



Contents lists available at ScienceDirect

## Journal of Cleaner Production

journal homepage: [www.elsevier.com/locate/jclepro](http://www.elsevier.com/locate/jclepro)

# Decentralised by-product valorisation in the dairy value chain: An opportunity for sustainable intensification

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## ABSTRACT

Increasing the sustainability of the livestock sector is a vital goal in lowering the environmental burden of food production globally. The dairy sector is of particular interest in this context since it is responsible for a significant share of this burden. In the past, research has focused on approaches to lower the impacts at the farming stage of production, while fewer efforts have been directed at the later stages of the value chain. By-product valorisation is a tool within the wider framework of Circular Economy that allows to increase the efficiency of resource use by increasing the product output at high quality, potentially leading to a sustainable intensification. The present study aims to test this hypothesis. For this purpose, data was collected from a cheese production case study and pilot-scale experiments on whey valorisation, to model several scenarios of by-product valorisation in the dairy value chain. This includes a decentralised valorisation scenario modelled for the purpose of supporting a local Circular Economy and three scenarios representing common valorisation approaches. The impacts of the entire value chain are then assessed based on an attributional LCA considering three different functional units in order to examine the potential for a relative reduction of impacts per unit of product output. The results suggest that while there is no clear favourite among the investigated valorisation scenarios, by-product valorisation in general can lower the relative impacts of the value chain significantly as compared to the base scenario without valorisation. Depending on the valorisation scenario and impact category, impact reductions of up to 14%, 20% and 32% can be achieved for the three functional units, respectively. Hence, by-product valorisation allows for a sustainable intensification. While centralised lower quality valorisation is favourable in terms of product mass and overall process efficiency, decentralised and high-quality valorisation performs better when the economic value of the products is taken into consideration. Thus, the choice for the most suitable approach for a production site will depend on the context of the production and the intentions of the stakeholders.

## 1. Introduction

Improving the sustainability of food production is a key objective in reducing the environmental impacts of human activities, as it contributes significantly to several impact categories. In 2020, the European agri-food industry was responsible for 10% of the greenhouse gas emissions within the European Union (EEA, 2022). Within the agri-food industry, in particular livestock farming causes vast environmental impacts, with beef and dairy having a large relevance due to the low feed conversion rates and enteric fermentation as well as high phosphorus and nitrogen output. In fact, animal husbandry contributed up to 60% to the total emissions of greenhouse gases in the EU-27 in 2018 (EC, 2020). It is estimated that in the EU the production of dairy goods is responsible for 10% of the eutrophication impact, 6% of the acidification impact and 4% of the photochemical oxidant formation from all anthropogenic sources (Tukker et al., 2006). Thus far, a majority of efforts to improve the sustainability of the dairy production have been directed at the

farming stages in order to reduce enteric fermentation and improve feed conversion rates as well as waste management (Bacchetti et al., 2016; Cecchini et al., 2016; Gislón et al., 2020; Zucali et al., 2018). However, possible points for improvement can also be identified further down the production chain.

Evidently, agricultural processes require vast amounts of resources, in particular land and water, and generate significant emissions, which should be utilized as efficiently as possible. Hence, products should be valorised to the largest possible extent, including the main agricultural outputs as well as by-products and other side streams leaving the productive processes. Lowering the emissions in the farming stages would decrease the environmental impacts per product mass output. The same effect can be reached by increasing the output from the production processes, hence improving the production efficiency. One option for achieving this is an increased by-product valorisation. If the valorisation requires less resources per product unit than the agricultural activities associated to it, the relative impacts of the output should sink, hence the

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<https://doi.org/10.1016/j.jclepro.2024.143958>

Received 4 February 2024; Received in revised form 30 September 2024; Accepted 12 October 2024

Available online 12 October 2024

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ratio of resources to output would improve leading to a sustainable intensification (Garnett et al., 2013; Godfray and Garnett, 2014; Pretty and Bharucha, 2014). One of the key components set by the EU in order to reach a sustainable economy (EC and Commission, 2020) is the establishment of a Circular Economy (CE). Since one of the main goals of CE is to recirculate value and material into the economy, by-product valorisation could help increasing the circularity of the dairy industry.

Searching the terms “Circular Economy” and “dairy” on Scopus, a total of 225 literature references were identified (date of search: May 29, 2024). Among the relevant studies focusing on the dairy value chain, a few topics stand out. Waste minimisation as the central goal is most often achieved through energy recovery and fertilizer production via anaerobic digestion. This approach can be applied both at farm level (Ghisellini et al., 2014; Herbstritt et al., 2023; Sandoval and Salazar, 2021; Zhang et al., 2021) and at the dairy plant (Casallas-Ojeda et al., 2021; Giuliani de Almeida et al., 2023). The potential treatment of dairy wastewater through microbial processes (e.g., with algae or yeast) is also studied. Possible products are microbial biomass (Athanasiadou et al., 2023), bacterial cellulose (Lappa et al., 2021), bioethanol (Carvalho et al., 2021) and biodiesel (Bencresciuto et al., 2024). However, the most relevant waste stream and potential by-product of the dairy industry is whey (Lavelli and Beccalli, 2022; Uvarova et al., 2020), since whey contains different substances that can be valorised into high-value products. Literature investigating the potential of integrating whey into CE mostly focus on possible business models and the economic viability (Lavelli and Beccalli, 2022; Uvarova et al., 2020).

At the moment, whey is often used as a feed in the dairy, beef, and pork production, but many other applications are possible (Barba, 2021; Costa et al., 2021; Kaur et al., 2019; Tsermoula et al., 2021). One of the most common high-quality applications is the protein supplementation for elderly, athletes and other population groups with high protein demands, since whey has a very high protein quality (Hoffman and Falvo, 2004). Moreover, it contains several bioactive proteins and peptides (Tsermoula et al., 2021; Yadav et al., 2015), for which reason purified whey proteins can be applied as nutraceuticals for humans and animals. Additionally, whey proteins can be used in cosmetics as well as surgical materials. Lactose, another important substance contained in whey generally has a lower value than the proteins but can be used for a range of applications in the food, cosmetics and pharmaceutical industries (Barba, 2021). Several studies investigated the suitability of lactose valorisation for a CE (Orrego and Klotz-Ceberio, 2022; Rico-Rodriguez et al., 2021).

While literature discusses the manifold possibilities to apply CE in the dairy value chain, environmental assessments of such practices are scarce. It is mostly the energy recovery through anaerobic digestions that is investigated (Casallas-Ojeda et al., 2024; Ghisellini et al., 2014; Stanchev et al., 2020; Zhang et al., 2021). For this reason, the present manuscript aims to shift the focus towards by-product valorisation.

One of the most powerful tools currently available to assess the environmental sustainability of processes and products is the life cycle assessment (LCA) (ISO, 2006a, 2006b). In a LCA environmentally relevant inputs and outputs of a system are associated to a functional unit. Based on the material and energy flows, impact assessment models are then used to evaluate the potential environmental impacts per functional unit. Thus far, whey production and by-products in the dairy industry have mostly been accounted for in allocation scenarios, where the environmental impacts are divided between the different output flows from the dairy production based on economic relevance or mass of the streams (Famiglietti et al., 2019; Palmieri et al., 2017). Little research exists that focuses on the whey products and the different processes that can be applied in order to valorise it into a range of potential products (Bacenetti et al., 2018; Depping et al., 2020). To the knowledge of the authors, no research has thus far investigated the effect that by-product valorisation in the dairy value chain would have on the sustainability of the entire chain in a holistic perspective and therefore the potential for a sustainable intensification in a Circular Economy. The present work

aims to answer that question and to verify the suitability of by-product valorisation in efforts to improve the sustainability of the dairy value chain. The following two research questions were considered in the present study.

1. From a holistic value chain perspective, does an increase in by-product valorisation within the dairy value chain, with the aim of high-quality by-product valorisation at source, reduce the relative environmental impacts and thereby allow for a sustainable intensification?
2. How do different valorisation scenarios compare against each other, including low and high value as well as small- and large-scale approaches?

