sustainability

*Supplementary materials for*

# Comparative Life Cycle Assessment of Five Greek Yogurt Production Systems: A Perspective beyond the Plant Boundaries

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## S1. Processing Options Literature Overview

At an industrial scale, GY processing options may be classified into two main categories and several alternatives. Protein concentration may be increased either before or after milk fermentation. Protein concentration post-fermentation may be increased using mechanical separators (i.e. centrifugation (CE)) or a membrane of ultrafiltration (UF). Protein concentration may also be increased before fermentation through milk fortification with protein ingredients (FO), milk pre-concentration with UF or a combination of microfiltration (MF) and UF (Jørgensen et al., 2019). UF concentration prior to fermentation has the added benefit of generating neutral pH milk permeate with no fermentation residue (galactose and metabolites). It also has the potential to be used directly as ingredients in other food products (Jørgensen et al., 2019; Shamsia and El-Ghannam, 2012). However, the preconcentration of milk modifies the kinetics of fermentation, acidity and sensory properties of the final GY product (Damin et al., 2009; Paredes Valencia et al., 2018). On the other hand, fortifying milk with proteins before fermentation avoids the production of whey at the processing site. Several fortification alternatives with different protein ingredients are proposed in the literature, using milk protein concentrate (MPC), milk casein concentrate (MCC), whey protein concentrate (WPC) (Bong and Moraru, 2014; Jørgensen et al., 2019; Uduwerella et al., 2018), hydrocolloids or a combination of WPC with pectin (Gyawali and Ibrahim, 2018, 2016). The level of concentration, type and formulation of the protein ingredient can affect GY sensory properties (Desai et al., 2013). Some manufacturers also combine pre-concentration before fermentation by UF or FO and final concentration after fermentation by CE to reduce the amount of acid whey produced without overly altering the typical sensory characteristics of GY (Jørgensen et al., 2019; Uduwerella et al., 2017). CE after fermentation is the traditional way of making GY and is recommended by purists, since it provides GY with its authentic texture and taste. An attempt to use UF instead of CE after fermentation was reported by (Paredes Valencia et al., 2018). This alternative reduces the amount of energy input and space taken up in the plant as compared to CE equipment. However, it presents other technical challenges. The filtration membrane is susceptible to fouling due to the high viscosity of the fermented milk, which affects processing yields and costs. In addition, the mechanical pressure exerted on the fermented milk as it passes through the UF membrane can damage the gel structure and sensory properties of the finished product. In fact, there is no simple answer to determine the best approach to produce GY. The processing method influences the volume and composition of the by-product generated, as well as the composition and sensory properties of GY (Desai et al., 2013; Jørgensen et al., 2019; Paredes Valencia et al., 2018; Tamime et al., 2014; Tong, 2013). It may also impact production yields, resources, utilities consumption such as energy, water, chemicals at the manufacturing plant and the capital 3 cost of the processing equipment (Bong and Moraru, 2014; Jørgensen et al., 2019; Tong, 2013). There are actually many parameters to be considered. Manufacturers may balance the trade-offs between cost and quality differently depending on their strategic positioning and technical constraints.

## S2. Description of the three processing technologies: CE, FO, UF

### *S2.1. Centrifugation (CE)*

The raw milk is received at the plant and stored at 4°C in insulated tanks for one hour. It is then heated to 55°C and sent to a nozzle separator to be skimmed. The skimming operation separates the cream from the other milk solids. Then, the skimmed milk is routed to a heat exchanger, heated to 90°C for five minutes then cooled to 42°C. This heat treatment has two functions: it destroys the pathogen microorganisms and denatures the whey proteins. Whey protein denaturation is a critical step in gel formation, since it gives the yogurt its final texture. Optionally, some manufacturers also include a homogenization process at this step to improve the final texture. The milk is then routed to isothermal fermentation tanks inoculated with a starter culture and maintained between at 40–45°C for five hours until the cultured milk reaches a pH of 4.5. The fermented milk resulting from this operation is centrifugated with nozzle separators to concentrate the yogurt solid contents to 15% and proteins to 10% by separating the aqueous part of the acid whey. The concentrated yogurt is then cooled to 15°C in thirty seconds with a tubular heat exchanger that stabilizes the pH and sent to the packaging area.

### *S2.2. Fortification (FO)*

The fortification process includes an additional step between the skimming and heat treatment operations as compared to the CE option. The solid milk protein concentrate (MPC) powder is first rehydrated with water to 24% (w/w) concentration and mixed with the skimmed milk in order to reach 4.2% (w/w) proteins in the fortified skimmed milk. Liquid or solid milk protein concentrate (MPC) with different concentrations may be used in the fortification process. In this study, MPCs are manufactured by concentrating skimmed milk at 20% proteins (w/w) by diafiltration. Liquid MPCs are transported as is to the dairy plant and mixed directly into the skimmed milk. Powders require the additional operations of evaporation, spray-drying and packing before transportation and a rehydration step at the GY plant. We used MPC 80 powder concentrated at 80% proteins (w/w) sourced from the USA as the FO reference option and assessed two sourcing alternatives, diafiltered milk from the USA and diafiltered milk from Québec, resulting in three FO alternatives.

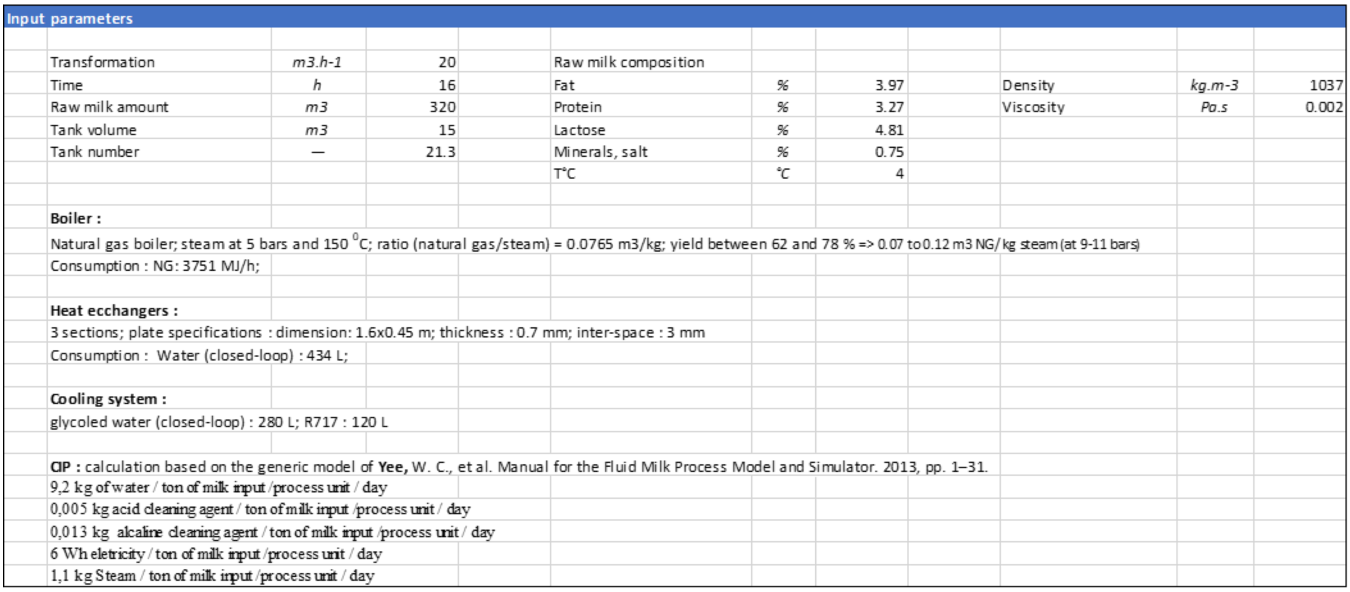
### *S2.3. Ultrafiltration (UF)*

This option differs from CE in three main areas: (1) the protein concentration by UF is performed right after the milk skimming and before the fermentation process. The UF process separates the milk molecules according to their sizes through a membrane under pressure. The skimmed milk is concentrated to a volumetric concentration factor of (VCF) 3.1X using a 30 KDa molecular weight spiral polyester membrane at a transmembrane pressure of $5.51.10^5$ Pa at 55°C. Most of the lactose and minerals permeate through the membrane in the aqueous phase constituting the permeate (or sweet whey), whereas the proteins are retained in the retentate and concentrated up to 10% (w/w). The pre-concentrated milk from the retentate is then routed to the heat treatment and fermentation 4 operation (2). The volume of milk treated during these subsequent operations is lower as compared to CE due to the pre-concentration step (3). The inoculation time is increased to eight hours as compared to the CE fermentation process due to the lower lactose/protein ratio in the preconcentrated milk, which modifies the fermentation kinetics and increases the buffering capacity.

## **S3. Process simulation data and results**

The simulation modelling was based on generic high-capacity lines processing 20,000 L $h^{-1}$ of raw milk for 16 h a day with one cycle of clean-in-place (CIP) per day and producing GY with 10% protein and 0% fat in the operating conditions specified in tables 1 to 5. The simulation accounted for heat regeneration and water recirculation. Such systems are generally implemented in factory to optimize cooling and heating energy and water consumption. Natural gas consumption was based on boiler requirements to produce steam for the heat exchangers and CIP system. CIP modeling was based on a generic calculation methodology accounting for the quantity of milk processed between each cycle and number of unit processes (Yee et al., 2013). All material (chemicals, tap water, wastewater) and energy flows (electricity, natural gas) determined by the simulation are reported in the inventory. Based on discussions with the manufacturers, the refrigerant losses were assumed to be negligible and not considered in the simulation. Packaging, final product cooling and storage operations, general utilities consumption and L and W of products were not part of the simulation but are included in the inventory based on literature data, as described in the main manuscript.

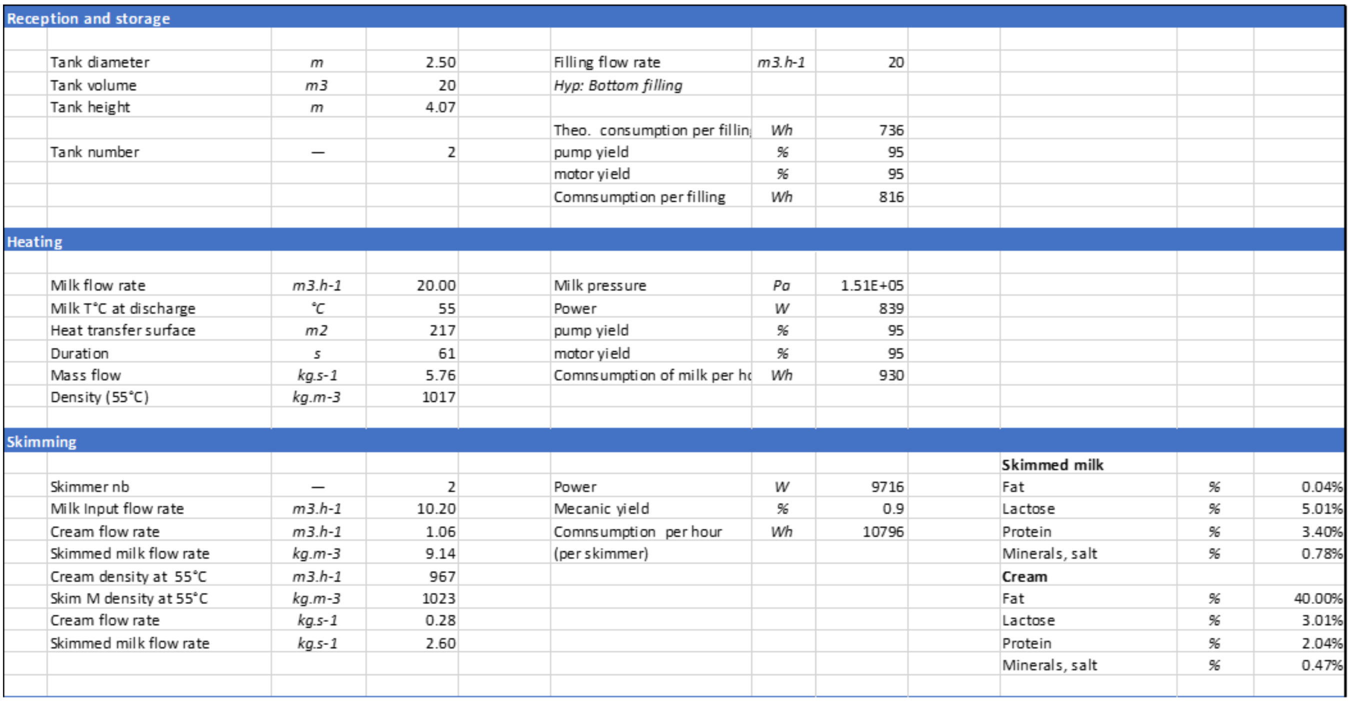
**Table 1.** Input parameters for CE, FO and UF.



| Input parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Transformation | *m3.h-1* | 20 | Raw milk composition | | | | | |
| Time | *h* | 16 | Fat | % | 3.97 | Density | *kg.m-3* | 1037 |
| Raw milk amount | *m3* | 320 | Protein | % | 3.27 | Viscosity | *Pa.s* | 0.002 |
| Tank volume | *m3* | 15 | Lactose | % | 4.81 | | | |
| Tank number | — | 21.3 | Minerals, salt | % | 0.75 | | | |
| | | | T°C | °C | 4 | | | |
| **Boiler :** | | | | | | | | |
| Natural gas boiler; steam at 5 bars and 150 $^{0}$C; ratio (natural gas/steam) = 0.0765 m3/kg; yield between 62 and 78 % => 0.07 to0.12 m3 NG/kg steam (at 9-11 bars) | | | | | | | | |
| Consumption : NG: 3751 MJ/h; | | | | | | | | |
| **Heat ecchangers :** | | | | | | | | |
| 3 sections; plate specifications : dimension: 1.6x0.45 m; thickness : 0.7 mm; inter-space : 3 mm | | | | | | | | |
| Consumption : Water (closed-loop) : 434 L; | | | | | | | | |
| **Cooling system :** | | | | | | | | |
| glycoled water (closed-loop) : 280 L; R717 : 120 L | | | | | | | | |
| **CIP :** calculation based on the generic model of **Yee,** W. C., et al. Manual for the Fluid Milk Process Model and Simulator. 2013, pp. 1–31. | | | | | | | | |
| 9,2 kg of water / ton of milk input /process unit / day | | | | | | | | |
| 0,005 kg acid cleaning agent / ton of milk input /process unit / day | | | | | | | | |
| 0,013 kg alcaline cleaning agent / ton of milk input /process unit / day | | | | | | | | |
| 6 Wh eletricity / ton of milk input /process unit / day | | | | | | | | |
| 1,1 kg Steam / ton of milk input /process unit / day | | | | | | | | |

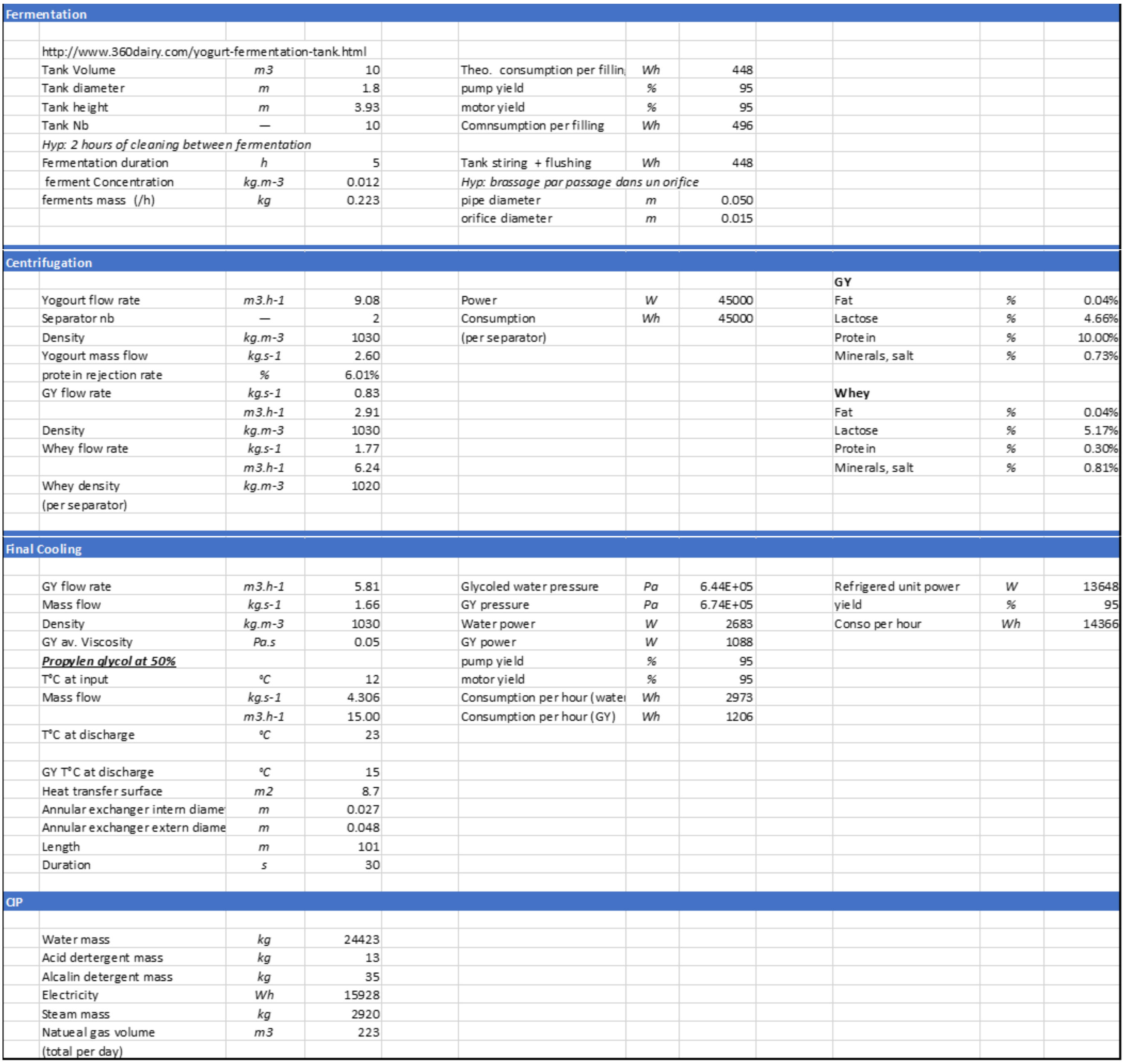
## S3.1. Centrifugation (CE)

