JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2023, 24(10), 86–104
https://doi.org/10.12911/22998993/169505
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.07.05
Accepted: 2023.07.24
Published: 2023.08.19

Whey Valorization – Innovative Strategies for Sustainable Development and Value-Added Product Creation

Bouchra Soumati[1*], Majid Atmani[1], Asmae Benabderrahmane[1], Meryem Benjelloun[1]

[1] Functional Ecology and Environmental Engineering Laboratory, Faculty of Sciences and Techniques, Sidi Mohamed Benabdellah University, Fez, Morocco

* Corresponding author's e-mail: soumatibouchra1991@gmail.com

ABSTRACT

In recent years, the pursuit of sustainable practices and the efficient utilization of resources has become paramount in various industries, including the food and beverage sector. One such challenge faced by the dairy industry is the management of whey, a byproduct generated during cheese and yogurt production. Historically, whey has been perceived as a discarded waste product, leading to environmental concerns due to its high organic load and disposal challenges. However, with the increasing emphasis on sustainability, researchers and industry leaders have recognized the potential of developing innovative approaches to valorize whey, transforming it into valuable products while minimizing waste and environmental impact. Essentially turning it from "gutter-to-gold. This review provides an overview of the technologies used for whey valorization, with a focus on new approaches, innovative products, and emerging perspectives. It aims to stimulate research and innovation in this critical field, fostering the development of a more sustainable and circular dairy industry.

Keywords: whey, health benefits, functional properties, whey valorization strategies, circular economy, value-added products, bioprocess integration

INTRODUCTION

Whey, a major by-product of the dairy industry, has a history dating back to the 1970s when it was primarily used in whey baths due to its beneficial active ingredients known for their anti-inflammatory properties and skin-nourishing qualities (Walzem et al., 2002). However, over time, whey's reputation declined, it became regarded as a burdensome and environmentally harmful waste generated by the dairy industry. The majority of whey was either used as animal feed (such as pigs, sheep, and cattle) or disposed of as fertilizer or dumped directly into rivers or the sea (Ryan and Walsh, 2016). Farmers commonly used the expression "out of sight out of mind" "To convey their worry regarding whey. The International Dairy Federation (IDF) reported a remarkable 13% increase in cheese production across 56 countries globally, and this upward trend persisted in 2018, with an additional surge of 16% (IDF, 2017, 2018). (FAO, 2017) . These findings point to significant growth within the cheese industry. Therefore, "the challenge" continues to grow. Each year, the total production of whey experiences a 1-2% increment. However, less than 50% of the total whey produced undergoes utilization or processing through various technologies and processes. Approximately 40 % of whey is discarded globally, leading to a substantial loss of precious nutrients. It shows that a significant portion of milk nutrients is not effectively utilized for human consumption, which has severe sustainability implications. In this sense, the valorization of whey through various technologies and in different products is an essential aspect in developing multiple dimensions of sustainability, including environmental, economic, and societal aspects. Whey comprises around 50% of total milk solids with lactose being the major component, followed by proteins 20% of the total proteins in milk, with exceptional nutritional value and beneficial function and biological properties, it is also rich in vitamins and minerals that are worth their recovery from this by product.(Pires et al., 2021) Due to its versatility, whey can be considered as a valuable raw material with a wide range of applications across different industrial sectors. In response to this challenge, extensive research and development efforts have been undertaken to explore different technologies and approaches for the effective valorization of whey. This review covers a wide range of topics, providing insights into the effective utilization of whey. It delves into physicochemical methods like microfiltration, ultrafiltration, and nanofiltration, which enable the extraction and concentration of valuable components such as proteins, lactose, and bioactive compounds. Additionally; fermentation processes play a crucial role in the valorization of whey. The review examines the application of fermentation techniques to convert whey into high-value products, including bioethanol, bioplastics, beverages, and traditional dairy products like ricotta and whey butter. This broadens the possibilities for utilizing whey in various industries. Moreover, the review recognizes the importance of bioremediation and bioaugmentation techniques in whey valorization. These techniques involve the use of microorganisms to remediate and enhance the quality of whey, further expanding the potential for its utilization. In addition to these approaches, the literature reveals numerous other innovative techniques for whey valorization. These techniques aim to surpass traditional methods by achieving complete recovery from whey, minimizing waste generation, and maximizing the utilization of its components in diverse applications. By encompassing physicochemical methods, fermentation processes, bioremediation, and bioaugmentation, this review provides a thorough understanding of the various avenues for whey valorization. It highlights the immense potential for transforming whey into precious and sustainable products, contributing to improved efficiency and environmental friendliness in utilizing this abundant byproduct.

WHEY COMPOSITION AND NUTRITIONAL VALUE

Whey "sometimes called milk serum" (Guo, 2019) is a residual product generated during the processing of dairy, particularly in the production of cheese. Characterized as an aqueous liquid extracted from the coagulum during cheese-making (Zadow, 2012), it has a yellow-green color (Bintsis and Papademas, 2023; Pires et al., 2021), or sometimes even a bluish tinge, but the color depends on the quality and type of milk used (Guo and Wang, 2019). Among the different sources of whey, including goat, sheep, and buffalo milk, the primary focus of this review will be on whey derived from cow milk. This is due to its predominant production volume and economic significance (Ramos et al., 2016). There are two main types of whey that can be classified based on the method used for milk coagulation (Rocha-Mendoza et al., 2021). Sweet Whey (SW) is the most common form of whey, produced through rennet coagulation during cheese-making (hard, semi-hard, and soft cheese). It has a higher pH level (>5.6) and contains more lactose (46–52 g/L), protein (6–10 g/L), and minerals (2.5–4.7 g/L). Acid Whey (AW), also known as sour whey, is produced through acidification using lactic acid bacteria or other acidifying agents. Acid-induced coagulation increases calcium levels and mineral content compared to Sweet Whey due to the conversion of calcium phosphate. Acid Whey has a lower pH level (<5.6) and higher acidity and mineral content (4.3–7.2 g/L), lactose (44–46 g/L), and protein (6–8 g/L) (Guo and Wang, 2019; Buchanan et al., 2023; Mulcahy, Eve M., 2017; Monnier and Schlienger, 2018).

The composition of whey can vary due to factors such as the milk source, its chemical composition, processing methods, and cheese-making process. Other factors like genetic heritage, seasonal variations, feed, and lactation stage also influence the composition of milk and whey. (Bintsis and Papademas, 2023; Pires et al., 2021). Whey, including both SW and AW, is predominantly water, making up around 93–95% of its content (Ramos et al., 2016). Whey represents approximately 50% of milk nutrients, with lactose being the largest component at around 70% of milk's different components. Proteins are the next abundant component in whey, constituting around 20% of the total protein content in milk. (Papademas and Kotsaki, 2020), additionally, whey contains essential minerals, B-complex vitamins, and other minor compounds (Tsermoula et al., 2021; Panghal et al., 2018; Mollea et al., 2013). Lactose and proteins will be discussed below.

