such figures reported in literature vary significantly (Das *et al*. 2016; Chwialkowska *et al*. 2019; Pandey *et al*. 2020; Zotta *et al*. 2020; Dufrene *et al*. 2021; Luo *et al*. 2021).

The COD values of 1 kg of milk fat, lactose and protein are 3 kg, 1.13 kg and 1 kg respectively (Kasmi *et al*. 2017). However, cheese whey is comprised of water (93.0–94.0%), lactose (4.5–6.0%), proteins (0.6–1.1%), minerals (0.8–1.0%), lactic acid (0.05–0.9%) and fats (0.06–0.5%) sequentially (Prazeres *et al*. 2012). Consequently, lactose, which comprises 70–75% of cheese whey total solids, is responsible for around 90% of the COD and BOD values of SW. By comparison, AW is lower in lactose (44–46 g/L), compared to sweet whey (46–52 g/L) which may allude to the generally lower COD and BOD values reported in literature (Pires *et al*. 2021; Xia *et al*. 2021).

Although cheese whey may be processed into secondary products, such as ricotta, this process generates a secondary cheese whey biowaste, with the disposal of waste products now prohibited by traditional means by EU and national legislation due to the significant environmental damage. Furthermore, utilisation of waste whey as animal feed is now seldom advised due to the harmful effects to animal health of the high lactose content, alongside the possible acidification of the waste whey, particularly where farms are not in a close vicinity to processing plants (Isipato 2021). Nevertheless, the new waste framework directive (WFD) seeks to minimise waste disposal given the associated environmental damages. However, this shall be discussed in this paper later.

In a report prepared for DEFRA (Department of Environment, Food and Rural Affairs, UK Government), special information was provided on life cycle of many food products and their global warming potential (GWP). There are now several meta-analyses of GHG emission data that are reported in life cycle inventories that support the development of LCA and the GWP outputs of LCA are the carbon footprint reporting of a product (Clune *et al*. 2017). A large amount of data

Table 1 Types of whey, their composition and their production

Type	Protein (g/L)	Lactose (g/L)	Minerals (g/L)	pH	Production
Sweet whey (SW)	6–10	46–52	2.5–4.7	5.6–7	Produced by rennet coagulation during cheese manufacture. Also referred to as cheese whey.
Acid whey (AW)	6–8	44–46	4.3–7.2	4.3 < 5.6	Produced from coagulation by fermentation of lactose to lactic acid; such as in Greek yoghurt manufacture, or through acid addition during acid casein production. Acid-induced coagulation greatly increases calcium levels owing to changes in equilibrium of the milk salt system. Low pH causes calcium phosphate in casein micelles to transition equilibrium to solubilised calcium and phosphate, thus leading to increased mineral content in AW compared to SW.

Table 2 Applications and challenges of sweet and acid whey

Category	Applications	Challenges	References
Sweet Whey (SW)	• Raw material for dairy-based beverages; such as kefir. • Whey protein concentrate • Whey protein isolate • Ingredient in production of processed cheese types.	• May contain residual compounds from cheese manufacture, which may impart flavour or cause nutritional issues. Glycomacropeptide (GMP) is one example, which is removed by whey separation before cheesemaking using microfiltration. GMP is removed due to the influence on the amino acid profile of infant formula; though its removal significantly reduces the protein content of whey by around 20%.	Bansal and Bhandari (2016), Huffman and de Barros Ferreira (2011), Zargar *et al.* (2015), Bolwig *et al.* (2019), Shon *et al.* (2007), Tallapragada and Rayavarapu (2019), and Božanić *et al.* (2014)
Acid whey (AW)	• Generally used as animal feed. • Valorisation of AW may involve producing alcoholic spirits from fermentation of lactose contained in whey, which reduces the biological oxygen demand of whey by approximately 75%. • AW could be used as a substrate for biogas to produce electricity as a potential replacement for non-renewable energy. • The low pH attributed to AW (at pH $\leq$5.2), the majority of calcium phosphate is solubilised into a soluble calcium salt, which may yield greater stability of AW and AW-derived products.	• Cannot be valorised through membrane filtration due to compositional differences that affect lactose behaviour; specifically crystallisation. • The high mineral content of AW renders it unfavourable for whey protein production due the complexities of processing compared to using SW. • AW has a pH closer to the isoelectric point of whey proteins, thus it causes an increased protein fouling, rendering it unsuitable for membrane recovery of milk minerals. • The thermoplastic and hygroscopic nature of contained lactic acid makes AW difficult to dry, particularly when over 2% lactic acid is present.	Chandrapala *et al.* (2015), Bansal and Bhandari (2016), Huffman and de Barros Ferreira (2011), Zargar *et al.* (2015), Bolwig *et al.* (2019), Risner *et al.* (2019), Shon *et al.* (2007), Farkye (2004), and Božanić *et al.* (2014)

Table 3 Chemical and biochemical oxygen demand of cheese and acid whey

Material	Biochemical oxygen demand (BOD) (g/L)	Chemical oxygen demand (COD) (g/L)
Whey	30–50	60–80
Sweet whey	40–102	27–60
Acid whey	52–62	35–51

Table 4 Total global warming potential of dairy products in literature at processor gate

Dairy product	Global warming potential (KG CO_2 eq./KG)
Whey powder	13.108
Whole milk	1.589
Butter	9.680–39.16
Milk powder	12.353
Dried whey (animal feed)	12.100
Cheddar cheese	14.02
Cheese (average)	6.7–9.47
Cream	3.5–4.5
Yoghurt	1.42–3.35

was collected, and details about products, processes and energy sources were specified. Dairy categories were highlighted as energy intensive with respect to GWP values and this has heightened the requirement to seek greater energy efficiency in heat processes (Ladha-Sabur *et al*. 2019). The production of whey powder has greater GWP than other dairy products, such as milk powder. Although both whey and milk powders need to be dried to remove water, some researchers included the energy consumed during cheese processing to obtain the whey (Foster *et al*. 2006). The typical energy consumption and GWP of different dairy products are summarised in Table 4 (Pal and Nayak 2016; Finnegan *et al*. 2017; Gosalvitr *et al*. 2019; Kumar and Choubey 2022). The GWP is an output of the LCA and it is the carbon footprint of the functional unit assessed in the LCA. Manufacturing of whey powder consumes more electricity and water than liquid milk processing (kWh/ kg of product) with 8.69 kWh/kg and 2.9 L/kg for whey powder respectively, compared to 0.32 kWh/kg and 2.9 L/kg for liquid milk. However, the production of milk powders is similarly high at 6.51 kWh/kg and 19.3 L/kg (Finnegan *et al*. 2017).

The ability to increase the efficiency of heat processing and pasteurisation with the valorisation treatments of whey offers opportunities. A novel method of steam infusion has been reported by Brooks *et al*. (2021) where heat processing is improved to cut processing time by at least half, reduce downtime for maintenance and cleaning in place and reduce energy consumption. These approaches demonstrate defined routes to reducing the GWP of whey processing and to net carbon zero outcomes for dairy processing factories (Allen *et al*. 2018).

ENVIRONMENTAL IMPACT ASSESSMENT

Life cycle assessment and hotspot analysis

Life cycle assessment (LCA) is a standardised methodology that measures the environmental impact of a product throughout its life cycle from creation, through to consumption and disposal, whilst identifying and providing impact outcomes of eutrophication potential and ozone destruction, amongst others (Roy *et al*. 2009). It also identifies the GWP of the functional unit identified in the LCA (Finnegan *et al*. 2018a; Berardy *et al*. 2019). Energy consumption for cheese manufacturing and storage was set to 0.91 kWh/kg cheese (Flysjö *et al*. 2014). Although processing has an electrical requirement, waste whey can be converted into electricity, perhaps reducing the overall environmental impact. It is possible to utilise AW as a substrate for biogas to produce electricity as a potential replacement for non-renewable energy. Whey (both AW and SW) can be used in place of fossil fuels and can generate the required energy to cover most of a dairies' energy demand through cheese whey anaerobic digestion. It is often considered that 78–85% of the carbon footprint in the dairy industry occurs prior to the farm gate. This is in part due to methane emissions from enteric fermentation and nitrous oxide emissions from manure management and fertiliser utilisation. These gaseous emissions account for 70–90% of total farm level GHG emissions. Comparatively, post farm gate processing activities, namely packaging, transport and fossil fuel combustion, comprise approximately 8%, 4% and 3% of total emissions respectively, from farm to consumer in a major dairy processers' value chain (Flysjö *et al*. 2014). The LCA methodology has been investigated for livestock systems and a re-assessment of biogenic methane emissions has shown there is a need to rethink how livestock systems impact on climate (Allen *et al*. 2018). The most recent assessments do suggest that livestock systems and dairying systems of nations such as New Zealand could actually be GHG emission net zero in that they produce as much GHG emissions as they absorb within a short time period.