**Table S2.** Centrifugation simulation results (Benoit and Houssard, 2017).



| Reception and storage | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tank diameter | *m* | 2.50 | Filling flow rate | *m3.h-1* | 20 | | | |
| Tank volume | *m3* | 20 | *Hyp: Bottom filling* | | | | | |
| Tank height | *m* | 4.07 | | | | | | |
| | | | Theo. consumption per fillin | *Wh* | 736 | | | |
| Tank number | — | 2 | pump yield | % | 95 | | | |
| | | | motor yield | % | 95 | | | |
| | | | Comnsumption per filling | *Wh* | 816 | | | |
| **Heating** | | | | | | | | |
| Milk flow rate | *m3.h-1* | 20.00 | Milk pressure | *Pa* | 1.51E+05 | | | |
| Milk T°C at discharge | °C | 55 | Power | *W* | 839 | | | |
| Heat transfer surface | *m2* | 217 | pump yield | % | 95 | | | |
| Duration | *s* | 61 | motor yield | % | 95 | | | |
| Mass flow | *kg.s-1* | 5.76 | Comnsumption of milk per hc | *Wh* | 930 | | | |
| Density (55°C) | *kg.m-3* | 1017 | | | | | | |
| **Skimming** | | | | | | | | |
| | | | | | | **Skimmed milk** | | |
| Skimmer nb | — | 2 | Power | *W* | 9716 | Fat | % | 0.04% |
| Milk Input flow rate | *m3.h-1* | 10.20 | Mecanic yield | % | 0.9 | Lactose | % | 5.01% |
| Cream flow rate | *m3.h-1* | 1.06 | Comnsumption per hour | *Wh* | 10796 | Protein | % | 3.40% |
| Skimmed milk flow rate | *kg.m-3* | 9.14 | (per skimmer) | | | Minerals, salt | % | 0.78% |
| Cream density at 55°C | *m3.h-1* | 967 | | | | **Cream** | | |
| Skim M density at 55°C | *kg.m-3* | 1023 | | | | Fat | % | 40.00% |
| Cream flow rate | *kg.s-1* | 0.28 | | | | Lactose | % | 3.01% |
| Skimmed milk flow rate | *kg.s-1* | 2.60 | | | | Protein | % | 2.04% |
| | | | | | | Minerals, salt | % | 0.47% |

**Table S2.** (continued and end).

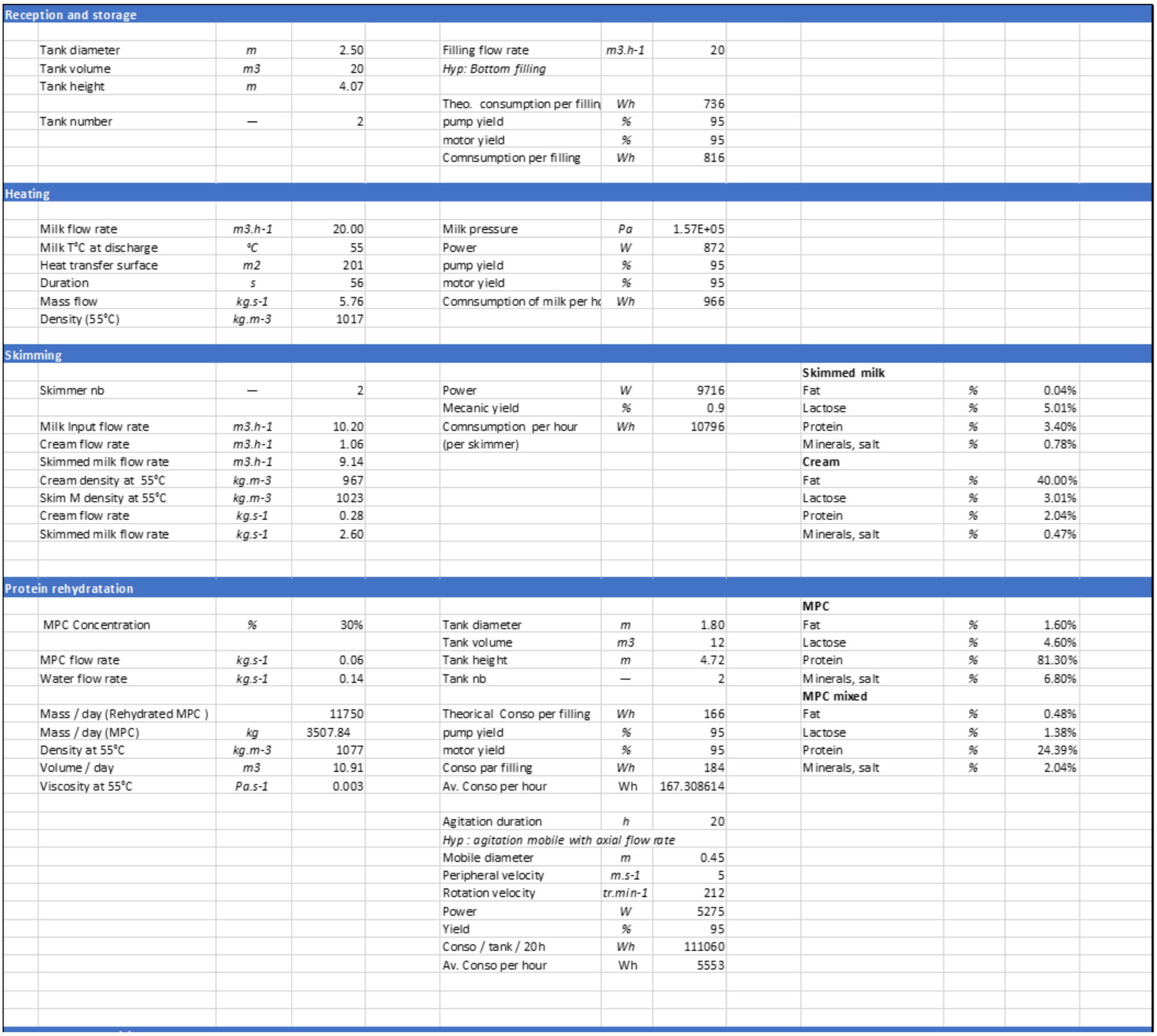


| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Fermentation** | | | | | | | | | |
| | http://www.360dairy.com/yogurt-fermentation-tank.html | | | | | | | | |
| | Tank Volume | *m3* | 10 | Theo. consumption per fillin | *Wh* | 448 | | | |
| | Tank diameter | *m* | 1.8 | pump yield | *%* | 95 | | | |
| | Tank height | *m* | 3.93 | motor yield | *%* | 95 | | | |
| | Tank Nb | — | 10 | Comnsumption per filling | *Wh* | 496 | | | |
| | *Hyp: 2 hours of cleaning between fermentation* | | | | | | | | |
| | Fermentation duration | *h* | 5 | Tank stiring + flushing | *Wh* | 448 | | | |
| | ferment Concentration | *kg.m-3* | 0.012 | *Hyp: brassage par passage dans un orifice* | | | | | |
| | ferments mass (/h) | *kg* | 0.223 | pipe diameter | *m* | 0.050 | | | |
| | | | | orifice diameter | *m* | 0.015 | | | |
| **Centrifugation** | | | | | | | | | |
| | | | | | | | **GY** | | |
| | Yogourt flow rate | *m3.h-1* | 9.08 | Power | *W* | 45000 | Fat | *%* | 0.04% |
| | Separator nb | — | 2 | Consumption | *Wh* | 45000 | Lactose | *%* | 4.66% |
| | Density | *kg.m-3* | 1030 | (per separator) | | | Protein | *%* | 10.00% |
| | Yogourt mass flow | *kg.s-1* | 2.60 | | | | Minerals, salt | *%* | 0.73% |
| | protein rejection rate | *%* | 6.01% | | | | | | |
| | GY flow rate | *kg.s-1* | 0.83 | | | | **Whey** | | |
| | | *m3.h-1* | 2.91 | | | | Fat | *%* | 0.04% |
| | Density | *kg.m-3* | 1030 | | | | Lactose | *%* | 5.17% |
| | Whey flow rate | *kg.s-1* | 1.77 | | | | Protein | *%* | 0.30% |
| | | *m3.h-1* | 6.24 | | | | Minerals, salt | *%* | 0.81% |
| | Whey density | *kg.m-3* | 1020 | | | | | | |
| | (per separator) | | | | | | | | |
| **Final Cooling** | | | | | | | | | |
| | GY flow rate | *m3.h-1* | 5.81 | Glycoled water pressure | *Pa* | 6.44E+05 | Refrigered unit power | *W* | 13648 |
| | Mass flow | *kg.s-1* | 1.66 | GY pressure | *Pa* | 6.74E+05 | yield | *%* | 95 |
| | Density | *kg.m-3* | 1030 | Water power | *W* | 2683 | Conso per hour | *Wh* | 14366 |
| | GY av. Viscosity | *Pa.s* | 0.05 | GY power | *W* | 1088 | | | |
| | ***Propylen glycol at 50%*** | | | pump yield | *%* | 95 | | | |
| | T°C at input | *°C* | 12 | motor yield | *%* | 95 | | | |
| | Mass flow | *kg.s-1* | 4.306 | Consumption per hour (wate | *Wh* | 2973 | | | |
| | | *m3.h-1* | 15.00 | Consumption per hour (GY) | *Wh* | 1206 | | | |
| | T°C at discharge | *°C* | 23 | | | | | | |
| | GY T°C at discharge | *°C* | 15 | | | | | | |
| | Heat transfer surface | *m2* | 8.7 | | | | | | |
| | Annular exchanger intern diame | *m* | 0.027 | | | | | | |
| | Annular exchanger extern diame | *m* | 0.048 | | | | | | |
| | Length | *m* | 101 | | | | | | |
| | Duration | *s* | 30 | | | | | | |
| **CIP** | | | | | | | | | |
| | Water mass | *kg* | 24423 | | | | | | |
| | Acid dertergent mass | *kg* | 13 | | | | | | |
| | Alcalin detergent mass | *kg* | 35 | | | | | | |
| | Electricity | *Wh* | 15928 | | | | | | |
| | Steam mass | *kg* | 2920 | | | | | | |
| | Natueal gas volume | *m3* | 223 | | | | | | |
| | (total per day) | | | | | | | | |

### *S3.2. Fortification (FO)*

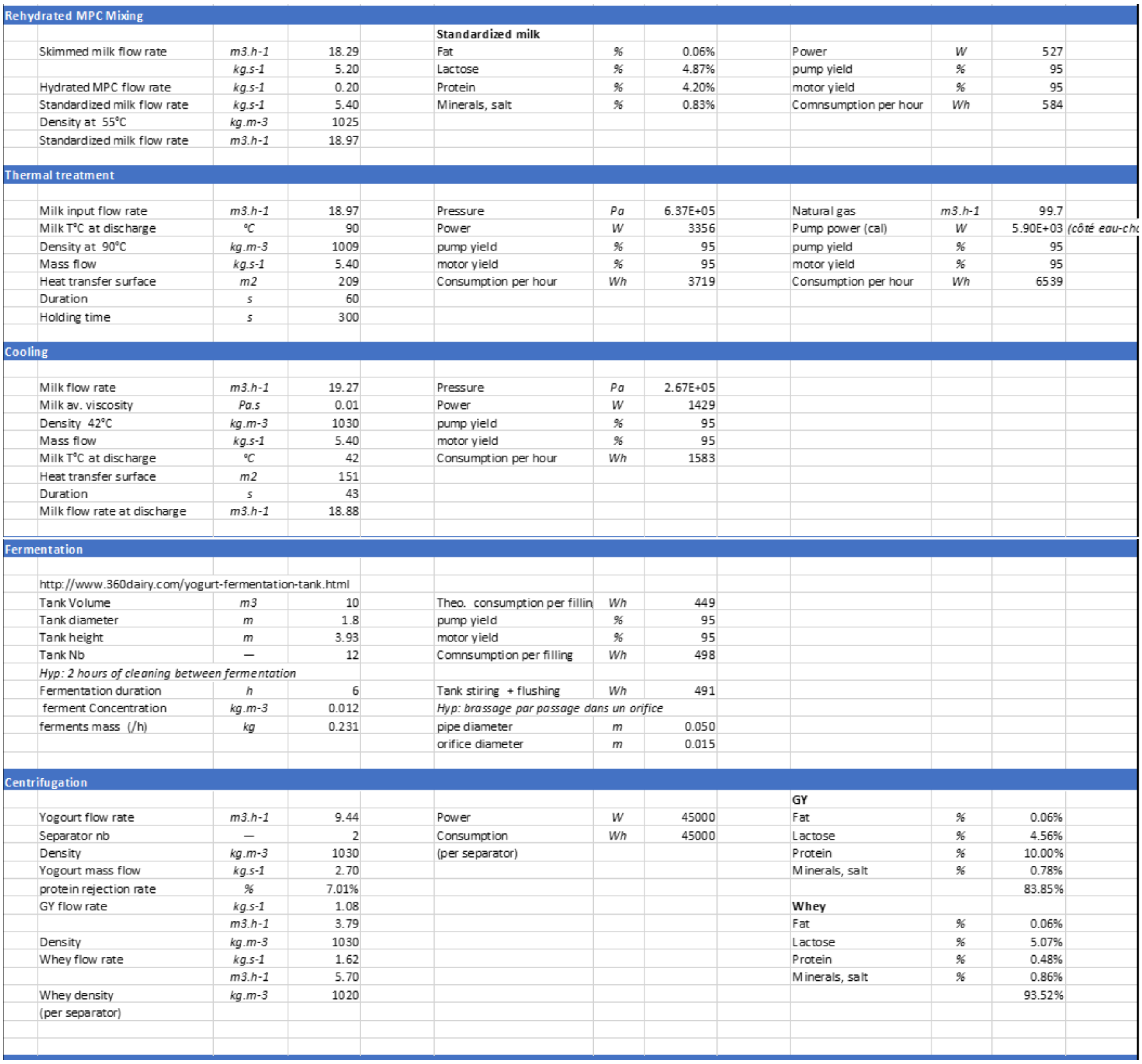
Simulation results differ from CE due to the additional operations of MPC powder rehydration and mixing before thermal treatment. More operations are also included in the CIP system. The change in the flow rate after fortification modifies the parameters from the heat exchanger and cooling systems.

**Table 3.** Fortification simulation results (Benoit and Houssard, 2017).



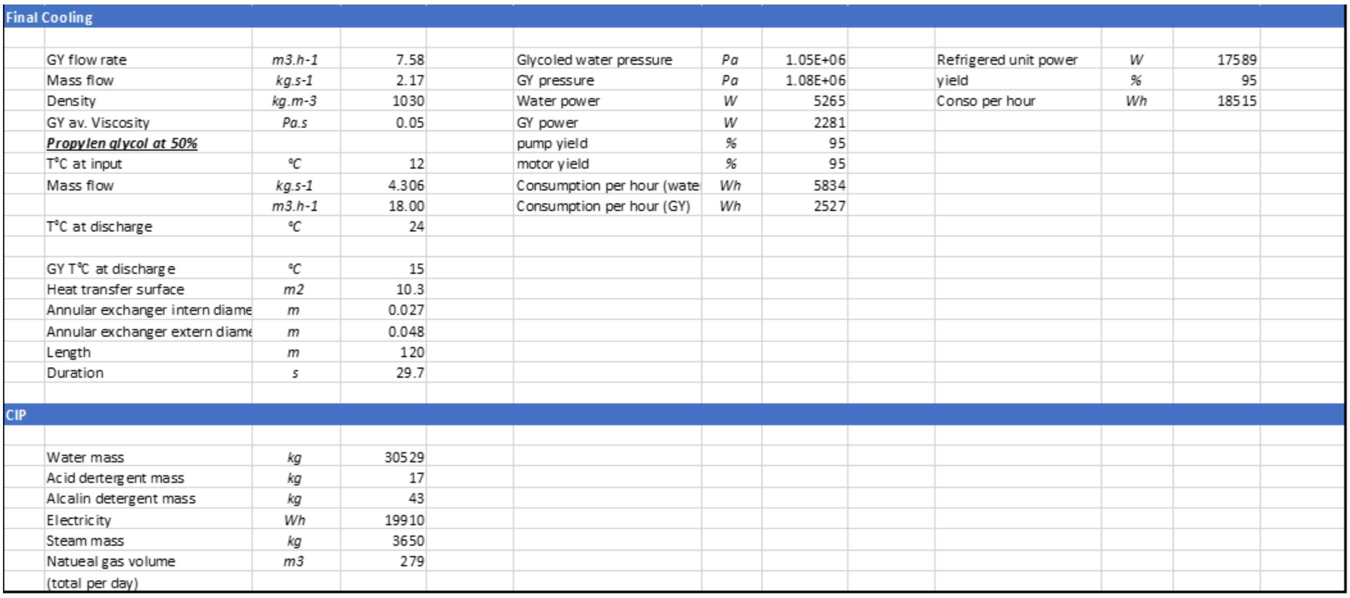
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Reception and storage** | | | | | | | | |
| Tank diameter | *m* | 2.50 | Filling flow rate | *m3.h-1* | 20 | | | |
| Tank volume | *m3* | 20 | *Hyp: Bottom filling* | | | | | |
| Tank height | *m* | 4.07 | | | | | | |
| | | | Theo. consumption per fillin | *Wh* | 736 | | | |
| Tank number | — | 2 | pump yield | *%* | 95 | | | |
| | | | motor yield | *%* | 95 | | | |
| | | | Comnsumption per filling | *Wh* | 816 | | | |
| **Heating** | | | | | | | | |
| Milk flow rate | *m3.h-1* | 20.00 | Milk pressure | *Pa* | 1.57E+05 | | | |
| Milk T°C at discharge | *°C* | 55 | Power | *W* | 872 | | | |
| Heat transfer surface | *m2* | 201 | pump yield | *%* | 95 | | | |
| Duration | *s* | 56 | motor yield | *%* | 95 | | | |
| Mass flow | *kg.s-1* | 5.76 | Comnsumption of milk per hc | *Wh* | 966 | | | |
| Density (55°C) | *kg.m-3* | 1017 | | | | | | |
| **Skimming** | | | | | | | | |
| | | | | | | **Skimmed milk** | | |
| Skimmer nb | — | 2 | Power | *W* | 9716 | Fat | *%* | 0.04% |
| | | | Mecanic yield | *%* | 0.9 | Lactose | *%* | 5.01% |
| Milk Input flow rate | *m3.h-1* | 10.20 | Comnsumption per hour | *Wh* | 10796 | Protein | *%* | 3.40% |
| Cream flow rate | *m3.h-1* | 1.06 | (per skimmer) | | | Minerals, salt | *%* | 0.78% |
| Skimmed milk flow rate | *m3.h-1* | 9.14 | | | | **Cream** | | |
| Cream density at 55°C | *kg.m-3* | 967 | | | | Fat | *%* | 40.00% |
| Skim M density at 55°C | *kg.m-3* | 1023 | | | | Lactose | *%* | 3.01% |
| Cream flow rate | *kg.s-1* | 0.28 | | | | Protein | *%* | 2.04% |
| Skimmed milk flow rate | *kg.s-1* | 2.60 | | | | Minerals, salt | *%* | 0.47% |
| **Protein rehydratation** | | | | | | | | |
| | | | | | | **MPC** | | |
| MPC Concentration | *%* | 30% | Tank diameter | *m* | 1.80 | Fat | *%* | 1.60% |
| | | | Tank volume | *m3* | 12 | Lactose | *%* | 4.60% |
| MPC flow rate | *kg.s-1* | 0.06 | Tank height | *m* | 4.72 | Protein | *%* | 81.30% |
| Water flow rate | *kg.s-1* | 0.14 | Tank nb | — | 2 | Minerals, salt | *%* | 6.80% |
| | | | | | | **MPC mixed** | | |
| Mass / day (Rehydrated MPC ) | | 11750 | Theorical Conso per filling | *Wh* | 166 | Fat | *%* | 0.48% |
| Mass / day (MPC) | *kg* | 3507.84 | pump yield | *%* | 95 | Lactose | *%* | 1.38% |
| Density at 55°C | *kg.m-3* | 1077 | motor yield | *%* | 95 | Protein | *%* | 24.39% |
| Volume / day | *m3* | 10.91 | Conso par filling | *Wh* | 184 | Minerals, salt | *%* | 2.04% |
| Viscosity at 55°C | *Pa.s-1* | 0.003 | Av. Conso per hour | Wh | 167.308614 | | | |
| | | | Agitation duration | *h* | 20 | | | |
| | | | *Hyp : agitation mobile with axial flow rate* | | | | | |
| | | | Mobile diameter | *m* | 0.45 | | | |
| | | | Peripheral velocity | *m.s-1* | 5 | | | |
| | | | Rotation velocity | *tr.min-1* | 212 | | | |
| | | | Power | *W* | 5275 | | | |
| | | | Yield | *%* | 95 | | | |
| | | | Conso / tank / 20h | *Wh* | 111060 | | | |
| | | | Av. Conso per hour | Wh | 5553 | | | |

