Whey protein concentrate (WPC) production: Environmental impact assessment

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Abstract

Cheese-making is a process that produces multiple coproducts, of which whey is the most abundant in terms of volume. It is often considered a waste product, but whey is rich in lactose, proteins and fats. The aim of the study was to evaluate the environmental impact of the production of whey protein concentrate (WPC) with an ultrafiltration process throughout a life cycle approach. The environmental impacts of three WPCs, characterized by different protein concentrations (WPC35, WPC60, WPC80), were estimated. A scenario analysis was performed to understand the mitigation effect of the pre-concentration process carried out in a pretreatment plant to obtain whey with a dry matter content of 20%. Two sensitivity analyses were performed: the first changing the transport distance of whey, the second using a different allocation method.

Transportation of the whey was one of the main hotspots in the life cycle assessment performed (28–70%); electricity use accounted for 18–20% of the impact. The alternative scenario, that involves the pre-concentration of whey, obtained a reduction of the impacts from 0.9% to 14.3%. The pre-concentration of whey in a pretreatment plant closer to the cheese factory reduces the environmental burden of the whole process. This occurs even if the energy consumption for pre-concentration increases due to the use of smaller and less efficient devices.

Keywords: cheese-making, coproducts, dairy production processes, environmental assessment, protein, reverse osmosis

1 Introduction

Whey is a coproduct of cheese-making and casein manufacture in the dairy industry (Smithers, 2008) and is considered a waste stream. Whey is rich in lactose (0.18–60 kg m^3), proteins (1.4–33.5 kg/m^3) and fats (0.08–10.58 kg/m^3), and this organic matter is around 99% biodegradable (Madureira et al., 2010; Prazeres et al., 2012). The volume of effluents produced in the cheese manufacturing industry has increased with the increase in cheese production (Prazeres et al., 2012), and its proper disposal has become a compelling issue.

Recently, the introduction in many countries of restrictive legislation regarding food waste treatment and the possibility of taking advantage of the interesting properties of whey components have contributed to the consideration of whey as a valuable and prized raw material instead of a waste (Smithers, 2008). Beneficial new uses for whey are possible from new technologies such as microfiltration, ultrafiltration and reverse osmosis that make separation and concentration of the whey protein component highly efficient. In particular, ultrafiltration is a pressure-driven membrane separation process, largely utilized in the dairy industry (Lujàn-Facundo et al., 2017), which is successfully used to recover whey proteins (whey protein concentrate, WPC) and separate smaller compounds in the permeate stream such as lactose, vitamins and minerals (Rebouillat and Ortega-Requena, 2015), while ion exchange and reverse osmosis are principally used to purify and concentrate lactose (Prazeres et al., 2012).

Whey proteins account for only about 20% (weight/weight) of the whole milk protein inventory, whereas caseins account for most of it. The major components among whey proteins are β-lactoglobulin, a-lactalbumin, bovine serum albumin and immunoglobulin, representing 50%, 20%, 10% and 10% of the whey fraction, respectively. Besides these, whey also contains numerous minor proteins such as lactoferrin, lactoperoxidase, proteose peptone, osteopontin and lisozyme (Mollea et al., 2013).

Whey proteins are characterized by interesting functional properties due to their physical, chemical and structural features. The most important property is the ability to form gels capable of holding water, lipids and other components that act as emulsifiers providing textural properties. For this property, whey proteins are included in processed meat and dairy and bakery products. Another aspect is its foaming property, which mainly depends on the degree of protein denaturation (Rebouillat and Ortega-Requena, 2015).

These abilities are also influenced by the grade of protein concentration in the WPC. For example, WPC containing 34–35% protein (WPC35) has good emulsification properties, is highly soluble and has a mild dairy flavor. This product is used in the manufacture of yogurt, processed cheese and infant formulae; in various bakery applications and in stews and sauces. WPC with about 80% protein (WPC80) has lower carbohydrate content, as compared to WPC35, and is characterized by good gelation, emulsification and foaming properties. WPC80 is an excellent ingredient for sports nutrition and weight management products as well as for meat products, thanks to its high gel strength and good water-binding properties (Rebouillat and Ortega-Requena, 2015).

Ultrafiltration represents an excellent separation process compared to other techniques: it allows simultaneous cost reduction and improvement of nutritional/functional protein properties (Lujàn-Facundo et al., 2017). However, from an environmental point of view, ultrafiltration (and also reverse osmosis) presents two important constraints: the use of high energy inputs for the pressure against membranes and the utilization of large amounts of cleaning agents for removing fouling and maintaining the membranes. The use of cleaning agents can cause the degradation of the membrane material and generate effluents possibly damaging to the environment. Moreover, the reverse osmosis could have limitations from an economic point of view due to the need for high pressures and the high cost of membrane.

Another problem regarding whey treatment is related to the spatial collocation of the industrial process and as a consequence the distance between the cheese factory where the whey is produced and the concentration plant. The best solution is to produce WPC directly in the cheese factory to avoid the transport of great volumes of diluted whey, but as previously explained, whey concentration is a complex operation that can only be performed in specialized companies able to cushion the high production costs. A possible alternative is to pre-concentrate the whey directly in the cheese factory, then transport the pre-concentrated whey to an ultrafiltration plant. Considering that in Italy there are only a few ultrafiltration plants, this last solution is adopted by many dairy factories in Italy.