An important development in the LCA and carbon footprinting of dairy productions is the application of allocating greenhouse gas (GHG) emissions to efficiencies, complete utilisation of raw materials and volume of product. A general point that is made by allocation models is that food commodities are rarely produced for one product. In the case of cattle production, dairy and meat are primary outcomes, but there are many other product supply chains associated with the raw material. This has been investigated using LCA methods, with novel approaches to reassessing milk and meat systems proposed that reportedly significantly reduce environmental impact (Ineichen *et al*. 2022).

The environmental impact of the dairy industry is difficult to define because of its fragmented structure with several thousand producers absence of recorded whey recovery and discharge in wastewater or via land applications results in poor data availability. Some propose that the valorisation of waste whey can reduce the environmental impact of some cheeses by up to 15% (González-García *et al*. 2013; Finnegan *et al*. 2018b). These valorisation processes are not always accessible or affordable for small-scale producers who lack the finances, resources or infrastructure, though waste whey may be sold for further processing.

Carbon footprint assessment

There is a requirement for assessment tools and mitigation options for world businesses' global warming contribution now that companies are required to assess the GHG emissions associated with their supply chain as well as the direct energy they utilise. Many companies have calculated their corporate carbon footprint (*CF*) by the total emissions associated with energy use and transport. This does not consider variation in total production between enterprises, different grazing systems and annual variation (Flysjö *et al*. 2014).

Arla Foods has proposed a model to calculate the farm-to-customer carbon footprint (*CF*) for different dairy products (Flysjö *et al*. 2014). As the largest share of the *CF* of dairy products occurs at farm level, it is decisive how the emissions from raw milk production are allocated between different products. Impacts associated with raw milk are allocated based on a weighted fat and protein content (1:1.4). Data from the dairy company Arla Foods give 1.1, 8.1, 6.5, 7.4 and 1.2 kg carbon dioxide equivalents per kg of fresh dairy product, butter and butter blend, cheese, milk powder and whey-based product, and 'other', respectively. One critical aspect is how the by-product 'whey' is dealt with. The approach does not consider the detrimental implications of whey production, as dairy producers are not paid separately for the lactose content of milk. No emissions are allocated to the milk solid whey, which is why products containing whey have an apparent low impact. Therefore, improvement to the model is required to encompass and accurately reflect other dairy components and products (Flysjö *et al*. 2014). This approach does not recognise the environmental detriment of whey and milk powder production and waste beyond the farm gate (Flysjö *et al*. 2014; Finnegan *et al*. 2017; Palmieri *et al*. 2017).

A universally applicable analysis uses an allocation matrix that obtains a realistic measure of product resource use by considering the benefits of not producing wastes and utilising or valorising co-product such as whey. This approach is called an input–output LCA approach and determines average operational data for individual dairy products, alongside the solid content of milk and dairy products. It ensures dairy products are assigned impacts from farming activities, with highly concentrated products, such as whey powders, possessing the greatest farm impact. However, such an approach may be somewhat reliant on different manufacturing facilities sharing a similar level of technology (Feitz *et al*. 2007). The approach is recommended by the International Dairy Federation's guidelines for calculating the carbon footprint of dairy products, whereby different inputs possess specific allocation factors, with raw milk allocated based on milk solids. Consequently, higher milk solids yield a higher carbon footprint. However, it does not differentiate between different milk solids (Flysjö *et al*. 2014). Hence, this approach may fail to realise the higher environmental impact associated with higher COD values of different milk components as discussed (Kasmi *et al*. 2017).

The methods fail to realise the wider implications of operations, whilst other LCA approaches considering the entirety of the dairy production chain may enable more effective mitigation of environmental detriment through appraising the greatest issues and taking steps to yield improvements. Such an approach reportedly assists manufacturers to engage in sustainable practices, thus mitigating environmental detriment, whilst benchmarking the performance of such efforts against industry averages (Kim *et al*. 2013).

STRATEGIES TO MITIGATE WHEY ENVIRONMENTAL IMPACT

Wastewater treatment

Wastewater from cheese manufacturing is different from cheese whey and comprises of wastewater generated by the staff and by the washing of equipment, floors, milk losses and milk transferring vehicles. It was reported (Valta *et al*. 2017) that in almost all the Greek yoghurt production units studied in Greece, cheese wastewater is collected separately from the cheese whey. At small-scale cheese manufacturing units, it is either disposed directly in the sewerage system or stored then transported for further treatment. At medium-scale cheese manufacturing units, wastewater is mainly treated in wastewater treatment plants.

Wastewater from the cheese industry contains organic matter, nutrients, mineral salts, oils, total suspended solids (TSS), acidity, salinity, amongst others which can be an environmental and public health concern. Low pH and high salinity must also be considered. Direct application of whey effluent on soil surfaces is one strategy as whey is rich in biodegradable organic nutrients (Prazeres *et al*. 2013). Nevertheless, TSS and fat accumulation on soil surface yields negative impacts on soil structure. Biological treatments such as anaerobic or aerobic degradation processes can be used to reduce the organic contamination. However, the need for specific microorganism and long hydraulic retention times, odour release, fat floatation and excessive sludge formation are some of the drawbacks of biological treatments (Martins and Quinta-Ferreira 2010; Rivas *et al*. 2011).

Other approaches to mitigate drawbacks of the biological processes have been studied. Physicochemical methods such as precipitation, coagulation–flocculation and oxidation can be applied before or after biological treatments to reduce biological impact (Martins and Quinta-Ferreira 2010; Rivas *et al*. 2011; Prazeres *et al*. 2013). Thus, studies on the effect of different operating variables in physicochemical processes are also limited. Additionally, the effect of cheese whey recovery on the physicochemical processes used for the cheese wastewater (CWW) treatment has not yet been considered. Chemical precipitation can reduce up to 50% of the organic matter in whey effluent (Prazeres *et al*. 2014, 2016), though it requires a pH neutralisation step, and carbonation using atmospheric CO_2 to neutralise the alkalinity of the effluent, increasing the costs of the treatment. Another alternative treatment for the wastewater has been reported using microalgae, in which the wastewater would offer the nutrients required by the microorganism (Kumar *et al*. 2010). However, CO_2 absorption is easier to control and produces a by-product (precipitate) rich in organic matter and nutrients (Lim *et al*. 2010). In a study under optimal conditions, the combination of 80% cheese whey recovery and lime application reportedly led to a 90% COD reduction. Precipitation with $Ca(OH)_2$ addition resulted in excellent settling properties of the generated sludge, which can be finally filtered, dried and potentially used as a fertiliser (Prazeres *et al*. 2016).

Nevertheless, alternative disposal methods are available. Waste may be stored in 'dairy-ponds' for anaerobic treatment. However, these yield foul odours, provide a habitat for vectors, such as mosquitos, and are prone to acidification during retention. Hence, dairy ponds may be converted into aerobic environments through aeration, thus providing a suitable bacterial environment for solid degradation. The disadvantage is that this process requires significant detention times and generates significant sludge (Rivas *et al*. 2011; Isipato 2021). However, the sludge may be pretreated by coagulation–flocculation, or alkaline precipitation with lime or sodium hydroxide to produce a sludge rich in organic matter that may find agricultural applications (Carvalho *et al*. 2013). Such techniques only reduce organic content without further benefits. Furthermore, they significantly influence production costs due to aeration, with the high organic content perhaps facilitating growth of filamentous bacteria (Isipato 2021). Additionally, use of traditional activated sludge techniques is economically unsustainable due to the high organic loads of dairy effluents and high volumes of oxygen required for aeration, alongside excessive sludge formation (Asunis *et al*. 2020).