Whey proteins, also known as milk serum proteins, are recognized for their high-quality protein content and excellent amino acid profile. They are considered to be one of the best sources of amino acids in terms of their digestibility and the presence of essential amino acids. The digestible indispensable amino acid score (DIAAS) is a measure of protein quality that takes into account both the amino acid composition and the digestibility of the protein. Whey proteins have been found to have a high DIAAS, indicating that they provide a complete and well-balanced profile of essential amino acids that are readily absorbed and utilized by the body (Sharma, 2019; Hasmukh Patel and Sonia Patel, 2015). Whey proteins are comprised of five several protein fractions, including: beta-Lactoglobulin, alpha-Lactalbumin, bovine serum albumin, Immunoglobulins, and Glycomacropeptide. Each fraction exhibits unique characteristics and functions (Sharma and Chauhan, 2018). Beta-Lactoglobulin, as the most abundant protein in whey, represents approximately half of the total whey proteins (SW and AW), it can be found in the milk of various mammalian species, it is notably absent in human milk (Guo, 2014), and is widely utilized in various applications. In addition to the major protein fractions, whey also contains minor protein fractions that contribute to its overall composition. These include Lactoferrin, Lactoperoxidase, and lysozyme. Although present in smaller amounts, these minor protein fractions possess specific functionalities and are of particular interest in specialized applications.(Deeth and Bansal, 2019; Hulmi et al., 2010). Figure 1 reports the average protein compositions of these two whey types (Sharma, 2019). While Lactose, the primary carbohydrate in whey, contributes to the absorption of key minerals like calcium, magnesium, and phosphorus in the intestines, as well as aids in the utilization of vitamin C. Whey also contains oligosaccharides, which have prebiotic and anti-infectious properties. Among these oligosaccharides, those containing sialic acid are particularly beneficial for human health, especially in the early brain development of infants (Macwan et al., 2016; Anand et al., 2013). Generally whey exhibits high nutritional value and is characterized by its ease of digestion and effective assimilation (Papademas and Kotsaki, 2020).

PROMOTING WELLNESS: THE BENEFITS OF WHEY PROTEIN

In our time, there is an expanding awareness among consumers of the beneficial influence that food can have on one's overall health and well-being. This heightened awareness has propelled scientific investigations to validate the idea that diet can meet nutritional requirements and play a significant role in promoting human health. The concept of functional food products is not a recent phenomenon; it dates back to over 2,500 years ago when Hippocrates, the father of medicine, emphasized the therapeutic potential of food with his famous statement "Let food be thy medicine and medicine be thy food (Otles and Cagindi, 2012). It is evident that whey transcends its role as an excellent protein source, as it offers numerous health benefits. (Hernández-Ledesma et al., 2011; Madureira et al., 2010; Ramos et al., 2016). The various whey protein fractions offer diverse benefits to human health through their distinct biological activities. Here are some key biological activities associated with specific whey protein fractions: Beta-Lactoglobulin: Acts as a carrier for essential nutrients, facilitates passive immunity transfer, exhibits immunomodulatory properties, and shows potential anti-carcinogenic activity. (Zapata et al., 2017; Teixeira et al., 2019). Alpha

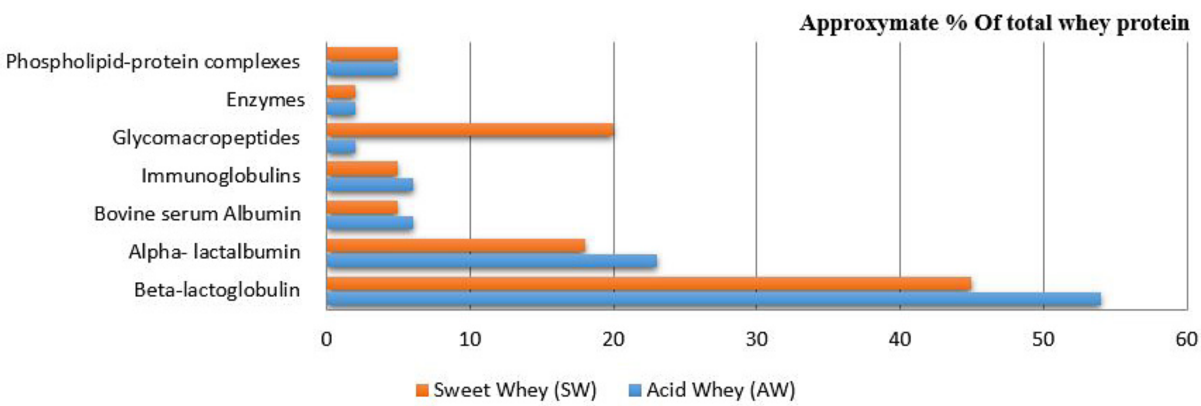

Figure 1. Protein composition analysis of AW and SW: examining the realtive abundance of individual proteins

Lactalbumin: plays a role in lactose synthesis, has calming and anxiolytic effects, demonstrates immune-modulating properties, and may have anticancer effects (Brew, 2011; Hallgren et al., 2008; Zarogoulidis et al., 2015). Bovine serum albumin: supports lipid synthesis, acts as a carrier protein for lipid transportation, exhibits antioxidant properties, and shows potential antitumor activity. (Fonseca et al., 2017; SreedharanNair et al., 2022). Lactoferrin: serves as an essential component of the body's defense mechanism, acting as an initial line of defense against microbial invaders. It possesses a diverse range of physiological functions, including antimicrobial (Olmo et al., 2009; Ward et al., 2005), antifungal (Olakanmi et al., 2002) antiviral (Valenti and Antonini, 2005; Berlutti et al., 2011), immunomodulatory (Xu et al., 2010; Wakabayashi et al., 2006) , and antioxidant activities (Rutherfurd and Gill, 2000). These properties make Lactoferrin a highly valuable protein found in whey, with immense potential in practical medicine. Its significant therapeutic attributes have sparked intensive research efforts aimed at uncovering its full capabilities and exploring its applications in various medical fields. Glycomacropeptide: Exhibits antimicrobial, prebiotic, satiety-inducing, and immunomodulatory properties, inhibits the growth of detrimental microbes, and stimulates the growth of beneficial intestinal bacteria (Jauregui-Rincón et al., 2019; Córdova-Dávalos et al., 2019). Immunoglobulins: Numerous studies have demonstrated the healthing capacity of Immunoglobulins due to their significant antimicrobial and antiviral qualities. Contribute to acquired immunity, provide protection against diseases, and have been associated with compounds that lower blood pressure., (Ramos et al., 2016; Heinrichs and Elizondo-Salazar, 2009). Lactoperoxidase: Exhibits antimicrobial properties, demonstrates antioxidant activity, and possesses immunomodulatory effects (Janet R. Ling, 2007; Shin et al., 2005). Additionally, Lactoperoxidase demonstrates strong antioxidant activity by neutralizing free radicals and reducing oxidative stress in the body (Wakabayashi et al., 2007; Mahdi et al., 2018).