**Table S3.** (continued).



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Rehydrated MPC Mixing** | | | | | | | | | |
| | | | **Standardized milk** | | | | | | |
| Skimmed milk flow rate | *m3.h-1* | 18.29 | Fat | *%* | 0.06% | Power | *W* | 527 | |
| | *kg.s-1* | 5.20 | Lactose | *%* | 4.87% | pump yield | *%* | 95 | |
| Hydrated MPC flow rate | *kg.s-1* | 0.20 | Protein | *%* | 4.20% | motor yield | *%* | 95 | |
| Standardized milk flow rate | *kg.s-1* | 5.40 | Minerals, salt | *%* | 0.83% | Comnsumption per hour | *Wh* | 584 | |
| Density at 55°C | *kg.m-3* | 1025 | | | | | | | |
| Standardized milk flow rate | *m3.h-1* | 18.97 | | | | | | | |
| **Thermal treatment** | | | | | | | | | |
| Milk input flow rate | *m3.h-1* | 18.97 | Pressure | *Pa* | 6.37E+05 | Natural gas | *m3.h-1* | 99.7 | |
| Milk T°C at discharge | *°C* | 90 | Power | *W* | 3356 | Pump power (cal) | *W* | 5.90E+03 | *(côté eau-cho* |
| Density at 90°C | *kg.m-3* | 1009 | pump yield | *%* | 95 | pump yield | *%* | 95 | |
| Mass flow | *kg.s-1* | 5.40 | motor yield | *%* | 95 | motor yield | *%* | 95 | |
| Heat transfer surface | *m2* | 209 | Consumption per hour | *Wh* | 3719 | Consumption per hour | *Wh* | 6539 | |
| Duration | *s* | 60 | | | | | | | |
| Holding time | *s* | 300 | | | | | | | |
| **Cooling** | | | | | | | | | |
| Milk flow rate | *m3.h-1* | 19.27 | Pressure | *Pa* | 2.67E+05 | | | | |
| Milk av. viscosity | *Pa.s* | 0.01 | Power | *W* | 1429 | | | | |
| Density 42°C | *kg.m-3* | 1030 | pump yield | *%* | 95 | | | | |
| Mass flow | *kg.s-1* | 5.40 | motor yield | *%* | 95 | | | | |
| Milk T°C at discharge | *°C* | 42 | Consumption per hour | *Wh* | 1583 | | | | |
| Heat transfer surface | *m2* | 151 | | | | | | | |
| Duration | *s* | 43 | | | | | | | |
| Milk flow rate at discharge | *m3.h-1* | 18.88 | | | | | | | |
| **Fermentation** | | | | | | | | | |
| http://www.360dairy.com/yogurt-fermentation-tank.html | | | | | | | | | |
| Tank Volume | *m3* | 10 | Theo. consumption per fillin | *Wh* | 449 | | | | |
| Tank diameter | *m* | 1.8 | pump yield | *%* | 95 | | | | |
| Tank height | *m* | 3.93 | motor yield | *%* | 95 | | | | |
| Tank Nb | — | 12 | Comnsumption per filling | *Wh* | 498 | | | | |
| *Hyp: 2 hours of cleaning between fermentation* | | | | | | | | | |
| Fermentation duration | *h* | 6 | Tank stiring + flushing | *Wh* | 491 | | | | |
| ferment Concentration | *kg.m-3* | 0.012 | *Hyp: brassage par passage dans un orifice* | | | | | | |
| ferments mass (/h) | *kg* | 0.231 | pipe diameter | *m* | 0.050 | | | | |
| | | | orifice diameter | *m* | 0.015 | | | | |
| **Centrifugation** | | | | | | | | | |
| | | | | | | **GY** | | | |
| Yogourt flow rate | *m3.h-1* | 9.44 | Power | *W* | 45000 | Fat | *%* | 0.06% | |
| Separator nb | — | 2 | Consumption | *Wh* | 45000 | Lactose | *%* | 4.56% | |
| Density | *kg.m-3* | 1030 | (per separator) | | | Protein | *%* | 10.00% | |
| Yogourt mass flow | *kg.s-1* | 2.70 | | | | Minerals, salt | *%* | 0.78% | |
| protein rejection rate | *%* | 7.01% | | | | | | 83.85% | |
| GY flow rate | *kg.s-1* | 1.08 | | | | **Whey** | | | |
| | *m3.h-1* | 3.79 | | | | Fat | *%* | 0.06% | |
| Density | *kg.m-3* | 1030 | | | | Lactose | *%* | 5.07% | |
| Whey flow rate | *kg.s-1* | 1.62 | | | | Protein | *%* | 0.48% | |
| | *m3.h-1* | 5.70 | | | | Minerals, salt | *%* | 0.86% | |
| Whey density | *kg.m-3* | 1020 | | | | | | 93.52% | |
| (per separator) | | | | | | | | | |

**Table S3.** (continued and end).

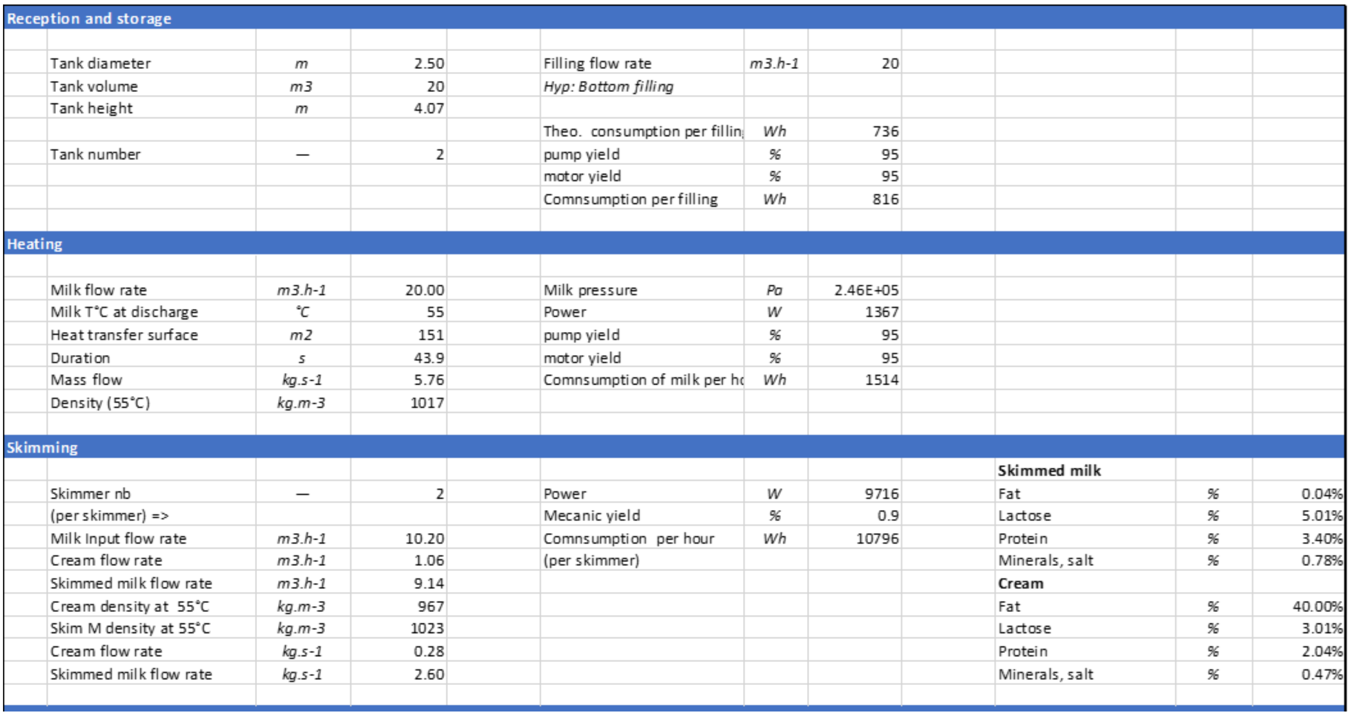


| Final Cooling | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| GY flow rate | m3.h-1 | 7.58 | Glycoled water pressure | Pa | 1.05E+06 | Refrigered unit power | W | 17589 |
| Mass flow | kg.s-1 | 2.17 | GY pressure | Pa | 1.08E+06 | yield | % | 95 |
| Density | kg.m-3 | 1030 | Water power | W | 5265 | Conso per hour | Wh | 18515 |
| GY av. Viscosity | Pa.s | 0.05 | GY power | W | 2281 | | | |
| ***Propylen glycol at 50%*** | | | pump yield | % | 95 | | | |
| T°C at input | °C | 12 | motor yield | % | 95 | | | |
| Mass flow | kg.s-1 | 4.306 | Consumption per hour (wate | Wh | 5834 | | | |
| | m3.h-1 | 18.00 | Consumption per hour (GY) | Wh | 2527 | | | |
| T°C at discharge | °C | 24 | | | | | | |
| | | | | | | | | |
| GY T°C at discharge | °C | 15 | | | | | | |
| Heat transfer surface | m2 | 10.3 | | | | | | |
| Annular exchanger intern diame | m | 0.027 | | | | | | |
| Annular exchanger extern diame | m | 0.048 | | | | | | |
| Length | m | 120 | | | | | | |
| Duration | s | 29.7 | | | | | | |
| **CIP** | | | | | | | | |
| Water mass | kg | 30529 | | | | | | |
| Acid dertergent mass | kg | 17 | | | | | | |
| Alcalin detergent mass | kg | 43 | | | | | | |
| Electricity | Wh | 19910 | | | | | | |
| Steam mass | kg | 3650 | | | | | | |
| Natueal gas volume | m3 | 279 | | | | | | |
| (total per day) | | | | | | | | |

## S3.3. Ultrafiltration (UF)

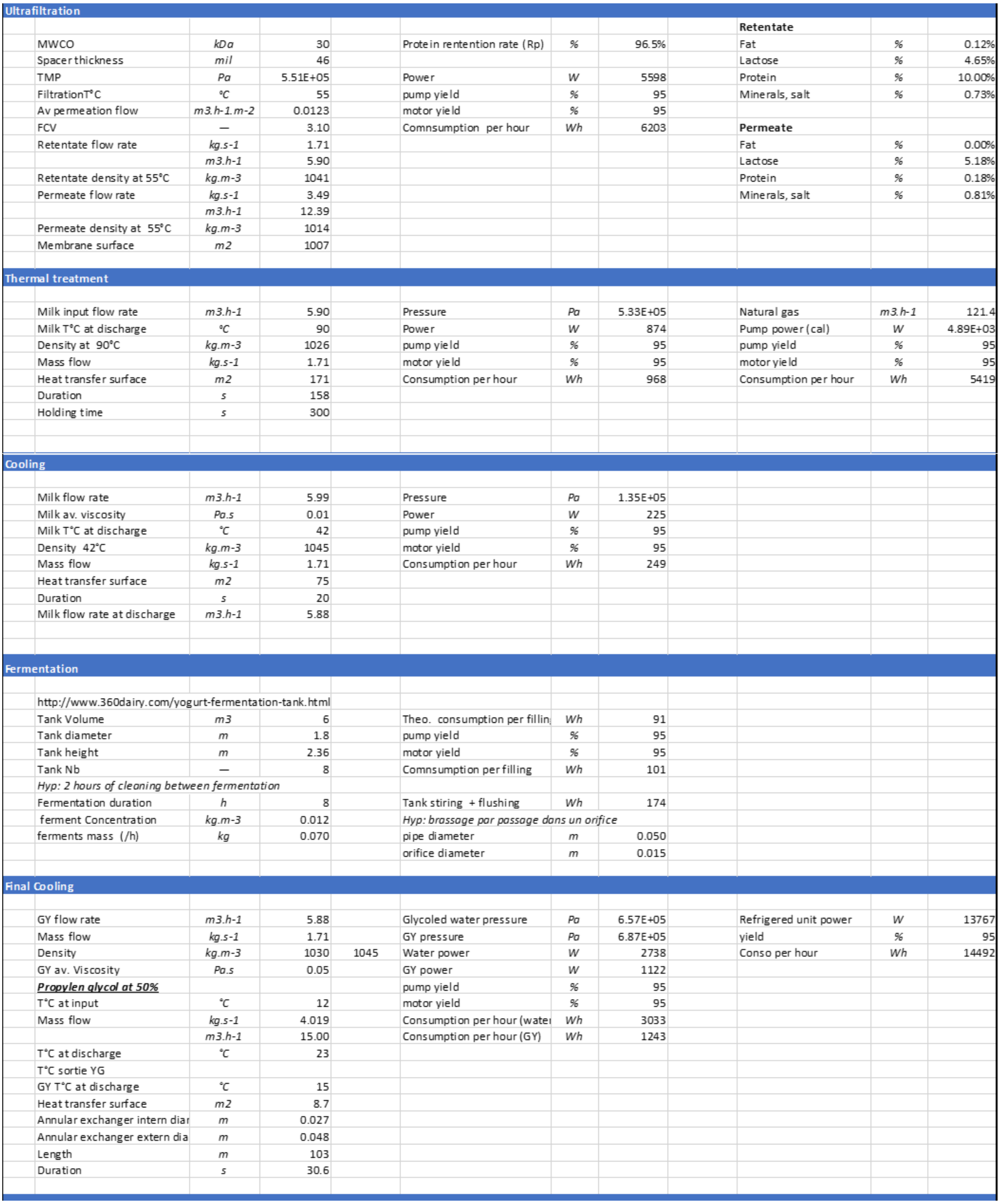
Simulation results differ from CE due to the additional ultrafiltration operation before the fermentation and removal of the centrifugation process. The significant change in flow rate after ultrafiltration modified the parameters from the heat exchanger and cooling systems.