Energy-saving and recovery technologies to reduce energy consumption

Varying energy-saving and recovery technologies have been applied to reduce energy consumption and CO_2 emissions in cheese production. These include heat integration, anaerobic digestion (AD) and fermentation of whey to produce biogas and bioethanol respectively. Biogas was reported to generate heat and/or electricity to be used in a combined heat and power plant (Okeke and Mani 2017). Furthermore, a common practice in Ireland, the United States and New Zealand is to use the lactose in whey to produce bioethanol (Jungbluth *et al*. 2007).

Life cycle assessment studies should not only focus on environmental impact assessment of different cheese types but also the energy-saving opportunities and valorisation of waste whey in cheese manufacturing which might outweigh the environmental impact. In this context, Gosalvitr *et al*. (2021) integrated a modelling system and process design with LCA and life cycle costing (LCC) to help improve the environmental and economic sustainability in the cheese manufacturing industry, in view of both production and consumption perceptions. This was possible by improvement in the cheese manufacturing process itself such as heat integration and recovery, followed by the valorisation of waste whey to produce biogas or bioethanol and animal feed, thus considering the whole life cycle of Cheddar cheese for the UK market. All approaches investigated decreased the environmental impact and showed to be cost-effective than the base case (no energy recovery or waste utilisation). Heat integration and regeneration for reuse in the cheese production, animal feed and bioethanol production proved to be the best option, with a 148% reduction in climate change impact and 15 net-negative impacts (−0.05 kg CO_2 eq./kg cheese), compared to the base case (Gosalvitr *et al*. 2021). This reportedly reduced the impact of the whole food sector by 0.15% and generated a £22.7 M/yr profit saving from co-product revenue.

Lactic acid whey (LAW), a by-product from fresh cheese and caseinate production, is difficult to dry and is very hygroscopic in nature due to its high organic acids and ash content. LAW needs to be demineralised prior to drying, either by ion exchange resins (Hoppe and Higgins 1992) or by electrodialysis, which generates a high volume of effluent from both treatments that needs to be treated in a wastewater treatment plant, increasing investment and cleaning costs. In a recent study to overcome these challenges and to increase sustainability (Bédas *et al*. 2017), nanofiltration (NF) was applied as a prestep for spray drying of LAW, and reported a 30% reduction in lactic acid content, a 46–60% reduction in monovalent ions and a 43% reduction in energy consumption needed for water removal compared to the standard process. This was attributed to the low-specific energy for water removal by membrane filtration, compared to vacuum evaporation and spray drying.

More recently, a redox-mediated electrodialysis system demonstrated energy efficient and sustainable desalination of whey waste streams, alongside the purification of valuable whey proteins from acidic, sweet and salty whey wastes. The developed process enabled 99% salt removal, which could be recycled back into cheese production, and > 98% whey proteins retained from whey solutions. The developed system's protein purification and salt recovery performance were maintained over multiple cycles, whilst consuming 51–73% less energy and lowering operating costs 51–62% compared to conventional desalination systems (Kim *et al*. 2022).

Anaerobic digestion of whey could render cheese production processes energy self-sufficient, alongside reducing production costs and generating income from energy production. Furthermore, it reduces the carbon footprint of Cheddar production from 0.12 kg/CO_2 per kilogram of cheese to −0.12 kg/CO_2 per kilogram, thus rendering the process effectively carbon negative through generating electricity and heat from biogas (Gosalvitr *et al*. 2019). Other work demonstrated a 97% COD reduction of cheese whey using a single-stage upflow anaerobic sludge blanket reactor, utilising whey with a COD of 47,350–58,350 mg/L, with a hydraulic retention time (HRT) of 2.06–4.95 days. However, the incoming whey possessed a high COD level, hence required a further stage with HRT of 1.8–3.5 days, producing a COD reduction of 27–60%. Hence, digestion of whey with concurrent use of a chemical buffer was deemed effective (Fallon 2018).

In non-food applications, waste whey may be utilised for electricity production using microbial fuel cells. Although applicable to various cheese whey types, the power production and its reproducibility are low (Prazeres *et al*. 2012). Others report the use of anaerobic digestion of waste whey to obtain electrical and calorific energy at 50–58 and 100–116 kWh/m^3 respectively. Use of stored whey that contains diminished organic matter content and pH is not thought to be an issue for electricity production. Hence, use of stored material in the absence of 'new' substrate is not concerning. Furthermore, energy generated may be utilised by dairy and agricultural producers, with the opportunity to store whey for energy production providing contingency options (Escalante *et al*. 2018). Such treatment of cheese whey may generate sufficient energy to cover the majority of a dairy plant energy demand; rendering production processes energy self-sufficient, generating surplus energy and thus additional income. The authors propose the use of similar technologies to enable waste treatment at local dairies, enabling generation of renewable energy for local areas and reducing transport and management requirements and costs (Gosalvitr *et al*. 2019; Mainardis *et al*. 2019). Such approaches may be beneficial for isolated or economically disadvantaged communities or economies, though the investment for digesters may be an issue. Furthermore, anaerobic digestion and bioenergy are not ultimate solutions to the waste whey issue, particularly as production rates are too small for an economically sustainable scale-up. Additionally, anaerobic digestion is susceptible to acidification, inhibition of methanogenic activity and thus reducing methane yield and process stability, resulting from volatile acid accumulation. Although mitigated through alkali addition or dilution, this increases operation costs and volumes to be treated. Hence, waste whey may be co-digested with waste materials, such as sewage sludge, manure and cattle slurry. However, this may mitigate further utility of waste streams as fertilisers. Nonetheless, more complex, two-stage systems may be utilised to generate hydrogen (H_2), which may be used in isolation or conjunction with methane as a fuel source (Asunis *et al*. 2020).

Due to its simple and efficient application on raw cheese whey (CW), the current and potential huge market size of its products (H2 and volatile fatty acids (VFAs)) and the increasingly stringent regulations on carbon emissions, fermentation is likely to gradually replace anaerobic digestion as the core of dairy biorefinery. H2 is indeed a key player towards decarbonisation of energy production systems, whereas VFAs have several industrial applications, and may also be regarded as precursors for bioplastic production, the market size of which is expected to increase in response to policies intending to reduce the use of traditional plastics (Dessì *et al*. 2020).

WHEY VALORISATION

As discussed, the pursuit of economical sustainability necessitates waste management enabling valorisation. Traditionally, this would entail protein and latterly lactose recovery through filtration processes, prior to application in economic chains and added value products, including beverages, jams and preserves, sauces, infant foods and formula, bakery goods, meat products, cosmetics, functional foods, dietetics and nutraceuticals. However, application of whey in consumer goods continues to increase with regard to volumes and economic value; this is perhaps promising in relation to the increasing waste whey generated year on year (Rocha and Guerra 2020). Although there is no single ultimate solution, a wide variety of valorisation techniques are reported in literature.

The nature of whey as a rich lactose and protein source renders the valorisation of waste whey into value-added products or components an attractive alternative, thus avoiding waste disposal issues (Das *et al*. 2016; Bolwig *et al*. 2019). Such valorisation is preponderant to the development of sustainability, whilst providing a 'cleaner' means of utilisation compared to traditional disposal means

(Panghal *et al*. 2018). However, a single valorisation process or approach cannot provide an ultimate solution, particularly due to the ever-increasing global waste generated, alongside the economical and sustainability challenges involved. Hence, a wide array of cost-effective and efficient techniques is necessary, which may subsequently provide opportunities and resilience for economically disadvantaged enterprises and economies (Isipato 2021). Furthermore, there is an increased awareness of the untapped potential of waste utilisation for the production of biofuels, bio-based chemicals and organic by-products. Consequently, significant adoption of processes is in line with the EU's efforts towards a circular bioeconomy, alongside the target of becoming the first climate neutral area in the world by 2050 (Asunis *et al*. 2020). Various valorisation strategies for whey waste are discussed hereafter and summarised in Table 5.

