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Cheese whey recycling in the perspective of the circular economy: modeling processes and the supply chain to design the involvement of the small and medium enterprises

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Abstract

Rationale: Cheese whey has relevant nutritional, health and functional properties that could address the dietary needs of a growing world population. Nevertheless, around 50% of whey produced globally is not reused in the food system. A significant role in cheese production is played by small and medium enterprises (SMEs) that process typical products labelled with a protected designation of origin (PDO), representing both the cultural heritage and the major economical resource of specific geographical regions.

Scope and Approach: This study is aimed at identifying the potential involvement of SMEs in the recycling of whey for food uses. Techno-economic analyses of whey recycling processes were reviewed to define efficient configurations and plant size. Safety and quality specifications for whey were then examined as well as traceability systems designed for improving transparency among the actors and stakeholders of the dairy supply chain.

Key Findings and Conclusion: The study led to conclude that a whey value chain could be built by various cheese SMEs and a stand-alone industrial unit for the downstream processing of whey into value-added foods. In this scenario, advantages could derive from the involvement of SMEs that belong to the same PDO cheese consortium, in terms of standardization of whey, third party certification and possible use of smart traceability tools. Hence, the SMEs producing PDO products could advance the application of the bioeconomy principles in the food system. Research challenges to promote the implementation of the conceived whey value chain are finally outlined.

Keywords: cheese whey, traceability, Protected Designation of Origin, Internet of Things, Blockchain technology, industrial symbiosis

1. Introduction

The concept of the bioeconomy has promoted the rethinking and redesign of food supply chains. In this context, food waste management has been identified as one potential solution for the transition towards the implementation of circular supply chains in the food system (Jurgilevich et al., 2016). Among various waste streams generated by the food systems, the materials that are diverted from the food chain but are still edible (or can be processed to become edible) are considered as the most relevant resources as they can be converted into new food ingredients and foods, thus addressing the dietary needs of a growing world population (Lavelli, 2021).

The cheese industry produces about 145 million tons of whey annually and only 79 million tons (i.e., 54%) are re-used in the food system, while 6 million tons are destined to non-food uses and 60 million tons are used as feed, fertilizer or waste (Ganju & Gogate, 2017).

Whey composition differs between sweet whey (pH 6.2 – 6.4) and acid whey (pH 4.6 – 5.0) and typically comprises: 93.0 – 93-7% of water, 4.4 – 5.2% of lactose, traces or up to 0.8% of lactic acid, 0.6 – 1% of protein, 0.5% – 0.8% of minerals (Table 1, Jelen, Roginski, Fuquay, & Fox, 2003). Whey is highly pollutant, since its chemical oxygen demand (COD) can vary from 50,000 to 80,000 mg/L, whereas its biochemical oxygen demand (BOD) is in the range from 40,000 to 60,000 mg/L (Chatzipaschali, & Stamatis, 2012). A number of recycling processes have been proposed to obtain value added products from whey for the food and non-food sectors (Ganju & Gogate, 2017; Lappa et al., 2019; Rocha, & Guerra., 2020; Zandona, Blažić, & Jambrak 2021; Barba, 2021). Focusing on food uses, recycling processes comprise re-use of whey in cheese factories to produce other dairy products, recycling to produce non-conventional products such as unfermented and fermented whey-derived beverages (Mehra, R.; Kumar, H.; Kumar, N.; Ranvir S., Jana, A. et al., 2021) or separation of the lactose and protein fractions and distinct valorization. Lactose upgrading technologies include enzymatic or microbial production of target molecules such as prebiotic compounds (galacto-oligosaccharides, lactulose, lactitol and lactobionic acid) and carotenoids or bioconversion in biomasses of mushrooms or microalgae. Protein upgrading technologies include use as source of essential amino acids, use as a functional ingredient (gelling agent, foaming agent and emulsifying agent) and enzymatic hydrolysis to obtain bioactive peptides (Lappa et al., 2019; Rocha, & Guerra., 2020; Zandona et al., 2021). Alternatively, lactose can also be reintroduced in the food system upon conversion via fermentation in bacterial cellulose and fatty acid esters, which are used as structural agents, such as components of edible film. Whey proteins can also be reintroduced in the food system after chemical and physical modification as structural agents or delivery systems to protect bioactive compounds (Lappa et al., 2019; Lavelli, & Sereikaite, 2022a; Lavelli, & Sereikaite, 2022b).

Whey, whey protein and lactose prices are constantly monitored (https://www.clal.it/en/index.php?section=grafici_siero#wo) indicating a general attention of the food companies towards these multifunctional ingredients. However, despite multiple options to convert whey into value added foods, the implementation of recycling processes remains a challenge as proven by low percentage of whey recovered in the food system. It is worth noticing that, within the European Community approximately 200 cheese products have a Protected Designation of Origin (PDO), i.e., they originate in a specific geographical area and all their production steps take place in the same geographical area. The PDO foods are processed at SMEs according to a specific and well-defined process and their conformity to the procedural document of the PDO is assessed by both a consortium of producers and a third party certification body (Reg. CE 1151/2012). The PDO foods represent an important part of the culture, history, identity, heritage and local economy of a region or country (Albuquerque, Oliveira, & Costa, 2018; Mattas et al., 2022).

The aim of this review was to identify the potential roles of SMEs in the dairy sector in supplying whey for further processing in the food system. First, a literature study was performed to define the unit operations involved in liquid whey processing and to draw the process configurations that have been modeled and validated at various industrial scales (from 100 to 3000 t of whey inflow/d). Subsequently, the literature study was directed to identify the safety and quality specifications of whey needed to address quality requirements for value-added food applications. Then, the traceability systems implemented in a cheesemaking process and in the entire dairy supply chain were reviewed, which served as a basis to propose a framework for a transparent and trustable whey value chain and to suggest future research challenges.

2. Unit operations and model processes for whey recycling in the food system

2.1. Overview of the main unit operations for whey recycling in the food system

One relevant feature of whey is its susceptibility to microbial growth due to the presence of viable starter microorganisms added during fermentation and possible microbial contaminants. Therefore, at industrial level pasteurization of whey is applied in the first steps of recycling (USDEC, 2006). Pasteurization is commonly performed at 75 °C for 15 s and can be combined with heat regeneration of about 90% to 95%, which makes an average energy consumption of around 0.789 MJ/kg product (as primary energy) (Ramirez et al., 2006). To further decrease the energy input, non-thermal technologies for pasteurization have been proposed and studied at laboratory scale. There has been considerable interest in the potential use of high-power/high-intensity ultrasounds, often in conjunction with mild heating (thermosonication), for the inactivation of microorganisms and enzymes in milk (D'Incecco, Limbo, Hogenboom, Pellegrino, 2021). An application was also designed for whey treatment, including heating at 55 °C combined with ultrasound treatment at 480 W with a 20 kHz ultrasonic probe for 10 min, which led to approximately 3 log10 cycles reduction in microbial load (Barukcic, Jakopovic, Herceg, Karlovic, & Bozanic, 2015). Pulsed electric field (PEF) treatments, generally combined with mild heating have also been explored for milk pasteurization and found to achieve about 3 log10 cycles of microbial reduction (Alirezalu, Munekata, Parniakov, Barba, Witt, et al. 2020). PEF treatment was specifically studied for microbial inactivation in a whey product, using a chamber with E set at 32 kV/cm, pulse width set at 3 μs, residence time at 1.8 s., inlet temperature in the range 20 – 40 °C and outlet temperature 58 °C. As a result, inactivation of up to 6.51 log10 cycles of the target microorganism *Lysteria innocua* was achieved (Schottroff, Gratz, Krottenthaler, Johnson, Bedard, & Jaeger, 2019). High hydrostatic pressure (HPP) treatments were investigated for inactivation of microorganisms in milk and it has been suggested that application of 600 MPa for 5 min is adequate to reduce the number of log10 cycles by 5 – 7, resulting in products comparable to traditionally pasteurized ones (Serna-Hernandez, Escobedo-Avellaneda, García-García, Rostro-Alanis, & Welti-Chanes, 2021). However, specific information on HPP application for whey pasteurization is lacking. In general, research is still necessary to efficiently replace heat pasteurization oh whey with non-thermal technologies.

Another relevant feature of whey composition is its high water content, hence evaporation and drying technologies are applied at industrial level. Drying is performed by spray-driers (USDEC, 2006). The impact of the spray drier system on energy consumption is in the range 4.9 – 3.4 MJ/kg water evaporated (as primary energy), where the highest consumption is for one stage system and the lowest for a tree stages system. Commonly, evaporation is applied prior to spray-drying to remove water with less energy input, which decreases in the range 0.9 – 0.2 MJ/kg water evaporated (as primary energy), with increasing the number of stages from one to seven for evaporators with a thermal vapor compressor, and decreases to 0.050 MJ/kg water evaporated (as primary energy) for a single stage evaporator with a mechanical vapor compressor (Ramirez et al., 2006). Pre-concentration of whey is performed by membrane processes such as reverse osmosis (RO), in which only water can permeate through the semi-permeable membrane, upon application of pressure to overcome the osmotic pressure. Membrane processes also include forward osmosis (FO) where a concentrated draw solution (2 M NaCl) is placed on the other side of the RO membrane to drive the transport of water molecules from whey and membrane distillation (MD), which is performed at 50 °C to selectively transport vapor molecules through the semi-permeable membrane due to surface tension forces. Overall, membrane filtration is efficient for water removal, with energy demand of 0.014 – 0.036 MJ/kg water removed (as primary energy). Nonetheless, membrane concentration can only reach a maximum dry weight of 12–20% due to the increasing viscosity of the retentate with increasing solid content (Ramirez et al., 2006).