Starting from this consideration, it is important to evaluate the environmental benefits arising from the valorization of liquid whey. This is particularly important in Italy where the production of liquid whey from cheese-making was 9,467,004 tons in 2014 (Clal, 2017).

A significant and widely appreciated approach to evaluate the environmental impact of a process or product is the Life Cycle Assessment (LCA), which considers the impact throughout the entire life cycle. LCA is largely used in the dairy sector, in particular for the primary phase (Roy et al., 2008; Biswas and Naude, 2016), while few studies have considered cheese production. In studies such as van Middelar et al. (2011) for a semi hard cheese in the Netherlands, Kristensen et al. (2014) in Denmark and Gonzalez-Garcia et al. (2013a, 2013b) in Spain, the liquid whey obtained from the cheese-making process was not considered ("surplus approach" in which all the environmental load is associated with the main product—the cheese), or it was considered a by-product whose impact was assessed by allocation. In other studies (Kristensen et al., 2014; Palmieri et al., 2017), liquid whey was regarded as feed and included in an alternative scenario at the dairy farm level. Only the study of Kim et al. (2013) took into account the environmental impact of drying whey obtained from mozzarella and cheddar production. Omont et al. (2012), using the LCA approach, underlined the differences in terms of the environmental impacts of two industrial processes to separate purified whey protein from whey (one method based on chromatography separation and one based on microfiltration).

In the literature, many studies describe different and innovative methods to concentrate liquid whey (Makardij et al., 1999; Rinaldoni et al., 2009; Walmsley et al., 2013; Méthot-Hains et al., 2016), but there is a lack of information about the generated environmental impact. The aim of this study is to evaluate, using a life cycle approach, the environmental impact of the production of WPC with an ultrafiltration process. In order to understand the mitigation effect of the pre-concentration process of whey in a pretreatment plant, an alternative scenario was also considered. Finally, two sensitivity analyses were performed: the first changing the transport distance of whey, the second using a different allocation method.

2 Materials and methods

2.1 System description and alternative scenarios

The production systems of WPC can be divided into two subsystems.

- Subsystem 1 (SS1): This subsystem involves the transport of whey (characterized by a dry matter [DM] content of 6%) to the factory and its pretreatment. More in detail, the whey is treated (bactofugation, skimming and pasteurization) and pre-concentrated (by means of reverse osmosis) until it reaches a DM content of 20%.
- Subsystem 2 (SS2): The pre-concentrated whey is further treated (bactofugation, skimming and pasteurization) and ultrafiltrated to produce WPC with a DM content of 30%. Although all with the same dry matter content, three different WPCs are produced: WPC35 (35% protein content on DM basis), WPC60 (60% protein content on DM basis) and WPC 80 (80% protein content on DM basis).

Two scenarios were considered (**Figure 1**).

- Baseline scenario (BS): Whey with a dry matter content of 6% is transported from the cheese factories to the WPC production factory. In this scenario, all operations needed to produce the WPCs are carried out at the WPC factory.
- Alternative scenario (AS): The pre-concentration of whey is carried out close to the cheese factory in a pre-treatment plant; therefore, only whey with a dry matter content of 20% is transported to the WPC factory.

Figure 1 – Around here

2.2 Functional unit and system boundary

The functional unit (FU) provides a reference unit for which the inventory data are normalized (ISO 14040, 2006). In this study, 1 ton of protein in the different WPCs was selected as the FU.

In this study, a "cradle-to-industry-gate" perspective was applied. The core system is the process of concentrating whey into WPC; the upstream system involves the whey production while the downstream system includes the delivery of the produced WPC to the factory in which it is completely dried. The distribution as well as the final drying of the WPC were excluded from the system boundaries as they are equal in the two scenarios (BS and AS).

The system boundary considers the life cycle of the following processes: raw material extraction (e.g., fossil fuels and minerals), consumption of whey (6% of dry matter), heat, electricity, diesel fuel, water and cleaning agents, transport of whey to the WPC factory as well as the emissions into water and air. The impact of capital goods (e.g. infrastructures of the cheese-factory and to the whey concentration plant) was not considered according to their minor contribution proved by previous LCA studies related to food products (Fusi et al., 2014; Siracusa et al., 2014; Notarnicola et al., 2015; Bacenetti et al., 2015; Garofalo et al., 2017; De Marco and Iannone, 2017).

2.3 Inventory analysis

For the BS, all the activities performed in SS1 and SS2 were identified by means of interviews and surveys carried out at the WPC factory as well as in the cheese-making industries.

More in detail, all the information regarding the annual volume of processed whey, produced WPC and coproducts as well as all the consumption of electricity, natural gas and cleaning agents was collected by means of questionnaire and a survey at the factory. **Table 1** summarizes the main inventory data for SS1 and SS2 while in **Table 2** the specific energy consumption for the different WPC is reported. Over the considered year, the WPC factory produced 10,532, 6,629 and 3,923 t of WPC35, WPC60 and WPC80, respectively, corresponding to a whey protein content of 1,080, 1,193 and 942 t, respectively.