Whey protein-based beverages

Whey proteins' basic properties, including chemistry, analysis, heat sensitivity, interactions with other proteins and carbohydrates, modifications (hydrolysis, aggregation, conjugation), their industrial preparation, processing and applications, quality aspects including flavour and effects of storage, as well as their role in nutrition, sports and exercise, and health and wellness, can be used in the fields of sports and exercise science, infant nutrition and medicine (Deeth and Bansal 2018).

Although whey is traditionally considered a waste product or utilised as an ingredient in composite foods, there is growing interest in commercial whey-based food and drink products. Although the production of commercial whey beverages began in the 1970s, interest and variety of whey-based beverages has increased in recent years (Panghal *et al*. 2018). During the last decade, whey and whey components have been increasingly used commercially in the manufacture of whey-based beverages, either plain or supplemented fruit juice, milk or milk permeate, or nutraceutical compounds and/or probiotics/prebiotics (Özer and Evrendilek 2022). Many available whey protein beverages are now available in the market. In this context, the production of a naturally carbonated, whey-based probiotic drink with good antimicrobial activity against pathogenic strains has been reported in more recent literature (Kadyan *et al*. 2021). However, antimicrobial activity was influenced by fermentative strain applied, largely due to the production of associated bacteriocins and acids. Nevertheless, production processes developed could be easily incorporated into production lines, thus minimising effluent volume and treatment costs (Kadyan *et al*. 2021).This may introduce options for new product development and offer potential market opportunities. Nonetheless, a large array of whey-based beverages has been developed in literature (Panghal *et al*. 2018).

There is a high demand for dairy beverages worldwide, especially healthy, and functional beverages. Fermentation of whey by-products, especially using probiotic microorganisms, could provide beverages with high organic acid content, or low alcohol tonics, both of which are considered as value-added products for dairy industry. Some examples of these beverages produced by aerobic fermentations include kombucha or kefir which are high in organic acids (acetic and lactic acids). In a recent study, Marcus *et al*. (2021) reported that it was possible to produce new value-added and sustainable organic acid or alcoholic beverages and also to increase the pH of acidic by-products using reconstituted whey permeate using yeast species (*Kluyveromyces marxianus, Kluyveromyces lactis, Dekkera anomala, Brettanomyces claussenii, Brettanomyces bruxellensis*) and mould species (*Mucor genevensis* and *Aureobasidium pullulans*).

Whey protein and lactose recovery

Lactose can be directly fermented or hydrolysed to produce glucose and galactose, whereas proteins are widely used in food and pharmaceutical products, because they possess high nutritional value and versatile functional properties (Jayaprakasha and Yoon 2005). Therefore, the recovery of lactose and protein can help to reduce the BOD and COD loading of whey and can help in solving the problem of environmental pollution being caused by the disposal of whey.

Proteins and lactose comprising whey can be recovered or removed from whey solutions (Božanić *et al*. 2014). A two-stage ultrafiltration process using a 30-kDa membrane retains bovine serum albumin (BSA), lactoferrin (LF) and immunoglobulins (Igs). A sequential 10 kDa membrane retains beta-lactoglobulin (ß-LG) and alpha-lactalbumin (α-La). A 1-kDa nanofiltration membrane separates isolated peptides from lactose contained in the ultrafiltered permeate. The pH influences membrane selectivity. A pH above or below isoelectric point (pI) influences whey protein size, thus influencing permeation (Bonnaillie and Tomasula 2008). Selective separation using carefully selected membrane molecular weight cut-offs is possible and avoids protein denaturation (Zydney 1998).

Ion exchange chromatography (IEC) produces high-purity whey proteins. Separation consists of four steps (Figure 2; Huffman and de Barros Ferreira 2011) and is based on electrical charges and pI of proteins (Table 6). At pH below pI, proteins are positively charged, thus absorbed by cationic ion exchangers. At pH above pI, proteins are negatively charged, thus absorbed by anionic ion exchangers. Manipulation of pH enables selective elution of proteins. However, denatured proteins may bind irreversibly to ion exchangers, decreasing process efficiency; thus, extreme pH should be avoided (Huffman and de Barros Ferreira 2011). The characteristics of proteins recovered from whey are summarised in Table 6.

There could be further development of fractions of individual whey proteins with specific enhanced physical

Table 5 Overview of valorisation techniques

Valorisation	Example techniques	Products	References
Whey protein and lactose recovery	Two-stage Ultrafiltration Nanofiltration Ion exchange Chromatography Membrane filtration	Recovery of: • Bovine serum albumin • Lactoferrin • Immunoglobins • ß-Lactoglobulin • α-Lactalbumin • High purity whey proteins • Lactose	Bonnaillie and Tomasula (2008), and Huffman and de Barros Ferreira (2011)
Whey protein-based beverages	Fermentation of whey by-products Deproteinised whey or whey permeate remaining after ultrafiltration Fermentation of whey-derived lactose Ethanol distillation	• Probiotic beverages • Sports Beverages • Functional beverages • Non-fermented functional beverages • Ethanol • Whey vodka, white whisky and craft spirits	Lawton *et al.* (2021), Tirloni *et al.* (2020), Risner *et al.* (2018), and Barukčić *et al.* (2019)
Whey fermentation by-products	Fermentation and distillation Dark fermentation	• Ethanol • Biohydrogen and volatile fatty acids	Risner *et al.* (2018), Koushki *et al.* (2012), Asunis *et al.* (2020), and Lovato *et al.* (2021)
Food and Ingredients	Evaporation, reverse osmosis, crystallisation and drying Membrane technologies Acid heat coagulation Membrane filtration Microparticulated whey protein Acid–heat-induced coagulation	• Whey powders • Whey protein isolates and concentrates • Cheeses such as Paneer, Queso Blanco and Ricotta • Whey cream • Fortification of dietetic/functional foods • Use as a fat replacer • Lor cheese production • Ricotta production	Bansal and Bhandari (2016), Wang and Guo (2019), Farkye (2017), Panghal *et al.* (2018), Lappa *et al.* (2019), Chudy *et al.* (2021), and Akan *et al.* (2021)
Chemicals and preservatives	Autoclaving acid whey with mustard Hydrolysis or fermentation of whey to release bioactive compounds Enzymatic and microbial catalysed hydrolysis and fermentation Mesophilic lactic acid bacteria fermentation Membrane-integrated hybrid reactor system Acidogenic fermentation using anaerobic sludge as inoculum	• Preservatives • Food preservation • Bioethanol • Bactericidal disinfectant • Acetic acid (98% purity) • Production of hydrogen, acetate, butyrate, propionate, valerate, lactate and ethanol	Wójciak *et al.* (2014), Addai *et al.* (2020), Santos *et al.* (2019), Pal and Nayak (2016), and Xiong *et al.* (2019)
In line processes	Biorefineries and bioprocess integration In-line ultrafiltration Fed-Batch Bioreactor	• Biofuels and biochemicals • Nutrient, antioxidant and bioactive recovery • Hydrogels, bioplastics and biofuels • Protein and lactose recovery • Food gels, protein concentrates, whey cheeses with probiotics	Asunis *et al.* (2020), Macedo *et al.* (2021a; 2021b), and Sarenkova *et al.* (2022)

(continued)

Table 5 (Continued).