As a result, whey protein has evolved from being a mere by-product of dairy processing to a highly regarded nutrient endorsed by an increasing number of nutritionists. This growing recognition has sparked a surge of interest in harnessing the potential of whey. Various whey protein-enriched formulas can be developed to cater to specific target groups, including infants, individuals with heart disease risks, and those with diabetes. Notably, whey protein is emerging as an immune-nutrient with the potential for dietary interventions in cancer management, representing a promising avenue for further research.

FUNCTIONAL ATTRIBUTES OF WHEY PROTEIN

In addition to their high nutritional value, whey proteins possess excellent functional properties

Table 1. The main industrial uses of whey constituents and their functional characteristics in food manufacturing

Food category	Uses	Functionality
Dairy items	Reduced-fat cheese Processed cheese Yogurt alternatives	Fat substitutes Emulsifying/ water binding properties Protein enrichment/fat replacement
Beverages	Dairy-based flavored drinks, Carbonated beverages Fruit-based beverages	Colloidal state, stability, flow resistance, creaminess, nutritional supplementation
Sport supplements	Drinks, protein enriched bars	Nutritional supplementation
Dessert products	Ice-cream, frozen juice bars, frozen dessert coatings	Whipping properties, milk powder alternatives, Emulsifying agent, body/texture, foaming.
Infant formula	Formula for infants and young children, formula for preterm and full-term babies	Nutritional balance
Dietetic foods	Therapeutic diets, nutrition for older adults.	Nutritional
Convenience meals Prepared food	Preserved creamy soups and sauces, dehydrated cream products, salad dressings, microwavable foods, low fat convenience meals	Flavor enhancer, emulsifier, stabilizer, viscosity controller, freeze thaw stability, egg yolk replacement, water binding capacity, acid solubility
Bakery items	Pastries, loaves, cupcakes, crescent rolls, breads	Flavor, stabilization, foaming and egg substitution
Confectionery items	Whipped candy mixes, sponge desserts, meringue-based treats	Emulsifying agent, aerating properties, egg substitute, fat binding, , foam stabilizer

that make them highly versatile in various food applications. These functional attributes include water binding, emulsifying, gelling, viscosity control, solubility, foaming, and the ability to enhance flavor and color (Minj and Anand, 2020). These properties make whey proteins suitable for use in the production of a diverse array of food products such as bread products, meat and fish preparations, dairy items, confections, beverages, as well as in medical and nutritional uses. They also play a crucial role in the formulation of specialized foods that cater to specific dietary requirements, including infant formulas and dietetic foods. Additionally, whey proteins contribute to the development of nutraceutical foods, including fortified products and functional beverages (Jyotsna et al., 2007). Table 1 provides an overview of some of the main industrial uses of whey constituents and their functional characteristics in food manufacturing (Kaur et al., 2020; García-Garibay et al., 2008; Rama et al., 2019; Prazeres et al. 2012).

WHEY VALORIZATION STRATEGIES

Before 1970, whey was primarily considered a waste product in the cheese industry and was primarily used as animal feed or fertilizer. However, the introduction of stringent environmental regulations triggered a change in perception towards whey (Guo and Wang, 2019; Smithers, 2008). It is now acknowledged as a valuable by-product with diverse potential applications. Improper disposal of whey presents significant environmental risks and is recognized as a major pollutant. Consequently, there is a concerted effort to develop sustainable and cost-effective strategies for whey management (Macwan et al., 2016). The UN Agenda 2030 for Sustainable Development, adopted in 2015, underscores the significance of sustainable waste management and emission reduction (Sustainable Development, 2015; Valta et al., 2017). The transformation of whey from a waste material to a valuable resource has spurred research endeavors to explore its potential in the food and chemical industries. Moreover, the nutritional value of whey has been acknowledged, leading to its incorporation into high-value products. Multiple methods, including membrane filtration techniques, biological treatments, and biotechnological approaches, are being employed to efficiently manage and extract value from whey. These environmentally-friendly alternatives, such as bioremediation and bioaugmentation, offer sustainable alternatives to conventional methods. (Kaur et al., 2020; Punnagaiarasi et al., 2017). Overall, there is a growing emphasis on maximizing the value of whey while mitigating its environmental impact.

Bioremediation and bioaugmentation strategies

Bioaugmentation is a sustainable approach used in whey treatment for bioremediation. It involves introducing specific microorganisms to enhance the breakdown of organic compounds in whey. By supplementing the natural microbial community, bioaugmentation accelerates the overall bioremediation process and improves pollutant removal. This technique allows for tailored treatment and greater control, promoting the efficient degradation of whey and reducing its environmental impact (Kosseva et al., 2003). A comparative study examined different strategies for bioremediating blue Stilton cheese whey. The study aimed to compare the effectiveness of mesophilic anaerobic and thermophilic aerobic approaches. The thermophilic process, utilizing a newly identified Bacillus sp. strain, demonstrated superior results in reducing Chemical Oxygen Demand (COD) and protein levels compared to the mesophilic approach. A one-step thermophilic aerobic process achieved significant COD reductions and generated valuable pasteurized biomass called single cell protein (SCP) for animal feed. Overall, the findings highlight the potential of thermophilic aerobic digestion for efficient whey treatment and the recovery of valuable products. (Steve Taylor, 2009; Loperena et al., 2009).

In a separate study, microorganisms (*Bacillus*, *Pseudomonas*, and *Acinetobacter* sp.) capable of degrading milk fat and protein were isolated from dairy wastewater. They were tested for their ability to reduce COD, protein, and lactose levels in the wastewater. When used together as a consortium, they showed a significant reduction in organic load. Additionally, a mixed culture of yeast and bacteria from dairy sludge demonstrated efficient biodegradation of dairy effluent, outperforming individual bacterial and yeast isolates in terms of organic load reduction. These findings indicate the potential of both bioremediation and bioaugmentation approaches for effectively reducing the organic load in whey and similar waste streams (Loperena et al., 2009; Porwal et al., 2015).