**Table 4.** Ultrafiltration simulation results (Benoit and Houssard, 2017).



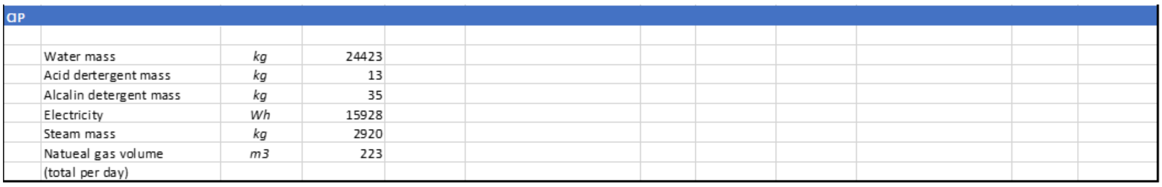
| Reception and storage | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tank diameter | m | 2.50 | Filling flow rate | m3.h-1 | 20 | | | |
| Tank volume | m3 | 20 | *Hyp: Bottom filling* | | | | | |
| Tank height | m | 4.07 | | | | | | |
| | | | Theo. consumption per fillin | Wh | 736 | | | |
| Tank number | — | 2 | pump yield | % | 95 | | | |
| | | | motor yield | % | 95 | | | |
| | | | Comnsumption per filling | Wh | 816 | | | |
| **Heating** | | | | | | | | |
| Milk flow rate | m3.h-1 | 20.00 | Milk pressure | Pa | 2.46E+05 | | | |
| Milk T°C at discharge | °C | 55 | Power | W | 1367 | | | |
| Heat transfer surface | m2 | 151 | pump yield | % | 95 | | | |
| Duration | s | 43.9 | motor yield | % | 95 | | | |
| Mass flow | kg.s-1 | 5.76 | Comnsumption of milk per ho | Wh | 1514 | | | |
| Density (55°C) | kg.m-3 | 1017 | | | | | | |
| **Skimming** | | | | | | | | |
| | | | | | | **Skimmed milk** | | |
| Skimmer nb | — | 2 | Power | W | 9716 | Fat | % | 0.04% |
| (per skimmer) => | | | Mecanic yield | % | 0.9 | Lactose | % | 5.01% |
| Milk Input flow rate | m3.h-1 | 10.20 | Comnsumption per hour | Wh | 10796 | Protein | % | 3.40% |
| Cream flow rate | m3.h-1 | 1.06 | (per skimmer) | | | Minerals, salt | % | 0.78% |
| Skimmed milk flow rate | m3.h-1 | 9.14 | | | | **Cream** | | |
| Cream density at 55°C | kg.m-3 | 967 | | | | Fat | % | 40.00% |
| Skim M density at 55°C | kg.m-3 | 1023 | | | | Lactose | % | 3.01% |
| Cream flow rate | kg.s-1 | 0.28 | | | | Protein | % | 2.04% |
| Skimmed milk flow rate | kg.s-1 | 2.60 | | | | Minerals, salt | % | 0.47% |

**Table S4.** (continued).



| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ultrafiltration** | | | | | | | | | | | |
| | | | | | | | | | **Retentate** | | |
| | MWCO | *kDa* | 30 | | Protein rentention rate (Rp) | *%* | 96.5% | | Fat | *%* | 0.12% |
| | Spacer thickness | *mil* | 46 | | | | | | Lactose | *%* | 4.65% |
| | TMP | *Pa* | 5.51E+05 | | Power | *W* | 5598 | | Protein | *%* | 10.00% |
| | FiltrationT°C | *°C* | 55 | | pump yield | *%* | 95 | | Minerals, salt | *%* | 0.73% |
| | Av permeation flow | *m3.h-1.m-2* | 0.0123 | | motor yield | *%* | 95 | | | | |
| | FCV | — | 3.10 | | Comnsumption per hour | *Wh* | 6203 | | **Permeate** | | |
| | Retentate flow rate | *kg.s-1* | 1.71 | | | | | | Fat | *%* | 0.00% |
| | | *m3.h-1* | 5.90 | | | | | | Lactose | *%* | 5.18% |
| | Retentate density at 55°C | *kg.m-3* | 1041 | | | | | | Protein | *%* | 0.18% |
| | Permeate flow rate | *kg.s-1* | 3.49 | | | | | | Minerals, salt | *%* | 0.81% |
| | | *m3.h-1* | 12.39 | | | | | | | | |
| | Permeate density at 55°C | *kg.m-3* | 1014 | | | | | | | | |
| | Membrane surface | *m2* | 1007 | | | | | | | | |
| **Thermal treatment** | | | | | | | | | | | |
| | Milk input flow rate | *m3.h-1* | 5.90 | | Pressure | *Pa* | 5.33E+05 | | Natural gas | *m3.h-1* | 121.4 |
| | Milk T°C at discharge | *°C* | 90 | | Power | *W* | 874 | | Pump power (cal) | *W* | 4.89E+03 |
| | Density at 90°C | *kg.m-3* | 1026 | | pump yield | *%* | 95 | | pump yield | *%* | 95 |
| | Mass flow | *kg.s-1* | 1.71 | | motor yield | *%* | 95 | | motor yield | *%* | 95 |
| | Heat transfer surface | *m2* | 171 | | Consumption per hour | *Wh* | 968 | | Consumption per hour | *Wh* | 5419 |
| | Duration | *s* | 158 | | | | | | | | |
| | Holding time | *s* | 300 | | | | | | | | |
| **Cooling** | | | | | | | | | | | |
| | Milk flow rate | *m3.h-1* | 5.99 | | Pressure | *Pa* | 1.35E+05 | | | | |
| | Milk av. viscosity | *Pa.s* | 0.01 | | Power | *W* | 225 | | | | |
| | Milk T°C at discharge | *°C* | 42 | | pump yield | *%* | 95 | | | | |
| | Density 42°C | *kg.m-3* | 1045 | | motor yield | *%* | 95 | | | | |
| | Mass flow | *kg.s-1* | 1.71 | | Consumption per hour | *Wh* | 249 | | | | |
| | Heat transfer surface | *m2* | 75 | | | | | | | | |
| | Duration | *s* | 20 | | | | | | | | |
| | Milk flow rate at discharge | *m3.h-1* | 5.88 | | | | | | | | |
| **Fermentation** | | | | | | | | | | | |
| | http://www.360dairy.com/yogurt-fermentation-tank.html | | | | | | | | | | |
| | Tank Volume | *m3* | 6 | | Theo. consumption per fillin | *Wh* | 91 | | | | |
| | Tank diameter | *m* | 1.8 | | pump yield | *%* | 95 | | | | |
| | Tank height | *m* | 2.36 | | motor yield | *%* | 95 | | | | |
| | Tank Nb | — | 8 | | Comnsumption per filling | *Wh* | 101 | | | | |
| | *Hyp: 2 hours of cleaning between fermentation* | | | | | | | | | | |
| | Fermentation duration | *h* | 8 | | Tank stiring + flushing | *Wh* | 174 | | | | |
| | ferment Concentration | *kg.m-3* | 0.012 | | *Hyp: brassage par passage dans un orifice* | | | | | | |
| | ferments mass (/h) | *kg* | 0.070 | | pipe diameter | *m* | 0.050 | | | | |
| | | | | | orifice diameter | *m* | 0.015 | | | | |
| **Final Cooling** | | | | | | | | | | | |
| | GY flow rate | *m3.h-1* | 5.88 | | Glycoled water pressure | *Pa* | 6.57E+05 | | Refrigered unit power | *W* | 13767 |
| | Mass flow | *kg.s-1* | 1.71 | | GY pressure | *Pa* | 6.87E+05 | | yield | *%* | 95 |
| | Density | *kg.m-3* | 1030 | 1045 | Water power | *W* | 2738 | | Conso per hour | *Wh* | 14492 |
| | GY av. Viscosity | *Pa.s* | 0.05 | | GY power | *W* | 1122 | | | | |
| | ***Propylen glycol at 50%*** | | | | pump yield | *%* | 95 | | | | |
| | T°C at input | *°C* | 12 | | motor yield | *%* | 95 | | | | |
| | Mass flow | *kg.s-1* | 4.019 | | Consumption per hour (wate | *Wh* | 3033 | | | | |
| | | *m3.h-1* | 15.00 | | Consumption per hour (GY) | *Wh* | 1243 | | | | |
| | T°C at discharge | *°C* | 23 | | | | | | | | |
| | T°C sortie YG | | | | | | | | | | |
| | GY T°C at discharge | *°C* | 15 | | | | | | | | |
| | Heat transfer surface | *m2* | 8.7 | | | | | | | | |
| | Annular exchanger intern diar | *m* | 0.027 | | | | | | | | |
| | Annular exchanger extern dia | *m* | 0.048 | | | | | | | | |
| | Length | *m* | 103 | | | | | | | | |
| | Duration | *s* | 30.6 | | | | | | | | |

**Table S4.** (continued and end).



| CIP | | | |
|---|---|---|---|
| | | | |
| | Water mass | *kg* | 24423 |
| | Acid dertergent mass | *kg* | 13 |
| | Alcalin detergent mass | *kg* | 35 |
| | Electricity | *Wh* | 15928 |
| | Steam mass | *kg* | 2920 |
| | Natueal gas volume | *m3* | 223 |
| | (total per day) | | |

Note explaining the difference between UF and CE for steam and natural gas consumption: The regenerative design of the heat exchangers (Figure S1) uses the hot skimmed-milk circulating in the system after thermal treatment at 90 °C to pre-heat the raw milk up to 55°C before skimming. The upper flow rate of the hot skimmed milk (18.56 $m^3 h^{-1}$) for CE improves heat exchange with the cold raw milk section before skimming as compared to the outgoing hot concentrated skimmed milk (5.90 $m^3 h^{-1}$) from the thermal treatment section for UF.

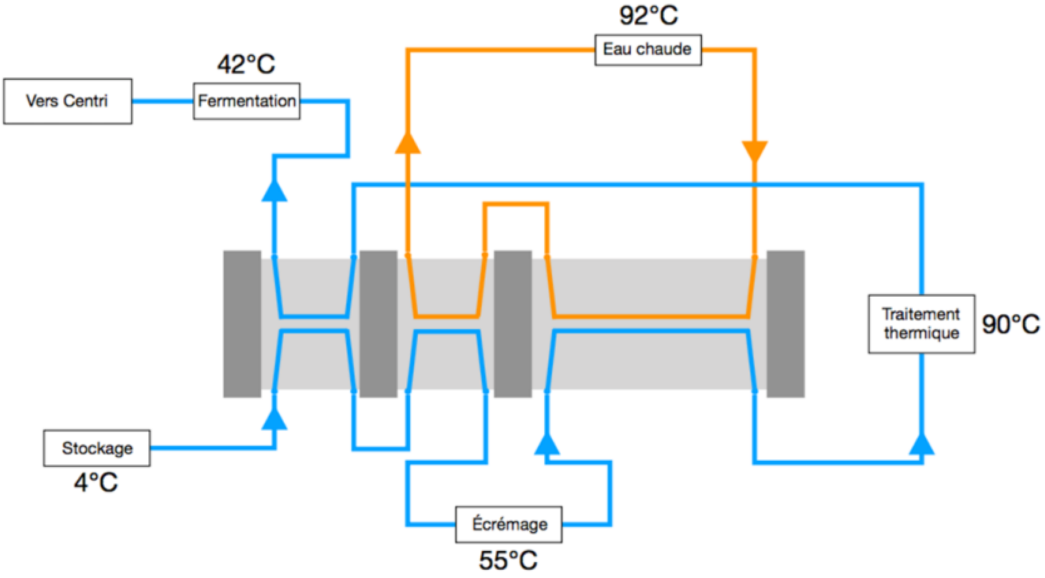
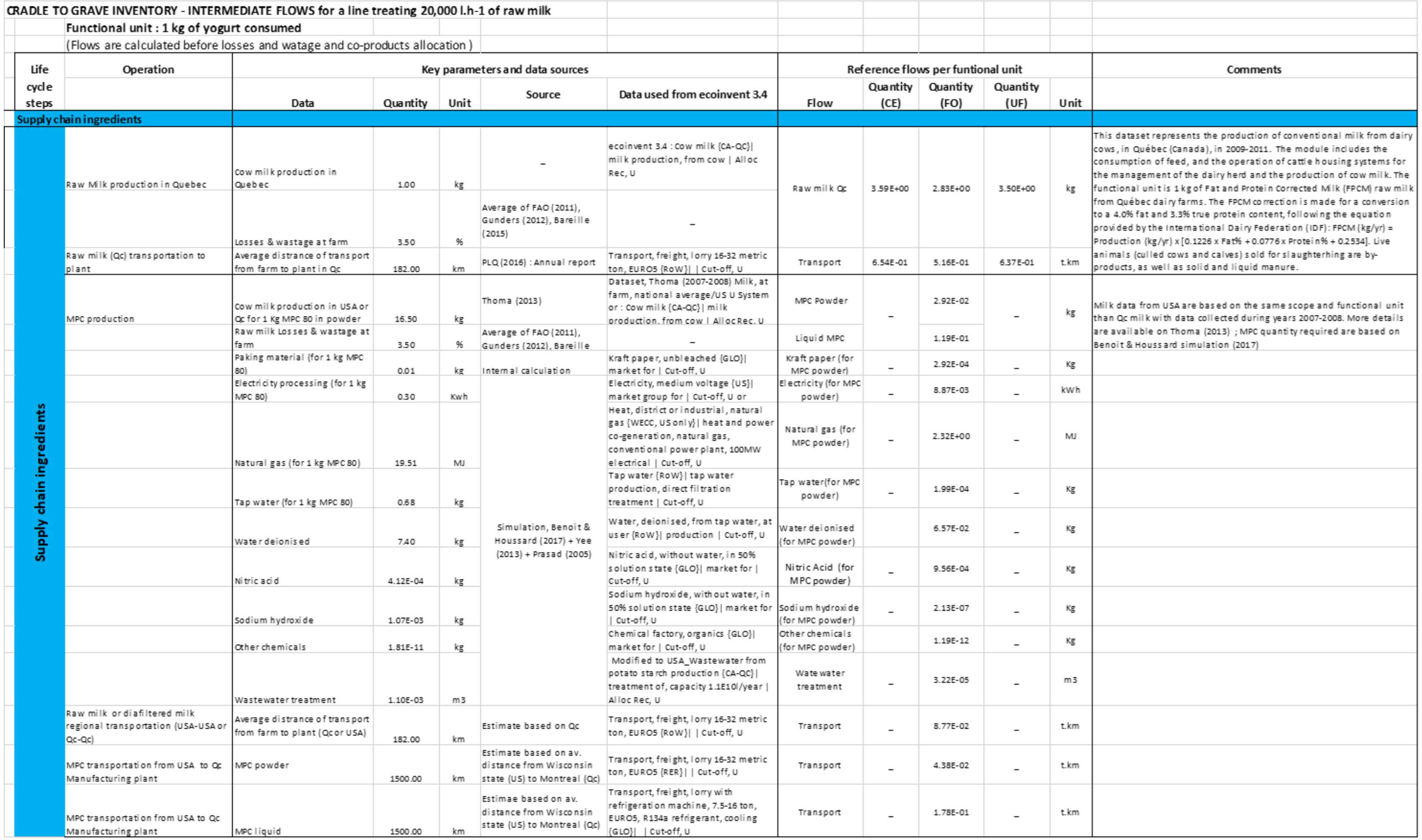


**Figure 1.** CE, FO and UF Heat exchanger design: cooling and heating regeneration system.

## S4. Life Cycle Inventory: Key Parameters and Reference Flows

**Table S5.** LCA key parameters and reference flows.



**CRADLE TO GRAVE INVENTORY - INTERMEDIATE FLOWS for a line treating 20,000 l.h-1 of raw milk**

**Functional unit : 1 kg of yogurt consumed**

(Flows are calculated before losses and watage and co-products allocation )

| Life cycle steps | Operation | Key parameters and data sources | | | | | Reference flows per funtional unit | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Data | Quantity | Unit | Source | Data used from ecoinvent 3.4 | Flow | Quantity (CE) | Quantity (FO) | Quantity (UF) | Unit | |
| **Supply chain ingredients** | | | | | | | | | | | | |
| **Supply chain ingredients** | Raw Milk production in Quebec | Cow milk production in Quebec | 1.00 | kg | – | ecoinvent 3.4 : Cow milk {CA-QC}\| milk production, from cow \| Alloc Rec, U | Raw milk Qc | 3.59E+00 | 2.83E+00 | 3.50E+00 | kg | This dataset represents the production of conventional milk from dairy cows, in Québec (Canada), in 2009-2011. The module includes the consumption of feed, and the operation of cattle housing systems for the management of the dairy herd and the production of cow milk. The functional unit is 1 kg of Fat and Protein Corrected Milk (FPCM) raw milk from Québec dairy farms. The FPCM correction is made for a conversion to a 4.0% fat and 3.3% true protein content, following the equation provided by the International Dairy Federation (IDF): FPCM (kg/yr) = Production (kg/yr) x [0.1226 x Fat% + 0.0776 x Protein% + 0.2534]. Live animals (culled cows and calves) sold for slaughterhing are by-products, as well as solid and liquid manure. |
| | | Losses & wastage at farm | 3.50 | % | Average of FAO (2011), Gunders (2012), Bareille (2015) | – | | | | | | |
| | Raw milk (Qc) transportation to plant | Average distrance of transport from farm to plant in Qc | 182.00 | km | PLQ (2016) : Annual report | Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}\| \| Cut-off, U | Transport | 6.54E-01 | 5.16E-01 | 6.37E-01 | t.km | |
| | MPC production | Cow milk production in USA or Qc for 1 Kg MPC 80 in powder | 16.50 | kg | Thoma (2013) | Dataset, Thoma (2007-2008) Milk, at farm, national average/US U System or : Cow milk {CA-QC}\| milk production, from cow \| Alloc Rec. U | MPC Powder | – | 2.92E-02 | – | kg | Milk data from USA are based on the same scope and functional unit than Qc milk with data collected during years 2007-2008. More details are available on Thoma (2013) ; MPC quantity required are based on Benoit & Houssard simulation (2017) |
| | | Raw milk Losses & wastage at farm | 3.50 | % | Average of FAO (2011), Gunders (2012), Bareille | – | Liquid MPC | | 1.19E-01 | | | |
| | | Paking material (for 1 kg MPC 80) | 0.01 | kg | Internal calculation | Kraft paper, unbleached {GLO}\| market for \| Cut-off, U | Kraft paper (for MPC powder) | – | 2.92E-04 | – | Kg | |
| | | Electricity processing (for 1 kg MPC 80) | 0.30 | Kwh | Simulation, Benoit & Houssard (2017) + Yee (2013) + Prasad (2005) | Electricity, medium voltage {US}\| market group for \| Cut-off, U or | Electricity (for MPC powder) | – | 8.87E-03 | – | kWh | |
| | | Natural gas (for 1 kg MPC 80) | 19.51 | MJ | | Heat, district or industrial, natural gas {WECC, US only}\| heat and power co-generation, natural gas, conventional power plant, 100MW electrical \| Cut-off, U | Natural gas (for MPC powder) | – | 2.32E+00 | – | MJ | |
| | | Tap water (for 1 kg MPC 80) | 0.68 | kg | | Tap water {RoW}\| tap water production, direct filtration treatment \| Cut-off, U | Tap water(for MPC powder) | – | 1.99E-04 | – | Kg | |
| | | Water deionised | 7.40 | kg | | Water, deionised, from tap water, at user {RoW}\| production \| Cut-off, U | Water deionised (for MPC powder) | | 6.57E-02 | – | Kg | |
| | | Nitric acid | 4.12E-04 | kg | | Nitric acid, without water, in 50% solution state {GLO}\| market for \| Cut-off, U | Nitric Acid (for MPC powder) | – | 9.56E-04 | – | Kg | |
| | | Sodium hydroxide | 1.07E-03 | kg | | Sodium hydroxide, without water, in 50% solution state {GLO}\| market for \| Cut-off, U | Sodium hydroxide (for MPC powder) | – | 2.13E-07 | – | Kg | |
| | | Other chemicals | 1.81E-11 | kg | | Chemical factory, organics {GLO}\| market for \| Cut-off, U | Other chemicals (for MPC powder) | | 1.19E-12 | – | Kg | |
| | | Wastewater treatment | 1.10E-03 | m3 | | Modified to USA_Wastewater from potato starch production {CA-QC}\| treatment of, capacity 1.1E10l/year \| Alloc Rec, U | Wate water treatment | – | 3.22E-05 | – | m3 | |
| | Raw milk or diafiltered milk regional transportation (USA-USA or Qc-Qc) | Average distrance of transport from farm to plant (Qc or USA) | 182.00 | km | Estimate based on Qc | Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}\| \| Cut-off, U | Transport | – | 8.77E-02 | – | t.km | |
| | MPC transportation from USA to Qc Manufacturing plant | MPC powder | 1500.00 | km | Estimate based on av. distance from Wisconsin state (US) to Montreal (Qc) | Transport, freight, lorry 16-32 metric ton, EURO5 {RER}\| \| Cut-off, U | Transport | – | 4.38E-02 | – | t.km | |
| | MPC transportation from USA to Qc Manufacturing plant | MPC liquid | 1500.00 | km | Estimae based on av. distance from Wisconsin state (US) to Montreal (Qc) | Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, cooling {GLO}\| \| Cut-off, U | Transport | – | 1.78E-01 | – | t.km | |