Valorisation	Example techniques	Products	References
		• Use of acid whey as a substrate for lactobionic acid production by *Pseudomonas taetrolens*	
Plastics, films and coatings	Biorefineries Dehydration of protein–polysaccharide/antimicrobial agent biofilms Whey fermentation and preparation of a polyvinyl alcohol film	• Polyhydroxyalkanoates • Edible films • Whey protein–polysaccharide/antimicrobial agents coatings for cheese • Antifungal plastic films carrying lactic acid bacteria fermented whey for the preservation of cheese slices	Asunis *et al.* (2021), Lappa *et al.* (2019), Tamošaitis *et al.* (2022), and Dopazo *et al.* (2022)
Advanced technologies	Multistage membrane filtration for concentration and fractionation Nanofiltration electrodialysis	• Whey protein concentrates or isolates with potentially increased functional properties due to removal of undesirable protein aggregates, caseins, microorganisms and fat globules causing fouling or quality issues • Minerals contained in acid whey (calcium and magnesium)	Blais *et al.* (2022), and Nielsen *et al.* (2022)
Microbial and Enzymatic Bioprocesses	Biomass production by oleaginous microorganism Microbial cultivation Microbial and enzymatic bioprocesses Fermentation by *Saccharomyces cerevisiae* Submerged fermentation	• Production of single-cell oils of industrial interest using whey as a substrate • Use of whey as a substrate and inducer for technical enzyme production • Production of nutraceuticals and bioactive peptides, prebiotics, exopolysaccharides, organic acids, bacteriocins, isoflavone aglycones and industrially important enzymes • Enriched whey with bioactive compounds for functional and nutritional enhancement of foods and development of novel functional foods • Resveratrol production using cheese whey powder as a lactose source • Use of cheese whey and orange molasses for fungal biomass production for sustainable feed	Gutierrez-Hernandez *et al.* (2022), Hausjell *et al.* (2019), Chourasia *et al.* (2022), Costa *et al.* (2022), and Ibarruri and Hernández (2019)
Non-conventional Processing	Thermal, ultrasonic and thermosonication pretreatments Ultrasonic modification of whey protein isolate Pulsed electric fields Ohmic Heating pH shift and ultrasound treatment Multiple frequency divergent ultrasound High hydrostatic pressure/electrotechnologies/ultrasound Electroactivation	• Enhanced lactose recovery from whey • Production of whey protein isolate with altered structural and functional properties • Use of pulsed electric fields as non-thermal pathogenic controls in cheese-making and generated whey for further processing, or for enhanced whey removal from cottage cheese • Production of whey protein isolate with altered physiochemical properties for new functionalities	Khaire and Gogate (2018), Meng *et al.* (2021), Gentès *et al.* (2022), Rocha *et al.* (2018), Jiang *et al.* (2022), Cheng *et al.* (2022), Barba (2021), and Karim and Aïder (2020)

(continued)

Table 5 (Continued).

Valorisation	Example techniques	Products	References
		• Modification of physicochemical properties, including emulsion stability of whey protein isolate • Modification of whey protein emulsion gels to enhance gelling characteristics of emulsions • May be used for bespoke processes to produce new food products/compounds whilst avoiding pitfalls of thermal processing on whey • Enhanced lactulose production over traditional chemical isomerisation	

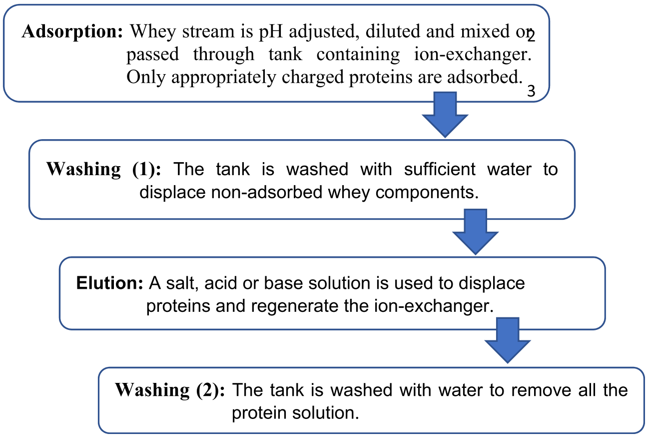

Figure 2 Steps involved in ion exchange chromatography (IEC).

functionality or nutritional/physiological functionality. Chromatographic and membrane separation methods are currently used to fractionate whey proteins, but there are alternative methods such as aqueous two-phase extraction and magnetic fishing that hold promise for the future (El-Sayed and Chase 2011). Nevertheless, two-phase aqueous systems of whey protein concentrate and hydroxypropylmethylcellulose may be used for selective separation of α-lactalbumin and β-lactoglobulin (Jara and Pilosof 2011).

Lactose is typically isolated from ultrafiltered, deproteinized permeate. Permeate is concentrated by evaporation, followed by the crystallisation of lactose and separation using centrifugation or decanters (Božanić *et al*. 2014). Lactose crystals are then harvested and dried (Chandan 2014). 74% of lactose with a purity of 99.8% may be recovered from whey using microfiltration with a 0.2-μm pore size, ultrafiltration with a molecular weight cut-off of 5 kDa, ion exchange and reverse osmosis (RO; de Souza *et al*. 2010). However, 87.5% of lactose can be recovered by subjecting cheese whey to electrodialysis or using ion exchange membranes to reduce salt content (demineralisation), then evaporation, crystallisation, centrifugation and drying processes sequentially (Figure 3). Higher lactose purity of around 97% may be obtained when whey is not treated with ion exchange resins to remove protein (Patel and Murthy 2012; Chandan 2014; Bansal and Bhandari 2016).

Whey fermentation by-products

Conversion of the lactose present in whey into ethanol is an effective means of reducing the environmental impact of whey, in which the BOD is reduced by approximately 75%, in addition to enabling valorisation of whey that would have previously been disposed of (Risner *et al*. 2019). The lactose content of whey presents opportunity for fermentation into ethanol and subsequent distillation into whey-derived alcoholic spirits. Previous research has utilised *Kluyveromyces marxianus*; a yeast strain, to hydrolyse lactose into glucose and galactose, subsequently metabolising the monosaccharides into ethanol by fermentation. However, other yeast strains have been utilised, such as *Saccharomyces cerevisiae* alongside exogenous enzymes. The production efficiency of ethanol from whey varies from 75.9% to 96.6%. It is proposed that this difference results from differing fermentation substrates (Risner *et al*. 2019).

Fermentation of whey with a low lactose content (3–5% w/v) yields low ethanol concentrations (2–3% v/v). However, use of concentrated whey permeate (9.8% lactose) yields high ethanol content (average of 5.45% v/v). Use of concentrated permeate also increases production efficiency, albeit insignificantly so with 89.4% efficiency using concentrated compared to 87.4% for non-concentrated permeate (Koushki *et al*. 2012; Risner *et al*. 2018). However, the production of concentrated whey permeate necessitates additional processing, subsequently increasing production time and costs, thus decreasing overall efficiency, likely negating the marginally improved production efficiency. Similarly, it

Table 6 Composition and physical properties of whey proteins

Protein	Whey content (%)	Molecular weight (kDa)	Isoelectric point (pH)	Nutritional and functional benefits
ß-Lactoglobulin	48–58	18.0–18.36	5.2–5.5	Source of essential and branched amino acids. Enhances retinol uptake and has excellent gelling, emulsifying and foaming properties. It is recognised as an allergen.
α-Lactoglobulin	13–25	14.0–14.15	4.2–4.8	Major human milk protein. Source of essential and branched amino acids. Binds calcium. It is a non-gelling protein.
Glycomacropeptide	10–20	7.0–8.6	<3.8	Source of branched amino acids.
Bovine Serum Albumin	5–10	66.0–69.0	4.7–5.1	Source of essential amino acid.
Immunoglobulins	8–15	150–1000	5.0–8.3	May provide a 'passive immunity'.
Lactoferrin	1–2	77.0–78.0	7.9	A bactericidal protein. Binds iron and may inhibit tumour formation.
Lactoperoxidase	0.5	78.0–89.0	9.6	Possesses antibacterial activity.
Lysozyme	0.0002	14.30	11.0	Possesses antimicrobial activity.