Innovative strategies for valorization the value of whey: Transforming waste into optimal utilization

One notable advancement is the development of more sophisticated processing equipment, such as membrane filtration (MK, UF, NF, RO) centrifugation, and chromatography, allow for precise separation and purification of whey components. These methods enable the extraction of specific fractions, such as proteins or lactose, with high purity and yield (Lappa et al., 2019; Marx et al., 2018). As well as, ion exchange whey processing is a valuable technique for the purification and concentration of whey protein, enabling the production of high-quality whey protein products with customized mineral profiles (Jungbauer and Hahn, 2009). Another area of advancement is in drying technologies. Spray drying, for example, is a widely used method to convert liquid whey into a powdered form, extending its shelf life and facilitating storage and transportation. Innovations in spray drying techniques have led to improved product quality, reduced energy consumption,

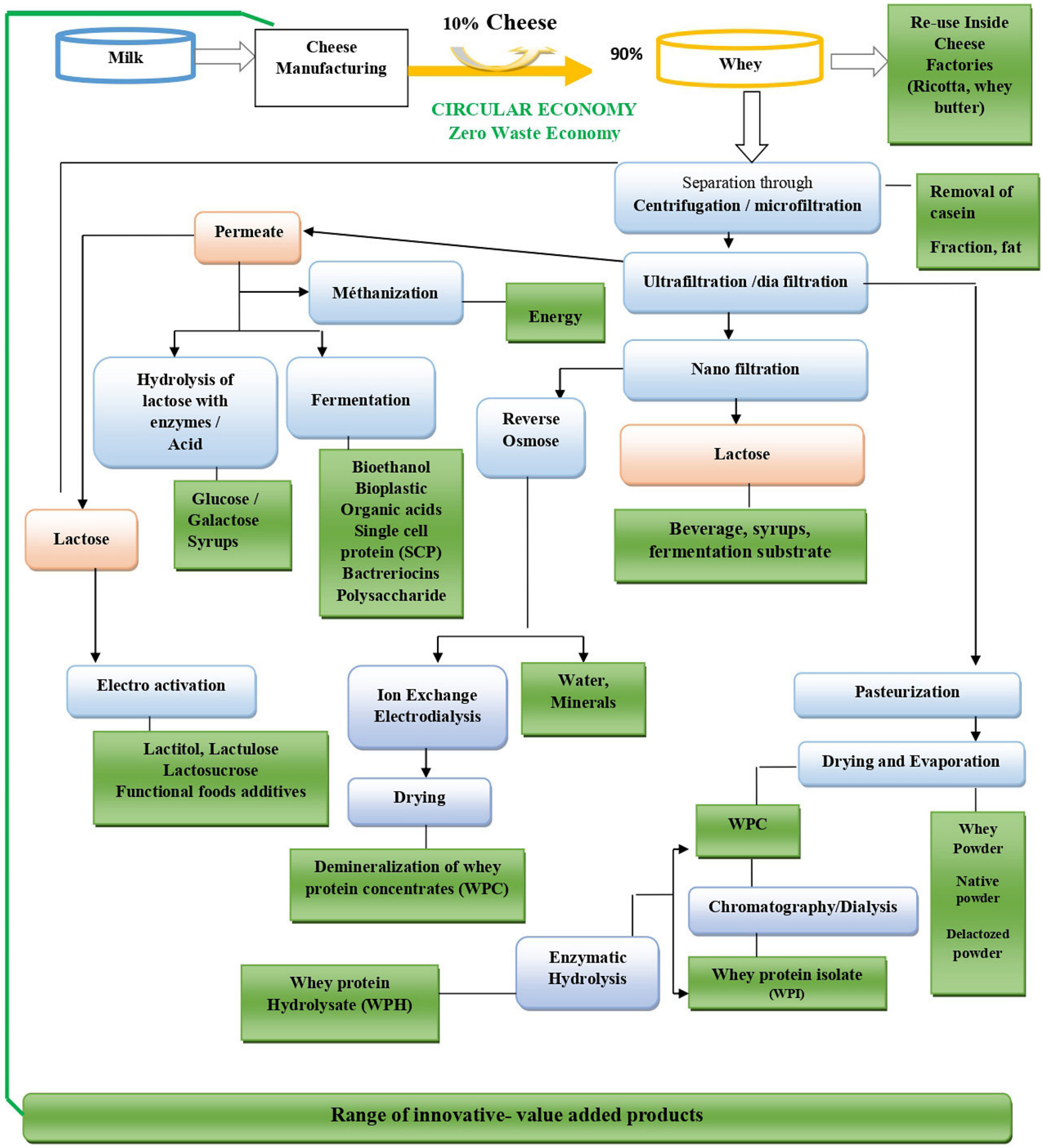

Figure 2. Various strategies and techniques utilized for converting whey into valuable products

and enhanced control over particle size and moisture content (Písecký, 2005).

Enzymatic processing techniques have also advanced in recent years. Enzymes are used to modify the functional and nutritional properties of whey proteins, resulting in enhanced solubility, emulsifying properties, and digestibility. Enzymatic hydrolysis is employed to produce protein hydrolysates with specific peptide profiles and bioactive properties, catering to the increasing demand for specialized nutritional products (Severin and Xia, 2006). Furthermore, there have been advancements in the application of biotechnology for whey processing. Microbial fermentation processes using specific strains of bacteria, yeast, or fungi have been developed to convert Whey components into valuable products, such as organic acids, bio-fuels, enzymes, and specialty chemicals. This approach offers sustainable and environmentally friendly alternatives to traditional chemical-based processes. Overall, advances in processing technology have revolutionized the utilization of whey, enabling the production of a diverse range of value-added products. These technological innovations have not only improved the economic viability of whey processing but also contributed to a more sustainable and resource-efficient dairy industry. The various strategies and techniques utilized for converting whey into valuable products are shown in Figure 2 (Tsermoula et al., 2021; Gösta Bylund, M.Sc., 2015). Among the different possibility of whey valorization, reported in Figure 2, non-conventional techniques will be discussed.

Whey protein valorization: whey powder

Whey powder is a highly versatile ingredient derived from the processing of whey. It undergoes various processing techniques to obtain different types of whey powder, each with its own specific composition and properties (Jeewanthi et al., 2015; Anand et al., 2013; Kadam et al., 2018). Whey Protein Concentrate (WPC): This type of whey powder contains moderate protein content along with some lactose and fat. It is produced by removing water from whey through processes like filtration and evaporation. WPC typically has protein concentrations ranging from 30% to 80% and is commonly used in a wide range of applications, including sports nutrition products, protein bars, beverages, dairy items, and baked goods (De La Fuente et al., 2002). Its moderate protein content and presence of lactose and fat contribute to its desirable taste and texture in various food products (Pereira et al., 2015; Henriques et al., 2011; Dullius et al., 2018). Whey Protein Isolate (WPI): is a more refined form of whey powder that undergoes additional processing steps to remove a significant portion of lactose, fat, and other non-protein components. This results in a higher protein content (usually 90% or more) and a lower lactose content. WPI is a popular choice for individuals with lactose intolerance or those seeking a highly concentrated protein source. It is commonly used in protein powders, nutritional supplements, clinical nutrition products, and sports nutrition formulations. Whey Protein Hydrolysates (WPH): is produced by subjecting whey protein to enzymatic hydrolysis, breaking down the protein into smaller peptides. This process enhances the digestion and absorption of proteins, making WPH an easily digestible and rapidly absorbed protein source. WPH is often used in infant formulas, medical nutrition products, and sports supplements due to its quick availability of amino acids for muscle recovery and growth (Sinha et al., 2007). Specialty Whey Powders: In addition to the aforementioned types, there are also specialty whey powders available. One example is whey permeate powder, which is produced by further processing whey to remove a significant portion of protein, resulting in a powder rich in lactose and minerals. Whey permeates powder finds applications as a cost-effective ingredient in various food products, including baked goods, confectionery, and dairy products. Another very interesting powder Lactose-free whey protein has emerged as a prominent trend in the health and fitness sector. This innovative protein option caters to individuals who face challenges with lactose intolerance or prefer to avoid lactose in their diet. Lactose-free whey protein offers a range of benefits, including high-quality protein content and essential amino acids, making it an ideal choice for those seeking a reliable protein source. With a focus on meeting the needs of athletes, fitness enthusiasts, and individuals with specific dietary requirements, lactose-free whey protein products have gained significant popularity for their ability to provide a convenient and effective solution for obtaining essential nutrients without the discomfort associated with lactose intolerance (Kadam et al., 2018).