| Life cycle steps | Operation | Key parameters and data sources | | | | | Reference flows per funtional unit | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Data | Quantity | Unit | Source | Data used from ecoinvent 3.4 | Flow | Quantity (CE) | Quantity (FO) | Quantity (UF) | Unit | |
| **Supply chain primary packaging** | | | | | | | | | | | | |
| Supply chain - Primary Packaging | PP Polypropylene container | PP container size | 500.00 | g | Manufacturers Survey, Houssard (2017-2018) | – | **Total PP containers** | **1.77E-02** | **1.77E-02** | **1.77E-02** | kg | Major part of GY production in Quebec & Ontario is sold in 500 ml container (of 612 ml / 500 g product capacity) mostly thermoformed, but thermoformed pack of 100 g in PS are growing. For the purpose of this study only bulk container of 612 ml are included. |
| | | Weight | 17.50 | g | Manufacturers Survey, Houssard (2017-2018) | Polypropylene, granulate {GLO}\| market for \| Cut-off, U | Thermoformed PP containers | 1.51E-02 | 1.51E-02 | 1.51E-02 | kg | |
| | | Rate of thermoformed PP containers | 85.00 | % | Manufacturers Survey, Houssard (2017-2018) + Plastipak interview (2014) | Modified_Thermoforming of plastic sheets {CA}\| processing \| Alloc Rec, U | Injected PP containers | 2.55E-03 | 2.55E-03 | 2.55E-03 | kg | |
| | | Rate of injected PP containers | 15.00 | % | Manufacturers Survey, Houssard (2017-2018) + Plastipak interview (2014) | Injection moulding {CA-QC}\| injection moulding \| Cut-off, U | Thermoforming process | 3.76E-02 | 3.76E-02 | 3.76E-02 | kg | Incuding thermoformed PS containers and PP containers |
| | | Rate of PP containers on total (PS+PP) | 50.00 | % | Manufacturers Survey, Houssard (2017-2018) + ecoinvent 3.4 documentation, yogurt production, from cow milk CA-QC | – | Injection process | 2.94E-03 | 2.94E-03 | 2.94E-03 | kg | Including injection of HDPE lids |
| | | Injection process yield | 99.40 | % | ecoinvent documentation | Injection moulding {CA-QC}\| injection moulding \| Cut-off, U | | | | | | |
| | | Thermoformed process yield | 94.60 | % | ecoinvent documentation | Modified_Thermoforming of plastic sheets {CA}\| processing \| Alloc Rec, U | | | | | | |
| | | Pastic waste at plant | 0.0040 | kg/kg of GY | Gonzalez-Garcia (2013) | – | | | | | | Plastic waste at plant is attributed at 50 % to PP containers and 50 % to PS containers |
| | | PP Recycling rate | 14.70 | % | Recyc-Québec (2017); Recyc-Québec (2015) | – | | | | | | Recycling rate is deducted from raw material quantity based on end of life recycling methodology. PP is recycled but PS is not recycled in current Quebec facilities. |
| | PS Polystyrene container | PS container size | 100.00 | g | Manufacturers Survey, Houssard (2017-2018) | | | | | | | |
| | | Weight | 3.49 | g | Calculated based on ecoinvent 3.3 documentation, yogurt production, from cow milk CA-QC + Manufacturers Survey, Houssard (2017-2018); direct weighting Liberté container = 4 g | Polystyrene, general purpose {GLO}\| market for \| Cut-off, U | Thermoformed PS containers | 2.04E-02 | 2.04E-02 | 2.04E-02 | kg | Containers are thermoformed on line at milk processor plant |
| | | Rate of thermoformed PS containers | 100.00 | % | Manufacturers Survey, Houssard (2017-2018) | Modified_Thermoforming of plastic sheets {CA}\| processing \| Alloc Rec, U | Thermoforming process | 2.04E-02 | 2.04E-02 | 2.04E-02 | kg | |
| | | Rate of PS containers on total (PS + PP) | 50.00 | % | Manufacturers Survey, Houssard (2017-2018) | | | | | | | There is a swich in trend towards individual containers in PS to high volumes 500 g and + PP containers. Current estimation is tested in the sensibility analyses. |
| | Sealing | Weight of PET Seal for 500 g PP container | 0.50 | g | Extrapolated from Keoleian (2004) | Polyethylene terephthalate, granulate, amorphous {GLO}\| market for \| Cut-off, U | PET seal | 5.12E-04 | 5.12E-04 | 5.12E-04 | kg | |
| | | Extrusion process yield | 97.60 | % | ecoinvent documentation | Extrusion, plastic film {CA-QC}\| production \| Cut-off, U | Extrusion process | 7.68E-03 | 7.68E-03 | 7.68E-03 | Kg | Including extrusion of HDPE lids and PET seals |
| | | Weight of laminated paper Seal for 100 g PS container | 0.24 | g | Manufacturers Survey, Houssard (2017-2018) | Proxy Paper, melamine impregnated {GLO}\| market for \| Cut-off, U | Laminated paper seal | 1.20E-03 | 1.20E-03 | 1.20E-03 | kg | |
| | Lid HDPE | Weight of Lid for 500 g PP container | 7.00 | g | Manufacturers Survey, Houssard (2017-2018) | Polyethylene, high density, granulate {GLO}\| market for \| Cut-off, U | HDPE Lid | 7.17E-03 | 7.17E-03 | 7.17E-03 | kg | |
| | Cardboard | Average Weight for 100 g container wraping (4 or 8 packs) | 22.68 | g | Extrapolated from Keoleian (2004); direct measure : Liberté GY 4 paks : 19 g | Solid bleached board {CA-QC}\| production \| Cut-off, U | Cardboard | 5.73E-03 | 5.73E-03 | 5.73E-03 | kg | Estimated average of 6 containers per pack. 73 % is recycled. Recycled material is credited with the cut-off mdeling and not included here. |
| | | Cardboard waste at plant | 2.15 | g/kg YG | Gonzalez-Garcia (2013) | – | | | | | | |
| **Supply chain secondary packaging** | | | | | | | | | | | | |
| S. chain - 2ry packaging | Corrugated board | Weight for 6 packs of 500 g countainer per tray | 95.00 | g | Manufacturers Survey, Houssard (2017-2018) + Estimation based on Keoleian (2004) per Interpolation | Corrugated board box {CA-QC}\| production \| Cut-off, U | Corrugated board | 1.33E-02 | 1.33E-02 | 1.33E-02 | kg | Mix of trays (6*500 g) and boxes (24*100g) recycled at 73 % (0.79*0.0.925). Recycled material is credited with the cut-off mdeling and not included here. |
| | | Weight for a box of 24 units of | 158.00 | g | Keoleian (2004) | | | | | | | |
| | Wood pallet | Weight | 18.14 | Kg | | | | | | | | |
| | | Number of reused | 300.00 | times | Keoleian (2004) | EUR-flat pallet {GLO}\| market for \| Cut-off, U | Wood Pallet | 1.41E-04 | 1.41E-04 | 1.41E-04 | kg | |
| | | Number of 500 g countainer per | 780.00 | u | | | | | | | | |
| | | Number of 100 g container per | 4800.00 | u | | | | | | | | |
| | Stretch Wrap film (LLDPE) | LLDPE Weight per pallet | 331.00 | g | Keoleian (2004) | Polyethylene, linear low density, granulate {GLO}\| market for \| Cut-off, U | LLDPE | 7.88E-04 | 7.88E-04 | 7.88E-04 | kg | Recycling and losses included in PP and PS containers. |
| | | Extrusion process yield | 97.60 | % | ecoinvent documentation | Extrusion, plastic film {CA-QC}\| production \| Cut-off, U | Extrusion process | 7.88E-04 | 7.88E-04 | 7.88E-04 | kg | |

| Life cycle steps | Operation | Key parameters and data sources | | | | | Reference flows per funtional unit | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Data | Quantity | Unit | Source | Data used from ecoinvent 3.4 | Flow | Quantity (CE) | Quantity (FO) | Quantity (UF) | Unit | |
| **GY plant processing** | | | | | | | | | | | | |
| **Plant processing** | Milk filling & storage at 4°C | Electricity consumption at 20000 l.h-1 | 816 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.36E-04 | 1.07E-04 | 1.33E-04 | kWh | Simulation is based on a line running at 20000 l.h-1 (raw milk input) eq. to treating 20747 kg.h-1 of milk (based on a density of 1037 g.l-1 at 4 °C.<br>Raw milk is stored into 2 insulated silos of 10 m3 filled by the buttom to avoid air incorporation in milk. Milk stays around 1 hour in silo. |
| | | Raw milk flow at input | 20,000 | l.h-1 | Manufacturers Survey, Houssard (2017-2018) | | | | | | | |
| | | Milk density at 4°C | 1,037 | kg.l-1 | Amiot (2010) Science et technologie du lait | | | | | | | |
| | | CE : GY output | 5,979 | kg.h-1 | Simulation Benoit & Houssard (2017) | | | | | | | |
| | | FO : GY output | 7,597 | kg.h-1 | | | | | | | | |
| | | UF : GY output | 6,145 | kg.h-1 | | | | | | | | |
| | Heating raw milk at 55°C | CE : electricy consumption | 930 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.55E-04 | 1.27E-04 | 2.46E-04 | kWh | Raw milk is heated from 4 to 55 °C in a heat exchanger of 217 m2 in 61s. Energy required is optimized by a heat exchanger regeneration system all along the process line (skimming heating, thermal treatment and fermentation). Natural gas consumption for all the heating processes is attributed to the heating treatment process only. There is no need for external heating source in between 4 and 55°C (heat exchanged with |
| | | FO : electricy consumption | 966 | Wh | | | | | | | | |
| | | UF : electricy consumption | 1514 | Wh | | | | | | | | |
| | Skimming | skimmer | 10,796 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 3.61E-03 | 2.84E-03 | 3.51E-03 | kWh | 2 skimmers with a capacity of 10 m3.h-1 of milk at entrance and 1.06 m3.h-1 of cream at discharge each are used. Simulation results provide a good fat yield : Only 0.04 % of fat remained in skimmed milk after skimming. |
| | | Number of skimmer | 2 | u | | | Skimmed milk | 3.13E+00 | 2.46E+00 | 3.04E+00 | kg | |
| | | Skimmed milk | 9354 | kg.h-1 | | | Cream | 3.41E-01 | 2.69E-01 | 3.32E-01 | kg | |
| | | Cream | 1020 | kg.h-1 | | | | | | | | |
| | Protein rehydratation (FO-P-US only) | FO-P-US : electricy consumption | 5720 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity FO-P-US | – | 7.53E-04 | – | kWh | The milk protein concentrate (MPC) powder is first rehydrated with water to reach 24 % (w/w) concentration, then mixed to the skimmed milk in order to reach 4,2% (w/w) proteins in the fortified skimmed milk. When the MPC comes in liquid form instead of power, the first step of rehydration is avoided resluting in water and energy savings. |
| | | FO-P-US : water consumption | 512 | kg | | Adapted to Qc-CA from - Water, deionised, from tap water, at user {CH}\| production \| Alloc Rec, U | Water deionised FO-P-US | – | 6.73E-02 | – | kg | |
| | Mixing (FO only) | FO : electricity consumption (mixing only) | 584 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity FO-L-US & Qc | – | 7.68E-05 | – | kWh | |
| | Ultrafiltration | UF : electricy consumption | 6203 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | – | – | 1.01E-03 | kWh | molecular weight spiral PES membrane under a transmembrane pressure of 5,51E5 Pa at at 55°C |
| | | Retentate output | 6145 | kg | | | Retentate output | – | – | 1.00E+00 | Kg | |
| | | Permeate output (whey) | 12563 | kg | | | Whey output | – | – | 2.04E+00 | Kg | |
| | Thermal treatment at 90°C for 5 minutes | CE : electricy consumption | 8608 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.44E-03 | 1.35E-03 | 1.04E-03 | kWh | The heat exchanger is part of the regeneration system (see figure in CE, Fo, UF Simulation). All natural gas consummed on the line for water heating is included in this operation. The boiler makes steam water at 5 bar and 150 °C (ratio NG/Steam = 0.0765 m3.kg-1). Zero water/steam loss has been considered at the boiler. |
| | | FO : electricy consumption | 10258 | Wh | | | | | | | | |
| | | UF : electricy consumption | 6387 | Wh | | | | | | | | |
| | | CE : natural gas consumption | 99 | m3.h-1 | | Heat, district or industrial, natural gas {CA-QC}\| market for \| Cut-off, U | Natural gas | 6.18E-01 | 4.90E-01 | 7.37E-01 | MJ | |
| | | FO : natural gas consumption | 99.7 | m3.h-1 | | | | | | | | |
| | | UF : natural gas consumption | 121.4 | m3.h-1 | | | | | | | | |
| | | Natural gas converted rate in MJ | 37.3 | MJ.m3 | Office National de l'énergie du Canada (2018) | | | | | | | |
| | Homogeneisation at 65 °C & 170-200 bars (optional) | Cooling at 65°C electricy cons. | 1,824 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.74E-02 | – | – | KWh | Homogeneisation process has been simulated only for the CE option. Homogenisation is usually done before thermal treatment when partial skimming is operated and at this step (between thermal treatment and fermentation) when a full skimming is operated. |
| | | Hommogeneisation electricy | 101,812 | Wh | | | | | | | | |
| | | 42°C electricy cons. | 398 | Wh | | | | | | | | |
| | Cooling at 42°C | CE : electricy consumption | 1479 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 2.47E-04 | 2.08E-04 | 4.05E-05 | kWh | The heat exchanger is part of the regeneration system. Heat exchange with cold milk at 4°C in this section. |
| | | FO : electricy consumption | 1583 | Wh | | | | | | | | |
| | | UF : electricy consumption | 249 | Wh | | | | | | | | |
| | Fermentation at 42°C for 5 to 8 hours | CE : electricy consumption | 1718 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 2.87E-04 | 2.46E-04 | 4.39E-05 | kWh | Fermentation is done by batch of 5 to 8 hours. 1 hour of CIP is included between 2 batchs. Tank stiring is not included. Stiring is done at pump dischage. Electricity included is for pump at intrance and discharge. Cooling water to maintain tank temperature is not included at this step (all waterflows are supposed to be recirculated). |
| | | FO : electricy consumption | 1865 | Wh | | | | | | | | |
| | | UF : electricy consumption | 270 | Wh | | | | | | | | |
| | Centrifugation at 35 - 40°C | electricy consumption per separator | 45000 | Wh | GEA Technical sheet - Separator KDE 45-02-076 | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.51E-02 | 1.18E-02 | – | kWh | GY concentration is done using 2 separators. GY mathematical model of centrifugation were not available at time of simulation. Data has been collected directly from the manufacturer (GEA) and the GY manufacturers. Rejection rate are calculated based on % proteins in whey (0.3 % in CE and 0.48 % in FO). Final results reported here are slighty different from the 2017 data included in the simulation datasheets . |
| | | Nb of separators | 2 | u | GEA Technical sheet - Separator KDE 45-02-076 | | GY output | 1.00E+00 | 1.00E+00 | – | kg | |
| | | CE : protein rejection rate | 5.6 | % | Manufacturers Survey, Houssard (2017-2018) -> 0,3 % proteins in whey | | Whey output | 2.13E+00 | 1.56E+00 | – | kg | |
| | | FO : protein rejection rate | 8.4 | % | Manufacturers Survey, Houssard (2017-2018) -> 0.48 % proteins in whey | | | | | | | |
| | | CE : GY output | 5,979 | kg | Calculation - Mass balance | | | | | | | |
| | | FO GY output | 7,597 | kg | Calculation - Mass balance | | | | | | | |
| | | CE : whey output | 12,729 | kg | Calculation - Mass balance | | | | | | | |
| | | FO : whey output | 11,845 | kg | Calculation - Mass balance | | | | | | | |
| | Cooling at 15°C | CE : electricy consumption | 18,545 | Wh | Simulation Benoit & Houssard (2017) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 3.10E-03 | 3.54E-03 | 3.05E-03 | kWh | Cooling is done as quick as possible (30 s.) to reduce the bacteria activity and to stabilize the pH. The concentrated fermented milk is cooled in an annular heat exchanger of 8.7 m2 . The cooling circuit use propylène glycol at 50 % in a closed loop. 289 kg of propylen glycol circulate in the cooling circuit. Based on processing specialists recommandation, there is no product loss. Therefore propylen glycol impacts are supposed negligeable and are not included. |
| | | FO : electricy consumption | 26,875 | Wh | | | | | | | | |
| | | UF : electricy consumption | 18,768 | Wh | | | | | | | | |