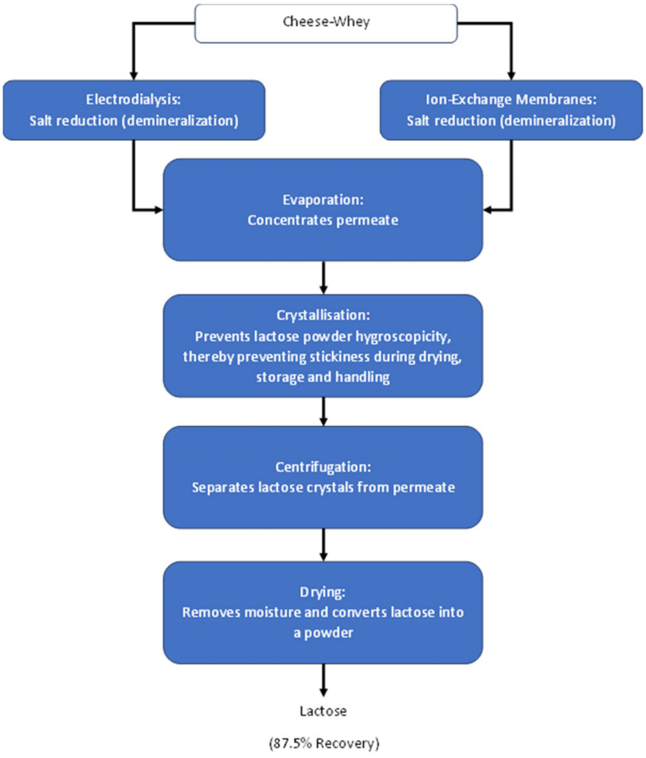

Figure 3 Increased lactose recovery from cheese whey.

was reported that demineralised whey with a lactose concentration of 80% demonstrated increasing ethanol concentrations (Yamahata *et al.* 2020). Demineralised whey concentrations of 10%, 15% and 20% w/v yielded ethanol concentrations of 5.0%, 7.6% and 9.5% v/v, respectively, with similarly increased acceptability compared to raw whey fermentation (Yamahata *et al.* 2020). Akin to other whey beverages, this may provide developmental opportunities, with the craft spirit market expanding steadily in the previous decade. Development of whey-based novel products may provide businesses with an economic edge, whilst also providing a craft product that may be sold at a premium price. Contrarily, distillation of fermented whey has been shown to reduce CO_2 emissions by 8.4 kg per functional unit and requires 0.44 kg less water to be added to the production process compared to malted barley equivalents (Risner *et al.* 2018). Nevertheless, production of alcohol from waste whey is an effective means of valorisation, with the utilisation of readily available microorganism cultures and cheese whey an inexpensive methodology suitable for developing countries and small organisations (Koushki *et al.* 2012).

Another, perhaps more promising option for waste whey management is dark fermentation (DF). DF is an indirect technology in which several genera of bacteria (namely Clostridium and Enterobacter) can use the carbohydrates, proteins and lipids as substrates to produce H_2, CO_2,and organic acids, through the acidogenic pathway (Ferreira and Gouveia 2020). DF involves biohydrogen and volatile fatty acid (VFA) production by anaerobiosis utilising the high carbohydrate content of waste whey. However, DF is thermodynamically unfavourable, difficult to control and sensitive to substrate composition, organic loading rate, inoculum type and pretreatment, reactor type and operating regime, temperature, pH, hydraulic and cell residence time. This results in a yield of 1–4 mol H_2 mol^{-1}, despite a theoretical maximum of 8 mol H_2 mol^{-1} due to the generation of lactose and VFAs (Asunis *et al.* 2020; Lovato *et al.* 2021). Nevertheless, DF can produce renewable H_2, with a high potential for large-scale implementation, compared to alternative biological processes due to the use of renewable substrates, process simplicity and independence from light.

However, hydrogen yield and production rates are often too low for industrial implementation, though operation of high-rate reactors, use of a two-stage system of DF and subsequent methanogenic stage may significantly alleviate these issues. However, such techniques and configurations require further extensive research (Weide *et al*. 2021).

Currently, the raw materials used for biofuel production, biodiesel or bioethanol, are generally food- and agriculture-related crops (Srivastava *et al*. 2021). Research has shown that VFAs can be used by oleaginous microorganisms as cheap alternative carbon sources, which could be converted into lipids and subsequently to biodiesel (Zhang *et al*. 2009). However, the concentration of VFAs in the fermented wastewater is very low, which is a limitation for commercialisation (Reyhanitash *et al*. 2016). The full-scale applications of sewage sludge fermentation for VFAs production that fully meet the demands for commercial production are still rarely reported, due to weak fermentation intensity, low VFAs concentration and poor substrate conversion rate. A novel strategy of liquid fermentation using anaerobic dynamic membrane reactor (AnDMBR) was proposed by Liu *et al*. (2019) to enhance VFAs production from sewage sludge for potential commercial application in VFAs production. VFAs productivity and concentration as well as substrate conversion rate reached as high as 7.8 kg VFA − COD/m3 d, 60 g/L and 0.38 kg VFA − COD/kg *VS* respectively. Moreover, dynamic membrane was stably operated for approximately 70 days. Producing VFAs using such technologies would help in the future commercial production of biodiesel.

FOOD INGREDIENTS

Whey may also be utilised within foods as an ingredient or to produce composite food products from waste whey using solid component recovery techniques, such as nano-, micro- and ultrafiltration. Consequentially, whey cream with a fat content of 25–30% can be removed from waste whey and used for milk standardisation in cheese or butter production. Similarly, sweetened condensed whey may be produced using reverse osmosis and nanofiltration used either in combination or as individual techniques. Such techniques increase whey solids up to 65% to form a viscous product (Panghal *et al*. 2018). Similarly, contained lactose may be recovered through a similar series of ultrafiltration, ion exchange and reverse osmosis can yield a purity of 99.8% and overall recovery of 74%. Nevertheless, similar filtration processes enable lactose and whey protein recovery of 90% and 80% respectively (Panghal *et al*. 2018).

Such by-products may be utilised as an ingredient within beverages as discussed previously, or to enhance protein, essential amino acid and vitamin C content of beverages. Consequently, these products may be suitable for those suffering from ailments and degenerative diseases (Panghal *et al*. 2018). Similarly, whey proteins are functional nutraceuticals due to significant biological activities and high proportion of branched chain amino acids crucial to blood glucose homeostasis, metabolism and neural function (Lappa *et al*. 2019). Additionally, bioactive whey components may modulate adiposity, cardiovascular and gastrointestinal systems. Hence, they have attracted significant research and consumer interest, with the potential for these compounds to be used in fortification of functional or dietary foods (Lappa *et al*. 2019).

Alternatively, whey protein-derived peptides (protein hydrolysates produced via different enzymatic treatments using protease enzyme) are considered as capable iron chelation alternatives than traditional salt-based fortification methods, which have limited gastrointestinal stability and bioavailability. Hence, whey proteins may provide an alternative for iron fortification in foodstuffs and supplements through a purported increase to iron absorption and bioavailability. Peptides released during whey protein hydrolysis with alcalase demonstrate potent iron-chelating properties. As such, whey-derived peptide–iron complexes are potential novel functional ingredients that can be used as a bioavailable iron carrier (Athira *et al*. 2021).

Chemicals and preservatives

Waste whey has been used as a preservative in some food products to replace nitrate salts, which are used in curing meat, to produce a clean label meat. This evades the negative stigmas attached to nitrite and nitrate application (Wójciak *et al*. 2014). Sea salt with autoclaved mustard and acid whey at the 1.0% level (w/w) of model cooked sausage had positive effects on the physicochemical and sensory qualities of organic sausage. When sea salt was applied to meat with autoclaved mustard and acid whey at 1.0% w/w, vacuum packed meat remained wholesome and palatable for up to 30 days under refrigeration, with quality ultimately similar to control samples with curing salts. However, acid whey and acid whey mixtures were less effective antimicrobial agents compared to traditional nitrites (Wójciak *et al*. 2014).