Each type of whey powder offers specific functionalities and nutritional profiles, making them suitable for different applications in the food, beverage, and nutritional industries. The choice of whey powder depends on factors such as desired protein content, lactose tolerance, taste requirements, and processing needs.

Whey lactose valorization

In addition to the valorization routes, recovery of lactose (Saleh, 2012). One common approach for whey lactose valorization is enzymatic hydrolysis, where lactose is broken down into its constituent sugars, glucose and galactose, using specific enzymes. The resulting hydrolyzed whey can be used as a sweetener in food and beverage products or as a source of fermentable sugars for the production of bio-fuels, organic acids, or other biochemical (Jurado et al., 2002). Another method of whey lactose valorization is fermentation. Lactose can be fermented by selected microorganisms, such as lactic acid bacteria or yeast, to produce various products. For example, lactose fermentation can yield lactic acid, which is widely used in the food industry as a preservative, flavor enhancer, or pH regulator. It can also be used for the production of ethanol, which has applications as a bio-fuel or as an ingredient in the pharmaceutical and chemical industries. Additionally it has applications for the advancement of an environmentally-friendly plastic component (polylactide, polymers, and polyhydroxyyalkanoates) (Saleh, 2012). Furthermore, whey lactose can be converted into lactulose through isomerization reactions. Lactulose is a non-digestible sugar that exhibits prebiotics properties and is used as a functional ingredient in food and dietary supplements to promote gut health and improve calcium absorption (Olano and Corzo, 2009). In addition to these methods, advancements in biotechnology and bioprocessing have led to the development of novel approaches for whey Lactose valorization. This includes the use of engineered microorganisms or enzymatic processes to produce specific compounds or bioactive ingredients from lactose.

Bioplastic & edible packaging

Waste cheese whey offers promising opportunities for the development of sustainable packaging materials and reducing the environmental impact in the food industry. Through comprehensive life cycle assessments, researchers have examined various valorization strategies for whey, including the production of polylactic acid (PLA), and polyhydroxyalkanoates (PHAs) through anaerobic digestion as well as the use of whey protein isolates (WPI) and whey protein concentrate (WPC) to create edible films.

PLA and PHAs are bio-based polymers that offer a promising and environmentally friendly substitute for petroleum-based plastics (Boey et al., 2021; Sarkar et al., 2023). These biodegradable materials have gained significant attention in recent years due to their sustainable characteristics and potential to mitigate the environmental impact of conventional plastics. The market for PLA and PHAs has been steadily growing, with projections indicating an increase from 2.11 million tons in 2018 to 2.63 million tons by 2023, according to European Bioplastics (2018) (Asunis et al., 2020; Rosenheim et al., 2018). This growth reflects the increasing demand for sustainable alternatives in various industries, including packaging, textiles, and consumer goods. One notable approach is the utilization of waste cheese whey as a feedstock for the production of PHAs. This innovative valorization technique has been subject to a comprehensive life cycle assessment, comparing it to conventional anaerobic digestion methods. The assessment demonstrates that an improved PHAs production system can achieve comparable environmental performance while effectively utilizing waste cheese whey. The resulting carbon footprint of 50.3 kgCO_2 eq. per ton of cheese whey (Asunis et al., 2021; Chalermthai et al., 2021), highlights the potential of PHAs as an environmentally friendly solution. (PHAs), derived from whey, possess versatile properties that make them suitable for a wide range of applications. These biopolymers find use in packaging materials, disposable products, agricultural films, and even medical applications (Reddy et al., 2003). Their biodegradability and versatility contribute to reducing the environmental impact associated with plastic waste and provide opportunities for a more sustainable approach in various industries. In addition to PHAs, whey-based PLA has emerged as another sustainable alternative to traditional plastics. PLA derived from whey is commonly used in packaging films, food containers, and textile applications (Montané et al., 2020). Its biodegradability and compatibility with existing manufacturing processes make it a viable choice for reducing reliance on fossil fuel-derived plastics and promoting a circular economy. In addition to PHAs and PLA, whey protein isolates (WPI) and whey protein concentrate (WPC) have emerged as key ingredients in the development of edible films, offering a range of advantages for sustainable packaging solutions. These edible films, derived from whey proteins, present an innovative and environmentally friendly alternative to conventional packaging materials. One notable aspect of edible films made from WPI and WPC is their biodegradability, allowing for reduced environmental impact and waste generation. These films can be safely consumed, making them suitable for various food applications. Furthermore, the incorporation of bioactive compounds and antimicrobial agents, such as Lactoferrin, into the films enhances their functionality and extends the shelf life of packaged products. The inclusion of Lactoferrin in edible films provides valuable antimicrobial properties, effectively inhibiting the growth of spoilage microorganisms. This contributes to improved food preservation, ensuring that packaged products maintain their quality for a longer duration. By employing Lactoferrin as an active ingredient, edible films not only offer an eco-friendly packaging solution but also deliver tangible benefits in terms of enhanced food safety and extended product durability. Moreover, the use of nanomaterials in combination with WPI and WPC further enhances the properties of these edible films. Nanomaterials allow for precise modification and improvement of the film's characteristics, such as adhesion, strength, transparency, and clarity. For instance, the incorporation of Immunoglobulins as nanomaterials enhances the film's performance in various aspects. Innovative nanocomposites based on WPI can also be integrated into multilayer film packaging, providing sustainable alternatives to conventional packaging derived from fossil fuels (Lappa et al., 2019; Dinika et al., 2020). In recent years, the exploration of whey-based materials has expanded beyond PHAs and edible films. Researchers have delved into the copolymerization of whey with Polyethylene Glycol Methyl Ether Methacrylate (PEGMA) as a promising approach to develop whey plastics with improved environmental performance. This innovative method aims to reduce energy consumption and air emissions during the production process. Through life cycle assessments comparing whey plastics to other polymers, it has been observed that whey plastics exhibit similar environmental impacts, while showcasing a lower Global Warming Potential (GWP) when compared to conventional plastics. These findings highlight the potential of whey plastics produced via copolymerization with PEGMA as a viable and sustainable solution for packaging materials in various industries (Chalermthai et al., 2021). In addition to whey plastics, the utilization of waste whey in the production of three-dimensional carbon structures presents another innovative application. Life cycle assessments conducted on these porous carbons, derived from waste whey, have shown comparable flexural strength to those produced from polymeric resins. This finding indicates that waste whey can be effectively transformed into valuable carbon-based materials with promising mechanical properties. Although this valorization strategy is still in its early stages and may currently occupy a niche market, further research and development efforts in this area hold great potential for contributing to a more sustainable and circular economy. By exploring novel applications for waste whey, we can unlock its latent value and promote resource efficiency while minimizing environmental impacts (Llamas-Unzueta et al., 2022). These innovative strategies demonstrate the potential of waste cheese whey in the development of sustainable packaging materials and contribute to a more environmentally friendly food industry.