Table 1 around here

Table 2 around here

Concerning the SS2 and, in particular, ultrafiltration, the rejection coefficient, the whey protein recovery efficiency as well as the main inputs and outputs for the different WPCs are reported in **Table 3**.

The rejection coefficient was calculated as

$$\mathrm{RC} = 1 - \left(\frac{C_p}{C_R}\right)$$

where:

RC = rejection coefficient, which varies from 0 (the membrane is completely permeable) to 1 (the membrane is completely impermeable) and indicates the share of protein retained by the membrane;

C_P = concentration of the protein in permeate;

C_R = concentration of the protein in WPC.

Whey protein recovery efficiency was calculated as

$$\mathrm{WPRR} = \left(\frac{Q_P \text{ x } C_P}{Q_F \text{ x } C_F}\right)$$

where:

WPRR = whey protein recovery efficiency indicates the share of protein retained by the membrane;

Q_P = protein in the WPC flow in output from the ultrafiltration (kg/h);

Q_F = protein in whey at 20% dry matter flow in input to ultrafiltration (kg/h);

C_F = concentration of the protein in whey at 20% of dry matter (kg/h).

Table 3 around here

The whey (6% DM content and 12.5 % protein on DM) was collected in a cheese factory producing Grana Padano PDO cheese, a long-ripened cheese from skim milk. This cheese represents the most important PDO cheese in northern Italy (183,000 t in 2015), and from its production process comes the main proportion of the processed whey at the WPC factory. The products of the cheese factory were cheese, whey, cream, butter and buttermilk. The whey was considered a coproduct of cheese-making; the impact related to its production was assessed based on the data reported by Bava et al. (2016); according to the PCR for dairy products (EPD, 2016) dry matter content allocation was considered.

Considering the location of the whey processing plant and the area of Grana Padano PDO production, for the BS, an average transport distance of 150 km was considered for the whey at 6% DM.

Inventory data characterizing the SS1, in the AS, were collected by means of surveys and interviews in a plant that processes yearly about 40,000–60,000 t of whey coming from Grana Padano PDO cheese plants. The transport distance between the cheese factory and the pre-concentration plant and between this last and the WPC factory were assumed to be equal to 20 and 130 km, respectively. Regarding the energy consumption for pretreatment, no reliable information was collected during the surveys due to the impossibility of separating the electricity and heat consumption among the different processes. According to Ramirez et al. (2006), Giacone and Mancò (2012), Augustin et al. (2014) and Méthot-Hains et al. (2016), being bactofugation, skimming and pasteurization were performed using smaller devices than in BS, an increase of energy consumption ranging from 5 to 20% is expectable. Due to the lack of primary data, in this scenario, a 20% increase in energy consumption for the treatment of 6% DM whey was considered.

Concerning the transport of whey, empty return (from the WPC factory to the cheese-making factory in BS and to the pre-processing plant in AS) was taken into account.

Background data for the production of electricity, natural gas and cleaning agents as well as for the transport and wastewater treatment were retrieved from the Ecoinvent database v.3 (Weidema et al., 2013).

2.4 Allocation

During whey processing at the WPC factory, besides the three WPCs, a permeated stream is produced. The multifunctionality issue was solved by allocation. According to the ISO 14040 (ISO, 2006a), allocation is the "partitioning of the input and output flows of a product system between its main product and co-products" and allows one to calculate how much of the process impacts should be assigned to each product.

In this study, physical allocation based on the DM content of the different products and coproducts was applied. More in detail, allocation was performed taking into account the DM content of

- cheese, whey and other cheese coproducts such as buttermilk and butter at the cheese factory;
- the different WPCs and the permeate at the WPC factory.

Therefore, at the cheese factory, 46.3% of the impact is attributed to the cheese, 37.9% to the whey, 13.0% to the cream, 1.7% to the butter and 1.0% to the buttercream, while at the WPC factory, the allocation factor is 68.5% for WPC35, 69.4% for WPC60 and 67.3% for WPC80.

2.5 Impact assessment

Among the steps defined within the life cycle impact assessment phase of the standardized LCA methodology, only classification and characterization stages were undertaken (ISO 14040, 2006). The characterization factors reported by the ILCD method were used (Wolf et al., 2012). The following nine impact potentials were evaluated according to the selected method: climate change (CC); ozone depletion (OD); particulate matter (PM); photochemical oxidant formation (POF); acidification (TA); freshwater eutrophication (FE); terrestrial eutrophication (TE); marine eutrophication (ME) and mineral, fossil and renewable resource depletion (MFRD).

2.5.1 Sensitivity analysis

A sensitivity analysis was carried out in order to test the robustness of the results. To this purpose, a set of parameters was changed, and the influence of the change on the environmental results was evaluated. The aspects that were taken into account to run the sensitivity analysis were as follows.

i) Transport distance of the whey: More in detail, in both scenarios a halving and a doubling of the distance to the WPC factory was considered. In AS, the whey transport distance between cheese plant and preprocessing plant was not varied.

ii) Allocation method: In this regard an economic allocation was considered rather than a physical one based on DM content. The economic allocation is widely included in LCA studies about cheese production (Berlin, 2002; González-García et al., 2013a, 2013b). Therefore, the environmental burden among cheese, cream, butter, buttermilk and whey at the cheese factory and between WPC and permeate at the WPC factory was divided considering the products' economic values. More in detail, at the cheese factory, the allocation factor[1] is equal to 76.2%, 4.8%, 17.3%, 1.3% and 0.4% for the produced cheese, whey, cream, butter and buttermilk, respectively. Concerning WPC and permeate, considering the selling prices of the different WPCs (1,445, 2,670 and 3,835 €/t for WPC35, WPC60 and WPC80, respectively) and permeate (130 €/t), the allocation factor is equal to 78.25% for WPC35, 80.83% for WPC60 and 81.80% for WPC80.