Lactose, fat and protein that are the main solid components of whey are sometimes separated in industrial plants by membrane technologies to implement distinct applications. Microfiltration (MF) is applied because it allows the passage of small soluble proteins, peptides, lactose, minerals, non-protein nitrogen components and water, while fat globules are retained and can be reused in cream (USDEC, 2006). Moreover, ultrafiltration membranes (UF) are applied to separate protein in the retentate from lactose in the permeate. To further improve the separation of protein and lactose, diafiltration (DF) is performed, in which UF membranes are used and water is added to the retentate (USDEC, 2006). In the UF process, fouling limits the efficacy of the separation. Approaches were studied to increase the efficacy of UF, including the application of electric fields or ultrasounds for membrane cleaning. In one study using model solutions, electric fields were applied and the best operating conditions found included the use of 5 mM NaCl and an electric potential of 30 V (Corbaton-Baguena, Alvarez-Blanco, Vincent-Vela, Ortega-Navarro, Perez-Herranz, 2016). Use of ultrasounds was studied and positive effects were found upon using a power of 30 W/L cleaning solution, a frequency of 20 kHz for 30 min (Lujan-Facundo, Mendoza-Roca, Cuartas-Uribe, Alvarez-Blanco, 2017). However, these approaches were applied at pilot scale only. Upon UF, whey protein fraction is spray-dried while lactose is generally produced by concentrating the UF permeate at 65 °C by evaporation followed by a slow cooling process to 20 – 25 °C to achieve supersaturation, where lactose is crystallized. As for the other evaporation steps, lactose concentration is highly energy demanding (Ramirez et al., 2006). To increase the efficiency of the process alternative approaches have been proposed at laboratory scale. In one study, the application of ultrasounds was investigated and improved efficiency was observed using a power of 1.33×10^{-2} W/mL of whey at temperature of 7 °C for 20 min, followed by immediate addition of the ethanol (95%, v/v) as antisolvent (Bund, & Pandit, 2007). An alternative process was proposed in which subzero temperatures were reached, where eutectic freeze crystallization occurred (Halfwerk, Yntema, Van Spronsen, & Van der Padt, 2021).

Whey composition is also characterized by high amount of minerals, especially sodium, that is added to the cheese curd to lower the water activity and remains in significant amounts in whey, thus limiting its applications as food ingredient. Beside demineralization with membrane-based processes, ion exchange resins are used, with an average consumption of 0.128 MJ/kg of NF whey retentate (electric power) (Greiter et al., 2002). Electrodialysis was found to be more efficient than ion exchange resins, with an energy demand of 0.0459 MJ/kg of NF whey retentate (electric power) (Greiter et al., 2002). Similarly, an energy input of 0.058 MJ/kg of UF whey permeate (electric power) was also found to be required for demineralization (Chen et al., 2020). Eutectic freeze concentration is an emerging technology that operates at the eutectic temperature of the UF whey permeate (-24 °C) to enable simultaneous separation of ice and salt (Chen et al., 2020). The energy input for eutectic desalination is 0.288 MJ/kg feed for cooling at the eutectic point and 0.450 – 0.400 MJ/kg feed (electric power) for freeze crystallization, but the process was not studied at industrial scale (Chen et al., 2020).

In general, a critical aspect of the major unit operations involved in whey processing is the elevate energy demand. Moreover, the high hygienic standards require cleaning-in-place operations, which need an average energy input of 0.1 – 28 MJ/cleaning cycle (primary energy) (Ramırez et al., 2006). Finally, energy input for cold storage is on average 0.59 $MJ/m^3 \times d^{-1}$ (Evans et al., 2015). High energy demand is characteristic for the dairy sector as compared to the other food sectors (Ladha-Saburet al., 2019). For various dairy products, the energy demand was mapped from farm to fork (Malliaroudaki, Watson, Ferrari, Nchari, & Gomes, 2022), while among various alternatives for whey processing drying to powder was only considered. This led to identify an average energy input of 6.5 MJ/kg of whey, which is higher than the average input needed by its generating process, i.e., 3.3 MJ/kg of cheese (Malliaroudaki et al., 2022).

2.2 Model processes for whey recycling in the food system

Considering the technological equipment and high energy input necessary for whey recycling, a techno-economic analysis is necessary to define the plant size for the implementation of a sustainable process. The simplest process for whey recycling, i.e., drying to obtain whey powder (WP) was modeled for two cheese plants that operate with a milk inflow of 2000 – 3000 and 100 t/d, respectively (Peters, 2005). As a result, the relevant impact of the plant size on process efficiency was evidenced, since the process was validated for the highest plant while the feasibility of whey recycling in small cheese-making companies remained uncertain (Peters, 2005). Accordingly, other studies have pointed that the relatively low amount of cheese whey produced by the SMEs is one of the main barrier to the reutilization of this valuable byproduct (Rocha et al., 2020; Chalermthai et al., 2020; Lindsay et al., 2020). One interesting approach to increase process efficiency is the integrated recovery of both WP and water (Aydiner et al., 2014). Two technological configurations were validated with a whey inflow of 100 m^3/d. In the first configuration, whey was submitted to FO, using a concentrated draw solution made with 2 M NaCl. The resulting retentate was concentrated and spray-dried to obtain WP. The permeate was submitted to MD at 50 °C. In the second configuration, MD was used as a first stage and the permeate was submitted to RO. In both cases, 66% of water was recovered (Aydiner et al., 2014) (Figure 1). Another configuration was validated to produce WP with water recovery, but the plant size was 1500 t/d. In this latter process, whey was filtered to remove fines (vacuum filter), pasteurized (plate heat exchanger, 72 °C for 15 s), centrifuged to remove 90% of fats and then submitted to RO to recover water and the retentate, which was then evaporated (six-stage evaporator, final temperature 45 °C) and spray-dried to obtain WP (Chamberland, Scott Benoit, Doyen, & Pouliot, 2020).The WPs so far obtained contained lactose as the main component, at concentration of 53 – 75% and proteins in the range 11 – 15% (Table 1).

UF membranes represents the standard tool for production of whey protein concentrates (WPCs) (USDEC, 2006). Integrated processes that recover both WPC and lactose are emerging, with respect to the recovery of protein alone. A techno-economic analysis was performed for processing 700 m^3/d of whey, by comparing: a) the production of whey protein concentrates at 34 or 80 %, respectively

(WPC 34 and WPC 80); b) the production of WPC 34 or WPC 80 in combination with lactose; and c) the production of WPC 34 or WPC 80 with ethanol obtained via lactose fermentation. The integrated production of WPC 80 and lactose was found to be the optimal solution (da Silva et al., 2015). According to the best proposed process, whey was filtered to remove fines (vacuum filter), pasteurized (plate heat exchanger, 72 °C for 15 s), centrifuged to remove 90% of fats and then submitted to UF and DF. The retentate rich in protein, with 21% solids was spray-dried (final temperature of the powder 70 °C) to obtain WPC 80 with 96% solids (Table 1). The permeate was firstly concentrated by RO to 18% solids, evaporated to 50% solids (triple effect evaporator, final temperature 55 °C) and then lactose was crystallized (at 15 °C) and spray-dried to a moisture content of 4% (final temperature of the powder 70 °C) (da Silva et al., 2015) (Figure 2). A similar configuration was further analyzed in combination with enzymatic conversion of lactose to galacto-oligosaccharides by β-galactosidase and the process was found to be feasible for whey inflow of > 80 m^3/h (Scott et al., 2016). An integrated whey recovery process to obtain both WPC and glucose and fructose syrup was also found to be economically feasible with a whey inflow of 500 m^3/d. In this latter process, the technological configuration for WPC obtainment was similar to that reported previously (da Silva et al., 2015) but an evaporation step for the retentate (single stage, 80 °C) to 65% of solids (single effect, 80 °C) was included before spray drying (Gomes et al., 2020) and a final protein concentration of 50% was obtained (Table 1). The permeate stream was filtered using sodium bentonite in the filtration bed and submitted to the ion exchange to remove > 95% of cations in order to avoid inhibition of the enzymatic process with immobilized lactase and glucose isomerase. Then, the resulting liquid stream was bleached with activated carbon packed in columns and concentrated through vacuum evaporation up to a minimum of 70% total solids to obtain the sugar syrup (Gomes et al., 2020) (Figure 2). Alternatively, a plant was designed to treat 100 m^3/d of whey permeate from UF whey, for further production of food grade lactic acid via fermentation by *Lactobacillus helveticus*, followed by UF, ionic exchange, RO and evaporation (Gonzalez, lvarez, Riera, & lvarez, 2007).