To answer these questions, the manuscript first presents the materials and methods applied in the study. This includes the introduction of the scenarios, the primary data collection at a case study cheese producer and the experimental data collection at a pilot-plant for whey valorisation, as well as the subsequent environmental assessment. The results are presented first for the case study and then for the different valorisation scenarios. The relevance of scenario assumptions was tested in several sensitivity analyses. Lastly the implications of the results are discussed and put into relation with existing literature.

## 2. Material and methods

The system under investigation included the cheese production as well as the by-product valorisation activities. Four different models for by-product valorisation were compared. Three scenarios are based on common practices for whey treatment and valorisation in Northern Italy. The base scenario comprises scenarios in which whey is not valorised or valorised at low quality. In the whey powder scenario, whey is skimmed at a large-scale plant and then pulverised. The centralised valorisation scenario depicts a centralised large-scale plant that produces two types of whey protein concentrates and a lactose-rich dried product via membrane fractionation. Additionally, a scenario was developed, which focuses on a high-quality valorisation via membrane fractionation at source (Argenta and Scheer, 2020; Barba, 2021; Lavelli and Beccalli, 2022; Macedo et al., 2021). Due to the latter requirement, the model applies a decentralised valorisation approach. The main outputs of this scenario are an 80% whey protein concentrate (WPC80) and a lactose-rich dried fraction, which can both be further processed into a variety of products (Barba, 2021). A short overview of the scenarios is provided in Table 1. More detailed information can be found in the Supplementary Materials.

The goal of the assessment was to understand and quantify the environmental impact of valorising whole whey from cheese production

**Table 1**  
The four by-product valorisation scenarios modelled in the study.

Scenario	Size	Distribution	Processes	Products
<b>Base scenario</b>	n/a	n/a	n/a	low quality
<b>Whey powder valorisation</b>	large-scale	centralised	skimming drying	whey powder
<b>Centralised valorisation</b>	large-scale	centralised	skimming fractionating drying	60% whey protein concentrate 80% whey protein concentrate lactose-rich fraction
<b>Decentralised valorisation</b>	small-scale	decentralised	skimming fractionating drying	80% whey protein concentrate lactose-rich fraction

in a decentralised, small-to medium-scale fractionation process in relation to the entire value chain impact. Different alternative scenarios are offered for comparison, which are based on common practices observed in Northern Italy. An attributional assessment approach was chosen. The study addresses researchers, practitioners, and policy makers as its audience. The ISO standards for Life Cycle Assessments 14040 and 14044 (ISO, 2006a, 2006b, 2020a, 2020b) are followed throughout the study. The PEFCR (Product Environmental Footprint Category Rules) for dairy products were followed whenever applicable (EDA, 2018). The software SimaPro version 9.3 was used for calculations, applying the ReCiPe 2016 midpoint (H) method (Huijbregts et al., 2017) to assess the environmental impacts.

With regard to the functional unit, a decision is not straightforward since the main product (cheese) and by-products (whey and cream) are not functionally identical given the different solid contents and applications. There are several choices imaginable, considering potential applications of the products obtained from whey valorisation (Bacenetti et al., 2018; Depping et al., 2020; EDA, 2018). Moreover, since the goal of the present LCA study is to investigate the importance of whey valorisation for the entire value chain, the functional unit should be practical and reasonable for both the main product and the possible by-products.

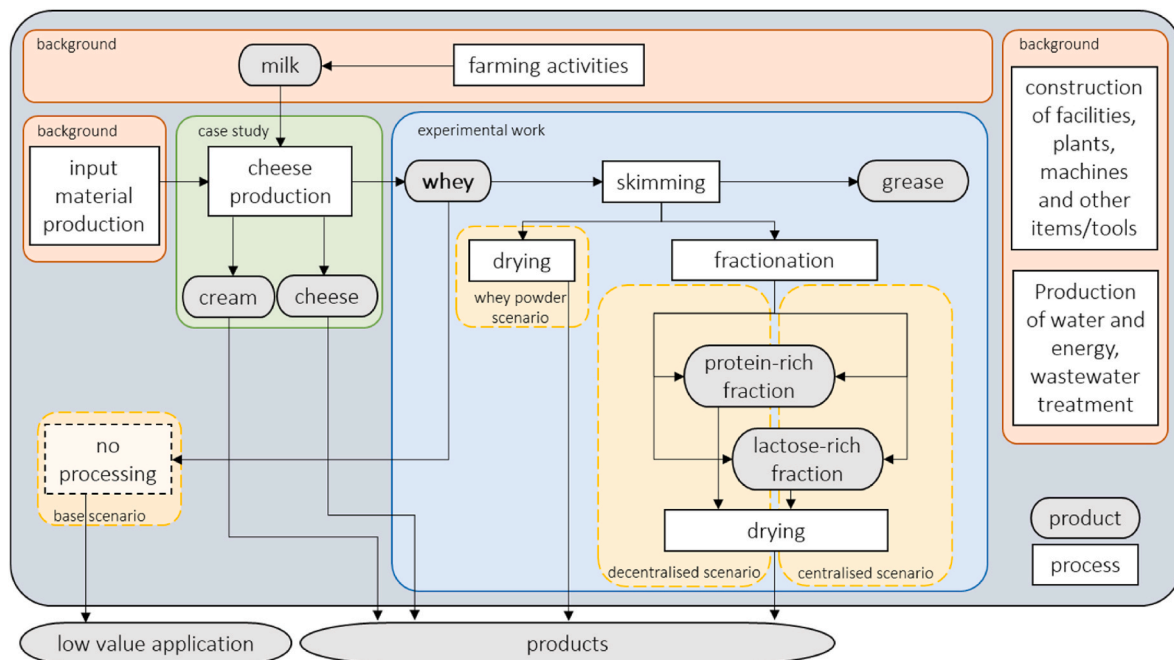
If products and by-products are considered to be consumed by humans or applied in equally or higher value applications, e.g., food and food supplements, cosmetics, nutraceuticals, and pharmaceuticals, a reasonable functional unit would be the weight of valorised dry matter ( $DM_v$ ) of the products. According to the PEFCR of dairy products (EDA, 2018), there is only one DM-based unit recommended, which is 10 g DM-equivalents for cheese. For dried whey products and butterfat products wet-mass-based units are recommended, namely 1000 kg and 50 g. To integrate all three products into one unit, 1 kg  $DM_v$  was chosen as a compromise. One shortcoming of a DM-based unit is that all nutrients within the dry matter are given the same value even though, for human requirements, different nutrients do not value equally (Meyers et al., 2006). Hence, another reasonable choice is the protein content (Bacenetti et al., 2018; EDA, 2018), the highest value macro nutrient contained in milk and its derivatives (Tsermoula et al., 2021), as amount of valorised protein (kg protein<sub>v</sub>). Yet, in that case fats and

carbohydrates would not be considered at all despite undoubtedly having a value of their own. Finally, neither of the two units considers that even if the nutrients are the same and the application is similar, such as human nutrition, the value of the products might still differ. While cheese is a common food, whey proteins are used as a high-quality protein source with higher kg prices (Tsermoula et al., 2021). Thus, a third useful functional unit is the dairy value chain revenue as monetary value (1 € value chain revenue) (Depping et al., 2020; González-García et al., 2018; Pereira et al., 2015), as it best represents the current value of the products. However, this unit is only meaningful in a precise time frame, as prices tend to change and it gives no information on material flows and efficiency, which is of major importance for sustainability and circularity considerations. As none of the three units can provide a full picture of the results nor allow a detailed interpretation individually, all three of them were applied and discussed thoroughly.

The three functional units are expected to show little sensitivity to the types of cheese produced, since the distribution of proteins and dry matter between cheese and whey does not differ notably for different cheese types. In most cases the price of cheese increases with lower water contents, hence the ratio of the price to the protein and DM content stays relatively stable. According to the data in this study, a maximum change of  $\pm 15\%$  in the revenue from cheese production can be observed for different types of cheese. Since the revenue from cheese production would remain the same in different valorisation scenarios, the effect on the comparison between the scenarios would be small.

The boundaries of the assessment entail all steps within the dairy value chain from the production of milk to the delivery of the products of the cheese making and by-product valorisation (Fig. 1). Data was collected starting with the transportation of the milk from the farm to the cheese maker and for all cheese making activities. Additionally, by-product valorisation activities were simulated in laboratory experiments. All transportation within these steps is considered.