Bioethanol

Based on recent studies, bioethanol production from whey has gained significant attention as a sustainable and economically viable process. Whey, a byproduct of the dairy industry, has high organic content and poses environmental challenges if not properly managed. However, innovative approaches have been developed to harness the potential of whey for bioethanol production. One of the main challenges in whey-based bioethanol production is the low lactose content and bioethanol yield (Christensen et al., 2011; Božanić et al., 2014). To overcome this limitation, concentration techniques such as ultrafiltration and reverse osmosis can be employed to increase lactose concentration in whey, resulting in higher bioethanol yields. Moreover, the use of Kluyveromyces marxianus strains, which possess lactose metabolism capabilities, has shown promising results in enhancing bioethanol production from whey. Genetic engineering techniques have also been explored to engineer Saccharomyces cerevisiae strains capable of efficiently utilizing lactose in whey for bioethanol production (Das et al., 2016). These advancements have the potential to further improve the overall process efficiency and yield. Industrial-scale bioethanol production units utilizing whey as a feedstock have been established in various countries, including Ireland, New Zealand, Denmark, and the USA (Božanić et al., 2014). These units highlight the commercial viability and scalability of whey-based bioethanol production. In addition to its environmental benefits, bioethanol derived from whey can find diverse applications in industries such as food, chemicals, pharmaceuticals, and cosmetics. Its renewable nature and reduced environmental impact make it an attractive alternative to fossil fuels. Overall, recent studies have demonstrated the feasibility and potential of utilizing whey as a valuable resource for bioethanol production. Ongoing research and technological advancements in this field hold promise for further optimizing the process and making bioethanol from whey a more sustainable and economically viable option in the future.

Whey: A new approach to human consumption

- **Whey-based beverages:** Whey-based beverages have undergone a remarkable transformation, evolving from overlooked byproducts to highly sought-after drinks. These beverages have gained popularity due to their nutritional value and their ability to cater to the changing needs and preferences of consumers. They offer a wide range of options, (Shraddha and Nalawade, 2015) including protein shakes, fruit smoothies, sports drinks, and carbonated beverages, providing a diverse and enticing selection for consumers. One of the key reasons for the rising popularity of whey-based beverages is their exceptional nutritional profile. Whey is rich in essential amino acids, which are vital for muscle growth, repair, and overall health. Additionally, whey contains vitamins, minerals, and antioxidants that contribute to overall well-being. By incorporating whey into beverage formulations, manufacturers can offer consumers a convenient and enjoyable way to access these beneficial nutrients. Another factor driving the success of whey-based beverages is their alignment with consumer preferences for clean label products. Consumers today are increasingly conscious of the ingredients they consume and seek products made with natural and wholesome ingredients. Whey-based beverages, when formulated with clean label principles, provide a transparent and trustworthy option for health-conscious individuals. They are free from artificial additives, preservatives, and unnecessary fillers, ensuring a pure and nutritious beverage experience. Furthermore, the utilization of whey in beverage production contributes to sustainability in the food industry. Whey is a byproduct of the dairy industry that was previously underutilized and often considered waste. However, by transforming it into delicious and nutritious beverages, the industry can reduce food waste and make efficient use of available resources. This approach aligns with the principles of a circular economy, where waste is minimized, and valuable ingredients are repurposed. Whey beverages come in various types, offering consumers a wide range of choices to suit their preferences and nutritional needs. Some of the common types of whey beverages include:

- **Sports drinks:** Whey-based sports beverages have gained significant popularity among athletes and sports enthusiasts due to their multitude of benefits for performance enhancement and post-workout recovery (Higgins et al., 2010). Renowned brands like Optimum Nutrition and Cytosport offer an extensive range of whey-based sports drink products, including widely favored options such as "Gold Standard 100% Whey" and "Muscle Milk Protein Shake." These beverages are meticulously formulated to provide a carefully balanced blend of top-quality whey protein, essential carbohydrates, and vital electrolytes, ensuring they meet the precise nutritional requirements of athletes. In terms of recommended daily intake, athletes are advised to consume between 1.2 and 2.0 grams of protein per kilogram of body weight, taking into account variables such as training intensity, frequency, and individual objectives (Volpi et al., 2003). Whey-based sports drinks provide a convenient and efficient solution to meet these requirements, as they offer a concentrated source of easily digestible whey protein that is rapidly absorbed by the body. Moreover, these beverages are fortified with key electrolytes like sodium and potassium, which play a vital role in maintaining proper hydration levels and preventing dehydration during intense physical exertion. Manufacturers are actively engaged in ongoing research and development endeavors to explore new formulations and further enhance the performance of whey-based sports beverages. They are investigating the inclusion of functional ingredients such as branched-chain amino acids, creatine, and antioxidants to augment their efficacy and address specific athlete needs. The industry's continuous research and development initiatives contribute to the constant evolution and refinement of these products, ensuring they stay at the forefront of sports nutrition (Roy, 2008; Chavan and Kumar, 2015).