To obtain a finished product with more than 90% of protein, i.e., whey protein isolate (WPI), two main processes are used. In one case pasteurized whey is submitted to MF to remove fat and then to extensive DF to remove lactose and salts. Alternatively, pasteurized whey is demineralized with ion exchange resins and then submitted to UF. In both processes, the resulting final retentate is concentrated and spray-dried to obtain WPI (USDEC, 2006). Most of non-protein components of whey are not present in WPI (Table 1). These processes are applied to large size plants, which operate with 2000 – 3000 t whey/d (Peters, 2005). An alternative process operating with a whey inflow of 500 m^3/d was proposed to recover whey protein without lactose and salts, including: heat treatment at 90°C for 30 min to achieve protein denaturation, followed by precipitation with carboxymethylcellulose (CMP) at 50°C, filtration and drying in a fluidized bed dryer to obtain whey protein precipitate (WPP). The permeate was concentrated in a multiple effect evaporator, then lactose was crystallized and dried in a fluidized bed drier (Raout et al., 2022) (Figure 3). According to this latter process, a complex of the denatured whey proteins and CMC was obtained, but the exact composition was not reported (Raout et al., 2022).

Value-added applications could be applied to WPC, WPI and lactose, such as the separation of whey proteins, production of bioactive peptides from whey protein (Brandelli, Daroit, & Folmer Corrêa, 2015), improvement of whey protein functionality by physical and chemical treatments (Foegeding, Davis, Doucet, & McGuffey, 2002; Doost, Nasrabadi, Wu, Ayun, & Van der Meeren, 2019) and fermentation of lactose to produce value–added compounds or biomasses (Lappa et al., 2019; Rocha, & Guerra., 2020; Zandona et al., 2021; Barba et al., 2021). However, these upgrading processes were not modeled to define the optimal plant size.

3. Safety and quality specifications for whey recycling in the food system

3.1 Safety specification for whey

The development of food applications from whey recovery imposes to meet safety requirements. Five hazard categories have been identified in the literature, namely mycotoxins, antibiotics, pathogenic microorganisms, heavy metals and organic environmental pollutants.

Considering mycotoxins, aflatoxin M1 exhibits a high genotoxic activity and it has been classified by IARC as a class 2B human carcinogen (IARC, 2002). Aflatoxin M1 derives from aflatoxin B1 that can be present in feed. Upon ingestion of contaminated feed by ruminants, aflatoxin B1 is converted in secondary metabolites, among which aflatoxin M1 is the major oxidation metabolite, primarily excreted in the urine and secondarily in the milk (Prandini et al., 2009). In one study, the carry-over of aflatoxin M1 in cheese and whey was investigated, indicating that on average 55% of aflatoxin M1 is recovered in whey (Costamanaga et al., 2019). The carry-over of aflatoxin M1 from milk to whey deserves attention. In fact, even in case that this contaminant is below the limits fixed by the EU regulation (Reg EC 1881/2006), whey drying causes an increase in its concentration.

Antibiotic residues in foods can lead to allergic reactions and to or transient disturbances in the microbiota (Oliver, Murinda, & Jarayao, 2011). Antibiotics used for the treatment of infectious disease of livestock are found in milk (Lupton, Shappell, Shelver, & Hakk, 2018). In one study, goat milk spiked with 18 antibiotics and then coagulated with rennet, the whey was separated and the transfer of antibiotics was investigated. The percent of antibiotic recovered in whey was found to depend on their hydrophilicity and ability to interact with Ca^{2+} ions, varying from 100% for amoxicillin, ampillicin, sulphadiazine to 90 – 60% for benzilpenicillin, cloxacillin, cefacetrile, cefquinome, ceftiofur, erythromycin, while the other cephalosporins, aminoglycosides, macrolides, quinolones, sulphonamides and tetracyclines were not recovered in whey (Giraldo, Althaus, Beltran, & Molina, 2017). A following study confirmed that some β-lactames (cephalexin, benzylpenicillin, ampicillin and cloxacillin) were transferred less into the cheese curd than into the whey (Lányi et al., 2022). As for aflatoxin M1, the carry-over of antibiotic compounds from milk to whey deserves attention, even if they are present at limits below the threshold fixed by the Regulation (Reg EU 37/2010), due to their concentration by drying.

Pathogenic microorganisms that can be present in milk, are also of concerns for their possible presence in whey, most likely due to inadequate hygienic practices (Wedel, Atamer, Dettling, Wenning, Scherer, et al., 2022). *Salmonella* spp. and *Cronobacter* spp. do not survive after thermal treatment. Afterward, post-heating handling can result in cross-contamination. *Salmonella* spp. was found to be able to survive on dairy plant surface for at least 30 d (Margas, Meneses, Conde-Petit, & Dodd, Holaha, 2014). Similarly, *Cronobacter* spp. was isolated from dairy plants (Kent, Fitzgerald, Hill, Stanton, & Ross, 2015). *Listeria monocytogenes* is a food-borne pathogen of great concern for the dairy industry. It is also inactivated during heating at the high temperatures (> 80 – 95 °C). Then, the psychrotrophic pathogen *L. monocytogenes* may outgrow in the absence or low presence of a protective background microbiota (Sameli, & Samelis, 2021). *Bacillus cereus* spores demonstrated the ability to survive to pasteurization. Evaporation, which is another thermal process applied in whey processing, is also unable to inactivate the total load of mesophilic and thermophilic spore formers; instead this treatment provides an environment where the spores can undergo outgrowth (Wedel et al., 2022). Spray-drying effect on *B. cereus* depends on the strain, since Log-reductions in the range 1 – 4.7 were observed (Alvarenga, Brancini, Silva, da Pia, Campagnollo et al., 2018). Moreover, *B. cereus* is able to form biofilm that facilitates spore dispersion, subsequent germination, multiplication and enterotoxins production (Tirloni et al., 2017). *Staphylococcus aureus* is one of the major etiological agents of mastitis in dairy cattle. These infections are a source of contamination of milk and dairy products since up to 50 – 70% of *S. aureus* strains are able to produce under suitable conditions extracellular heat stable staphylococcal enterotoxins (SEs) (Bogdanovicova, Necidov, Harustiakov, & Janstov 2017). *S. aureus* is ubiquitous: detected in animals, cowsheds, farm and dairy workers, processing environments and ultimately the dairy products including whey (Mehli, Hoel, Thomassen, Jakobsen, & Karlsen, 2017).

Heavy metals such as lead, cadmium, arsenic, chromium and mercury can accumulate in the body after intake for long years in high concentrations and lead to disorders in the heart, liver, kidney, nervous, blood, and lungs (Elgammal, Khorsheda, & Ismail, 2019; Bandara, Towle, & Monnot, 2021). Heavy metals can be found in milk due to intake of contaminated feed. Moreover, ruminant animals are exposed during grazing to intake a small portion from surface layers of soil and hence environmental pollution of the farming area due to industrial activities is also a vehicle for toxic metal intake (Campos de Aquino et al., 2017; Castro-Gonzales et al., 2018; Elgammal et al., 2019). Casein have a high affinity for metals, especially lead (Delavar et al., 2012). However, the transfer of heavy metals from milk to whey can occur. In fact, presence of toxic metals in whey was estimated to be a risk in case of elevated consumption (Ring, Sheehan, Lehane, & Furey, 2021).

Different polyhalogenated-compounds are present in the environment of industrialized areas and show high resistance to metabolism in humans. As a result, their concentrations can increase in tissues thus causing toxic effects such as immunosuppression, decrease in reproductive potential and tumor promotion (Van den Berget al., 2006). Compounds used as flame retardants tetrabromobisphenol A (TBBPA), 2,4',4,5,5'- pentabromodiphenyl ether (BDE-99) and β-hexchlorocyclododecane (ß-HBCD) and the coolant/ plasticizer/ hydraulic fluid/pesticide/flame retardant 2, 3', 4, 4', 5-pentachlorobiphenyl (PCB-118), were found to possess high affinity for whey protein and, if present in whey, upon UF are found in the retentate (Shelver, Lupton, Shappell, Smith, & Hakk, 2018).

The studies so far reported attest that for cheese-making companies that provide whey for further use in the food system, there is a need to guarantee that safety standards are met.

3.2 Quality specifications for whey

Multiple factors related to bovine and milk processing conditions, could affect whey composition and hence its performance in the production of value-added compounds, but information in literature is scattered.

One route to produce added value compounds from cheese whey is via lactose fermentation. In this context, bacteriophages infecting lactic acid bacteria are one concern related to the whey quality. In fact, bacteriophages can be present in raw milk, contaminate plant surfaces and generate aerosols, which remain in air for long periods (Pujato, Quiberoni, & Mercanti, 2018). Hence, when whey has to be recycled by lactic bacteria fermentation (Sipola et al., 2002; Pihlanto, 2001; FitzGerald, Murray, & Walsh, 2004), the presence of bacteriophages can cause failure or reduced process yield.