Primary data was collected in a case study from a small-scale cheese producer (3000 t/y milk) in the province of Brescia, Italy. The company produces a range of different hard, semi-hard and soft cheeses in different degrees of ripeness and with different additional ingredients such as saffron and truffles. The collected data spanned five years (2016–2020) for all major material streams (e.g., milk, products, water,



**Fig. 1.** Boundaries of the LCA. Background processes are highlighted in red, case study data in green and the experimental data in blue. The different investigated scenarios are marked in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

etc) and three years (2018–2020) for minor flows (detergents, lactic ferments, salt, truffles, etc). The case study data was collected from material and utility bills as well as sales invoices and covered all activities at the cheese producer. The major materials and energy flows are shown in Table 2, detailed inventory tables can be found in the Supplementary Materials.

Additional primary data was collected in laboratory experiments at small- and pilot-scale. The experimental data covers all valorisation steps, including the skimming, membrane fractionation and drying of the products. Material and energy consumption as well as product outputs were directly measured at the pilot plant. Information on the valorisation steps was additionally gathered in interviews with experts from the industry in order to verify the experimental data. Any missing data was estimated based on educated assumptions by experts in the field. All valorisation strategies were energy-intensive requiring a high electricity consumption. For the three scenarios whey powder, centralised and decentralised the electricity consumption of valorisation per kg of raw whey input was 0.366 kWh<sub>e</sub>, 0.341 kWh<sub>e</sub> and 0.426 kWh<sub>e</sub>, respectively. The inventory data can be found in the Supplementary Materials.

Background data was taken from the ecoinvent database v3.8 (Weidema et al., 2013). This included milk production, energy production, waste treatment, water production and treatment (besides the treatment on-site at the cheese maker), production of chemicals, and the construction of the facilities. The milk input was adjusted to fat- and protein-corrected milk (FPCM) (IDE, 2015). Transportation to and from the cheese producer as well as the by-product valorisation plant were modelled according to the available primary data. For the decentralised valorisation scenario, a distance of 10 km to the fractionation plant and 20 km to the drying plant were assumed.

When focus is placed on the value chain perspective, the allocation between the products and by-products of the cheese making process becomes irrelevant, since both by-products are valorised, and all value chain output is represented unitedly in the functional units. Nonetheless, to allow product-specific analyses and comparison with literature, different allocation scenarios are provided in the Supplementary Materials. In the scenarios, the cheese making process and the valorisation process are considered independently. Valorisation scenarios with low-quality products such as animal feed or biogas were not considered in the FUs of 1 kg DM<sub>v</sub> and 1 kg protein<sub>v</sub>, since no additional DM or protein would become available after the respective process. Moreover, the potential of biogas production from whey to lower the environmental impact of cheese production by replacing other energy sources is low (Gosalvitr et al., 2019). The selling of whey at low value is considered in the FU of 1 € value chain revenue, representing 1% of the revenue at the

**Table 2**

The major input and output flows to the cheese production process as average values. Data was collected for three years of production and for the most relevant flows for five years (shown in bold).

Input	Annual average	SD	Unit
<b>Milk (fat- and protein-corrected)</b>	3340	200	t
<b>Well water</b>	7690	670	m <sup>3</sup>
Electricity from grid	302,000	6100	kWh <sub>e</sub>
Electricity from photovoltaic modules	61,600	5300	kWh <sub>e</sub>
Diesel oil for heat (77%) and fuel (23%)	84,000	2400	L
Liquified petroleum gas for heating	15,200	800	L
Materials for cheese production	15,700	970	kg
Materials cleaning and hygiene	8500	510	kg
Packaging materials	25,600	2000	kg
<b>Output</b>			
<b>Cheese</b>	362	14	t
<b>Whey</b>	2210	170	t
<b>Cream</b>	113	12	t
<b>Solid waste</b>	43	20	t
<b>Wastewater</b>	6980	760	m <sup>3</sup>

case study cheese producer.

Background data was selected with reference to the Italian market whenever possible, otherwise the European market was applied. If no other option was available, a global market reference was used. All transportation was considered to be done by trucks with or without refrigeration depending on the materials transported.

### 3. Results

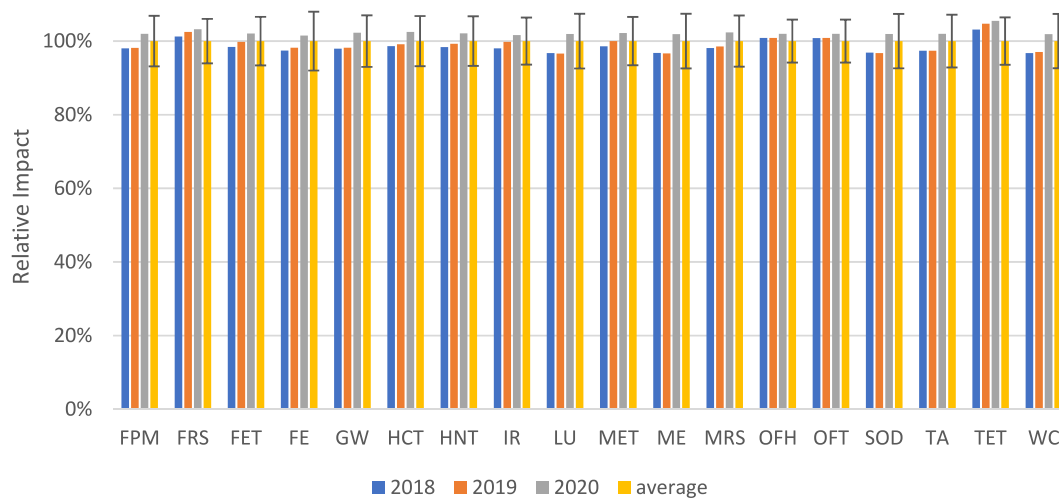
Firstly, it was investigated how the cheese production varied over the studied years to highlight how annual fluctuations in productivity can affect the environmental impacts of the products. The results for the years 2018–2020 are compared to the production average (based on three- and five-year averages). Fig. 2 visualises the results normalised in reference to the average, which includes error bars based on a Monte Carlo uncertainty analysis (1000 runs) of the input and output variations. The depicted average is also representing the base scenario since only cheese and cream production are considered in the functional unit of 1 kg DM<sub>v</sub>.

For all impact categories the variation between years stayed within a limit of 7% ( $\alpha = 0.01$ ). The year 2020 was more impactful than the previous two years, as there was less cheese produced relative to the milk input, increasing the burden of the processes on the products. Since the average represents five years of production for the major inputs and outputs, for some of the impact categories it may seem inconsistent with the three years presented, for example, in case of the fossil resource scarcity and the terrestrial ecotoxicity. In those cases, the two previous years of production (2016 and 2017) are responsible for the difference to the average.