3 Results and discussion

3.1 Baseline scenario

The hotspots analysis for the three WPCs highlights that the impact due to whey consumption is by far the main factor for environmental impact, ranging from 61% to 97% of the total score. The impact categories in which whey consumption has a higher incidence are TA and ME (>95%) while MFRD is at about 60% (**Table 4**). For the latter, the impact of whey is reduced because it is higher the impact related to the energy consumption at the WPC factory during pretreatment and ultrafiltration.

Table 4– around here

Figures 2 and 3 show the hotspots for WPC production, excluding the impact related to the whey.

Figures 2, 3, 4 – Around here

Excluding whey production, the transport of the whey from cheese factory to WPC factory is the main factor for most of the evaluated impact categories. More in detail,

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[1] The allocation factor indicates the proportion of the environmental impact that is allocated to the different products of the evaluated production system.

its role ranges from 28% to 30% in ME (mainly due to the emissions of ammonia in the air and nitrates in the water) to 69–71% in POF (mainly due to the emissions of nitrogen oxides, NMVOC and sulfur dioxide). Compared to heat, electricity consumption is responsible for a higher impact: >20% for CC, OD, PM, TA and FE and about 15% for POF, TE and ME. Among the different processes in which electricity is consumed, reverse osmosis has the most impact. On the contrary, the impact of heat consumption is negligible for all the evaluated impact categories except CC (10–11%). Cleaning agents, above all the ones consumed during SS2, are responsible for about half of OD (mainly due to sodium hydroxide production and the consumption of fossil fuels for their production) and 40% of FE (mainly due to electricity consumption during the production process).

With regard to the environmental hotspots, only small differences can be highlighted among the three WPCs; this should not be surprising. In fact, although different amounts of whey are needed for the production of the three WPCs (from 5.07 t of whey/t of WPC35 to 12.35 t of whey/t of WPC80), the specific energy consumption is also higher for the WPCs with higher proportions of protein content on a DM basis. **Table 5** reports the comparison of the different WPCs considering also the impact of whey. As expected, the impact goes up (from 2 to 7%) with the increase in protein concentration.

Table 5– around here

3.2 Alternative scenario

For the AS, which involves the pre-concentration of whey at the cheese-making plant, **Table 6** reports the environmental hotspots of the three different WPCs. For all the WPCs, the reduction of the amount of whey transported, achieved thanks to pre-concentrating, involves an impact reduction for all the evaluated impact categories. This reduction ranges from 0.9% to 14.3% and is higher for the impact categories such as

MFRD (about 14%) and POF (about 8%) that are more affected by transport and, in particular, by diesel consumption and exhaust gases emission. Even if the treatment carried out at the pre-concentration plant in smaller devices involves higher energy consumption for skimming, bactofugation and pasteurization, the reduction of the transport completely offsets the higher energy consumption and results in an impact reduction ranging from 8% to 20%.

Table 6– around here

3.3 Sensitivity analysis results

The results of the sensitivity analysis carried out considering the variation (halving and doubling) of the transport distance to the WPC factory are shown in **Table 7** while the impact variation related to the use of a different allocation method is reported in **Table 8**.

Table 7 – around here

The variation of the whey transport distance has a different impact on the environmental results in the two scenarios. In BS, the variation of the distance involves higher consequences, with respect to AS. The impact variation related to the halving of the distance ranges from -0.8% for TA and -11.8% for MFRD in BS and from -0.2% for TA and -3.6% for MFRD in AS. When the distance is doubled, the impact increases from +1.5% (TE) to +23.7% (MFRD) in BS and from +0.4% (TE) to +7.2% (MFRD) in AS. For both scenarios, for 7 of the 9 evaluated impact categories (CC, OD, PM, TA, TE, FE, ME), impact variations are small, while not negligible for POF and MFRD (the most affected by the consumption of fuel and the engine exhaust gas emissions that occur during transport).

Table 8 – around here

As expected, the use of economic allocation instead of DM deeply affects the environmental results for the different WPCs; more in detail, it involves an impact variation ranging from -59% to -88%. This variation is related to the different allocation factors between the WPCs and the permeate at the WPC factory but, above all, to the higher impact attributed to the cheese during cheese-making instead of the whey. Unlike the allocation based on dry matter content (that allocates about 40% of the impact related to cheese production to the whey), the economic allocation attributes only 4.8% of cheese-making impact to the whey. Consequently, whey consumption is the main hotspot for WPC production when economic allocation is performed; also, the WPC impact decreases.

In conclusion, the outcomes of the sensitivity analysis show how the environmental results are only slightly affected by the transport distance of whey. On the contrary, the choice of the allocation method plays a relevant role in the environmental profile of the different WPCs; in fact, if economic allocation is used, the environmental impact is reduced up to 88%.