Antibiotics present in whey are another feature related to whey quality since they can decrease the yield of microbial-based processes. *Kluyveromyces marxianus* sensitivity towards antibiotics was considered since it is an interesting yeast for whey valorization due to its ability to assimilate lactose directly, without hydrolysis pretreatment (Chandra, Castillo-Zacarias, Delgado, & Parra-Saldívar, 2018). The fermentative capacity of *K. marxianus* was found to be reduced in whey by the presence of antibiotics closed to the maximum residue limits fixed by the EU regulation (Eluk, Ceruti, Nagel, & Althaus, 2019).

The yield of enzymatic processes to convert lactose into valuable compounds, such as galacto-oligosaccharides, lactulose as prebiotics and lactose esters as emulsifiers is affected by the nature of whey (acid, sweet) and by lactose concentration (Guerrero, Vera, Acevedo, & Illanes, 2015; Staron, Dabrowski, Cichon, & Guzik, 2018; Fischer & Kleinschmidt, 2021). Moreover, high sodium content inhibits the enzymatic conversion of lactose to glucose and fructose syrup (Gómez et al., 2020).

The second route to produce added value compounds from cheese whey is the use of protein fraction. Hence, the quality of whey depends on total protein content, amino acid profile, protein digestibility and bioavailability of essential amino acids (Brandão da Costa, Rocha Roiffé, da Silva de la Cruz, 2021). Moreover, the use of enzyme technology for the hydrolysis of whey proteins is applied to generate bioactive peptides, which can exert physiological effects *in vivo*, such as antioxidant, antimicrobial, antihypertensive, antidiabetic, immunomodulatory, anticancer, opioid and hypocholesterolemic activities (Brandelli et al., 2015).

However, heating intensity applied during processing can affect nutritional quality and bioactivity of whey. In fact, during whey production, storage and processing, changes are induced in protein structure, including unfolding, cross-linking and aggregation (Zhang, Zhou, Zhang, & Zhou, 2021). Heating promotes the Maillard reaction between reducing sugars and amino acids, peptides, or proteins, with the main consequence to form the so-called blocked lysine, affecting bioavailability of this essential amino acid. Denaturation temperatures for α-lactalbumin, bovine serum albumin, immunoglobulin and β-lactoglobulin are 62, 64, 72 and 78 °C, while for lactoferrin denaturation temperatures are 71 and 91 °C for the apo- and holo-protein, respectively (Zang et al., 2021). Milk pasteurization at 72 °C for 15 s, does not affect the major whey protein, i.e., β-lactoglobulin. The second major whey protein, i.e., α-lactalbumin, is denatured upon pasteurization but it can refold upon cooling (deWit, & Klarenbeek, 1984). Interestingly, milk pasteurization at 72 °C for 15 s does not affect the immunoreactivity of lactoferrin (Navarro, Harouna, Calvo, Perez, & Sanchez, 2015) and immunoglobulin (Riera et al., 2014). However, significant heat damage was observed in commercial whey products. In fact, furosine that is an indicator of blocked lysine was found to be present at levels up to 1125.7 mg/100 g protein (150 mg average) in whey (Rufián-Henares, Delgado-Andrade, Jiménez-Pérez, & Morales, 2007). Accordingly, in one study, fifty-two commercial whey samples were analyzed and 9% of them presented blocked lysine values exceeding 20%, while 50% of them had over 6% of blocked lysine (Sánchez-Oliver, Contreras-Calderon, Puya-Braza, & Guerra-Hernández, 2018). Regarding the effect of heat treatments on the digestibility of whey protein, there are many reports but no consensus emerges, since either increased protein digestibility and decreased protein digestibility was observed after processing, which probably depends on the intensity of heating conditions (Zhang et al., 2021). Indeed, in fourteen commercial whey products *in vitro* protein digestibility ranged from 50.4 to 79.6% and different amino acid profiles were observed (Pehlivanoglu, Bardakci, & Yaman, 2022). The changes of whey proteins allergenicity during heat treatment also depend on heating temperature and processing time, resulting in either a decrease or an increase (Zhang et al., 2021). As a result, more investigations are necessary to unravel the effect of thermal processes on whey nutritional and health properties. On the other hand, another relevant feature for whey valorization relies on its techno-functional properties, such as foaming, gelling and emulsifying ability, which are of interest in the development and stabilization of particular food structures or for encapsulation of bioactive compounds (Lavelli & Serenikate, 2022a; Lavelli & Serenikate, 2022b). Whey techno-functional properties generally improve with increasing the intensity of the thermal treatment (Foegeding et al., 2002). To control and enhance protein functionality, emerging processes are also considered, such as ohmic heating (Ferreira, Machado, Pereira, Vicente, Rodrigues, 2021), high hydrostatic pressure (Serna-Hernandezet al., 2021), and ultrasound treatments (Carrillo-Lopez, Garcia-Galicia, Tirado-Gallegos, Sanchez-Vega, Huerta-

Jimenez, et al., 2021). Moreover, the covalent interaction between an amino group of a protein and a carbonyl group of a polysaccharide through Maillard reaction is applied to produce conjugates with improved characteristics such as heat, ionic strength and pH sensitivity (Doost et al., 2019). The conjugation of whey proteins with small molecular weight reducing sugars is another potential strategy to overcome the heat instability, aggregation and fouling (Wu et al., 2021a). Additionally, whey protein-phenolics interactions are also intensively studied to generate phenolic protection, improved delivery and bioavailability (Wu et al., 2021b). The route of protein conjugation will open a new area for whey applications. It can be assumed that protein conjugation processes also pose some quality requirements for the whey protein source, i.e. for instance protein purity, while a detailed information on this aspect is lacking.

In general, a deeper insight into the relationship between whey composition and functionality would support the development of target applications. To this aim, the application of foodomics tools is a promising approach to pave the road for the exploitation of whey streams (Tsermoula, Khakimov, Nielsen, & Engelsen, 2012). Nevertheless, even if advancing knowledge is advisable, specification of at least some basic quality parameters of whey would increase the range of possible applications in the food system.

4. Traceability systems for whey and for a smart whey supply chain

4.1 Whey traceability

As discussed above, efficient processing of whey requires an inflow of 100 – 700 t/d, which is higher than the amount produced at a SME. However, the SMEs could access the fresh whey market by providing whey with guaranteed safety and quality specifications for further collection in large batches and processing. In this scenario, the application of an efficient traceability system for whey would be necessary for food applications. Traceability systems enable the identification of the companies that are involved in its production and are responsible for its safety/quality, thus providing transparency within the value-added supply chain. The procedural document of a model PDO cheese (https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3340) was used as an example to draw a traceability scheme at a SME, considering the analogies in traditional cheesemaking processes (Fox, Guinee, Cogan, & McSweeney, 2017). The flow of materials and information for the model PDO cheese was described according to the basic requirements of the international standard ISO 22005:2007 (Table 2). The ISO 22005:2007 standard includes the identification of the relevant information capture points, "traceable materials" and information captured. Information capture points are the processing steps in which recording information is essential to maintain identification of raw materials, partially-processed materials and products. Traceable units are items upon which there is a need to retrieve predefined information and include products that can be exchanged between two parties in the supply chain as well as partially processed materials. In general, information to be captured includes product information, process information and quality information and comprised the answers to the following questions: a) who is responsible at that stage? (supplier, transporter, or organization); what are the product definition and safety/quality specifications? c) what quantity of product is being considered? d) when does the stage occur? (date); e) where does the stage occur? (within an organization: in which plant is the product processed, if more than one plant is present?) (Lavelli, 2013). The traceability plan for the model PDO cheese consists of 17 capture points (1 – 11 and 13 – 18 in Table 2) that altogether collect information on the materials involved in the production of a single whey lot, including all preceding materials, such as: milk, rennet, starters, brine. Two additional capture points (12 and 19) are necessary in case of whey recovery for food applications. The link among whey, curd and cheese is also important because in case of detection of curd or cheese contamination, whey safety has also to be assessed. Hence, the traceability procedure allows to retrieve the safety and quality control of every lot of cheese (and thus whey) produced, such as: cow identity and veterinary controls, analytical characterization of milk (content of fat, protein and lactose, pH, cryogenic index, absence of bacteriophages and antibiotics); processing parameters, including: temperature and time of pasteurization, scalding and ripening; quality control on the final cheese lots, including pathogenic microorganisms, hygiene indicators, content of fat, protein and lactose and furosine level. In this context, it is worth noticing that the food safety management systems of SMEs dedicated to PDO production are continuously controlled by self-assessment. Moreover, these companies are periodically submitted to audits performed by the producers' consortium and by the third party certification body. For a PDO cheese, processing conditions and final product specifications are strictly standardized by the PDO procedural document. As a result, whey lots obtained from a PDO cheese are characterized by standardized safety parameters, nutritional and functional properties, which could be further modulated by physical treatments, enzymatic hydrolysis or chemical conjugation for valuable target applications in the food system.