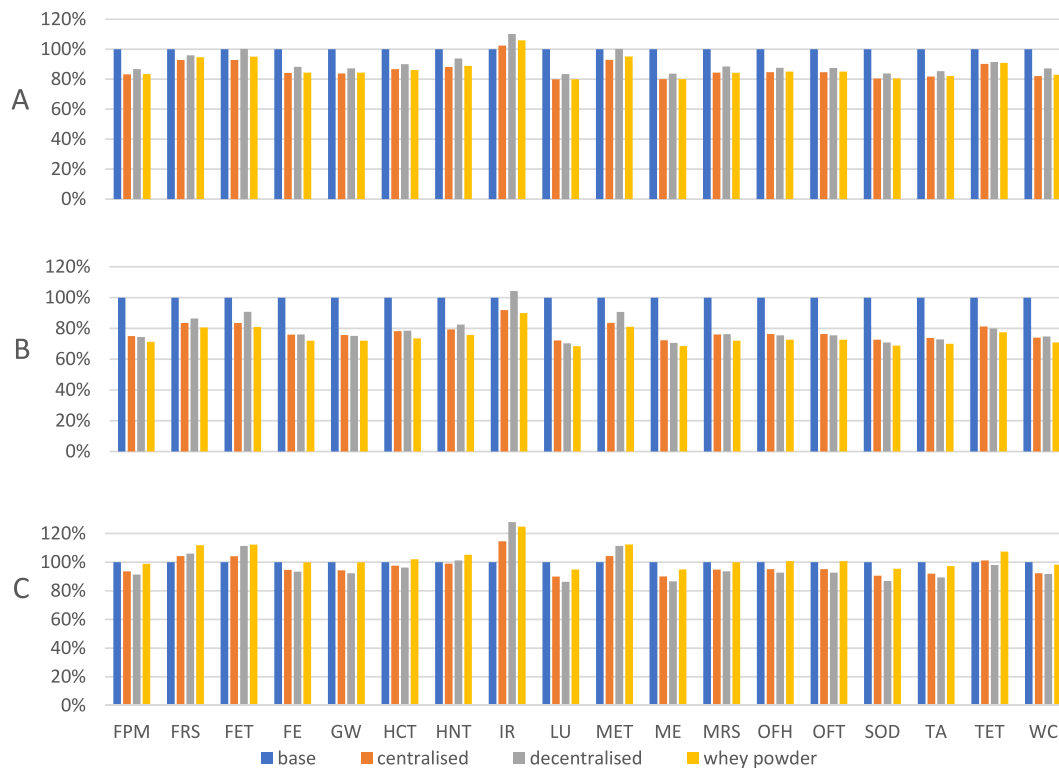
The production average, which equals the base scenario, was then compared to the three valorisation scenarios modelled in the present study. For each of the scenarios, the environmental impacts were calculated for the three functional units. The base scenario acted as the normalisation reference for the visualisation in Fig. 3, which includes all four valorisation scenarios and the three functional units in three separate graphs.

The graphs show that for the two functional units (FU) of 1 kg DM<sub>v</sub> and 1 kg protein<sub>v</sub> there is a clear benefit of by-product valorisation over the base scenario, as shown by the reduction of impacts per functional unit for all impact categories except the ionizing radiation. This means that for these categories the increase in product amounts is greater than the increase in impacts due to additional processing steps. For the FU of 1 kg DM<sub>v</sub>, the improvement in the different scenarios ranges from 9% to 19% for MET and FET to 28%–32% for LU and MEP. For the FU of 1 kg protein<sub>v</sub>, there is an improvement potential from 0% to 7% for MET, FET and FRS up to 17%–20% for LU. Ionizing radiation is mainly affected by the electricity consumption, which is substantially higher in case of the valorisation scenarios. Among the three valorisation scenarios, the two based on a centralised approach, i.e. the centralised and the whey powder scenario, perform best in case of the FU 1 kg protein<sub>v</sub>, with results 1%–7% lower than the decentralised scenario. For the FU of 1 kg DM<sub>v</sub>, the whey powder scenario again performs best, outscoring the other two valorisation scenarios by 2%–14%. Meanwhile, there is no clear favourite between the centralised and the decentralised scenario. The contribution of the different products and by-products to the total impacts according to the allocation are provided in the Supplementary Materials.

It should be noted that for the functional unit of 1 kg DM<sub>v</sub>, all valorisation scenarios considered the dry matter weight of lactose. This may be inaccurate in a realistic context, since it is unlikely that all lactose is valorised at food-quality or higher in the centralised approach due to the large amounts of lactose produced. Similar issues would arise for the decentralised scenario if it was applied at the same volume dimension as the centralised scenario. However, since the goal of this assessment was to investigate the effects of an extensive by-product valorisation, the dry matter content of lactose was considered.



**Fig. 2.** Environmental impacts for three years of production and a five-year average related to the functional unit of 1 kg DM<sub>v</sub> of products sold for human consumption. *FPM* – fine particulate matter, *FRS* – fossil resource scarcity, *FET* – freshwater ecotoxicity, *FE* – freshwater eutrophication, *GW* – global warming, *HCT* – human carcinogenic toxicity, *IR* – ionizing radiation, *LU* – land use, *MET* – marine ecotoxicity, *ME* – marine eutrophication, *MRS* – mineral resource scarcity, *OFH* – ozone formation human health, *OFT* – ozone formation terrestrial ecosystems, *SOD* – stratospheric ozone depletion, *TA* – terrestrial acidification, *TET* – terrestrial ecotoxicity, *WC* – water consumption.



**Fig. 3.** Normalised impacts of the four valorisation scenarios for each of the functional units. Graph A shows the results for 1 kg protein<sub>v</sub>, graph B for 1 kg of DM<sub>v</sub>, and graph C for 1 € of value chain revenue. Relative contributions of individual products are provided in the Supplementary Materials.

Moreover, this would allow for a fairer comparison between the valorisation scenarios (for the whey powder scenario, lactose is always considered) as an exclusion of lactose would affect the total DM notably. The results of excluding the lactose dry matter are shown in the Supplementary Materials as part of the sensitivity analyses, revealing the expected increase of relative impacts, while still being favourable over the base scenario in all categories besides ionizing radiation in the case of a decentralised valorisation.

For the functional unit of 1 € revenue the results are more complex, with the decentralised scenario being favoured in most categories, but

also performing worst or second worst in five categories. Overall, it is apparent that the decentralised and centralised scenarios show a benefit of by-product valorisation as compared to the base scenario in twelve categories, with improvement ranging from 3% to 14%. The decentralised scenario performs slightly better in most cases. Only in four categories, fossil resource scarcity, freshwater ecotoxicity, ionizing radiation and marine ecotoxicity, both perform worse than the base scenario, with a maximum reached for IR with 115% in the centralised and 128% in the decentralised scenario. In the case of human non-carcinogenic toxicity and terrestrial ecotoxicity, only one of them

performs worse, respectively. The whey powder scenario on the other hand does not seem to be clearly beneficial as compared to the base scenario, performing worse in seven categories with increases between 2% and 25%, better in six scenarios, with decreases of 1%–5%, and about the same in five scenarios.

In this context, the assumptions made for the scenarios should be noted. Since the goal of the decentralised scenario is to aim for high-quality valorisation at small- to medium-scale, a valorisation of all lactose at 1 €/kg is assumed. Meanwhile, a centralised large-scale valorisation may not achieve a complete high-quality valorisation of all lactose at the same price. This is due to the limited request for lactose on the market. In the US, the annual production volume of lactose ranges between 23,000 and 46,000 metric tons (CLAL, 2022b), which is the same magnitude as the permeate dry matter output observed for the centralised valorisation plant (30,000 t). For this reason, lower quality lactose-rich products need to be sold in order to be able to valorise all by-product streams. Hence, valorisation at lower quality was assumed and therefore a selling price at 0.5 €/kg considered, the average of the maximum of 1 €/kg and the minimum of 0 €/kg. This way the overall higher valorisation quality of the hypothetical decentralised scenario is modelled within the assessment. As part of the sensitivity analyses, the effect of assuming a high-quality lactose valorisation in the centralised scenario was investigated. It reveals that with the same valorisation quality of lactose in the decentralised and centralised scenarios, both perform more similarly, meaning that the benefits of valorising the proteins at higher value in the decentralised approach tends to be balanced out by the higher efficiency of the centralised approach.

Apart from the value of lactose and its integration in the DM output, the sensitivity of the results to changes in the selling prices of the different by-products as well as different degrees of efficiency improvements in the centralised valorisation scenarios were investigated. The results showed a clear influence of the selling prices on the impacts related to the FU of 1 € value chain revenue. Higher selling prices achieved better results, while lower selling prices led to worse ones for the tested decentralised scenario. However, the overall trend of favourable results through by-product valorisation is not affected. Meanwhile, a better efficiency does naturally lower the impacts per FU, yet the clear benefit of by-product valorisation is not affected. The performance of the centralised approach as compared to the decentralised approach remains the same for all categories for the functional unit of 1 kg protein<sub>v</sub>. Similar observations can be made for the other two FU, with no clear

trend being reversed.

As with the cheese production, Monte Carlo uncertainty analyses were performed to verify the statistical significance of the results. In this case, a comparative analysis was performed for the decentralised and the centralised scenarios against the base scenario for the functional units 1 kg DM<sub>v</sub> and 1 kg protein<sub>v</sub>, respectively. It showed that for a large majority of impact categories a complete advantage of the two valorisation scenarios is given. The only impact category with a considerable chance of increasing impacts in the valorisation scenarios is ionizing radiation. Between the two FU and the two scenarios this is more relevant for the FU of 1 kg protein<sub>v</sub> and for the decentralised scenario. As a matter of fact, the combination of both is the only case in which two other categories show chances of a worsened result, i.e., freshwater and marine ecotoxicity.