Alternative, more novel, valorisation techniques involve conversion of waste whey into chemicals. Other work utilised cheese whey to produce a low-cost disinfectant with high lactic acid and low lactose content through fermentation protocols using mesophilic lactic acid starter mixes over 120 hours (Santos *et al*. 2019). Such fermentation may promote the proteins and lactose removal, thus reducing COD. The produced disinfectant demonstrated bactericidal activity against *Listeria monocytogenes*, *Salmonella enterica*, *Escherichia coli* O157:H7 and 13 other pathogenic and spoilage organisms. The highest antibacterial activities were observed at 120 hours. However, this may prove impractical for real-world applications where efficiency is typically preponderant. Nonetheless, the whey solution reportedly achieved improved microbial quality and similar quality parameters when used to treat shredded lettuce compared to chlorine. Hence, production of disinfectant may be a promising, low-cost and efficient valorisation method (Santos *et al*. 2019). Although this may introduce allergenicity concerns, fermentation of dairy solutions by lactic acid bacteria may decrease whey protein allergenicity. However, failure to do so would render use of whey as a chlorine alternative inappropriate (Villa *et al*. 2018). Nonetheless, similar work demonstrates that compounds with antioxidant and antifungal activities may be obtained from enzymatic transformation or fermentation of cheese whey by common bacterial or fungal species. This may be attributable to the bioactive peptides produced during protein hydrolysis induced by enzymatic or fermentative processes. Such compounds possess in vitro antioxidant and antibacterial properties (Martí-Quijal *et al*. 2021).

Furthermore, waste whey may be utilised to produce acetic acid with a 98% purity according to use of a model membrane-integrated hybrid reactor system. This may improve yield over conventional acetic acid production plants to a similar concentration and purity, though with significantly lower energy requirements at 55 kWh compared to 5500 kWh, whilst also on a significantly smaller scale. However, it is worth noting the omission of pasteurisation and evaporation equipment in the model system (Pal and Nayak 2016).

In line processes

Recent studies focus on the integration of treatment processes, so-called biorefineries, for the purpose of waste whey valorisation through production of biofuels (methane, hydrogen and ethanol), electric energy and/or chemical commodities (carboxylic acids, proteins, and biopolymers) as discussed. Such processes are paramount for cost-effective and efficient valorisation. A combination of two or more physical, chemical and biological processes (also known as bioprocess integration) could be utilised to produce various valuable products and to attain a zero-waste approach within the dairy industry (Asunis *et al*. 2020). The main idea is to integrate all processes in a multistep biorefining strategy for total valorisation of cheese whey, including recovery of high-added value compounds (nutrients, antioxidant, bioactive molecules) for incorporation into new foods using advanced biotransformation extraction techniques. Other new materials such as hydrogels, bioplastics and biofuels can be also obtained from the remaining product. An excellent overview of example techniques is provided by Asunis *et al*. (2020).

More recent work focusses on integrated ultrafiltration processes within cheese waste streams, thus providing opportunities for small- and medium-scale dairy producers for further valorisation through recovery of proteins and lactose, thus contributing to their sustainability. An integrated process for the recovery of sweet goat whey components was carried out. It included filtration, centrifugation and pasteurisation, followed by sequential membrane processes, ultrafiltration/dilution, nanofiltration of ultrafiltration permeates in dilution mode and the concentration/dilution of nanofiltration retentates. Such processes may enable innovative whey-derived product production, including food gels, protein concentrates in powder and whey cheeses with probiotics. Hence, such systems are likely economically viable for small and medium enterprises (Macedo *et al*. 2021a; 2021b).

Plastics and films

Traditional food packaging materials, such as plastics, have many drawbacks in terms of their environmental impact, thus emphasising the importance and need for alternative packaging materials and formats. A major group of alternative and novel materials which possess future commercial potential are those derived from utilised and under-utilised food ingredients, or food grade ingredients—edible films and coatings.

Other novel uses of waste cheese whey include plastic and film production. A life cycle assessment was conducted to determine the feasibility of producing polyhydroxyalkanoates (PHA) from waste cheese whey as a novel valorisation technique, against conventional anaerobic digestion techniques (Asunis *et al*. 2021). PHA biopolymers are proposed to be a sustainable alternative to petroleum-based plastics given their various chemical compositions and applications. The authors demonstrate that an improved PHA production system may achieve comparable environmental performance against conventional anaerobic digestion, with a -50.3 kgCO$_2$ eq./tonne of cheese whey achieved (Asunis *et al*. 2021).

Similarly, edible films may be produced from whey protein isolates (WPI) and whey protein concentrate (WPC). Promoting compounds and nanomaterials may be added to alter the film functionality. For example, immunoglobulins may be incorporated to improve film adhesion and strength, whilst also increasing film transparency and clarity. Novel WPI-based nanocomposites may form part of multilayer film packaging. Thus, they are alternatives to conventional fossil-based packaging materials (Lappa *et al*. 2019).

Similar work utilised waste cheese whey to produce edible films, thus providing a sustainable and biodegradable alternative to plastic counterparts. Additionally, bioactive and antimicrobial whey proteins, such as lactoferrin, may be incorporated into edible films to produce functional packaging capable of increasing shelf-life. Lactoferrin has demonstrated particular efficacy against Gram-positive and Gram-negative bacteria, yeasts and viruses, hence may be applied to various foodstuffs (Dinika *et al*. 2020).

Nonetheless, others propose that whey plastics produced through copolymerisation with a copolymer called polyethylene glycol methyl ether methacrylate (PEGMA) possess a lower energy consumption and air emissions compared to other plastics, though a similar environmental impact compared to other polymers. Nonetheless, the environmental impact of whey plastics demonstrates a lower GWP compared to conventional plastics (Chalermthai *et al*. 2021).

Waste whey from biomass may be used in the production of 3-D carbon structures. The flexural strength of such 3-D porous carbons is comparable to those produced from polymeric resins. However, this is a novel; perhaps niche, valorisation strategy for waste whey (Raúl Llamas *et al*. 2021).

Other uses

The removal of carbon dioxide from the atmosphere is one of the recent attractive methods to reduce global warming. A potential application of whey could be the utilisation as a carbon dioxide sink (sorbent) to capture carbon dioxide. Such a technique exhibits promise, with a maximum 0.4% carbon capture capacity using commercial whey protein isolate (WPI), and 0.78% and 0.74% capture capacity using spray-dried WPI at inlet gas temperatures of 130°C and 170°C, respectively, under test conditions. However, this remains somewhat low. Furthermore, this strategy still generates waste in the form of spent WPI once capture capacity is reduced. Additionally, the production of WPI requires further processing of waste whey, thus generating further GHGs. Hence, the utility of WPI as a carbon sink may be negated by further greenhouse gas emissions associated with WPI production, though it may remain useful as an inline carbon sink within the same process used to produce it (Imtiaz-Ul-Islam *et al*. 2011).

Non-conventional techniques

Non-conventional valorisation techniques are reported in literature. These include the utilisation of unconventional, perhaps novel, processes to treat whey, including enhancement of valuable compound recovery from whey using thermal, ultrasonic and thermosonication pretreatments (Khaire and Gogate 2018); ultrasonic modification of whey protein isolate to alter structural and functional properties (Meng *et al*. 2021); use of electric technologies such as pulsed electric fields as non-thermal technologies in cheesemaking (Gentès et al. 2022); or to alter physiochemical properties for new functionalities using ohmic heating (Rocha *et al*. 2018). Additional non-conventional techniques are outlined in Table 5.

CURRENT AND FUTURE TRENDS IN LEGISLATIONS AND REGULATIONS RELEVANT TO WHEY PROCESSING AND ENVIRONMENTAL IMPACTS

Current trends

The New Waste Framework Directive (WFD; Directive 2008/98/EC) prioritises the prevention of waste generation, with subsequent focus on processing for reuse (valorisation), recycling and recovery, with disposal given the least emphasis (Figure 4). The WFD focuses on three key points for food waste: separate collection of biowaste, treatment of biowaste to ensure maximum environmental protection and development of techniques to produce environmentally safe materials from biowaste (Ravindran and Jaiswal 2016). The priorities of the WFD for waste management are purported to influence future legislation and policies. Co-product exploitation must be encouraged accordingly to prevent the generation of supplementary whey as waste. This is essential to increase the eco-sustainability of the food industry, not least whey processing. Similarly, the bio-economy strategy of the European Union must be followed to improve the management of biological resources, open new markets for food and biobased products, whilst ensuring environmental protection (Baiano 2014).