The traceability procedure was then exemplified with the indication of the history of a single cheese (and whey) lot recorded at a SME (Figure 4), which showed all the actors involved, i.e., seven farms, one milk transporter, three suppliers for rennet, starters, brine and packaging materials, respectively. The exemplary mass flow revealed that the amount of milk collected was 64047 L, while only 25231.7 kg was processed to obtain the selected cheese lot (Figure 4). The amount of whey obtained was 21469.7 kg, i.e., 85% of milk, which is similar to the percentage reported previously (Rocha et al., 2020). The total amount of cheese obtained was 13.9% of milk, i.e., 3517.02 kg (1620 packages, that is lower than the difference between processed milk and whey recovered, because of moisture loss during ripening). Based on the analysis of the exemplary PDO cheese, it can be calculated that a single whey lot of about 100 t, which is the minimum daily amount necessary to process whey into valuable products according to the techno-economic analysis previously proposed, a total of 35 farms and 5 cheese-making companies need to be involved as well as transporters and ingredients' suppliers. A scenario was also drawn to analyze the capability for SMEs to continuously supply whey to a potential stand-alone whey processor. To this aim, 36500 t/year would be necessary, corresponding to about 6000 t of cheese/year. Interestingly, according to the producers' association of the model PDO, 8400 t/year of cheese were produced in 2020 (https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3340). Hence, almost all the companies of the consortium, which are approximately 80, should be involved in the whey value chain.

4.2. Models of traceable whey supply chains

A whey value chain could be built with the participation of a large number of SMEs and would require tracing extensive information related to both product safety and quality, as well as responsible actors at each stage of processing and distribution. While studies on a sought after "whey value chain" are lacking, solutions to improve the milk and dairy supply chain transparency, involving large number of actors have been proposed in the literature and could easily be extended to guarantee whey traceability. One of the first traceability frameworks was developed to trace the whole supply chain of Parmigiano Reggiano PDO cheese (Regattieri, Gamberi, & Manzini, 2007). This latter study was based on collection of a part of the relevant data with sensors and another part with manual data entry in a centralized database, which was accessible by the stakeholders. After production, information was also traced by a radio-frequency identification (RFID) tag applied to a whole cheese (Regattieri et al., 2007). The number of sensors and devices developed to perform automatic food controls are continuously increasing and hence Internet of Thing (IoT) and the Distributed Ledger Technologies (DLT) such as the blockchain technology have become a new paradigm of how data can be collected, securely stored, integrated, and communicated among different stakeholders. The blockchain is a shared (distributed) and decentralized ledger, i.e., there are thousands of secure copies of data on different devices (nodes) worldwide. A unique blockchain account is created for every participant and authentication and authorization through blockchain guarantees that the data added to blockchain actually come from a specific participant. It is possible to insert blocks of information in the chain, but it is not possible to modify and remove the blocks previously added to the chain. The security and immutability of information within the blocks are guaranteed by a consensus protocol and encryption (Di Pierro, 2017). The blockchain technology can improve the transparency of the agri-food chain by creating a flow of immutable data that any stakeholder can consult. An application of the blockchain technology was proposed to manage data generated in a "smart" dairy supply chain in order to increase transaction efficiency, and create a flexible pricing mechanism (Zhang et al., 2019). According to this model supply chain, the actors involved (farms, factories, government, service providers) are intended to collect various data related to location, safety and quality of the products, mainly based on automatic systems such as drones, sensors (for temperature, humidity), timers, RFID tags as well as analytical procedures (for microbial counts, protein and fat determinations, etc.). Hence the blockchain is used as a data storage. Moreover, the blockchain provides a computational infrastructure to run smart contracts, which can be used to automate some procedures of quality control since they can directly execute the agreement once the specified conditions are met. A smart contract can be designed by the government to verify to what extent the process meets the regulatory standards: once all the requirements are met, the regulatory approval will be automatically granted. Moreover, smart contracts could introduce a more transparent and flexible pricing mechanism. For example, a range of values (target value and tolerance range) can be determined for each category of data related to product safety and quality, based on which, the finished products are categorized into different quality grades, with the first grade being the highest quality and last grade failing to meet the standards and therefore being illegal to sell in the market (Zhang et al., 2019).

An application study was performed to calculate the economic impact of implementing a blockchain technology to a milk supply chain including 80 affiliated dairy farms, a single dairy plant, seven transportation companies, five distribution centers and approximately three thousand retailers (Longo, Nicoletti, & Padovano, 2019). Based on the necessary information to track the history of the final food product, the transactions' frequency was calculated for each actor. For instance, at the farm level, considering fifty cows, two hundred and forty six transactions are recorded every day, namely fifty for rearing (one for each cow), a hundred for milking (two for each cow) and ninety six for milk temperature during storage (one every 15 min). The presented results were particularly interesting since it was demonstrated that the investments in hardware and software was not relevant for any of the actors involved. Moreover, the total cost due to the transactions' fee did not increase the product/service price (Longo et al., 2019).

Indeed, the blockchain technology is reputed as a useful tool for SMEs. Implementation of frameworks based on blockchain technology have been designed in the context of the PDO cheese production, to record relevant information bringing together the milk producers, the dairy companies, transporters, distributors, PDO consortium, third-party auditors, and the final consumer (Giacalone et al., 2021; Varavallo et al., 2022). Implementation of blockchain technology was also studied in emerging economy contexts, i.e., the biggest cooperative of dairy farmers in Turkey (Mangla et al., 2021), the domestic dairy supply chain in Vietnam, which involves all parties in the supply chain and the Vietnamese government (Tan and Ngan, 2020), as well as the smallholder farmers and local milk collection centers in Kenya (Rambim, & Awuor, 2020).

The availability of big data by IoT and DLT poses additional challenges, one being the real-time analysis and response, pattern recognition and forecasting and the other being the bottleneck and congestion that may occur when dealing with millions of connected data sources. Hence, Edge Computing (EC) has emerged as a new paradigm to solve those problem. An EC architecture was proposed to manage the dairy supply chain, which consists of three principal layers: IoT, Edge and Business Solution layers. At the IoT level, sensors are located in livestock farms, crops used to feed livestock, cattle, dairy factories and means for transportation to collect data on ambient conditions (temperature and relative humidity, hazardous gas sensors), power consumption, cattle real-time location and health conditions, product real time location. At the edge level, the data are pre-processed and filtered by Data Analytics techniques, generating knowledge and reducing data traffic and transmission costs to the cloud. At the business solution layer, a virtual organization of agents works as a social machine, which provides the Decision Support System (DSS) and an alert management system which sends warning messages and corrective actions when the values obtained by heterogeneous IoT networks indicate a hazardous situation. This architecture was tested in a single dairy company and planned to be implemented on several dairy farms in the same region (Alonso et al., 2020).

Overall, these model traceability systems have been designed to implement smart system for data collection and sharing among stakeholders and producers. For instance, a network could be implemented among SMEs located in a confined geographical area, including those involved in PDO cheese production, and various stakeholders such as the PDO producer consortium, the third party certification body and the competent authority (Figure 5). As a result, these model traceability systems could also support collection of information on whey safety and quality and hence promote whey recovery processes. Moreover, this latter network would provide a comprehensive data assembly and analysis, which would result in a powerful tool that will increase dairy SMEs competitiveness.

5. Conclusions

The techno-economic analyses applied to whey recovery processes led to conclude that the downstream processing into valuable food products are associated to high energy input, which could be mitigated in large size plants operating 100 or more ton of whey daily. Risk assessment approaches evidenced that for the recycling of whey in the food system, the prevention of various chemical and microbial contaminants is needed. Moreover, the control and improvement of whey nutritional properties and functionality by physical and chemical treatments can potentially open up a new area of value-added applications.

A single SME could contribute to the circular economy by supplying small whey lots to whey processors, for collection in large batches and further transformation into value-added products. Interestingly, SMEs that operate according to the same PDO quality scheme could constitute a supply chain that provides whey processors with traceable whey lots with standardized safety and quality specifications through a shared smart traceability architecture based on IoT, DLT and EC solutions, within the context of industrial symbiosis. Hence, the PDO products, which have been conceived as a strategy for rural development, fostering local values such as environmental stewardship, culture and tradition could also support the strategies for by-product recovery, thus advancing the application of the bioeconomy principles in the food system.

To implement a whey value-chain, future research should aim at the advancement of cost-effective technological solutions for whey processing. Moreover, deepening knowledge on the required quality specification of whey as correlated to target applications would support the application of the best technology available as related to the end-use. Finally, the definition of standardized audit protocols with specific focus on whey processing conditions and quality parameters, would increase transparency and trust in the whey supply chain.

Declaration of competing interest

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Captions to the Figures

Figure 1. Processing schemes for whey recycling to recover whey powder (WP) and water. Routes [1a] and [1b] were modelled by techno-economic analysis for an inflow of 100 t whey/d (Aydiner et al., 2014); route [2] for 1500 t whey/d (Chamberland et al., 2022). Operations that need high energy input, possibly mitigated by increasing plant size, are indicated in orange. WPs compositions are indicated in Table 1.

Figure 2. Processing schemes for whey recycling to recover whey protein concentrates (WPC) and lactose-derived products. Route [3] was modelled by techno-economic analysis for 700 t whey/d (da Silva et al., 2015); route [4] for 80 t whey/h (Scott et al., 2016); route [5] for 500 t whey/d (Gomes et al., 2020); route [6] for 100 t whey/d (Gonzales et al., 2007). Operations that need high energy input, possibly mitigated by increasing plant size are indicated in orange. WPCs compositions are indicated in Table 1.