| Life cycle steps | Operation | Key parameters and data sources | | | | | Reference flows per funtional unit | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Data | Quantity | Unit | Source | Data used from ecoinvent 3.4 | Flow | Quantity (CE) | Quantity (FO) | Quantity (UF) | Unit | |
| **Plant processing** | CIP | Number of hours of operation per day (yogurt production) | 16 | h/d | Simulation, Benoit & Houssard (2017) + Yee (2013) | | | | | | | |
| | | CE and UF : Electricity consumption per day | 15,928 | Wh/d | | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | | | | | | |
| | | FO : Electricity consumption | 19,910 | Wh/d | | | Electricity | 1.67E-04 | 1.64E-04 | 1.62E-04 | kWh | |
| | | CE & UF : Water consumption per day | 24,423 | kg/d | | Modified from {CH}\|- Water, deionised, from tap water, at user {CA-Qc}\| production \| AllocRec, U | Water | 2.55E-01 | 2.51E-01 | 2.48E-01 | kg | |
| | | FO : Water consumption per | 30,529 | kg/d | | | Natural gas | 8.71E-02 | 8.57E-02 | 8.48E-02 | MJ | |
| | | boiler | 8,333 | MJ/d | | Heat, district or industrial, natural gas {CA-QC}\| market for \| Cut-off, U | Nitric Acid | 1.39E-04 | 1.37E-04 | 1.35E-04 | kg | |
| | | FO : Natural gas for boiler | 10,416 | MJ/d | | | Sodium hydroxyde | 3.61E-04 | 3.55E-04 | 3.51E-04 | kg | |
| | | CE and UF : Nitric Acid | 13 | kg/d | | Nitric acid, without water, in 50% solution state {GLO}\| market for \| Cut-off, U | | | | | | |
| | | FO : Nitric acid | 17 | kg/d | | | | | | | | |
| | | CE and UF : Sodium hydroxyde | 35 | kg/d | | Sodium hydroxide, without water, in 50% solution state {GLO}\| market for \| Cut-off, U | | | | | | |
| | | FO : Sodium hydroxyde | 43 | kg/d | | | | | | | | |
| | Packaging and storage at $4^{0}$C | Electricity consumption | 85,112 | Wh | Calculation based on Prasad 2004,2005) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.42E-02 | 1.42E-02 | 1.42E-02 | kWh | Prasad (2004,2005) : packaging up to 12 % of total energy cost and refrigeration and storage up to 18 % of total energycost. Since it is based on general data, identical flows are attributed to each option (not a factor of differenciation between options). |
| | General utilities | Plant ventilation and lighting | 56,741 | Wh | Calculation based on Prasad 2004,2005) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Eletricity | 9.49E-03 | 9.49E-03 | 9.49E-03 | kWh | Prasad (2004,2005) : up to 19 % of total energy cost |
| | | General waterusage | 17,586 | kg.h-1 | Calculation based on Gonzalez-Garcia (2013) | Tap water {CA-QC}\| market for \| Cut-off, U corrected | Tap water | 2.94E+00 | 2.31E+00 | 2.86E+00 | Kg | Difference of Gonzalez-Garcia (2013) study and water consumption flow from CIP included in the simulation. |
| | Wastewater treatment | CE & UF : Water treatment | 19.11 | m3 | Calculated based on CIP anf general water flow. | Proxy based on COD =2 kg/m3. Adapted Wastewater from {CH} Wastewater from potato starch production {CA-QC}\| treatment of, | Wastewater treatment | 3.20E-03 | 2.57E-03 | 3.11E-03 | m3 | |
| | | FO : Water treatment | 19.49 | m3 | | | | | | | | |
| | Plant solid wastes | Plastic per ton of yogurt | 4.00 | Kg/t | Gonzalez-Garcia (2013) | Waste plastic, mixture {RoW}\| treatment of waste plastic, mixture, sanitary landfill \| Cut-off, U | Platic Mix landfill disposal | 4.00E-03 | 4.00E-03 | 4.00E-03 | Kg | |
| | | Cardboard & paper per ton of yogurt | 2.15 | Kg/t | Gonzalez-Garcia (2013) | Waste paperboard {RoW}\| treatment of, sanitary landfill \| Cut-off, U or Paper (waste treatment) {GLO}\| recycling of paper \| Cut-off, U | Cardboard landfill disposal | 5.85E-04 | 5.85E-04 | 5.85E-04 | Kg | |
| | | Municipal Waste transportatio | 100 | km | Assumption | Municipal waste collection service by 21 metric ton lorry {RoW}\| processing \| Cut-off, U | Cardboard recycled | 1.56E-03 | 1.56E-03 | 1.56E-03 | Kg | |
| | | | | | | | Waste collection | 6.15E-04 | 6.15E-04 | 6.15E-04 | t.km | |

| Life cycle steps | Operation | Key parameters and data sources | | | | | Reference flows per funtional unit | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Data | Quantity | Unit | Source | Data used from ecoinvent 3.4 | Flow | Quantity (CE) | Quantity (FO) | Quantity (UF) | Unit | |
| **Distribution** | | | | | | | | | | | | |
| **Distribution** | Transportation | Average nb of km from plant to ditribution central and groceries | 145.00 | km | Calculation based on average distances (round trip) between Ste-Hyacinthe and the major towns in Quebec regrouping 85 % of the population | Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, cooling {GLO}\| market for \| Cut-off, U | Transportation in refrigerated truck | 1.45E-01 | 1.45E-01 | 1.45E-01 | t.km | Calculation based on av.distance between plant and cities regrouping 85 % of the population |
| | Refirgeration, lighting and air conditionning at retail | Average time of refrigeration at retailer | 186.10 | Kwh/t | Gonzalez-Garcia (2013) | Electricity, medium voltage {CA-QC}\| market for \| Cut-off, U | Electricity | 1.86E-01 | 1.86E-01 | 1.86E-01 | KWh | |
| | Solid Waste | Plastic wrap to landfill | 0.0008 | kg/kg GY | Calculation based on secondary packaging quantity | Waste plastic, mixture {RoW}\| treatment of waste plastic, mixture, sanitary landfill \| Cut-off, U | Platic waste | 7.88E-04 | 7.88E-04 | 7.88E-04 | kg | Plastic is assumed to be 100% landfill. % of plastic recycled is done on PP and PET containers. |
| | | Corrugated box landfill | 0.0133 | kg/kg GY | Calculation based on secondary packaging quantity | Paper (waste treatment) {GLO}\| recycling of paper \| Cut-off, U | Corrugated waste | 1.33E-02 | 1.33E-02 | 1.33E-02 | kg | |
| | | Corrugated box recycling | 0.0355 | kg/kg GY | Calculation based on packaging and end-of-life section | Paper (waste treatment) {GLO}\| recycling of paper \| Cut-off, U | Corrugated recycling | 3.55E-02 | 3.55E-02 | 3.55E-02 | kg | Recycled corugated board is not included in secondary packaging flow. It is a credit due to the cut off modeling. |
| | | Municipal Waste transportatio | 100 | km | Assumption | Municipal waste collection service by 21 metric ton lorry {RoW}\| processing \| Cut-off, U | Waste collection | 4.95E-03 | 4.95E-03 | 4.95E-03 | t.km | |
| **Consumption** | | | | | | | | | | | | |
| **Consumption** | Transportation | Average nb of km in car (round trip) from grocery to household in Québec | 4.75 | Km/trip | Calculation based on données de Institut de la statisitique du Québec - Régions - Panorama des régions du Québec, edition | Transport, passenger car, medium size, petrol, EURO 5 {RoW}\| transport, passenger car, medium size, petrol, EURO 5 \| Cut-off, U | Transportation | 1.46E-01 | 1.46E-01 | 1.46E-01 | km | |
| | | Number of kg of yogurt per household per year | 4.60 | kg/year | Calculation based on http://www.groupeageco.ca/fsl/; http://www.stat.gouv.qc.ca/statistiques/population-demographie/familles-menages/tableau_04.htm; Nielsen (2017) | | | | | | | Calculation is as followed : Av. Round trip (4.75 km)* x Nb of trip per year (52) x % of dairies in grocery basket (15%) x % of yogurt in dairies (10/110 = 9.09 %) x % Marjket share of GY (20%) / Nb of kg of yogurt/p/year (10 kg) x Market share of GY (20%) x Av. Nb of person/household (2.3 p).<br>(*) Av. Round trip is based on distance median in meter to the nearest grocery store. |
| | | % of greek yogurt in grocery basket | 0.0027 | % | https://www.inspq.qc.ca/sites/default/files/publications/1766_resume.pdf; http://www.groupeageco.ca/fsl/ | | | | | | | |
| | | Average nber of trip in car to grocery | 52 | u | Assumption | | | | | | | |
| | plastic bag used for transportation | Nb of platic bag per ton of yogu | 4.00 | kg/t | Hospido A, Vazquez ME, Cuevas A, Feijoo G, Moreira MT (2006) Environmental assessment of canned tuna manufacture with a life-cycle perspective. Resour Conserv Recy 47:56–72 | Polyethylene, high density, granulate {GLO}\| market for \| Cut-off, U and Extrusion, plastic film {CA-QC}\| production \| Cut-off, U | Pastic | 2.00E-03 | 2.00E-03 | 2.00E-03 | Kg | Data is divided by 2 because pastig bag consunmption has been reduced by 52 % in between 2007 and 2010 https://ici.radio-canada.ca/nouvelle/571093/reduction-sacs-quebec |
| | Refirgeration + heating water | Eletricity per ton of yogurt | 54.70 | kWh/t | Gonzalez-Garcia (2013) | Electricity, low voltage {CA-QC}\| market for \| Cut-off, U | Eletricity | 5.47E-02 | 5.47E-02 | 5.47E-02 | KWh | Gonzalez-Garcia has based its energy consumption calculation on the volume occupied per yogurt in the refrigerator. |
| | Water for cleaning | Tap water per ton of yogurt | 804.50 | kg/t | Gonzalez-Garcia (2013) | Tap water {CA-QC}\| market for \| Cut-off, U corrected | Tap water | 8.05E-01 | 8.05E-01 | 8.05E-01 | Kg | Spoon, cup and dishwashing are not considered - negligeable impacts |
| | Waste water treatment | Waste water from cleaning | 804.50 | Kg/t | Gonzalez-Garcia (2013) | Wastewater, average {CA-QC}\| treatment of wastewater, average, capacity 4.7E10l/year \| Cut-off, U | Waste water treatment | 8.05E-04 | 8.05E-04 | 8.05E-04 | m3 | |

| Life cycle steps | Operation | Key parameters and data sources | | | | | Reference flows per funtional unit | | | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Data | Quantity | Unit | Source | Data used from ecoinvent 3.4 | Flow | Quantity (CE) | Quantity (FO) | Quantity (UF) | Unit | |
| **Product final disposal** | | | | | | | | | | | | |
| **Final disposal** | Recycling | Paper, Cardboard | 79.00 | % | Recyc-Quebec (2015) Bilan de la gestion des matières résiduelles au Québec | | | | | | | |
| | | Pastic recovered | 16.00 | % | Recyc-Quebec (2015) | | | | | | | |
| | | Organic matter recovered | 21.00 | % | Recyc-Quebec (2015) | | | | | | | |
| | | Av. Reject rate | 7.90 | % | Recyc-Quebec (2015) | | | | | | | |
| | | PS is not recycled in Quebec | | | | | | | | | | |
| | Final disposal | Landfill | 96.72 | % | Recyc-Quebec (2015) | | | | | | | Has been approximate to 100 % landfill |
| | | Incinerator | 3.28 | % | Recyc-Quebec (2017) Bilan de la gestion des matières résiduelles au Québec | | | | | | | |
| | Pastic bag final disposal | Plastic bag recycling | 0.5894 | Kg/t | Calculation based on packaging and recycling data | Mixed plastics (waste treatment) {GLO}\| recycling of mixed plastics \| Cut-off, U | PET recycling | 2.95E-04 | 2.95E-04 | 2.95E-04 | kg | Data is divided by 2 because pastic bag consunmption has been reduced by 52 % in between 2007 and 2010 https://ici.radio-canada.ca/nouvelle/571093/reduction-sacs-quebec |
| | | Plastig bag to landfill | 3.4106 | Kg/t | Calculation based on packaging and recycling data | Waste plastic, mixture {RoW}\| treatment of waste plastic, mixture, sanitary landfill \| Cut-off, U | PP recycling | 2.30E-03 | 2.30E-03 | 2.30E-03 | | Data is divided by 2 because pastic bag consunmption has been reduced by 52 % in between 2007 and 2010 https://ici.radio-canada.ca/nouvelle/571093/reduction-sacs-quebec |
| | GY containers disposal | Plastic recycling | 0.0023 | kg/kg GY | Calculation based on packaging and recycling data | | PET waste | 1.71E-03 | 1.71E-03 | 1.71E-03 | | |
| | | Plastic to landfill | 0.0395 | kg/kg GY | Calculation based on packaging and recycling data | | Plastic waste | 3.95E-02 | 3.95E-02 | 3.95E-02 | kg | |
| | | Cardboard recycling | 0.0138 | kg/kg GY | Calculation based on packaging and recycling data | | Cardboard recycling | 1.38E-02 | 1.38E-02 | 1.38E-02 | Kg | |
| | | Cardboard to landfill | 0.0063 | kg/kg GY | Calculation based on packaging and recycling data | | Cardboard to landfill | 6.35E-03 | 6.35E-03 | 6.35E-03 | kg | |

## S5. MPC allocation factors

**Table 6.** MPC production systems in the USA or Québec: mass and economic allocation factors at each point of substitution.

| **Allocation factor (AF)** | **Mass allocation** | | | | **Economic allocation** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Cream** | **S. milk** | **Permeate** | **Retentate** | **Cream** | **S. milk** | **Permeate** | **Retentate** |
| **Raw milk production and its transportation (SB1)** | | | | | | | | |
| USA | 35% | | 23% | 42% | 50% | | 2% | 47% |
| Qc | 35% | | 23% | 42% | *57%* | | *15%* | *28%* |
| **Reception, storage, pasteurization & skimming (SB2)** | | | | | | | | |
| USA | 35% | 65% | | | 50% | 50% | | |
| Qc | 35% | 65% | | | *57%* | *43%* | | |
| **Ultrafiltration and diafiltration (SB2)** | | | | | | | | |
| USA | | | 35% | 65% | | | 5% | 95% |
| Qc | | | 35% | 65% | | | *34%* | *66%* |
| **Spray-drying (*), packing (*) and transportation (SB2)** | | | | | | | | |
| USA | | | | 100% | | | | 100% |
| Qc | | | | 100% | | | | 100% |
| **CIP** | | | | | | | | |
| USA | 35% | | 23% | 42% | 50% | | 2% | 47% |
| Qc | 35% | | 23% | 42% | *57%* | | *15%* | *28%* |

The economic allocations are based on milk component prices in the USA:

- USA class IV (proteins: 3.98 USD.kg$^{-1}$; fat 5.35 USD.kg$^{-1}$; lactose 0.12 USD.kg$^{-1}$)
- Québec class 7 (proteins: 1.58 CAD.kg$^{-1}$; fat 7.24 CAD.kg$^{-1}$; lactose 1.58 CAD.kg$^{-1}$) in 2017.

To facilitate comparison, results with economic allocations were based on USA prices for MPC from the USA and Québec or Québec but not a mix of USA prices for MPC USA and Québec prices for MPC Québec.

## S6. Losses and wastage (L and W) literature overview

**Table S7.** Compiled data on dairy product losses and wastage (L and W).

| Source | Region | Product | Units | Value chain stage<br>Production & transportation | Manufacturing | Distribution | Consumption | Total |
|---|---|---|---|---|---|---|---|---|
| Burek (2018) | USA | Fluid milk | % (kg) | | 1.20% | 12.00% | 20-35 % | – |
| Parfitt (2016) | UK | Dairy | % (kg) | – | 3.50% | – | – | – |
| AAFC (2015) | Canada | Dairy | % (kg) | | | 11.00% | 21.00% | – |
| Bareille (2015) | France | Yogurt | % (kg) | 3.20% | 2 à 4 % | – | – | – |
| González-García (2013) | Portugal | Yogurt | % (kg) | | | | 10.00% | – |
| Thoma (2013a) | USA | Fluid milk | % (kg) | – | | 12.00% | 20.00% | – |
| Gunders (2012) | USA, Canada, Australia, New Zealand | Milk | % (kg) | 3.25% | 0.50% | 0.25% | 17.00% | 20.00 % |
| *Buzby and Hyman, (2013)* | *USA* | *Fluid milk* | *%($)* | *–* | *–* | *12.00%* | *18.00%* | *–* |
| | | *Other dairy product* | *%($)* | *–* | *–* | *8.00%* | *14.00%* | *–* |
| Abdulla (2012) | Canada | Dairy products | % (kg) | – | – | – | – | 27.57 % |
| FAO (2011) | North America and Oceania | Milk | % (kg) | 4.00% | 1.20% | 0.50% | 15.00% | 20.70 % |
| Mena (2011) | UK and Spain | Milk | % (kg) | – | – | 1-3% | – | – |
| | | yogurt | % (kg) | – | – | >7% | – | – |
| Flysjö (2011) | Denmark | butter | % (kg) | – | 1.00% | – | 10.00% | – |
| Alonso (2010) | Spain | yogurt | % (kg) | – | 1.00% | – | – | – |
| Berlin and Sonesson (2008) | Sweden | yogurt | % (kg) | – | 5.00% | – | – | – |
| Kantor (1997) | USA | Fluid milk | % (kg) | – | – | 2.00% | 30.00% | NA |
| | | Other dairy product | % (kg) | – | – | 2.00% | 30.00% | NA |
| | | Lower estimate | % (kg) | 3.20% | 0.50% | 0.25% | 10.00% | 13.95 % |
| | | Upper estimate | % (kg) | 4.00% | 5.00% | 12.00% | 30.00% | 51.00 % |
| | | **Average** | **% (kg)** | **3.48%** | **3% (*)** | **5.47%** | **20.33%** | **29.29 %** |

Note: Data in grey are not included in the average. (*) includes only data from yogurt.

## S7. LCA detailed results

### *S7.1. LCA Main Numerical Results*

Method: IMPACTWorld + (Default_Recommended_Endpoint 1.41) V1.41/IMPACT World + (Stepwise 2006 values) and IMPACTWorld + (Default_Recommended_Midpoint 1.23) V1.23

Indicators: damage assessment for HH and EQ; characterization midpoint for CC short term and FEU. Climate change contribution to HH and EQ endpoint indicators was purposely removed to avoid double counting.

General legend: CE: centrifugation; FO-P-US: fortification by MPC powder from the USA; FO-L-US: fortification by liquid MPC from the USA; FO-L-Qc: fortification by liquid MPC from Québec.