Since according to literature, milk production poses the main contribution to most impacts caused by the dairy value chain (Cecchini et al., 2016; Colombini et al., 2015; Dalla Riva et al., 2015; Guerzi et al., 2014; Hietala et al., 2014), the same was tested for the present assessment. Table 3 provides the contribution of milk production to all impact categories for the base scenario. Additionally, it shows how much the inclusion of a by-product valorisation step would contribute to the total impact for the three valorisation scenarios. The ratios are presented for the FU of 1 kg DM<sub>v</sub>.

In line with the findings in literature, for all considered impact categories, milk production is by far the largest contributing process. The lowest contribution can be seen for the category of ozone formation, with around 70%, and the highest one for land use, with practically 100% of the impact due to milk production. In impact categories associated with agricultural practices the highest contributions of milk production were observed at over 95% (e.g., land use, marine eutrophication, acidification, and water consumption). Meanwhile impact categories related to energy production such as fossil resource scarcity, ionizing radiation, and ozone formation show slightly lower, though still major, contributions of 70–80%. None of the valorisation processes have a contribution of more than one third within any of the impact categories. Hence, even when by-product valorisation is applied, milk production remains the largest contributor to the environmental impacts of the dairy value chain.

**Table 3**

Percentual contribution of the stand-alone valorisation process to the total value chain impact in the three valorisation scenarios. The right column depicts the contribution of milk to the cheese production. Allocation scenarios to distribute the impacts between individual products and by-products are provided in the Supplementary Materials.

Impact category	Decentralised valorisation	Centralised valorisation	Whey powder valorisation	Contribution of milk to cheese production <sup>a</sup>
Global warming	6%	5%	5%	93%
Stratospheric ozone depletion	1%	1%	1%	99%
Ionizing radiation	33%	21%	24%	80%
Ozone formation, Human health	7%	5%	6%	69%
Fine particulate matter formation	6%	4%	4%	90%
Ozone formation, Terrestrial ecosystems	7%	5%	6%	70%
Terrestrial acidification	3%	2%	2%	95%
Freshwater eutrophication	8%	5%	5%	89%
Marine eutrophication	0%	0%	0%	99%
Terrestrial ecotoxicity	12%	11%	12%	86%
Freshwater ecotoxicity	23%	14%	16%	83%
Marine ecotoxicity	22%	14%	16%	83%
Human carcinogenic toxicity	10%	8%	7%	90%
Human non-carcinogenic toxicity	15%	9%	10%	87%
Land use	0%	0%	0%	100%
Mineral resource scarcity	8%	5%	5%	92%
Fossil resource scarcity	19%	14%	15%	76%
Water consumption	6%	2%	4%	97%

<sup>a</sup> This column only considers the cheese production. Hence, at the example of ionizing radiation in the decentralised scenario, 33% of the impacts are caused by the valorisation and 67% by the cheese making of which 80% are due to the milk production. Therefore, in the decentralised valorisation scenario, 54% of the ionizing radiation is caused by the milk production step.

#### 4. Discussion

The results show that the by far largest impact within the dairy value chain is due to the milk production, as seen in literature as well (Cecchini et al., 2016; Colombini et al., 2015; Dalla Riva et al., 2015; Guerici et al., 2014; Hietala et al., 2014). In consequence, many research efforts are directed at reducing the impact of the milk production. Meanwhile, less attention has been given to later steps in the value chain, such as cheese production (Bava et al., 2018; Dalla Riva et al., 2017a, 2017b; Famiglietti et al., 2019; Forleo et al., 2018; Palmieri et al., 2017), and whey valorisation (Bacenetti et al., 2018; Depping et al., 2020), with none of the studies focusing on the entire value chain including the production of milk, cheese, and by-products, but rather accounting for by-production through allocation (Bava et al., 2018). For the present study, this holistic value chain perspective was taken. Thus, it became possible to understand if it was environmentally feasible to invest additional resources in order to generate more products at high quality and to minimise waste production to reach a more Circular Economy. If the increase in resource use is comparably smaller than the increase in productivity, the resource-to-product ratio is improved and the impacts relative to the products reduced. The results verified the assumption for all tested valorisation approaches and a grand majority of the impact categories.

##### a. Scenario performance

Among the valorisation efforts, the energy production was the largest contributor to the increase of the total impacts before the consumption of sodium hydroxide as cleaning agent, and transportation. Similar observations were made by Bacenetti et al. (2018). The main difference to the presented results is the relatively lower contribution of electricity. For this, it should be noted that Bacenetti et al. (2018) did not account for a potential valorisation of lactose, which increases the use of electricity for the decentralised valorisation approach. Moreover, they assumed a transportation distance of 150 km, while in the decentralised approach the transportation of whey is at 10 km and the transportation to the drying plant at 20 km. Hence, a much lower contribution of transportation is expected.

Comparing the three different valorisation scenarios to one another, no clear conclusion can be drawn on which of the scenarios is the most favourable since especially the decentralised and the centralised scenarios perform almost identically. While the centralised scenario performs slightly better with regard to the functional unit of 1 kg protein, the decentralised one has a minimal advantage for the functional unit of product chain value. However, the sensitivity analyses showed that much of that difference is due to the assumptions taken in the beginning of the LCA, for which reason more detailed case study data is needed to improve the robustness of the results. Moreover, the interpretation of the results may also depend on the intentions of the practitioner since, e. g., the whey powder scenario performs well in terms of material valorised, yet the value of valorisation is lower than in the other two scenarios for which reason it performs worst with regard to the value-based unit. Hence, a practitioner interested in high-value products might not be interested in this approach while someone interested purely in the total impacts of the value chain activities might prefer it, as it involves fewer steps and less additional resources for the whey to be valorised. Additionally, the preference of one approach over the other will also depend on the market situation for different products and their price development and stability.

##### b. Comparison to literature results

To verify the findings of the study and to put them more into context, the results were compared to literature data on cheese production and other protein sources. Two papers on cheese production in Italy (Bava et al., 2018; Dalla Riva et al., 2017a) as well as two reviews on food LCA

studies were identified (Nijdam et al., 2012; Poore and Nemecek, 2018). In Table 4 the study results are presented for the cheese production alone, the three valorisation scenarios for the entire value chain outputs, and for the whey product WPC80 under the decentralised valorisation scenario. In the latter case, the results are presented for the case of no allocation and protein mass allocation. For comparison, literature data on beef, cheese and plant-based protein sources is shown. Results for other impact categories, functional units and allocation scenarios are provided in the Supplementary Materials.

The results of the present study on the global warming impact of cheese production are comparable to those reported in literature. While they are slightly higher than those reported by Bava et al. (2018) and Dalla Riva et al. (2017a), they are similar or lower than those reported in the international reviews. For the land use, the comparison is more difficult due to the different units reported.

Among the different valorisation scenarios, the impacts per kg protein are reduced notably as compared to only the cheese production. Looking at the whey protein concentrate of the decentralised

**Table 4**

Comparison of the study results with different food items from literature based on a functional unit of 1 kg protein. *GW* – global warming, *LU* – land use.