Figure 3. Processing schemes for whey recycling to recover whey protein isolate (WPI) and whey protein precipitate (WPP). Routes [7a] and [7b] were modelled by techno-economic analysis for 2000 – 3000 t whey/d (Peters, 2005); route [8] was modelled for 100 t whey/d (Raout et al., 2022). Operations that need high energy input, possibly mitigated by increasing plant size are indicated in orange. WPI and WPP compositions are indicated in Table 1.

Figure 4. Exemplary traceability scheme for a cheese lot. The mass flow, process timing and materials' lot numbers are indicated in the red, light blue and dark blue boxes, respectively.

Figure 5. A model smart whey supply chain, indicating the actors involved and the communication tools.

Table 1. Composition of sweet and acid whey and whey products (g in 100 g).

Product	**Moisture**	**Protein**	**Fat**	**Lactose**	**Ash**	**Reference**
Sweet whey	93 – 93.7	0.6 – 1	0.5	4.6 – 5.2	0.5	Jelen et al., 2003
Acid whey	93 – 93.7	0.6 – 0.8	0.04	4.4 – 4.6	0.8	Jelen et al., 2003
WP (FO/MD)	4.89	14.02	1.86	53.36	13.91	Aydiner et al., 2014
WP (MD/RO)	4.51	11.99	5.36	57.85	9.12	Aydiner et al., 2014
WP (RO)	n.d.	15	0.57	75.4	n.d.	Chamberland et al., 2021
WPC 80	4.0	81.86	8.28	4.88	0.98	daSilva et al., 2016
WPC 50	4.99	50.24	n.d.	35.39	n.d.	Gómez et al., 2020
WPI	4.5	92	1	0.5	2	USDEC, 2006

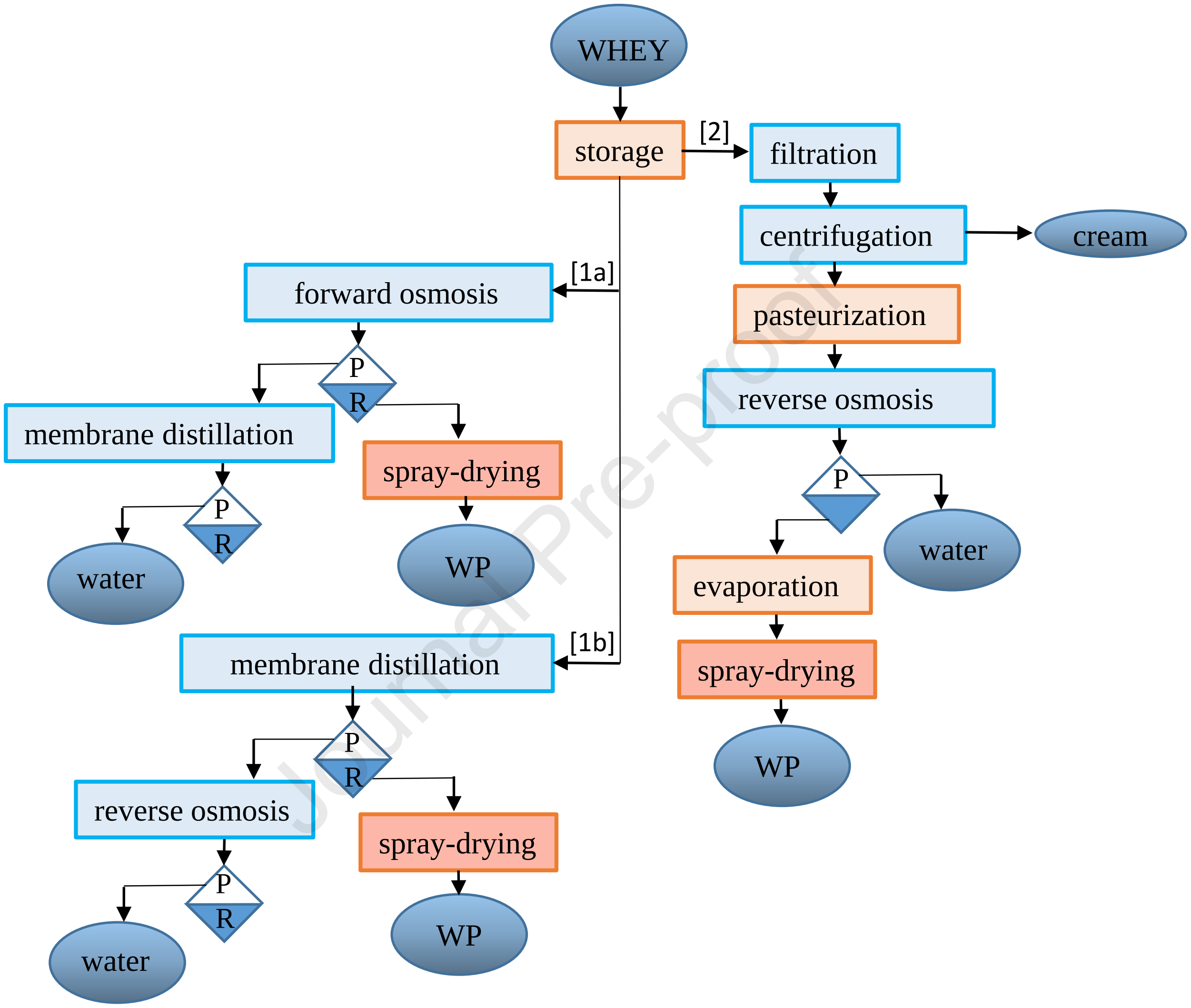
WP, whey powder; WP (FO/MD), WP concentrated by forward osmosis and membrane distillation; WP (MD/RO), WP concentrated by membrane distillation and reverse osmosis; WP (RO), WP concentrated by reverse osmosis; WPC 80, whey protein concentrates at 80%, WPC 50, whey protein concentrates at 50%, WPI, whey powder isolates. n.d., not determined.

Table 2. Traceability plan for a model PDO cheese according to the ISO 22005:2007 standard.

CP. Processing step	Traceable unit(s)	Information tracked	Note
At the farm			
1. Rearing	Cow	- Animal code - Sanitary controls and eventual drug treatments	Geographical location of the farms, breeding practices and admitted feed are indicated in the PDO procedural document
2. Milking	Raw milk in the cistern	- Cow - Milk lot number and amount - Date	
3. Milk storage	As for point 2	- Temperature - Date and duration	
At the transporter			
4. Milk transport	As for point 2	- Transporter name - Milk supplier name - Milk lot number and amount - Temperature - Date and duration	
At the cheesemaking SME			
5. Receiving of milk	As for point 2	- Milk supplier name - Milk lot number and amount - Transporter's name - Temperature - Safety/quality specification - Date	Milk characteristics are indicated in the procedural document of the PDO. Limits are fixed for fat: 4.01 – 4.25 %; protein: 3.25 – 3.35 %; lactose: 5.00 – 5.15 %; cryoscopic index: -0.520 - 0.525 °C; pH 6.74
6. Milk storage	Raw milk mixture stored in the tank	- Milk lot numbers and amount - Number of the tank - Temperature - Date and duration	Maximum storage duration indicated in the PDO procedural document is 24 h at 4 °C
7. Milk pasteurization	Pasteurized milk mixture intended for the scheduled cheese production	- Mixed milk lot number and amount - Storage tank number - Time and temperature - Date	Pasteurization conditions: 72°C 15 s The lot number of the mixed milk is the same as that of the scheduled cheese
8. Receiving of rennet, starters, salt and packaging materials	Rennet/starters, salt and packaging materials in the suppliers' packages	- Supplier name - Rennet/starters/salt/packaging materials' lot numbers and amounts - Transporter's name - Temperature (for rennet and starters) - Date	Rennet form young calves and cultures of *L. bulgaricus* and *S. thermophilus* are only admitted by procedural document of the PDO. Rennet performance and fermentation ability are checked to standardize cheese yield.
9. Rennet and starters storage	As for point 7	- Temperature - Date and duration	Storage is performed at 4 °C.