**Table S8.** Cradle-to-grave LCA results with mass allocation.

| | | | Canadian Milk | Proteins (MPC) | Primary Packaging | Secondary Packaging | GY Process | Distribution | Consumption | Distribution & consumption Losses | Final disposal | Total impact |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CE | 1.62E+00 | 0 | 1.50E-01 | 1.19E-02 | 3.29E-02 | 6.85E-02 | 4.19E-02 | 5.61E-01 | 2.36E-02 | **2.51E+00** |
| | | FO-P-US | 1.32E+00 | 5.77E-01 | 1.50E-01 | 1.19E-02 | 2.80E-02 | 6.85E-02 | 4.19E-02 | 6.40E-01 | 2.36E-02 | **2.86E+00** |
| | | FO-L-US | 1.32E+00 | 5.95E-01 | 1.50E-01 | 1.19E-02 | 2.80E-02 | 6.85E-02 | 4.19E-02 | 6.45E-01 | 2.36E-02 | **2.88E+00** |
| | | FO-L-QC | 1.32E+00 | 4.56E-01 | 1.50E-01 | 1.19E-02 | 2.80E-02 | 6.85E-02 | 4.19E-02 | 6.05E-01 | 2.36E-02 | **2.70E+00** |
| Climate Change | kg CO2 eq | UF | 1.63E+00 | 0 | 1.50E-01 | 1.19E-02 | 6.59E-02 | 6.85E-02 | 4.19E-02 | 5.73E-01 | 2.36E-02 | **2.56E+00** |
| | | CE | 2.48E-06 | 0 | 2.69E-07 | 2.31E-08 | 1.28E-08 | 2.84E-08 | 2.32E-08 | 8.41E-07 | 6.56E-08 | **3.74E-06** |
| | | FO-P-US | 2.02E-06 | 7.57E-07 | 2.69E-07 | 2.31E-08 | 1.21E-08 | 2.84E-08 | 2.32E-08 | 9.26E-07 | 6.56E-08 | **4.13E-06** |
| | | FO-L-US | 2.02E-06 | 7.54E-07 | 2.69E-07 | 2.31E-08 | 1.20E-08 | 2.84E-08 | 2.32E-08 | 9.26E-07 | 6.56E-08 | **4.12E-06** |
| | | FO-L-QC | 2.02E-06 | 6.91E-07 | 2.69E-07 | 2.31E-08 | 1.20E-08 | 2.84E-08 | 2.32E-08 | 9.07E-07 | 6.56E-08 | **4.04E-06** |
| Human Health | DALY | UF | 2.49E-06 | 0 | 2.69E-07 | 2.31E-08 | 1.81E-08 | 2.84E-08 | 2.32E-08 | 8.46E-07 | 6.56E-08 | **3.77E-06** |
| | | CE | 1.86E+00 | 0 | 1.37E-01 | 5.30E-02 | 2.80E-02 | 6.79E-02 | 3.66E-02 | 6.57E-01 | 9.83E-02 | **2.93E+00** |
| | | FO-P-US | 1.51E+00 | 9.62E-01 | 1.37E-01 | 5.30E-02 | 2.63E-02 | 6.79E-02 | 3.66E-02 | 8.36E-01 | 9.83E-02 | **3.73E+00** |
| | | FO-L-US | 1.51E+00 | 9.48E-01 | 1.37E-01 | 5.30E-02 | 2.61E-02 | 6.79E-02 | 3.66E-02 | 8.32E-01 | 9.83E-02 | **3.71E+00** |
| Ecosystem Quality | | FO-L-QC | 1.51E+00 | 5.17E-01 | 1.37E-01 | 5.30E-02 | 2.61E-02 | 6.79E-02 | 3.66E-02 | 7.07E-01 | 9.83E-02 | **3.15E+00** |
| | PDF*m2*yr | UF | 1.86E+00 | 0 | 1.37E-01 | 5.30E-02 | 3.43E-02 | 6.79E-02 | 3.66E-02 | 6.62E-01 | 9.83E-02 | **2.95E+00** |
| | | CE | 3.21E+00 | 0 | 4.02E+00 | 2.09E-01 | 4.95E-01 | 5.82E-01 | 7.11E-01 | 2.67E+00 | 1.17E-01 | **1.20E+01** |
| | | FO-P-US | 2.61E+00 | 2.21E+00 | 4.02E+00 | 2.09E-01 | 4.18E-01 | 5.82E-01 | 7.11E-01 | 3.11E+00 | 1.17E-01 | **1.40E+01** |
| Fossil and nuclear energy use | | FO-L-US | 2.61E+00 | 2.43E+00 | 4.02E+00 | 2.09E-01 | 4.17E-01 | 5.82E-01 | 7.11E-01 | 3.18E+00 | 1.17E-01 | **1.43E+01** |
| | | FO-L-QC | 2.61E+00 | 9.99E-01 | 4.02E+00 | 2.09E-01 | 4.17E-01 | 5.82E-01 | 7.11E-01 | 2.76E+00 | 1.17E-01 | **1.24E+01** |
| | MJ deprived | UF | 3.22E+00 | 0 | 4.02E+00 | 2.09E-01 | 1.03E+00 | 5.82E-01 | 7.11E-01 | 2.83E+00 | 1.17E-01 | **1.27E+01** |

**Table S9.** LCA results from plant manufacturing to final disposal (excluding raw milk and MPC); mass allocation.

| | | | PP containers | PS containers | Other Pakaging | Heat exchangers | CIP & water | Centrifugation/Ultrafiltration | Other process | Distribution | Household | Plant losses | Distrib & household losses | Final disposal | Total impact |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CE | 3.78E-02 | 8.03E-02 | 3.15E-02 | 2.66E-02 | 3.23E-03 | 1.40E-04 | 2.41E-03 | 6.85E-02 | 4.19E-02 | 5.51E-02 | 5.06E-01 | 2.36E-02 | **8.77E-01** |
| | | FO-P-US | 3.78E-02 | 8.03E-02 | 3.15E-02 | 2.19E-02 | 3.21E-03 | 1.14E-04 | 2.63E-03 | 6.85E-02 | 4.19E-02 | 6.33E-02 | 5.77E-01 | 2.36E-02 | **9.52E-01** |
| | | FO-L-US | 3.78E-02 | 8.03E-02 | 3.15E-02 | 2.19E-02 | 3.21E-03 | 1.14E-04 | 2.60E-03 | 6.85E-02 | 4.19E-02 | 6.38E-02 | 5.82E-01 | 2.36E-02 | **9.57E-01** |
| | | FO-L-QC | 3.78E-02 | 8.03E-02 | 3.15E-02 | 2.19E-02 | 3.21E-03 | 1.14E-04 | 2.60E-03 | 6.85E-02 | 4.19E-02 | 5.96E-02 | 5.46E-01 | 2.36E-02 | **9.17E-01** |
| Climate Change | kg CO2 eq | UF | 3.78E-02 | 8.03E-02 | 3.15E-02 | 5.99E-02 | 3.27E-03 | 9.74E-06 | 2.41E-03 | 6.85E-02 | 4.19E-02 | 5.63E-02 | 5.17E-01 | 2.36E-02 | **9.22E-01** |
| | | CE | 4.75E-08 | 1.53E-07 | 6.77E-08 | 4.29E-09 | 1.97E-09 | 4.47E-11 | 6.39E-09 | 2.84E-08 | 2.32E-08 | 8.59E-08 | 7.55E-07 | 6.56E-08 | **1.24E-06** |
| | | FO-P-US | 4.75E-08 | 1.53E-07 | 6.77E-08 | 3.53E-09 | 1.91E-09 | 3.65E-11 | 6.54E-09 | 2.84E-08 | 2.32E-08 | 8.78E-08 | 8.39E-07 | 6.56E-08 | **1.32E-06** |
| | | FO-L-US | 4.75E-08 | 1.53E-07 | 6.77E-08 | 3.53E-09 | 1.91E-09 | 3.65E-11 | 6.45E-09 | 2.84E-08 | Distribution | 8.66E-08 | 8.39E-07 | 6.56E-08 | **1.30E-06** |
| | | FO-L-QC | 4.75E-08 | 1.53E-07 | 6.77E-08 | 3.53E-09 | 1.91E-09 | 3.65E-11 | 6.45E-09 | 2.84E-08 | 2.32E-08 | 8.49E-08 | 8.22E-07 | 6.56E-08 | **1.30E-06** |
| Human Health | DALY | UF | 4.75E-08 | 1.53E-07 | 6.77E-08 | 9.67E-09 | 1.99E-09 | 3.11E-12 | 6.39E-09 | 2.84E-08 | 2.32E-08 | 8.69E-08 | 7.59E-07 | 6.56E-08 | **1.25E-06** |
| | | CE | 1.96E-02 | 5.25E-02 | 6.54E-02 | 6.96E-03 | 2.94E-03 | 2.18E-03 | 1.19E-02 | 6.79E-02 | 3.66E-02 | 6.49E-02 | 5.92E-01 | 9.83E-02 | **1.02E+00** |
| | | FO-P-US | 1.96E-02 | 5.25E-02 | 6.54E-02 | 5.76E-03 | 2.72E-03 | 1.78E-03 | 1.51E-02 | 6.79E-02 | 3.66E-02 | 7.46E-02 | 7.61E-01 | 9.83E-02 | **1.20E+00** |
| | | FO-L-US | 1.96E-02 | 5.25E-02 | 6.54E-02 | 5.76E-03 | 2.72E-03 | 1.78E-03 | 1.49E-02 | 6.79E-02 | 3.66E-02 | 7.27E-02 | 7.59E-01 | 9.83E-02 | **1.20E+00** |
| Ecosystem Quality | | FO-L-QC | 1.96E-02 | 5.25E-02 | 6.54E-02 | 5.76E-03 | 2.72E-03 | 1.78E-03 | 1.49E-02 | 6.79E-02 | 3.66E-02 | 6.42E-02 | 6.43E-01 | 9.83E-02 | **1.07E+00** |
| | PDF*m2*yr | UF | 1.96E-02 | 5.25E-02 | 6.54E-02 | 1.54E-02 | 2.97E-03 | 1.52E-04 | 1.19E-02 | 6.79E-02 | 3.66E-02 | 6.57E-02 | 5.96E-01 | 9.83E-02 | **1.03E+00** |
| | | CE | 1.34E+00 | 1.86E+00 | 8.21E-01 | 4.32E-01 | 4.47E-02 | 9.01E-04 | 1.27E-02 | 5.82E-01 | 7.11E-01 | 2.40E-01 | 2.43E+00 | 1.17E-01 | **8.58E+00** |
| | | FO-P-US | 1.34E+00 | 1.86E+00 | 8.21E-01 | 3.55E-01 | 4.52E-02 | 7.35E-04 | 1.43E-02 | 5.82E-01 | 7.11E-01 | 2.76E-01 | 2.84E+00 | 1.17E-01 | **8.96E+00** |
| Fossil and nuclear energy use | | FO-L-US | 1.34E+00 | 1.86E+00 | 8.21E-01 | 3.55E-01 | 4.52E-02 | 7.35E-04 | 1.39E-02 | 5.82E-01 | 7.11E-01 | 2.68E-01 | 2.91E+00 | 1.17E-01 | **9.02E+00** |
| | | FO-L-QC | 1.34E+00 | 1.86E+00 | 8.21E-01 | 3.55E-01 | 4.52E-02 | 7.35E-04 | 1.39E-02 | 5.82E-01 | 7.11E-01 | 2.39E-01 | 2.52E+00 | 1.17E-01 | **8.60E+00** |
| | MJ deprived | UF | 1.34E+00 | 1.86E+00 | 8.21E-01 | 9.73E-01 | 4.52E-02 | 6.28E-05 | 1.27E-02 | 5.82E-01 | 7.11E-01 | 2.58E-01 | 2.57E+00 | 1.17E-01 | **9.29E+00** |

**Table S10.** US raw milk versus Québec cow milk; FU: 1 kg of raw milk.

| | | Cow milk {CA-QC} | Milk, at farm, national average/USA | R5 : West Coast USA | R4 : South west plus high plains USA | R3 : Upper Midwest USA | R2 : Southeast USA | R1 : Northeast USA |
|---|---|---|---|---|---|---|---|---|
| **Climate Change** | **kg CO2 eq.** | 1.27E+00 | 1.58E+00 | 1.70E+00 | 1.81E+00 | 1.42E+00 | 1.73E+00 | 1.30E+00 |
| **Human health** | **DALY** | 1.97E-06 | 2.05E-06 | 3.08E-05 | 1.49E-05 | 5.31E-06 | 1.27E-05 | 6.25E-06 |
| **Ecosystem Quality** | **PDF*m2*yr** | 1.48E+00 | 2.69E+00 | 2.68E+00 | 4.82E+00 | 1.68E+00 | 1.96E+00 | 1.84E+00 |
| **Fossil and nuclear energy use** | **MJ deprived** | 2.20E+00 | 5.06E+00 | 5.73E+00 | 5.20E+00 | 4.56E+00 | 6.47E+00 | 4.17E+00 |

Datasets: ecoinvent 3.4: cow milk {CA-QC} milk production, from cow | Alloc Rec, U for Québec and Thoma (2007-2008) milk, at the farm, /US U System for the USA.

### *S7.2. Midpoint Indicators Contributing to the Human Health and Ecosystem Quality Impact Categories*

**Table S11.** Cradle-to-grave impact indicators at midpoint; FU: 1kg of GY consumed; mass allocation.

| **Impact category** | **Unit** | **CE** | **FO-P-US** | **FO-L-US** | **FO-L-QC** | **UF** |
|---|---|---|---|---|---|---|
| Climate change, short term | kg CO2 eq | 2.51E+00 | 2.86E+00 | 2.88E+00 | 2.70E+00 | 2.56E+00 |
| Climate change, long term | kg CO2 eq | 1.64E+00 | 1.83E+00 | 1.85E+00 | 1.77E+00 | 1.69E+00 |
| Land occupation, biodiversity | m2 arable la | 1.72E+00 | 2.06E+00 | 2.06E+00 | 1.87E+00 | 1.73E+00 |
| Land transformation, biodiversity | m2 arable la | 2.69E-03 | 3.85E-03 | 3.84E-03 | 2.93E-03 | 2.70E-03 |
| Fossil and nuclear energy use | MJ deprived | 1.20E+01 | 1.40E+01 | 1.43E+01 | 1.24E+01 | 1.27E+01 |
| Mineral resources use | kg deprived | 5.95E-04 | 1.59E-03 | 1.60E-03 | 6.35E-04 | 5.98E-04 |
| Water scarcity | m3 world-eq | 9.36E-01 | 4.05E+00 | 4.05E+00 | 1.01E+00 | 9.39E-01 |
| Freshwater acidification | kg SO2 eq | 4.19E-03 | 5.77E-03 | 5.76E-03 | 4.50E-03 | 4.29E-03 |
| Terrestrial acidification | kg SO2 eq | 1.38E-02 | 1.95E-02 | 1.95E-02 | 1.50E-02 | 1.40E-02 |
| Freshwater eutrophication | kg PO4 P-lim | 1.23E-03 | 2.09E-03 | 2.08E-03 | 1.33E-03 | 1.23E-03 |
| Marine eutrophication | kg N N-lim e | 5.27E-04 | 1.73E-03 | 1.73E-03 | 5.66E-04 | 5.30E-04 |
| Freshwater ecotoxicity | CTUe | 9.65E+02 | 1.23E+03 | 1.19E+03 | 9.99E+02 | 9.71E+02 |
| Particulate matter formation | kg PM2.5 eq | 1.17E-06 | 1.62E-06 | 1.62E-06 | 1.26E-06 | 1.18E-06 |
| Photochemical oxidant formation | kg NMVOC eq | 3.87E-03 | 5.37E-03 | 5.44E-03 | 4.13E-03 | 3.95E-03 |
| Human toxicity cancer | CTUh | 9.62E-09 | 1.26E-08 | 1.22E-08 | 9.97E-09 | 9.69E-09 |
| Human toxicity non cancer | CTUh | 6.91E-08 | 8.34E-08 | 8.33E-08 | 7.21E-08 | 6.95E-08 |
| Ionizing radiations | Bq C-14 eq | 2.93E+00 | 3.50E+00 | 3.60E+00 | 3.12E+00 | 2.93E+00 |
| Ozone Layer Depletion | kg CFC-11 e | 1.04E-07 | 1.14E-07 | 1.22E-07 | 1.10E-07 | 1.19E-07 |

**Table S12.** Cradle-to-grave HH impacts characterization at endpoint; FU: 1kg of GY consumed; mass allocation.

| | **Unit** | **CE** | **FO-P-US** | **FO-L-US** | **FO-L-QC** | **UF** |
|---|---|---|---|---|---|---|
| Water availability, human health | DALY | 2.28E-06 | 2.14E-06 | 2.13E-06 | 2.47E-06 | 2.29E-06 |
| Particulate matter formation | DALY | 1.17E-06 | 1.62E-06 | 1.62E-06 | 1.26E-06 | 1.18E-06 |
| Photochemical oxidant formation | DALY | 1.36E-10 | 1.92E-10 | 1.94E-10 | 1.45E-10 | 1.39E-10 |
| Human toxicity cancer, short term | DALY | 1.10E-07 | 1.43E-07 | 1.39E-07 | 1.14E-07 | 1.11E-07 |
| Human toxicity cancer, long term | DALY | 8.74E-10 | 1.31E-09 | 1.29E-09 | 9.18E-10 | 8.92E-10 |
| Human toxicity non-cancer, short term | DALY | 1.52E-07 | 1.77E-07 | 1.77E-07 | 1.58E-07 | 1.53E-07 |
| Human toxicity non-cancer, long term | DALY | 3.45E-08 | 4.77E-08 | 4.80E-08 | 3.64E-08 | 3.49E-08 |
| Ionizing radiation, human health | DALY | 6.04E-10 | 7.10E-10 | 7.32E-10 | 6.44E-10 | 6.05E-10 |
| Ozone layer depletion | DALY | 2.11E-10 | 2.34E-10 | 2.50E-10 | 2.24E-10 | 2.43E-10 |

**Table S13.** Cradle-to-grave EQ impacts characterization at endpoint; FU: 1 kg of GY consumed; mass allocation.

| | Unit | CE | FO-P-US | FO-L-US | FO-L-QC | UF |
|---|---|---|---|---|---|---|
| Marine acidification, short term | PDF.m2.yr | 1.02E-02 | 1.22E-02 | 1.25E-02 | 1.08E-02 | 1.09E-02 |
| Marine acidification, long term | PDF.m2.yr | 9.44E-02 | 1.13E-01 | 1.15E-01 | 9.92E-02 | 1.00E-01 |
| Land occupation, biodiversity | PDF.m2.yr | 1.24E+00 | 1.48E+00 | 1.47E+00 | 1.35E+00 | 1.24E+00 |
| Land transformation, biodiversity | PDF.m2.yr | 8.16E-01 | 1.10E+00 | 1.10E+00 | 8.83E-01 | 8.18E-01 |
| Water availability, freshwater ecosystem | PDF.m2.yr | 1.16E-05 | 3.93E-05 | 3.93E-05 | 1.24E-05 | 1.16E-05 |
| Water availability, terrestrial ecosyste | PDF.m2.yr | 2.74E-04 | 2.89E-04 | 2.89E-04 | 2.98E-04 | 2.76E-04 |
| Thermally polluted water | PDF.m2.yr | 4.92E-07 | 4.93E-07 | 4.94E-07 | 5.16E-07 | 4.94E-07 |
| Freshwater acidification | PDF.m2.yr | 1.75E-02 | 2.46E-02 | 2.46E-02 | 1.90E-02 | 1.78E-02 |
| Terrestrial acidification | PDF.m2.yr | 1.96E-01 | 2.76E-01 | 2.76E-01 | 2.13E-01 | 1.98E-01 |
| Freshwater eutrophication | PDF.m2.yr | 3.89E-03 | 6.22E-03 | 6.23E-03 | 4.23E-03 | 3.91E-03 |
| Marine eutrophication | PDF.m2.yr | 6.61E-03 | 2.16E-02 | 2.16E-02 | 7.10E-03 | 6.65E-03 |
| Freshwater ecotoxicity, short term | PDF.m2.yr | 1.73E-03 | 4.29E-03 | 4.40E-03 | 1.83E-03 | 1.74E-03 |
| Freshwater ecotoxicity, long term | PDF.m2.yr | 5.49E-01 | 6.96E-01 | 6.77E-01 | 5.68E-01 | 5.53E-01 |
| Ionizing radiation, ecosystem quality | PDF.m2.yr | 4.70E-10 | 4.60E-10 | 4.87E-10 | 5.01E-10 | 4.70E-10 |