Product	source	GW	unit	LU	unit
Cheese (no alloc.)	This study	67	kg CO <sub>2</sub> eq	310	m <sup>2</sup> crop eq
Cheese (prot. alloc.)	This study	52	kg CO <sub>2</sub> eq	240	m <sup>2</sup> crop eq
Dairy production (decentralised)	This study	58	kg CO <sub>2</sub> eq	260	m <sup>2</sup> crop eq
Dairy production (centralised)	This study	56	kg CO <sub>2</sub> eq	250	m <sup>2</sup> crop eq
Dairy production (whey powder)	This study	56	kg CO <sub>2</sub> eq	250	m <sup>2</sup> crop eq
WPC80 (decentr., no alloc.)	This study	15	kg CO <sub>2</sub> eq	0.46	m <sup>2</sup> crop eq
WPC80 (decentr., prot. alloc.)	This study	89	kg CO <sub>2</sub> eq	340	m <sup>2</sup> crop eq
WPC80 (decentr., no alloc., solar)	This study	4.1	kg CO <sub>2</sub> eq	0.14	m <sup>2</sup> crop eq
Grana Padano (econ. alloc.)	Bava et al. (2018)	57	kg CO <sub>2</sub> eq		
Asiago (econ. alloc.)	Dalla Riva et al. (2017a)	40 <sup>a</sup>	kg CO <sub>2</sub> eq	32 <sup>a</sup>	m <sup>2</sup> y
Beef	Nijdam et al. (2012)	45–640	kg CO <sub>2</sub> eq	37–2100	m <sup>2</sup> y
Cheese	Nijdam et al. (2012)	28–68	kg CO <sub>2</sub> eq	26–54	m <sup>2</sup> y
Eggs	Nijdam et al. (2012)	15–42	kg CO <sub>2</sub> eq	29–52	m <sup>2</sup> y
Vegetable meat substitutes	Nijdam et al. (2012)	6–17	kg CO <sub>2</sub> eq	4–25	m <sup>2</sup> y
Beef (beef herd, mean)	Poore and Nemecek (2018)	500	kg CO <sub>2</sub> eq	1640	m <sup>2</sup> y
Cheese (mean)	Poore and Nemecek (2018)	110	kg CO <sub>2</sub> eq	410	m <sup>2</sup> y
Tofu (mean)	Poore and Nemecek (2018)	20	kg CO <sub>2</sub> eq	22	m <sup>2</sup> y
Peas (mean)	Poore and Nemecek (2018)	4	kg CO <sub>2</sub> eq	34	m <sup>2</sup> y

<sup>a</sup> The protein content was calculated based on the reported data in Dalla Riva et al. (2017a).

valorisation scenario individually, depending on the allocation at the cheese producer, a global warming impact between 15 kg CO<sub>2</sub> eq (0% to whey) and 89 kg CO<sub>2</sub> eq (22% to whey) per kg protein<sub>v</sub> can be achieved.

To set a better context for evaluating the relevance of these findings, it was investigated how other protein sources perform in terms of environmental impacts per kg protein. Focus was laid on the global warming and the land use since they are the most commonly reported impact categories. [Nijdam et al. \(2012\)](#) reviewed LCAs on different animal-based and plant-based proteins in a cradle-to-retail perspective and found that animal proteins in general have higher impacts with beef having the highest impacts between 45 and 640 kg CO<sub>2</sub> eq per kg protein, while cheese (28–68 kg CO<sub>2</sub> eq per kg protein) and eggs (15–42 kg CO<sub>2</sub> eq per kg protein) perform notably better. Purely vegetal meat substitutes showed a global warming impact of 6–17 kg CO<sub>2</sub> eq per kg protein. [Poore and Nemecek \(2018\)](#) find a mean global warming impact of 20 kg CO<sub>2</sub> eq for tofu and 4 kg CO<sub>2</sub> eq for peas.

It can be seen that the whey products of the present study can be produced at global warming impacts comparable to the best performing animal-based protein alternatives and even some of the plant-based protein alternatives presented in literature. Moreover, looking at the entire value chain, a reduction of the global warming impact by 10 kg CO<sub>2</sub> eq per kg protein (15% decrease) is a notable progress which can improve the environmental competitiveness of the dairy value chain as compared to other animal-protein sources, though it still remains comparatively high. Another common approach to minimise waste in the dairy industry for the purpose of Circular Economy is the energy recovery through anaerobic digestion. Literature reports that it can lower the carbon footprint of cheese by 2% ([Gosalvitir et al., 2019](#)), showing that the by-product valorisation scenarios introduced in the present manuscript are promising alternatives to existing CE strategies from an environmental perspective.

In a hypothetical scenario of whey valorisation based entirely on renewable electricity production (solar), impacts as low as 4.1 kg CO<sub>2</sub> eq per kg protein might be achievable (Supplementary Materials), which would be comparable to some of the lowest impact plant-based protein sources.

[Nijdam et al. \(2012\)](#) as well as [Poore and Nemecek \(2018\)](#) report a land use in m<sup>2</sup>y per kg protein. Even though this comparison should be treated with care since the units are not identical, it is visible that whey products perform comparably well due to their low land use while the overall dairy value chain is impactful as compared to other protein sources.

#### c. Method limitations

The methodological approach for the LCA of this study was chosen for the purpose of understanding the implications of by-product valorisation in different scenarios on the value chain impacts. The results suggest that this function was met to a satisfying end. However, the data used for the study was limited to a single case study and experimental activities at pilot scale. Estimations and assumptions had to be made whenever data was not available, which led to a large sensitivity of the results as presented in the Supplementary Materials. These sensitivities did not show effects on the overall conclusion that by-product valorisation at high quality lowers the relative environmental impacts of the dairy value chain. Nonetheless, more data needs to be collected in case studies and analysed in order to verify and improve the robustness of the results.

#### d. Implications and outlook

Currently, milk production in Italy almost entirely supplies the cheese production ([CLAL, 2022a](#)) and therefore depends on the cheese market. Hence, the resources invested into producing milk are invested independently of whether or not whey is valorised. Thus, valorising whey at high quality and for comparably little resources and impacts

will mean that the milk production resources are used more efficiently. This is true even though the investigated valorisation scenarios require high amounts of electricity, as the most relevant impact categories are not as heavily influenced by the electricity usage.

Indeed, more valorisation is more beneficial from a value chain perspective since that way the high burden of livestock production is divided between more products. As might be expected, this is a risky interpretation since overall, the industry releases more emissions and utilizes more raw materials. Thus, if in consequence of valorisation more products are consumed, the global effect of the intervention is still negative. Only if consumption stays the same, hence other products are replaced, an overall reduction may be achieved. For this reason, it is important to investigate the materials that might be replaced and how the whey valorisation efforts compare to the production of the potentially replaced materials. Only if the resource investment and product output of valorisation is more efficient than that of the alternative materials, valorisation is truly desirable from an environmental perspective. Hence, a consequential LCA ([Depping et al., 2020](#); [Ekvall and Weidema, 2004](#)) should be performed to investigate the consequences of increased high-value whey valorisation. If other high-value products are replaced, advantageous results could be expected due to the avoided burdens of the replaced products. The reduced application of whey as feed and the resulting need for additional feed production would have to be accounted for. In addition, the other dimensions of sustainability should be considered in this context to avoid a burden shift.

## 5. Conclusion

The results of the study show a clear benefit of by-product valorisation for the purpose of Circular Economy with regard to the relative environmental impacts of the dairy value chain. Therefore, valorising whey at high quality can indeed be considered an example of sustainable intensification. Among the investigated scenarios, no clear favourite could be identified with the modelled decentralised valorisation scenario performing better with regard to the functional unit of value chain revenue and the whey powder valorisation scenario performing best for the functional unit of dry matter content. The choice for the most suitable approach will therefore depend on the priorities during implementation as well as the case study context considering the location, infrastructure, scale of production and investment options. Thus, the other dimensions of sustainability, i.e. economy and society, will need to be considered alongside the environmental dimension.

Comparing the results of the LCA to the impacts of proteins from other animal- and plant-based sources reported in literature, the whey-proteins valorised in the proposed model are produced with comparatively low impacts in the categories of global warming and land use even with regard to plant-based competitors. Accounting for the impacts of cheese and milk production in an allocation annuls these advantages, however it also reduces the impacts of the main product cheese notably by as much as 22% when choosing a protein-based allocation. The findings of this study should be verified in a consequential LCA in the future, considering a variety of potentially replaced products.

Despite the visible advantages of by-product valorisation, this approach can only be part of a larger set of efforts to reduce the environmental impacts of food production such as dietary changes and process efficiency increases. Nonetheless, as long as dairy products are consumed by humans, resource should be utilized as efficiently as possible.

## CRedit authorship contribution statement

**Eric Mehner:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Valentina Fantin:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Conceptualization. **Daniele Pizzichini:** Writing – review & editing, Validation,

Supervision, Resources, Methodology, Investigation, Conceptualization. **Mentore Vaccari:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The study was funded by the Lombardy Region as part of a joint UNIBS-ENEA doctorate (35th cycle). We want to thank Concooperative for their support of this work and Emanuele from Formaggi Boccea for his cooperation.