4 Conclusions

Cheese-making involves the production of a considerable amount of whey. Due to its low DM content, whey management can be challenging above all for big cheese-making plants where the produced volume is remarkable. Considering that the use of whey as feed or as a feedstock for biogas production is not profitable, the whey concentration to produce a product with a higher value is an attractive solution. In this study, the environmental impacts related to whey concentration were assessed using the LCA approach and considering real data collected in the biggest Italian cheese-making plant. The achieved results show how whey consumption is the main factor responsible for the WPC impact, followed by whey transport and energy consumption. The pre-concentration of whey in pretreatment plants closer to the cheese factory reduces the amount of whey transported for long distances and, consequently, reduces the environmental burdens of the whole process. This occurs even if the energy consumption for pre-concentration increases due to the use of smaller and less efficient devices.

Up to now, no studies quantified the environmental impacts related to WPC production as well as the impact reduction related to a different logistical organization of the supply chain of the WPC factories. The outcomes of this study are the starting point for further studies on the WPCs used as food components (e.g., production of baby food, substitution of fat during the production of dietetic cheese).

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TABLES

Table 1 – Main inventory data for baseline scenario (BS)

Input	**Subsystem**	**Amount**
Whey (6%)	1	409,610 t
Electricity	1	2,553 MWh for whey treatment and reverse osmosis
Natural gas	1	502,000 m^3 for whey treatment and reverse osmosis
Electricity	2	981,517 MWh for whey treatment 1,370 MWh for ultrafiltration
Natural gas	2	370,000 m^3 for whey treatment 52,000 m^3 for ultrafiltration
Whey (20%)	2	226,882 t (from subsystem 1)
Cleaning agent	2	
Electricity	1 & 2	1,320 MWh for refrigeration 1,231 MWh for general consumption 298,000 kWh water well
WPC35	2	10,532 t of dry matter
WPC60	2	6,629 t of dry matter
WPC80	2	3,923 t of dry matter
Permeated	2	23,860 t of dry matter

Table 2 – Specific energy consumption for the different WPCs in BS

Energy source	**Unit**	**WPC35**	**WPC60**	**WPC80**
Electricity SS1	$MWh/t_{\text{of protein}}$	0.70	0.87	0.82
Natural Gas SS1	$m^3/\ t_{\text{of protein}}$	152.36	171.36	161.95
Electricity pre-treatment SS2	$MWh/\ t_{\text{of protein}}$	0.298	0.303	0.317
Natural Gas pre-treatment SS2	$m^3/\ t_{\text{of protein}}$	112.30	114.27	119.37
Electricity ultrafiltration SS2	$MWh/\ t_{\text{of protein}}$	0.416	0.423	0.442
Natural gas ultrafiltration SS2	$m^3/\ t_{\text{of protein}}$	15.78	16.06	16.78

Table 3 – Input and output of the ultrafiltration carried out in SS2

WPC	**Whey (20%) consumption**	**Water consumption**	**Permeated t/t_{WPC}**	**Rejection Coefficient**	**Whey Protein Recovery Efficiency**

	t/t_{WPC}	t/t_{WPC}	t/t_{WPC}	%	%
WPC35	5.07	0	4.08	99.49	97.9
WPC60	8.86	1.25	9.12	99.65	96.5
WPC80	12.35	3.12	14.46	99.60	94.6

Table 4 – Relative contribution of whey and the other production factors and processes.

Impact Category	**Whey consumption**			**Energy, Cleaning agents & whey transport**		
	WPC35	**WPC60**	**WPC80**	**WPC35**	**WPC60**	**WPC80**
CC	88.7%	88.7%	88.7%	11.3%	11.3%	11.3%
OD	86.1%	86.0%	86.3%	13.9%	14.0%	13.7%
PM	91.7%	91.6%	91.7%	8.3%	8.4%	8.3%
POF	80.6%	80.5%	80.6%	19.4%	19.5%	19.4%
TA	96.5%	96.5%	96.6%	3.5%	3.5%	3.4%
TE	97.7%	97.7%	97.7%	2.3%	2.3%	2.3%
FE	80.0%	79.8%	80.1%	20.0%	20.2%	19.9%
ME	97.3%	97.3%	97.3%	2.7%	2.7%	2.7%
FEx	84.0%	84.0%	84.2%	16.0%	16.0%	15.8%
MFRD	61.2%	61.2%	61.5%	38.8%	38.8%	38.5%

Table 5 – Environmental impact of the different WPCs in BS (FU = 1 t of protein in the WPC)

Impact category	**Unit**	**WPC35**	**WPC60**	**WPC80**
CC	kg CO_2 eq	38,053	39,167	40,652
OD	g CFC-11 eq	3.579	3.684	3.815
PM	kg PM2.5 eq	20.39	20.98	21.77
POF	kg NMVOC eq	91.99	94.67	98.23
TA	molc H+ eq	649.61	668.15	693.86
TE	molc N eq	2,784.8	2,863.8	2,974.7
FE	kg P eq	3.331	3.432	3.552
ME	kg N eq	214.69	220.78	229.33
FEx	CTUe	114,420	117,736	122,037
MFRD	kg Sb eq	0.349	0.359	0.371