10. Filling of the cheesemaking vats	Mixture in the cheese-making vats	- Pasteurized milk mixture lot number and amount - Rennet/starters lot numbers and amounts - Date	
11. Empting of the cheesemaking vats and filling of the mould	Curd in the moulds Whey in the tank	- Curd lot number, amount and number pieces - Whey lot number and amount - Date	The lot number of the curd and whey obtained is the same as that of the scheduled cheese
12. Whey storage	Whey in the tank	- Whey lot number and amount - Temperature - Quality specifications - Date and duration	This step is needed to implement whey recovery
13. Curd scalding	Curds in the scalding room	- Curd lot number, amount and number pieces - Temperature and relative humidity - Date and duration	Scalding conditions are indicated in the PDO procedural document. Temperature is 22-25 °C and duration is 8-16 h. Relative humidity is 90%.
14. Brine preparation	Brine in the can	- Salt lot number and amount - Brine lot number and amount - Date	
15. Curd ripening	Curds in the ripening room	- Curd lot number, amount and number of pieces - Brine lot number and amount - Temperature and relative humidity - Date and duration	Ripening conditions are indicated in the PDO procedural document. Temperature is 2-6 °C and minimum ripening duration is 35 d. Relative humidity is 85-90%.
16. Pressing of the brand, primary and secondary packaging of cheese	Cheese in single packages assembled in boxes	- Cheese lot number, amount and number of final portions obtained - Quality specifications - Date	Quality specifications for cheese are indicated in the procedural document of the PDO. Limits are fixed for dry matter: 46%; fat: 23%; protein: 17%; furosine <14 g/100g protein; pH 5.5; pathogenic microorganisms: absent; *Enterobacteriaceae* < 100 CFU/g; Staphylococci coagulase+ < 20 CFU/g.
17. Cheese storage	As for point 16	- Time and temperature	Shelf-life is 30 d at 4 °C.
At the transporter			
18. Cheese transport	As for point 16	- Cheese lot number, amount and number of portions delivered - Customer' s name - Temperature - Date and duration	
19. Whey transport	Whey in the tanker	- Whey lot number and amount - Whey processor name - Temperature - Date and duration	This step is needed to implement whey recover processes at a plant size larger than the SME

CP, capture point


WHEY
storage
[2]
filtration
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spray-drying
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membrane distillation
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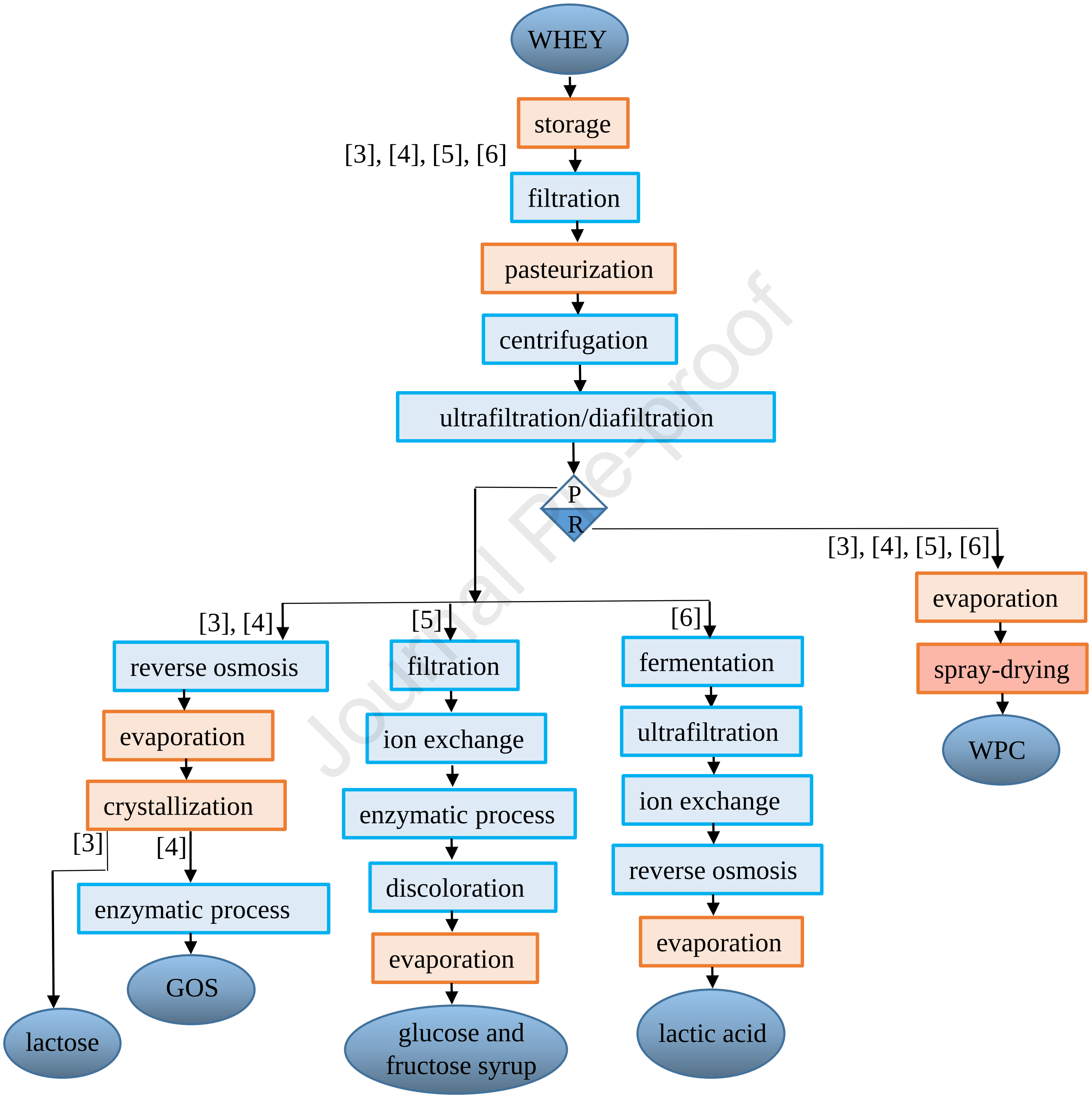
Figure 1


WHEY
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filtration
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[3], [4], [5], [6]
evaporation
spray-drying
WPC
[3], [4]
reverse osmosis
evaporation
crystallization
[3]
[4]
enzymatic process
GOS
lactose
[5]
filtration
ion exchange
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ion exchange
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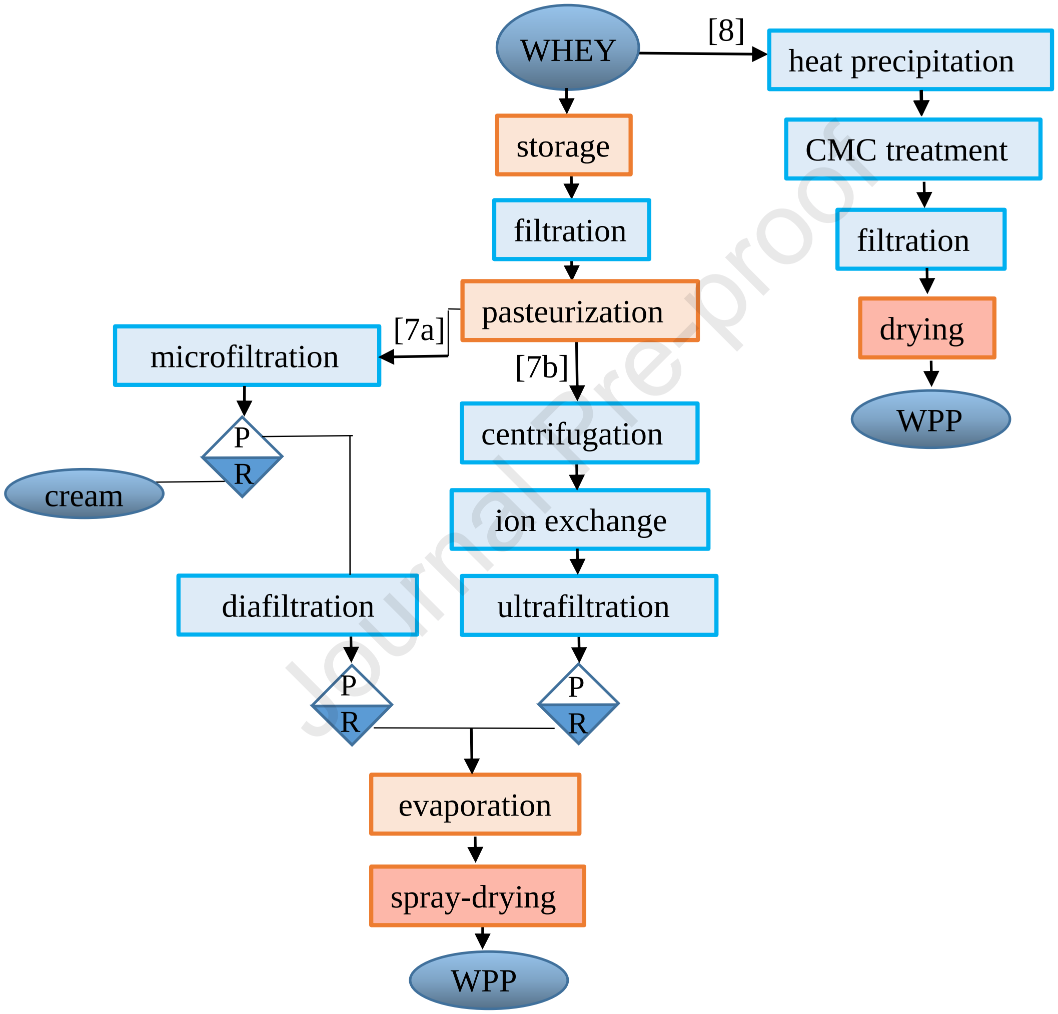
evaporation
lactic acid