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2024.143958>.

### Data availability

Data will be made available on request.

### References

- Argenta, A.B., Scheer, A.D.P., 2020. Membrane separation processes applied to whey: a review. *Food Res. Int.* 36 (5), 499–528. <https://doi.org/10.1080/87559129.2019.1649694>.
- Athanasiadou, V., Klontza, E.E., Dimitriou-Christidis, P., Fountoulakis, M., Lekkas, D.F., 2023. Evaluation of *Arthrospira* (*Spirulina*) platensis growth on cheese whey in the context of circular economy. *Sustainable Chemistry and Pharmacy* 34, 101173. <https://doi.org/10.1016/j.scp.2023.101173>.
- Bacenetti, J., Bava, L., Schievano, A., Zucali, M., 2018. Whey protein concentrate (WPC) production: environmental impact assessment. *J. Food Eng.* 224, 139–147. <https://doi.org/10.1016/j.jfoodeng.2017.12.018>.
- Bacenetti, J., Bava, L., Zucali, M., Lovarelli, D., Sandrucci, A., Tamburini, A., Fiala, M., 2016. Anaerobic digestion and milking frequency as mitigation strategies of the environmental burden in the milk production system. *Sci. Total Environ.* 539, 450–459. <https://doi.org/10.1016/j.scitotenv.2015.09.015>.
- Barba, F.J., 2021. An integrated approach for the valorization of cheese whey. *Foods* 10 (3), 564. <https://doi.org/10.3390/foods10030564>.
- Bava, L., Bacenetti, J., Gison, G., Pellegrino, L., D'Incecco, P., Sandrucci, A., Tamburini, A., Fiala, M., Zucali, M., 2018. Impact assessment of traditional food manufacturing: the case of Grana Padano cheese. *Sci. Total Environ.* 626, 1200–1209. <https://doi.org/10.1016/j.scitotenv.2018.01.143>.
- Bencresciuto, G.F., Mandalà, C., Migliori, C.A., Giansante, L., Di Giacinto, L., Bardi, L., 2024. Microbial biotechnologies to produce biodiesel and biolubricants from dairy effluents. *Fermentation* 10 (6). <https://doi.org/10.3390/fermentation10060278>.
- Carvalho, P., Costa, C.E., Baptista, S.L., Domingues, L., 2021. Yeast cell factories for sustainable whey-to-ethanol valorisation towards a circular economy. *Biofuel Research Journal* 8 (4), 1529–1549. <https://doi.org/10.18331/BRJ2021.8.4.4>.
- Casallas-Ojeda, M., Cabeza, I., Sanchez, N., Caicedo-Concha, D.M., Astals, S., 2024. Cheese whey and dairy manure anaerobic co-digestion at psychrophilic conditions: technical and environmental evaluation. *Environ. Res.* 251, 118525. <https://doi.org/10.1016/j.envres.2024.118525>.
- Casallas-Ojeda, M., Torres-Guevara, L.E., Caicedo-Concha, D.M., Gómez, M.F., 2021. Opportunities for waste to energy in the milk production industry: perspectives for the circular economy. *Sustainability* 13 (22). <https://doi.org/10.3390/su132212892>.
- Cecchini, L., Torquati, B., Paffarini, C., Barbanera, M., Foschini, D., Chiorri, M., 2016. The milk supply chain in Italy's umbria region: environmental and economic sustainability. *Sustainability* 8 (8). <https://doi.org/10.3390/su8080728>.
- CLAL, 2022a. Italia: settore lattiero caseario. [www.clal.it/?section=quadro\\_europa&country=IT](http://www.clal.it/?section=quadro_europa&country=IT). (Accessed 12 January 2023), 2023.
- CLAL, 2022b. Lactose, US. [www.clal.it/en/index.php?section=lattosio](http://www.clal.it/en/index.php?section=lattosio). (Accessed 23 January 2023), 2023.
- Colombini, S., Zucali, M., Rapetti, L., Crovetto, G.M., Sandrucci, A., Bava, L., 2015. Substitution of corn silage with sorghum silages in lactating cow diets: in vivo methane emission and global warming potential of milk production. *Agric. Syst.* 136, 106–113. <https://doi.org/10.1016/j.agry.2015.02.006>.
- Costa, C., Azola, N.G., Coelho, L., Freixo, R., Batista, P., Pintado, M., 2021. Proteins derived from the dairy losses and by-products as raw materials for non-food applications. *Foods* 10 (1), 135. <https://doi.org/10.3390/foods10010135>.
- Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., De Marchi, M., 2015. The environmental impact of cow milk in the northeast of Italy. *Poljoprivreda/Agriculture* 21 (1 Suppl. ment), 105–108. <https://doi.org/10.18047/poljo.21.1.sup.24>.
- Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., De Marchi, M., 2017a. Environmental life cycle assessment of Italian mozzarella cheese: hotspots and improvement opportunities. *J. Dairy Sci.* 100 (10), 7933–7952. <https://doi.org/10.3168/jds.2016-12396>.
- Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., De Marchi, M., 2017b. The environmental analysis of asiago PDO cheese: a case study from farm gate-to-plant gate. *Ital. J. Anim. Sci.* 17 (1), 250–262. <https://doi.org/10.1080/1828051x.2017.1344936>.
- Depping, V., Grunow, M., Kulozik, U., 2020. A methodological framework for comparing fractionated and non-fractionated products in life cycle assessments: the case of milk concentrates. *J. Clean. Prod.* 257, 120478. <https://doi.org/10.1016/j.jclepro.2020.120478>.
- EC, 2020. *EU Agricultural Outlook for Markets, Income and Environment, 2020-2030*. European Commission, DG Agriculture and Rural Development, Analysis and Outlook Unit, Brussels.
- EC, 2020. In: Commission, E. (Ed.), *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*. European Commission, Brussels.
- EDA, 2018. *Product Environmental Footprint Category Rules for Dairy Products*. European Dairy Association, Brussels.
- EEA, 2022. *Greenhouse Gas Emissions by Sector Source, 10.06.2022 ed.* European Environment Agency. Eurostat.
- Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. *Int. J. Life Cycle Assess.* 9 (3), 161–171. <https://doi.org/10.1007/BF02994190>.
- Famiglietti, J., Guerci, M., Proserpio, C., Ravaglia, P., Motta, M., 2019. Development and testing of the product environmental footprint milk tool: a comprehensive LCA tool for dairy products. *Sci. Total Environ.* 648, 1614–1626. <https://doi.org/10.1016/j.scitotenv.2018.08.142>.
- Forleo, M.B., Palmieri, N., Salimei, E., 2018. The eco-efficiency of the dairy cheese chain: an Italian case study. *Ital. J. Food Sci.* 30 (2). <https://doi.org/10.14674/IJFS-1077>.
- Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., 2013. Sustainable intensification in agriculture: premises and policies. *Science* 341 (6141), 33–34. <https://doi.org/10.1126/science.123448>.
- Ghisellini, P., Protano, G., Viglia, S., Gaworski, M., Setti, M., Ulgiati, S., 2014. Integrated agricultural and dairy production within a circular economy framework. A comparison of Italian and Polish farming systems. *J. Environ. Account. Manag.* 2, 367–384. <https://doi.org/10.5890/JEAM.2014.10.007>.
- Gison, G., Ferrero, F., Bava, L., Borreani, G., Prà, A.D., Pacchioli, M.T., Sandrucci, A., Zucali, M., Tabacco, E., 2020. Forage systems and sustainability of milk production: feed efficiency, environmental impacts and soil carbon stocks. *J. Clean. Prod.* 260. <https://doi.org/10.1016/j.jclepro.2020.121012>.
- Giulianetti de Almeida, M.P., Mockaitis, G., Weissbrodt, D.G., 2023. Got whey? Sustainability endpoints for the dairy industry through resource biorecovery. *Fermentation* 9 (10). <https://doi.org/10.3390/fermentation9100897>.
- Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. *Phil. Trans. Biol. Sci.* 369 (1639), 20120273. <https://doi.org/10.1098/rstb.2012.0273>.
- González-García, S., Gullón, B., Moreira, M.T., 2018. Environmental assessment of biorefinery processes for the valorization of lignocellulosic wastes into oligosaccharides. *J. Clean. Prod.* 172, 4066–4073. <https://doi.org/10.1016/j.jclepro.2017.02.164>.
- Gosalvitr, P., Cuellar-Franca, R., Smith, R., Azapagic, A., 2019. Energy demand and carbon footprint of cheddar cheese with energy recovery from cheese whey. *Energy Proc.* 161, 10–16. <https://doi.org/10.1016/j.egypro.2019.02.052>.
- Guerci, M., Bava, L., Zucali, M., Tamburini, A., Sandrucci, A., 2014. Effect of summer grazing on carbon footprint of milk in Italian Alps: a sensitivity approach. *J. Clean. Prod.* 73, 236–244. <https://doi.org/10.1016/j.jclepro.2013.11.021>.
- Herbstreit, S.M., Fathel, S.L., Reinford, B., Richard, T.L., 2023. Waste to worth: a case study of the biogas circular economy in Pennsylvania. *Journal of the ASABE* 66 (3), 771–787. <https://doi.org/10.13031/ja.14889>.
- Hietala, S., Smith, L., Knudsen, M.T., Kurppa, S., Padel, S., Hermansen, J.E., 2014. Carbon footprints of organic dairying in six European countries—real farm data analysis. *Organic Agriculture* 5 (2), 91–100. <https://doi.org/10.1007/s13165-014-0084-0>.
- Hoffman, J.R., Falvo, M.J., 2004. Protein - which is best? *J. Sports Sci. Med.* 118–130, 2004/09/01.
- Huijbregts, M.A., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment* 22 (2), 138–147. <https://doi.org/10.1007/s11367-016-1246-y>.
- IDF, 2015. *A Common Carbon Footprint Approach for the Dairy Sector*. International Dairy Federation, Brussels.
- ISO, 2006a. 14040, *Environmental Management - Life Cycle Assessment - Principles and Framework*. International Organization for Standardization, Geneva.
- ISO, 2006b. 14044, *Environmental Management - Life Cycle Assessment - Requirements and Guidelines*. International Organization for Standardization, Geneva.
- ISO, 2020a. 14040:2006/Amd 1:2020, *Environmental Management - Life Cycle Assessment - Principles and Framework*. International Organization for Standardization, Geneva.