- **Dairy type whey beverages:** Whey-based dairy beverages are available in two main forms: fermented and non-fermented. Fermented dairy beverages, such as "Gefilus," combine whey proteins with probiotics to create a drink that promotes digestive health. The fermentation process enhances the growth of probiotics, improving gut flora balance and nutrient digestibility. Probiotic whey beverages, like the one developed by (Rocha-Mendoza et al., 2021), are recognized for their probiotic benefits and potential to support intestinal health. On the other hand, non-fermented whey-based dairy beverages do not undergo fermentation but still contain high-quality whey proteins, making them a valuable source of essential amino acids for muscle recovery. These beverages are often chosen for their high protein content and comprehensive nutritional profile, including vitamins, minerals, and antioxidants. The whey-based dairy beverage industry continues to advance in production and fermentation techniques, while research focuses on evaluating different probiotic strains and their effects on intestinal health and the immune system. These advancements provide consumers with a diverse range of whey-based dairy beverages that cater to their nutritional needs and preferences.(Özer and Kirmaci, 2010; Papademas and Kotsaki, 2020; Skryplonek, 2018; Pereira et al., 2015).
- **Alcoholic whey beverages:** Alcoholic whey beverages have emerged as a unique and sustainable category of drinks that incorporate whey, a byproduct of cheese production, into the fermentation process. This innovative approach not only adds a distinct flavor but also helps reduce food waste. Brands like "Whey Ward Spirits" specialize in producing spirits such as whey-based vodka and gin, offering a smooth and flavorful drinking experience. "Whey Stout" replaces traditional malt with whey, resulting in a rich and creamy stout with a unique character. "The Blue Brew" uses whey from Stilton cheese production in beer brewing. As consumers increasingly seek novel and eco-conscious drinking options, the market for alcoholic whey beverages is expanding. These beverages not only provide a distinctive taste but also contribute to sustainability in the beverage industry by utilizing a valuable ingredient and reducing food waste (Chavan and Kumar, 2015; Ryan and Walsh, 2016; Papademas and Kotsaki, 2020).
- **Refreshing carbonated whey beverages:** Carbonated whey beverages are a popular and distinctive category of drinks that offer a refreshing and fizzy alternative to traditional soft drinks. Rivella is a notable example of a carbonated whey beverage that originated in Switzerland and has gained international recognition for its unique taste and composition. By combining whey, derived from the cheese-making process, with a blend of natural herbs and fruit extracts, Rivella creates a lightly carbonated beverage with a smooth and slightly tangy flavor profile. The demand for refreshing carbonated whey beverages continue to grow as consumers seeks alternatives to traditional soda and sugary drinks. These beverages offer a unique combination of flavors and potential health benefits, making them a satisfying and appealing choice for those looking to quench their thirst with a fizzy drink that goes beyond the ordinary. With brands like Rivella, Whey-Hey, and Superfrau. Whey expanding the range of carbonated whey beverages, consumers has a diverse selection to suit their taste preferences and wellness goals.(Chavan and Kumar, 2015; Joshi et al., 2020).
- **Ricotta & whey butter:** Whey, apart from its application in dairy beverages, serves as a vital component in the production of both ricotta cheese and whey butter. In ricotta production, the residual whey is heated, causing proteins to coagulate and form curds. These curds are then separated and drained to create ricotta cheese, which boasts a distinct flavor profile and a smooth consistency that adds to its appeal in various culinary applications. While the utilization of whey in ricotta cheese production is well-established, the exploration of whey butter is still an emerging research area (Modler, 1988; Ryan and Walsh, 2016). Whey butter is created by churning cream enriched

Table 2. Summary of diverse range of newly developed innovative products derived from whey

Product	Study purpose	Main outcomes	Reference
Sports drink	A hypertonic sports drink for athletes was developed using fermented whey. Acid whey with a lactose content of 3.32% was fermented with Lactobacillus bulgaricus and Streptococcus thermophilus cultures. The resulting fermented whey, with a concentration of 2.84%, was supplemented with different levels of stabilizer (T1: 0%, T2: 0.1%, T3: 0.125%, T4: 0.15%).	Among these combinations, T3 exhibited the most favorable properties and was identified as the optimal choice for the hypertonic sports drink formulation.	(Mehra et al. 2021) (Abella et al., 2016)
Beverage kefir grains	In this study, our goal was to investigate the potential of kefir grains as a starter culture for the production of both traditional milk kefir beverage and cheese whey-based beverages. Furthermore, we prepared a cheese whey-based beverage by utilizing the kefir grains as an integral part of the fermentation process.	The chemical properties and sensory evaluation results indicate that the kefir grains hold promise for the development of cheese whey-based beverages.	(Magalhães et al., 2011)
Guava-infused whey beverage for a unique flavor experience	Exploring the Potential of Cold Plasma Technology: Developing a Guava-Infused Whey Beverage with Enhanced Flavor A guava-flavored whey beverage was created by combining sweet whey and guava juice in different proportions, including 85/15, 80/20, 75/25, and 70/30 ratios.	Cold plasma technology presents a highly promising approach for creating whey-based beverages while minimizing the degradation of bioactive components. This innovative technology ensures that the beverages retain their optimal quality, preserving the valuable bioactive compounds present in the whey. The sensory evaluation of a beverage formulated with a ratio of 75% whey and 25% guava demonstrated favorable sensory properties. The combination of whey and guava resulted in a beverage that was well-received in terms of taste, aroma, and overall sensory experience.	(Silveira et al., 2019)
Whey-raspberry flavored beverage	The objective of this study was to prepare a raspberry-flavored whey beverage using ohmic heating and to investigate the effects of different ohmic heating conditions on the beverage. The study aimed to explore the impact of varying frequencies (10, 100, and 1000 Hz) at 25 V, as well as different voltages (45, 60, and 80 V) at a frequency of 60 Hz on the quality and characteristics of the final product.	The results indicated that the application of ohmic heating led to a decrease in the concentration of anthocyanin. Notably, the combination of 1000 Hz at 25 V and 80 V at 60 Hz demonstrated promise for processing pigmented fruits and developing beverages with reduced anthocyanin content.	(Ferreira et al., 2019)
Strawberry-flavored functional beverage.	The objective of this study was to prepare a strawberry-flavored whey beverage enriched with xylooligosaccharide by incorporating 1.25 g of xylooligosaccharide per 100 mL of whey.	The utilization of XOS in whey-based beverages proves to be an interesting approach, as demonstrated by the study findings, which highlight its significant impact on both the nutritional composition and sensory characteristics of the beverages.	(Souza et al., 2019)
Caproic acid	The objective of this study is to investigate the production of caproic acid through open culture fermentation using acid whey as a substrate.	An economically viable approach for caproic acid production	(Chwialkowska et al., 2019)
Bioplastic	The objective of this study was to investigate the utilization of dairy residues for the production of biodegradable plastics specifically (PHAs).	Whey was successfully utilized as a substrate for producing biodegradable plastics (PHAs) with a C/N ratio of 50. This demonstrates its potential as a sustainable alternative to conventional plastics. Non-aseptic conditions were also found to enable cost-effective and scalable production of PHAs from whey, contributing to the development of an eco-friendly plastic industry.	(Bosco and Chiampo, 2010)
Biomass	The aim of this study was to explore the potential of whey permeate as a substrate for cultivating the microalgae Chlorella protothecoide and evaluating its biomass and lipid production capabilities.	WP can be effectively utilized as a carbonaceous feedstock to facilitate the heterotrophic growth and lipid accumulation of Chlorella protothecoide.	(Espinosa-Gonzalez et al., 2014)
Bio-ethanol	The research aimed to produce bioethanol from ricotta cheese whey, also known as ”Scotta.” Scotta, with its lower protein levels and 4.5% to 5.0% lactose content, offers potential as a sustainable energy source. The fermentation process involved Kluyveromyces marxianus yeast.	This study demonstrates the feasibility of using K. marxianus yeast to ferment scotta for bioethanol production. The research highlights scotta’s effectiveness as a substrate, as it enables a high ethanol yield of 97%, which closely approaches the theoretical yield.	(Sansonetti et al., 2009)
Fertilizer	The objective of this study was to develop and evaluate the process of fermenting whey waste for the production of an organic liquid fertilizer known as ”PUCAFU”.	By combining whey with solid or liquid wastes, it becomes possible to produce a high-quality organic liquid fertilizer.	(Akib and Setiawati, 2017)
Vinegar	The study aimed to produce vinegar from lactose-enriched cheese whey. It involved fermenting whey lactose into ethanol using Kluyveromyces fragilis yeast, followed by acetic acid fermentation using Acetobacter pasteurianus bacteria from cider vinegar. This innovative approach utilizes abundant whey byproduct and cost-effective lactose, making it a viable and economical choice.	The vinegar production method followed the guidelines established by the Food and Agriculture Organization, ensuring that the final vinegar met the required safety standards for human consumption.	(Parrondo et al., 2003)
Organic acids	The objective of this study was to explore the potential of cheese whey for bioethanol and galactonic acid production.	Ethanol and galactonic acid were produced from cheese whey protein using Saccharomyces cerevisiae and Gluconobacter oxydans. This yielded 110 grams of ethanol, 320 grams of galactonate, and about 150 grams of other proteins from 1 kilogram of cheese whey protein.	(Zhou et al., 2019)