Table 6 – Environmental impact for the different WPCs in AS (FU = 1 t of protein in the WPC)

Impact category	AS - WPC35		AS - WPC60		AS - WPC80	
	Value	Δ % respect to BS	Value	Δ % respect to BS	Value	Δ % respect to BS
CC	36,966 kg CO_2 eq	-2.85%	38,053 kg CO_2 eq	-2.84%	3,9494 kg CO_2 eq	-2.85%
OD	3.502 g CFC-11 eq	-2.15%	3.605 g CFC-11 eq	-2.14%	3.733 g CFC-11 eq	-2.15%
PM	19.982 kg PM2.5 eq	-2.00%	20.559 kg PM2.5 eq	-1.99%	21.331 kg PM2.5 eq	-2.00%
POF	84.630 kg NMVOC eq	-8.00%	87.108 kg NMVOC eq	-7.99%	90.378 kg NMVOC eq	-8.00%
TA	643.6 molc H+ eq	-0.92%	662.0 molc H+ eq	-0.92%	687.5 molc H+ eq	-0.92%
TE	2,759.6 molc N eq	-0.90%	2,837.9 molc N eq	-0.90%	2,947.8 molc N eq	-0.90%
FE	3.250 kg P eq	-2.45%	3.348 kg P eq	-2.43%	3.465 kg P eq	-2.44%
ME	212.4 kg N eq	-1.07%	218.4 kg N eq	-1.07%	226.9 kg N eq	-1.07%
MFRD	0.299 kg Sb eq	-14.26%	0.308 kg Sb eq	-14.25%	0.318 kg Sb eq	-14.33%

Table 7 – Impact variation (%) considering the doubling or the halving of the transport distance to the WPC factory in BS e AS

Impact category	BS						AS					
	WPC35		WPC60		WPC80		WPC35		WPC60		WPC80	
	Halving	Doubling	Halving	Doubling	Halving	Doubling	Halving	Doubling	Halving	Doubling	Halving	Doubling
CC	-2.62%	5.24%	-2.62%	5.24%	-2.62%	5.24%	-0.70%	1.40%	-0.70%	1.40%	-0.70%	1.40%
OD	-1.93%	3.87%	-1.93%	3.87%	-1.94%	3.88%	-0.51%	1.03%	-0.51%	1.03%	-0.52%	1.03%
PM	-1.76%	3.53%	-1.76%	3.52%	-1.76%	3.53%	-0.47%	0.94%	-0.47%	0.93%	-0.47%	0.94%
POF	-6.79%	13.59%	-6.79%	13.57%	-6.80%	13.59%	-1.92%	3.84%	-1.92%	3.84%	-1.92%	3.84%
TA	-0.82%	1.63%	-0.82%	1.63%	-0.82%	1.63%	-0.21%	0.43%	-0.21%	0.43%	-0.21%	0.43%
TE	-0.77%	1.54%	-0.77%	1.54%	-0.77%	1.54%	-0.20%	0.40%	-0.20%	0.40%	-0.20%	0.40%
FE	-2.43%	4.87%	-2.43%	4.86%	-2.44%	4.88%	-0.65%	1.30%	-0.65%	1.29%	-0.65%	1.30%
ME	-0.91%	1.82%	-0.91%	1.82%	-0.91%	1.82%	-0.24%	0.48%	-0.24%	0.48%	-0.24%	0.48%
MFRD	-11.85%	23.70%	-11.84%	23.68%	-11.91%	23.82%	-3.59%	7.19%	-3.59%	7.18%	-3.62%	7.23%

Table 8 – Impact variation for the different WPC in the two scenarios considering Economic Allocation instead of the Dry matter allocation in AS e BS

Impact category	**Economic allocation**					
	BS			**AS**		
	WPC35	**WPC60**	**WPC80**	**WPC35**	**WPC60**	**WPC80**
CC	-80.2%	-80.5%	-81.1%	-80.2%	-82.7%	-83.3%
OD	-78.2%	-78.6%	-79.3%	-78.2%	-80.1%	-80.9%
PM	-82.5%	-82.8%	-83.3%	-82.5%	-84.3%	-84.8%
POF	-74.0%	-74.4%	-75.2%	-74.0%	-79.9%	-80.5%
TA	-86.2%	-86.4%	-86.8%	-86.2%	-87.2%	-87.5%
TE	-87.1%	-87.3%	-87.7%	-87.1%	-88.0%	-88.3%
FE	-73.7%	-74.1%	-75.0%	-73.7%	-75.9%	-76.8%
ME	-86.8%	-87.1%	-87.5%	-86.8%	-87.9%	-88.2%
MFRD	-59.2%	-60.0%	-61.3%	-59.2%	-67.7%	-68.9%