- ISO, 2020b. 14044:2006/Amd 2:2020, Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization, Geneva.
- Kaur, N., Sharma, P., Jaimmi, S., Kehinde, B.A., Kaur, S., 2019. Recent developments in purification techniques and industrial applications for whey valorization: a review. *Chem. Eng. Commun.* 207 (1), 123–138. <https://doi.org/10.1080/00986445.2019.1573169>.
- Lappa, I.K., Zachrimanidou, V., Papadaki, A., Stamatiou, A., Ladakis, D., Eriotou, E., Kopsahelis, N., 2021. A comprehensive bioprocessing approach to foster cheese whey valorization: on-site  $\beta$ -galactosidase secretion for lactose hydrolysis and sequential bacterial cellulose production. *Fermentation* 7 (3), 184. <https://doi.org/10.3390/fermentation7030184>.
- Lavelli, V., Beccalli, M.P., 2022. 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. *Trends Food Sci. Technol.* 126, 86–98. <https://doi.org/10.1016/j.tifs.2022.06.013>.
- Macedo, A., Azedo, D., Duarte, E., Pereira, C., 2021. Valorization of goat cheese whey through an integrated process of ultrafiltration and nanofiltration. *Membranes* 11 (7), 477. <https://doi.org/10.3390/membranes11070477>.
- Meyers, L.D., Hellwig, J.P., Otten, J.J., 2006. *Dietary Reference Intakes: the Essential Guide to Nutrient Requirements*. National Academies Press.
- Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Pol.* 37 (6), 760–770. <https://doi.org/10.1016/j.foodpol.2012.08.002>.
- Orrego, D., Klotz-Ceberio, B., 2022. Enzymatic synthesis of galacto-oligosaccharides from concentrated sweet whey permeate and its application in a dairy product. *Appl. Sci.* 12 (20). <https://doi.org/10.3390/app122010229>.
- Palmieri, N., Forleo, M.B., Salimei, E., 2017. Environmental impacts of a dairy cheese chain including whey feeding: an Italian case study. *J. Clean. Prod.* 140, 881–889. <https://doi.org/10.1016/j.jclepro.2016.06.185>.
- Pereira, L.G., Chagas, M.F., Dias, M.O.S., Cavalett, O., Bonomi, A., 2015. Life cycle assessment of butanol production in sugarcane biorefineries in Brazil. *J. Clean. Prod.* 96, 557–568. <https://doi.org/10.1016/j.jclepro.2014.01.059>.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392), 987–992. <https://doi.org/10.1126/science.aaq0216>.
- Pretty, J., Bharucha, Z.P., 2014. Sustainable intensification in agricultural systems. *Annals of botany* 114 (8), 1571–1596. <https://doi.org/10.1093/aob/mcu205>.
- Rico-Rodríguez, F., Strani, L., Grassi, S., Lancheros, R., Serrato, J.C., Casiraghi, E., 2021. Study of galactooligosaccharides production from dairy waste by FTIR and chemometrics as process analytical technology. *Food Bioprod. Process.* 126, 113–120. <https://doi.org/10.1016/j.fbp.2020.12.009>.
- Sandoval, M.A., Salazar, R., 2021. Electrochemical treatment of slaughterhouse and dairy wastewater: toward making a sustainable process. *Curr. Opin. Electrochem.* 26, 100662. <https://doi.org/10.1016/j.coelec.2020.100662>.
- Stanchev, P., Vasilaki, V., Egas, D., Colon, J., Ponsá, S., Katsou, E., 2020. Multilevel environmental assessment of the anaerobic treatment of dairy processing effluents in the context of circular economy. *J. Clean. Prod.* 261. <https://doi.org/10.1016/j.jclepro.2020.121139>.
- Tsermoula, P., Khakimov, B., Nielsen, J.H., Engelsen, S.B., 2021. Whey-The waste-stream that became more valuable than the food product. *Trends Food Sci. Technol.* 118, 230–241. <https://doi.org/10.1016/j.tifs.2021.08.025>.
- Tukker, A., Huppes, G., Guinée, J.B., Heijungs, R., Koning, A.d., Oers, L.v., Suh, S., Geerken, T., Holderbeke, M.v., Jansen, B., Nielsen, P., 2006. Environmental Impact of Products (EIPRO) Analysis of the life cycle environmental impacts related to the final consumption of the EU25. *Tech. Rep. Institute of Environmental Sciences (CML)*.
- Uvarova, I., Atstaja, D., Grinbergs, U., Petersons, J., Gegere-Zetterstroma, A., Kraze, S., 2020. Transition to the circular economy and new circular business models – an in-depth study of the whey recycling. *IOP Conf. Ser. Earth Environ. Sci.* 578 (1), 012019. <https://doi.org/10.1088/1755-1315/578/1/012019>.
- Weidema, B.P., Bauer, C., Hirschier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., Wernet, G., 2013. Overview and Methodology: Data Quality Guideline for the Ecoinvent Database Version 3. *Swiss Centre for Life Cycle Inventories, Ecoinvent*.
- Yadav, J.S.S., Yan, S., Pilli, S., Kumar, L., Tyagi, R.D., Surampalli, R.Y., 2015. Cheese whey: a potential resource to transform into bioprotein, functional/nutritional proteins and bioactive peptides. *Biotechnol. Adv.* 33 (6), 756–774. <https://doi.org/10.1016/j.biotechadv.2015.07.002>. Part 1.
- Zhang, J., Wang, M., Yin, C., Dogot, T., 2021. The potential of dairy manure and sewage management pathways towards a circular economy: a meta-analysis from the life cycle perspective. *Sci. Total Environ.* 779, 146396. <https://doi.org/10.1016/j.scitotenv.2021.146396>.
- Zucali, M., Bacenetti, J., Tamburini, A., Nonini, L., Sandrucci, A., Bava, L., 2018. Environmental impact assessment of different cropping systems of home-grown feed for milk production. *J. Clean. Prod.* 172, 3734–3746. <https://doi.org/10.1016/j.jclepro.2017.07.048>.