Figure 2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pasteurization
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microfiltration
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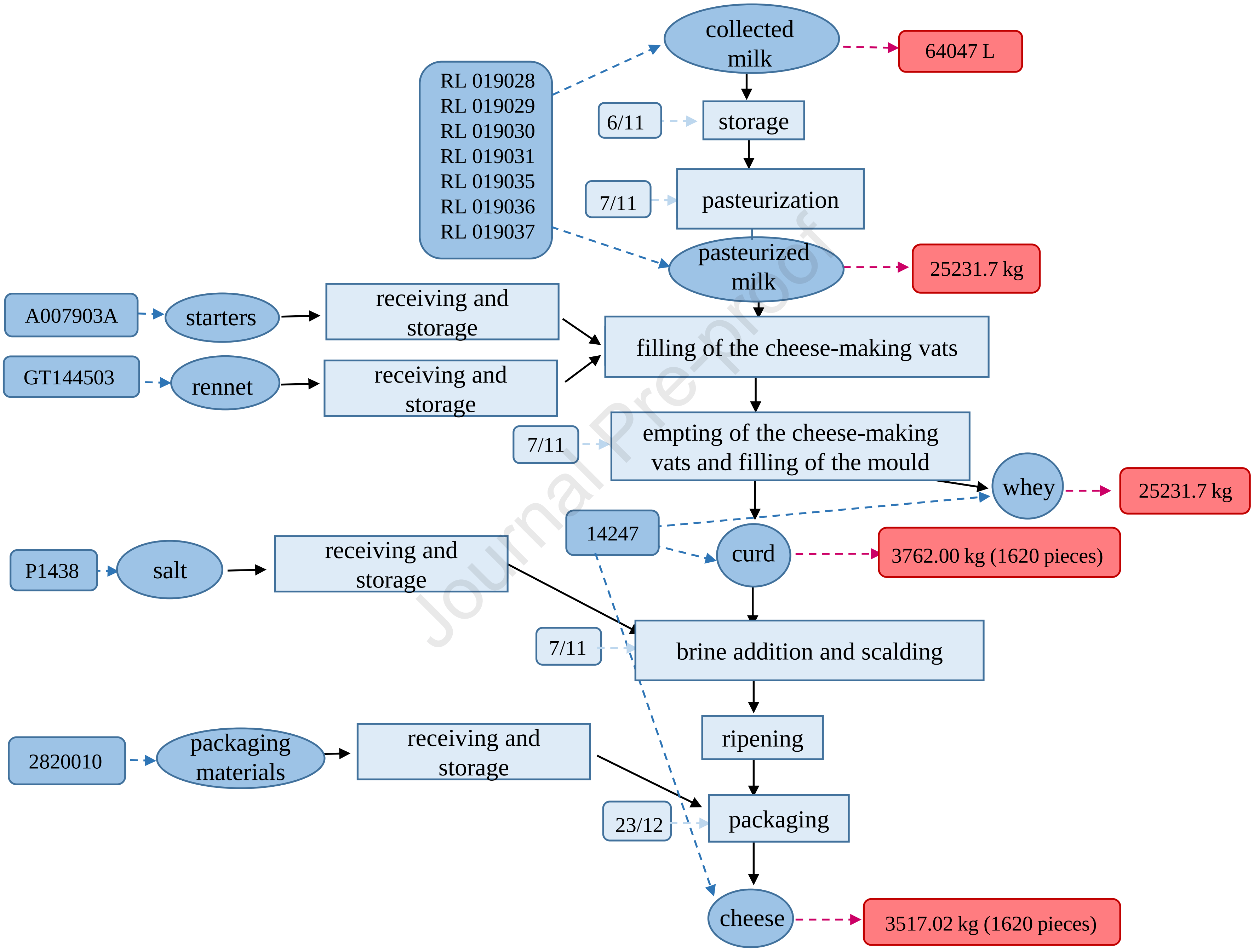
spray-drying
WPP

Figure 3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RL 019030
RL 019031
RL 019035
RL 019036
RL 019037
collected milk
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pasteurization
pasteurized milk
25231.7 kg
A007903A
starters
receiving and storage
GT144503
rennet
receiving and storage
filling of the cheese-making vats
7/11
empting of the cheese-making vats and filling of the mould
whey
25231.7 kg
14247
curd
3762.00 kg (1620 pieces)
P1438
salt
receiving and storage
7/11
brine addition and scalding
ripening
2820010
packaging materials
receiving and storage
23/12
packaging
cheese
3517.02 kg (1620 pieces)

Figure 4

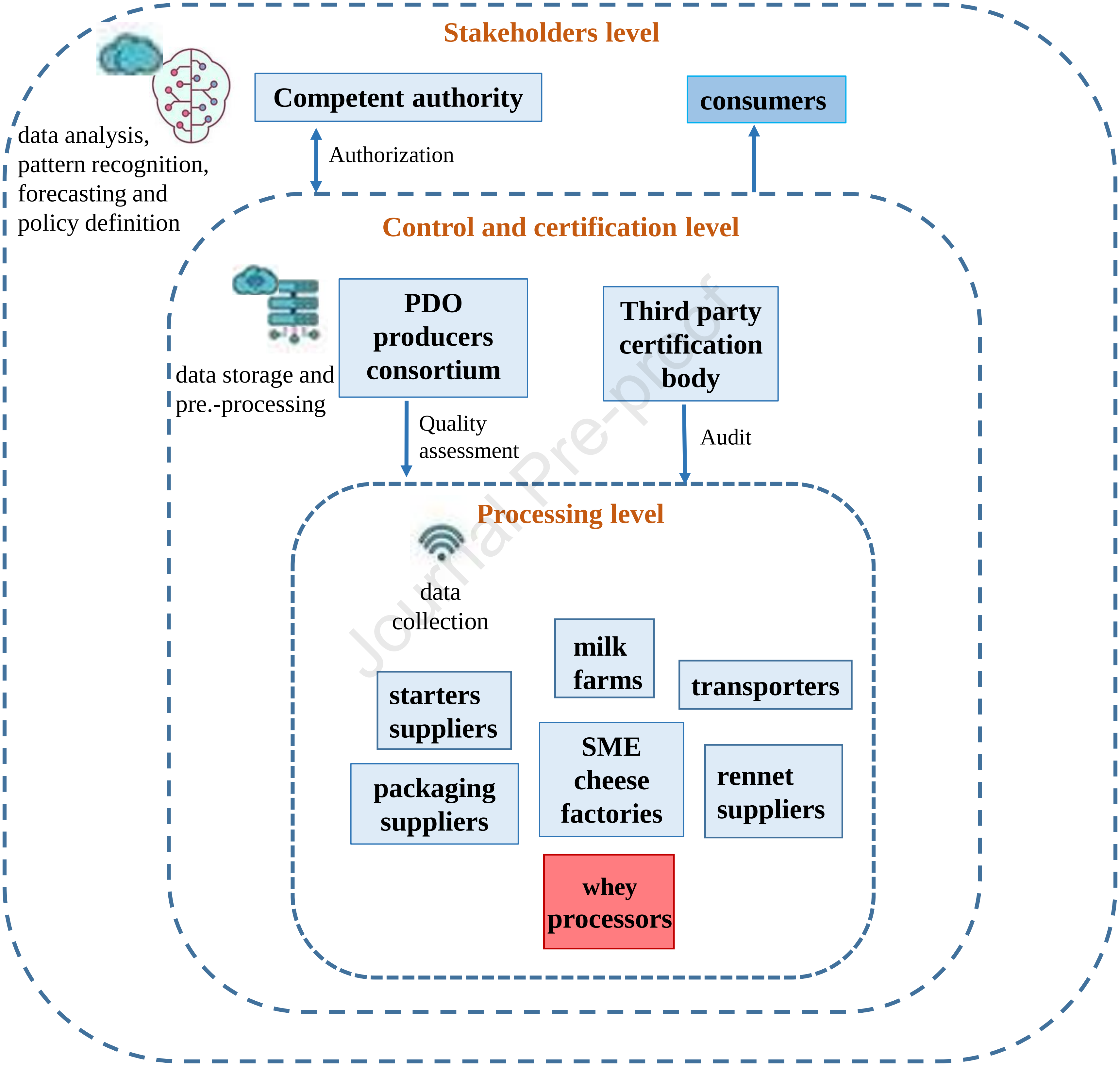
Stakeholders level
data analysis,
pattern recognition,
forecasting and
policy definition
Competent authority
consumers
Authorization
Control and certification level
data storage and
pre.-processing
PDO
producers
consortium
Third party
certification
body
Quality
assessment
Audit
Processing level
data
collection
milk
farms
transporters
starters
suppliers
SME
cheese
factories
rennet
suppliers
packaging
suppliers
whey
processors

Figure 5

Highlights

- Efficient whey recycling processes can be performed with large whey inflow (> 100 t/d)

- High-quality Protected Designation of Origin (PDO) cheeses are made at small/medium enterprises (SMEs)

- SMEs can produce whey that meets safety quality requirements for recycling

- SMEs could contribute to whey recycling by suppling traceable whey lots to industrial processors

- Smart traceability schemes support a trustable whey value chain involving a multitude of actors

- SMEs processing PDO cheeses could advance the application of the bioeconomy in the food system