FIGURE CAPTIONS

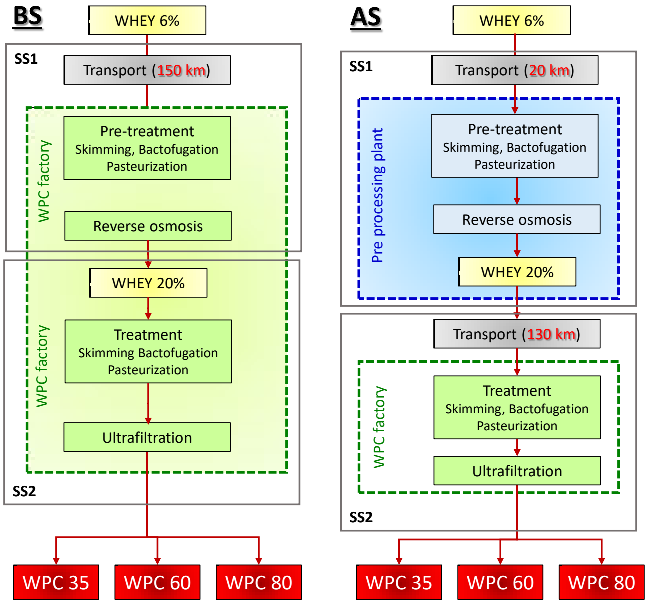

Figure 1 –Schematisation of the two considered scenarios (BS = baseline, AS = alternative).

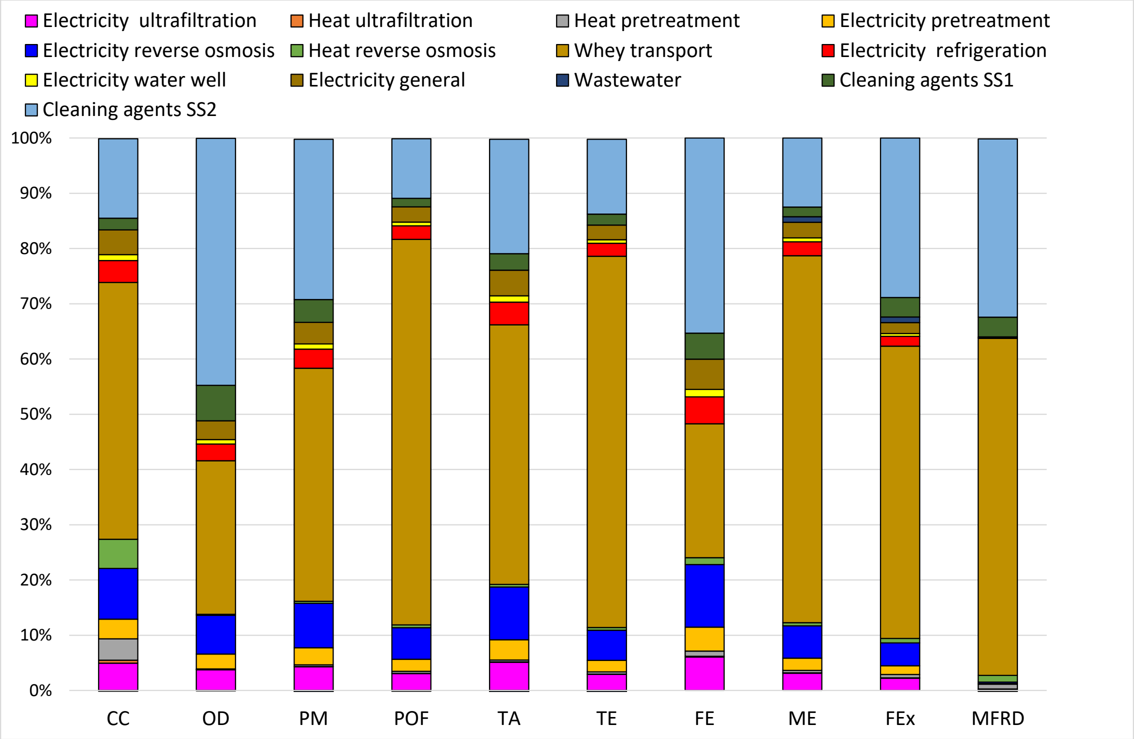

Figure 2 – Hotspots identification for the WPC35 in BS excluding whey production; climate change (CC), ozone depletion (OD), particulate matter (PM); photochemical oxidant formation (POF); acidification (TA), freshwater eutrophication (FE), terrestrial eutrophication (TE) marine eutrophication (ME), and mineral, fossil and renewable resource Depletion (MFRD).