with whey, resulting in a butter product with a unique flavor and subtle tanginess. Further investigation is required to determine the optimal processing techniques, flavor profiles, and potential health benefits associated with whey butter. Ongoing research endeavors aim to unlock the full potential of whey as an ingredient in butter production, expanding the range of dairy products available to consumers. The incorporation of whey in ricotta cheese production highlights its versatility and sustainability in the dairy industry, while the exploration of whey butter offers the opportunity to diversify the landscape of dairy products. Continued research in these areas will uncover new possibilities for utilizing whey in innovative culinary creations, maximizing its potential and value in the dairy industry (Jinjarak et al., 2006; Costa et al., 2022).

Non-conventional techniques

The valorization of whey involves the exploration of various non-conventional techniques to maximize its potential and extract valuable compounds. These techniques aim to enhance the recovery of valuable compounds by employing unconventional and innovative processes. For example, thermal, ultrasonic, and thermosonication pretreatments have been investigated to improve the extraction of compounds from whey (Khaire and Gogate, 2018). Ultrasonic modification of whey protein isolate has also been explored to alter its structural and properties (Meng et al., 2021). Electric technologies, such as pulsed electric fields, have shown promise as non-thermal alternatives in cheese making, allowing for the modification of physicochemical properties. Another approach is the use of ohmic heating to alter whey's physicochemical properties, leading to the development of new functionalities. These non-conventional valorization techniques reflect ongoing efforts to explore innovative ways to harness the potential of whey and create new applications in the food industry. In this context; electro-activation has emerged as a promising technique for utilizing whey efficiently and sustainably. This reagent-free method has gained attention due to its energy efficiency and environmental friendliness (Aider and Gimenez-Vidal, 2012; Karim and Aider, 2020). Recent studies have demonstrated the effectiveness of electro-activated whey in enhancing its functionalities, particularly as a source of lactulose and Maillard reaction products with prebiotic and antioxidant properties. These findings have significant implications for the development of probiotic formulations, as electro-activated whey has shown to support the growth and viability of probiotic strains, including Bifidobacterium, Lactobacillus, and Streptococcus. Comparative studies between electro-activated and non-electro-activated whey have provided valuable insights into the potential benefits of this technique. The incorporation of electro-activated whey into culture media offers a natural and cost-effective solution for commercial probiotic production. Additionally, it's observed prebiotic and antioxidant effects open up new avenues for its application in the pharmaceutical industry. The adoption of electro-activation aligns with the industry's pursuit of sustainable and environmentally friendly technologies in the agri-food sector. By maximizing the value and utilization of whey through electro-activation, the potential of this byproduct is further enhanced, contributing to the development of innovative and sustainable solutions in the food industry (Kareb et al., 2018).

Other innovations from whey

Whey offers a multitude of applications that extend well beyond the previously mentioned examples. Its versatility as a raw material and the many processes available make it an invaluable resource for sustainable production and the development of value-added products in a variety of industries. Many innovative products have recently been developed from whey, and their key characteristics are summarized in Table 2. This diversity of products demonstrates the creative potential and capacity for innovation that whey offers researchers and industry players alike. By fully exploiting whey's properties and components, new opportunities are opening up to create unique, sustainable products that benefit both the economy and the environment.

CONCLUSIONS

The increasing evidence highlighting whey as a valuable resource of various nutrients underscores the importance of its efficient utilization. The integration of multiple unit operations into a cohesive bioprocess offers a promising solution for maximizing the potential of whey. By combining physicochemical methods such as microfiltration, ultrafiltration, and nanofiltration with fermentation techniques, the extraction of proteins, lactose, and bioactive compounds becomes feasible, providing opportunities for the development of functional food ingredients. Moreover, the incorporation of advanced technologies like high hydrostatic pressures, electro technologies, and ultrasound addresses the challenge of microbial contamination in whey, ensuring the production of safe and high-quality products. These innovations not only enhance the nutritional and sensory qualities of whey-based food products but also contribute to the promotion of sustainable practices. By embracing these integrated approaches, the valorization of whey not only minimizes waste but also supports the achievement of Sustainable Development Goals (SDGs) and the principles of a circular economy (Zero waste). The utilization of whey as a valuable raw material offers economic and environmental benefits, paving the way for a more sustainable and resource-efficient food industry. Continued research and development efforts in whey valorization are essential to unlock the full potential of this valuable by-product. By exploring new possibilities and optimizing existing techniques, the food industry can further harness the nutritional and functional properties of whey, leading to the creation of innovative and sustainable products. Future research should prioritize conducting comprehensive comparative studies to evaluate the efficiency, cost-effectiveness, and environmental impact of different whey valorization techniques. This will drive advancements in maximizing the value of whey while minimizing resource consumption and environmental footprint.

Acknowledgments

The authors would like to extend their sincere gratitude to all those who have contributed to the successful completion of this research and the preparation of this manuscript.

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