However, Regulation (EC) No 1907/2006 requires manufacturer registration for the production and marketing of newly produced chemicals within the EU. This may act as a hurdle for the processing of whey waste streams into new chemicals, particularly for small-scale producers focussing on the production of novel compounds from waste whey, thus potentially hindering the potential for commercialisation of novel processes (Ravindran and Jaiswal 2016). However, the bio-economy strategy is one of the major food waste prevention policies in the EU, with European nations obliged to change their approach to production, recycling and disposal of biological resources, with further commitment of the EU to meeting the UN's sustainable development goals (SDGs), including to reduce food losses along the food production and supply chains (Devkota *et al*. 2017). Accordingly, dairy processors must develop productive and profitable means of whey waste management, particularly as the costs of current waste treatments are very high. Consequentially, waste disposal into agricultural land as a fertiliser or use for animal feed is still thought to be the most common waste disposal method (Roufou *et al*. 2021). However, in accordance with Council Regulations (EC) No. 834/2007 and No. 889/2008,

Figure 4 Hierarchy of the waste framework directive. Waste prevention is the preferred option, with Disposal to Landfill a Last Resort (European Commission, Undated).

deproteinised whey may be utilised to produce compost in combination with grape marc and pruning residues for organic farming. In doing so, the environmental sustainability of wine and dairy production chains may be increased, whilst perhaps reducing disposal costs of by-products (Alfonzo *et al*. 2022).

Future trends

The demand for animal products is anticipated to increase by 70% by 2050, therefore exacerbating the current issues to food waste and waste whey in particular and associated deleterious effects. Hence, the focus of food producers on sustainability and efficiency will likely increase (Henriques 2013; Torok *et al*. 2022). It is probably that future, more demanding legislation will be introduced that similarly increase the costs and requirements of waste whey management. This may lead to further recovery of valuable components from effluent streams for valorisation, with the correct use of recovered materials perhaps proving highly lucrative, thereby creating value throughout the entirety of production pipelines. Nonetheless, pressure from environmental and antipollution regulations will likely continue to challenge the dairy industry to act upon the whey waste issue (Henriques 2013), much akin to the pressures observed following introduction of plastic packaging taxes on plastic packaging processors.

Currently, handing and management of waste within the EU is encompassed by Directive 2008/98/EC. The use of environmentally safe materials produced from biowaste is encouraged. Furthermore, the concept of 'extended producer responsibility' is introduced, distinguishing between waste and by-products and confirms the 'polluter-pays principle', whereby the waste producer must pay for the cost of waste management. Nevertheless, legislation regulating products produced from waste valorisation will likely appear in response to the need for sustainable alternatives (Cass Talbott 2022). However, established legislative requirements must remain realistic and obtainable. Furthermore, some propose policy must encourage the adoption of circular economies, where product design fully considers the entire product life cycle, with consideration of problem development at every stage of the cycle, such as recyclability. However, this is not a simple endeavour to achieve, and migrations require substantial time, particularly where political pressure is absent or lacking. Furthermore, policy must be harmonised and apply to society, businesses and consumers alike (Momete 2020). Nonetheless, such circular systems would reduce the negative environmental impact of food production and waste (Torok *et al*. 2022). However, there is currently no coherent and ambition approaches to tackling food waste through the entire food supply chain in the EU, with some proposing that these areas of legislation lack adequate steering to significantly reduce food waste as required by international environmental targets. Hence, improvements must be made to current waste legislation, with some proposing economic instruments, for example, taxation, alongside increased food prices to change behaviours throughout the entirety of food chains (Garske *et al*. 2020). This is perhaps incredulous in this current economy. However, it is entirely possible that the currently increasing food prices will lead to reduced food wastage proposed by these authors?

Furthermore, the SDGs require that food producers and processers should take action to decrease by-product and side-stream generation, in favour of increased circularity through the development of nutrient-rich products by 2030 (Granato *et al*. 2022). However, the development of new, potentially functional, dairy and whey-derived foods is not simple, as compliance with local legislation must be maintained, whilst products must also remain economically, commercially and logistically feasible. Hence, novel food legislations must be updated and evolve concurrent with scientific advancement and new food product development to enable attainment of the SDGs (Granato *et al*. 2022). Additionally, new production systems must remain sustainable, and seek to reduce the environmental impact of the dairy industry, particularly as more demanding sustainability legislation is introduced (Henriques 2013). Nevertheless, industry must utilise appropriate disposal techniques to comply with waste disposal standards, with appropriate processing and sanitisation to mitigate environmental degradation. However, management techniques must remain productive, profitable and sustainable (Roufou *et al*. 2021).

CONCLUSIONS

Whey is rich in nutrients and has several commercial uses. However, the high volumes of waste whey produced present environmental risks. Whey is highlighted as energy intensive with respect to global warming potential (GWP) values and this has heightened the requirement to seek greater energy efficiency in heat processes.

Several methods have been used to assess whey environmental impact and carbon footprint. Although these methods are promising, they fail to recognise the environmental detriment of whey and milk powder production and waste beyond the farm gate and may be somewhat reliant on different manufacturing facilities sharing a similar level of technology. LCA approaches consider the entirety of the dairy production chain and assist manufacturers to engage in sustainable practices, thus mitigating environmental detriment, whilst benchmarking the performance of such efforts against industry averages.

The nature of whey as a rich lactose and protein source renders valorisation of waste whey into value-added products or components an attractive alternative, thus avoiding waste disposal issues. Whey can also be applied in consumer goods which is promising in relation to the increasing waste whey generated year on year. However, a single valorisation process or approach cannot provide an ultimate solution, particularly due to the ever-increasing global waste generated, alongside the economical and sustainability challenges involved. Strategies to reduce whey environmental impact include whey and wastewater treatment, application of varying energy-saving and recovery technologies to reduce energy consumption and CO_2 emissions including heat integration, anaerobic digestion (AD) and fermentation of whey to produce biogas and bioethanol. It is possible to utilise acid whey as a substrate for biogas to produce electricity as a potential replacement for non-renewable energy. Furthermore, there is an increased awareness of the untapped potential of waste utilisation to produce biofuels, bio-based chemicals and organic by-products. Although there is no single ultimate solution, a wide variety of valorisation techniques are reported in this paper.

The New WFD (Directive 2008/98/EC) prioritises the prevention of waste generation, with subsequent focus on processing for reuse (valorisation), recycling and recovery, with disposal given the least emphasis. However, the bio-economy strategy is one of the major food waste prevention policies in the EU, with European nations obliged to change their approach to production, recycling and disposal of biological resources, with further commitment of the EU to meeting the UN's sustainable development goals (SDGs), including to reduce food losses along the food production and supply chains. Future more demanding legislation is likely to be introduced that similarly increases the costs and requirements of waste whey management. This may lead to further recovery of valuable components from effluent streams for valorisation, with the correct use of recovered materials. Furthermore, the concept of 'extended producer responsibility' is introduced, distinguishes between waste and by-products and confirms the 'polluter-pays principle', whereby the waste producer must pay for the cost of waste management. Finally, novel food legislations must be updated and evolve concurrent with scientific advancement and new food product development to enable attainment of the UN's SDGs.

AUTHOR CONTRIBUTIONS

Dominic Buchanan: Data curation; investigation; writing – original draft; writing – review and editing. **Wayne Martindale:** Data curation; investigation; supervision; writing – original draft; writing – review and editing. **Ehab Romeih:** Data curation; investigation; supervision; writing – original draft; writing – review and editing. **Essam Hebishy:** Conceptualization; data curation; investigation; project administration; supervision; validation; visualization; writing – original draft; writing – review and editing.

CONFLICT OF INTEREST

The authors have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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