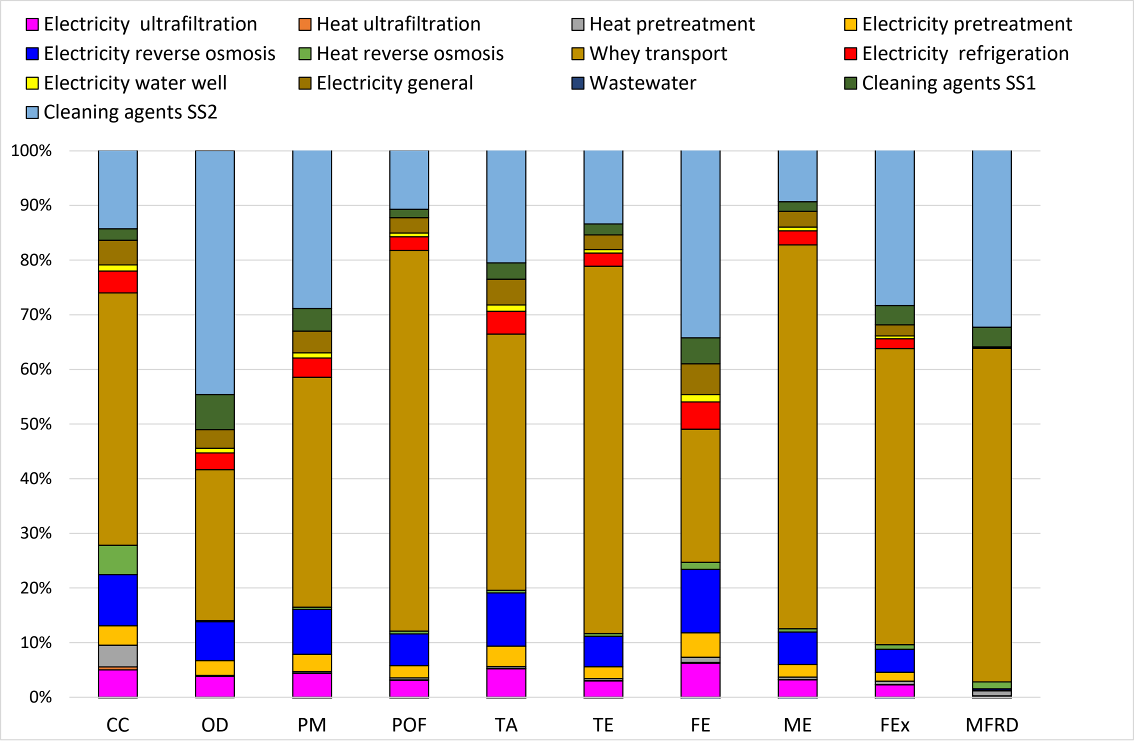

Figure 3 – Hotspots identification for the WPC60 in BS excluding whey production; climate change (CC), ozone depletion (OD), particulate matter (PM); photochemical oxidant formation (POF); acidification (TA), freshwater eutrophication (FE), terrestrial eutrophication (TE) marine eutrophication (ME), and mineral, fossil and renewable resource Depletion (MFRD).

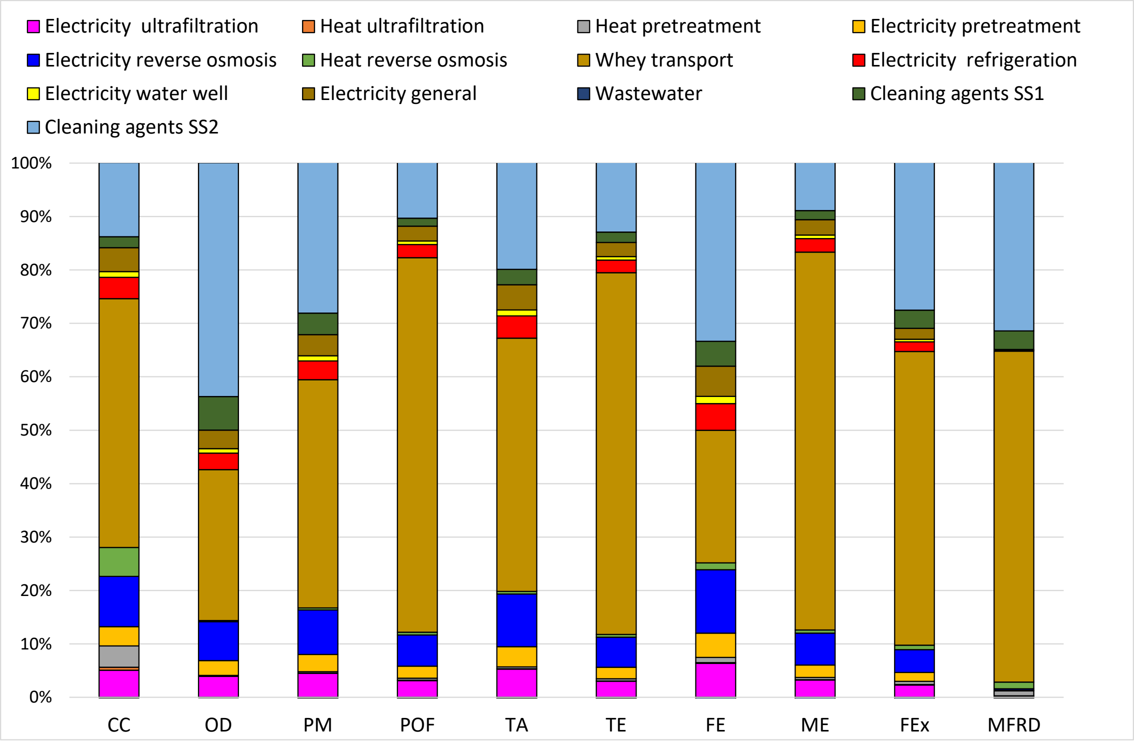

Figure 4 – Hotspots identification for the WPC80 in BS excluding whey production; climate change (CC), ozone depletion (OD), particulate matter (PM); photochemical oxidant formation (POF); acidification (TA), freshwater eutrophication (FE), terrestrial eutrophication (TE) marine eutrophication (ME), and mineral, fossil and renewable resource Depletion (MFRD).