**Table S14.** Raw milk HH impacts characterization; average US raw milk versus Québec cow milk; FU: 1 kg of raw milk.

| | Unit | Milk, at farm, national average/USA | Cow milk {CA-QC} |
|---|---|---|---|
| Water availability, human health | DALY | 4.43E-07 | 1.26E-06 |
| Particulate matter formation | DALY | 1.42E-06 | 6.44E-07 |
| Photochemical oxidant formation | DALY | 1.55E-10 | 5.45E-11 |
| Human toxicity cancer, short term | DALY | 8.08E-08 | 2.63E-08 |
| Human toxicity cancer, long term | DALY | 9.40E-10 | 2.12E-10 |
| Human toxicity non-cancer, short term | DALY | 7.62E-08 | 3.84E-08 |
| Human toxicity non-cancer, long term | DALY | 3.02E-08 | 8.95E-09 |
| Ionizing radiation, human health | DALY | 2.66E-10 | 1.93E-10 |
| Ozone layer depletion | DALY | 7.07E-11 | 6.05E-11 |

**Table S15.** Raw milk EQ impacts characterization; average US raw milk versus Québec cow milk; FU: 1 kg of raw milk.

|  | **Unit** | **Milk, at farm, national average/USA** | **Cow milk {CA-QC}** |
|---|---|---|---|
| Marine acidification, short term | PDF.m2.yr | 5.37E-03 | 2.83E-03 |
| Marine acidification, long term | PDF.m2.yr | 4.95E-02 | 2.61E-02 |
| Land occupation, biodiversity | PDF.m2.yr | 1.03E+00 | 7.45E-01 |
| Land transformation, biodiversity | PDF.m2.yr | 9.38E-01 | 4.53E-01 |
| Water availability, freshwater ecosystem | PDF.m2.yr | 6.53E-05 | 5.04E-06 |
| Water availability, terrestrial ecosystem | PDF.m2.yr | 1.41E-04 | 1.64E-04 |
| Thermally polluted water | PDF.m2.yr | 9.75E-08 | 1.56E-07 |
| Freshwater acidification | PDF.m2.yr | 2.18E-02 | 9.54E-03 |
| Terrestrial acidification | PDF.m2.yr | 2.52E-01 | 1.13E-01 |
| Freshwater eutrophication | PDF.m2.yr | 6.75E-03 | 2.30E-03 |
| Marine eutrophication | PDF.m2.yr | 3.58E-02 | 3.35E-03 |
| Freshwater ecotoxicity, short term | PDF.m2.yr | 5.75E-03 | 3.49E-04 |
| Freshwater ecotoxicity, long term | PDF.m2.yr | 3.48E-01 | 1.24E-01 |
| Ionizing radiation, ecosystem quality | PDF.m2.yr | 4.22E-12 | 1.41E-10 |

### *S7.3. Other Factors Influencing the Performances of the Five GY Systems*

UF has a 6% and 2% higher impact than CE in the FEU and CC impact categories, respectively, from cradle to grave (Table S8). This is partially attributable to the higher natural gas consumption of the heat exchangers at the plant (Table S9). FO-L-QC has 6% to 8% more impacts than CE and -2% to 7% more impacts than UF across all the impact categories (Table S8). This is mainly due to the largest amount of total raw milk required and, to a lesser extent, the transportation of MPC to the GY plant. The characterization of damages (Tables S10, S14 and S15) reveals two times more EQ impacts in the USA than Québec for land transformation and territorial acidification. In the HH category, particulate matter formation and human toxicity have 2.2 and 2.12 times more impacts in the USA than Québec, respectively, due to a higher level of maize crop and maize drying operations in the USA. The 19% discrepancy with respect to CC impacts is a combination of methane (CH4), oxide nitrous (N2O) and carbon dioxide (CO2) emissions from enteric fermentation, manure storage, soil fertilization and, to a lesser extent, crop production and farming energy consumption. The lower amplitude of CC (19%) compared to the FEU discrepancy (56%) between the USA and Québec may be explained by the higher nitrous oxide emissions caused by the more humid climate in Québec. A sensitivity analysis based on data collected by Thoma at farms and the regional level in USA (Thoma et al., 2013b) reveals notable gaps between regions, resulting in significant variations in CC scores (respectively +2.5% in northeast; + 26% in southeast; + 10% in upper Midwest; + 30% in southwest and high plains; + 25% on west coast) between Québec and the studied USA regions.

## S8. Complementary Sensitivity Analyses

### *S8.1. Key Parameters Local Sensitivity Analysis*

A local sensitivity analysis was performed. A total of 69 key parameters correlated to 93 calculated parameters were tested for the four impact categories. Results are illustrated in Figure S2. Sensitive parameters are consistent across categories. The findings show that the LCA results for each scenario are sensitive to parameters linked to the yield of the separation processes. These parameters (skimmed milk output, GY protein content, skimmed milk protein content, protein retention coefficient, etc.) influence the quantity of raw milk required at the input. Furthermore, the allocation factors attributed to coproducts significantly influence the magnitude of the impacts attributed to

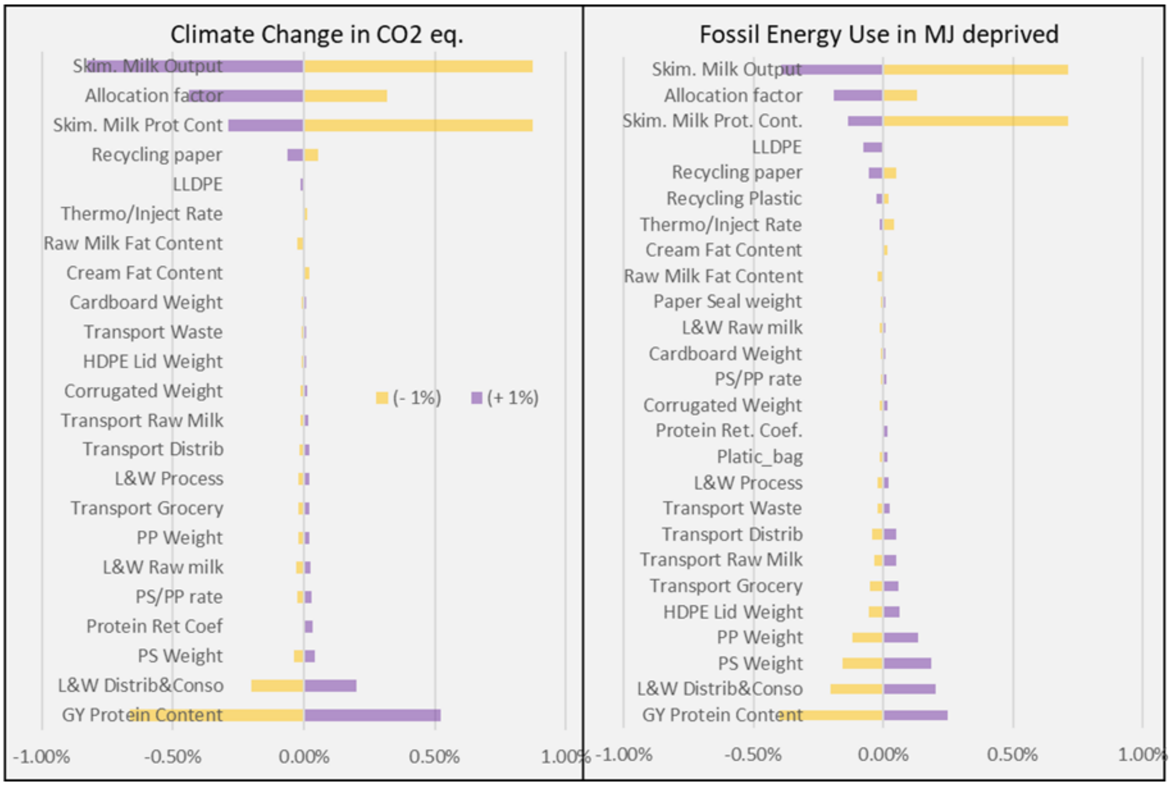
GY. The results are also sensitive to L and W and somewhat sensitive to the packaging parameters (PS versus PP rate, and plastic materials weight), recycled rates and transportation operations for milk production, distribution and consumption.

### *S8.2. Detailed Sensitivity Analysis of Modelling and Methodological Choices*

These analyses compare the environmental performances of the five studied scenarios based on the following modelling and methodological factors:

- Impact method: Impact World + results are compared to ReCiPe (E) results.
- Functional unit: 1kg of GY consumed is compared to 1 kg of milk treated in input.
- Allocation rule: mass allocation on dry matter is compared to economic allocation.
- Allocation factor: permeate from UF treated as waste (0% allocation) is compared to the valorization of milk components from UF permeate based on average Québec class VII prices in 2017.
- Protein yield of each technology: variation of the protein retention coefficient of CE, FO and UF are modified (± 0.01).
- Five milk sourcing regions are tested for the MPC from the USA (R1: north east; R2: southeast; R3: upper Midwest; R4: southwest plus high plains; R5: west coast).

Conclusions on the comparative environmental performances of the five scenarios are not sensitive to the environmental impact method (IMPACT World+ versus ReCiPe (E)), technology yield (illustrated by the variation in the protein retention coefficient) or functional unit (1 kg of yogurt consumed versus 1 kg of milk treated). However, as summarized in Table S16, the conclusions change with respect to the allocation rule (mass versus economic), allocation factor (value attributed to the whey) and milk sourcing region.



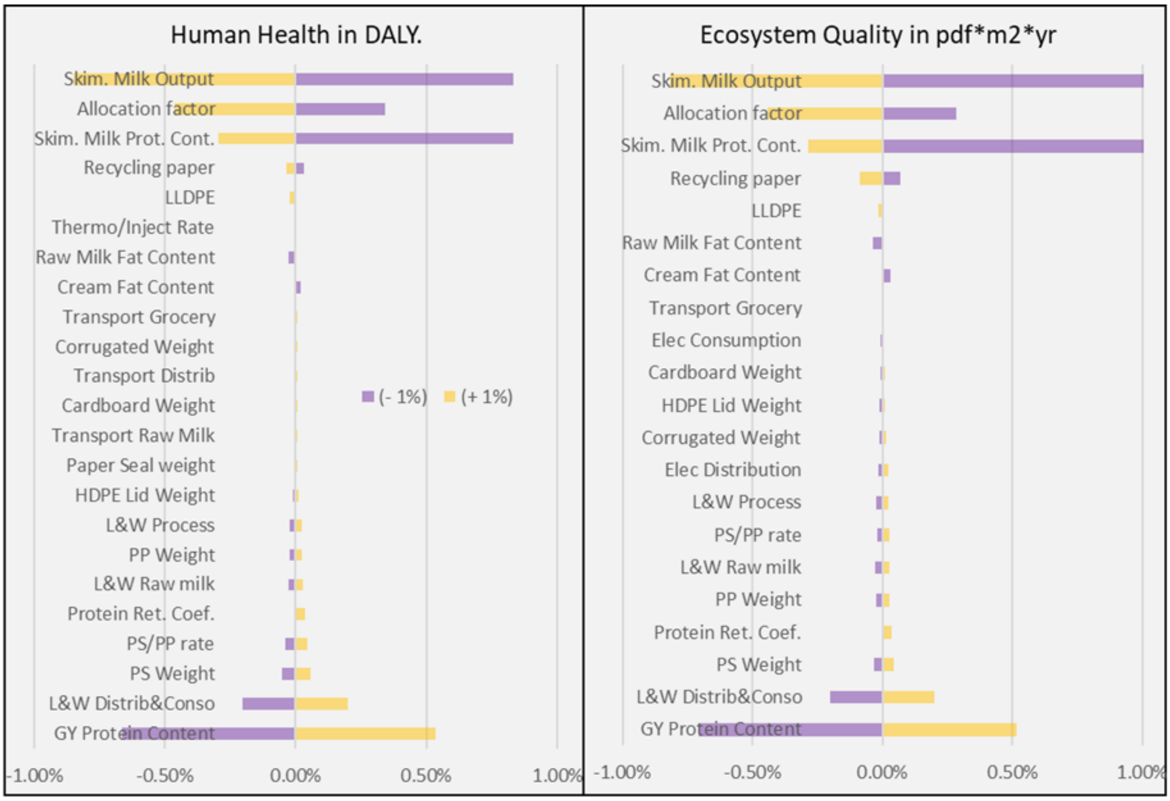


**Figure 2.** Change in CC, FEU, HH and EQ impacts for (+/− 1%) change in input parameters for CE option. Parameters causing less than 0.01% change in the four impact categories (CC, HH, EQ, or FEU) are not represented in the figure.

**Table S16.** Change in scenario classification according to sensitivity analyses.

| - | OBJECT | CHANGE | IMPACT CATEGORY | CONCLUSION VS REFERENCE | LCA RESULTS | GENERAL CLASSIFICATION |
|---|---|---|---|---|---|---|
| SENSIBILITY TO METHODOLOGY | Reference | NA | **CC** | NA | CE<UF<FO-L-QC <FO-P-US<FO-L-US | CE<UF<FO<br>except for FEU<br>FO alternatives vary |
| | | | **HH** | | CE<UF<FO-L-QC <FO-L-US<FO-P-US | |
| | | | **EQ** | | CE <UF<FO-L-QC <FO-L-US <FO-P-US | |
| | | | **FEU** | | CE<FO-L-QC <UF <FO-P-US <FO-L-US | |
| | **Impact Method** | RECIPE (E) versus IMPACT WORD+ | **CC** | Unchanged | CE<UF<FO-L-QC <FO-P-US<FO-L-US | CE<UF<FO<br>except for FEU<br>FO alternatives vary |
| | | | **HH** | **Changed** | CE<UF<FO-L-QC **<FO-P-US<FO-L-US** | |
| | | | **EQ** | **Changed** | CE<UF<FO-L-QC **<FO-P-US<FO-L-US** | |
| | | | **FEU** | Unchanged | CE<FO-L-QC <UF <FO-P-US <FO-L-US | |
| | Functional unit | 1 kg of equivalent milk (MPC milk+ Qc raw milk input) vs 1 kg GY at the output | **CC** | Unchanged | CE<UF<FO-L-QC <FO-P-US=FO-L-US | CE<UF<FO-L-QC <FO-P-US=FO-L-US |
| | | | **HH** | Unchanged | CE<UF<FO-L-QC <FO-L-US=FO-P-US | |
| | | | **EQ** | Unchanged | CE <UF<FO-L-QC <FO-L-US=FO-P-US | |
| | | | **FEU** | **Changed** | CE**<UF<FO-L-QC** <FO-P-US<FO-L-US | |
| | Allocation | Economic instead of mass allocation | **CC** | **Changed** | **UF<CE**<FO-L-QC <FO-P-US<FO-L-US | Lowest: UF<br>except for FEU<br>others vary |
| | | | **HH** | **Changed** | **UF<CE**<FO-L-QC <FO-L-US<FO-P-US | |
| | | | **EQ** | **Changed** | **UF<CE**<FO-L-QC <FO-L-US <FO-P-US | |
| | | | **FEU** | **Changed** | CE**<UF<FO-L-QC** <FO-P-US <FO-L-US | |
| | | Economic allocation with whey UF at 17.5 % instead of 0 % | **CC** | **Changed** | **UF<CE**<FO-L-QC <FO-P-US<FO-L-US | Lowest: UF<br>others vary |
| | | | **HH** | **Changed** | **UF<CE**<FO-L-QC <FO-L-US<FO-P-US | |
| | | | **EQ** | **Changed** | **UF<CE**<FO-L-QC <FO-L-US <FO-P-US | |
| | | | **FEU** | **Changed** | **UF=CE<FO-L-QC** <FO-P-US <FO-L-US | |

**Table 16.** (continued).

| - | OBJECT | CHANGE | IMPACT CATEGORY | CONCLUSION VS REFERENCE | LCA RESULTS | GENERAL CLASSIFICATION |
|---|---|---|---|---|---|---|
| SENSIBILITY TO KEY PARAMETERS | Protein retention coefficient | Variation ± 0.01 | **CC** | **Unchanged** | CE < UF < FO-L-QC < FO-P-US < FO-L-US | CE<UF<FO<br>FO alternatives vary |
| | | | **HH** | **Unchanged** | CE < UF < FO-L-QC < FO-L-US < FO-P-US | |
| | | | **EQ** | **Unchanged** | CE < UF < FO-L-QC < FO-L-US < FO-P-US | |
| | | | **FEU** | **Unchanged** | CE < FO-L-QC < UF < FO-P-US < FO-L-US | |
| | US region of milk sourcing | R1 350 km vs national average 1500 km | **CC** | **Changed** | CE < UF < FO-L-QC **< FO-L-US < FO-P-US** | FO-L-QC < FO-L-US < FO-P-US |
| | | | **HH** | Unchanged | CE < UF < FO-L-QC < FO-L-US < FO-P-US | |
| | | | **EQ** | Unchanged | CE < UF < FO-L-QC < FO-L-US < FO-P-US | |
| | | | **FEU** | **Changed** | CE<FO-L-QC<UF **<FO-L-US <FO-P-US** | |
| | | R2 2000 km vs national average 1500 km | **CC** | Unchanged | CE<UF<FO-L-QC <FO-P-US<FO-L-US | FO-L-QC <FO-P-US<FO-L-US except for EQ |
| | | | **HH** | **Changed** | CE<UF<FO-L-QC **<FO-P-US<FO-L-US** | |
| | | | **EQ** | Unchanged | CE <UF<FO-L-QC <FO-L-US <FO-P-US | |
| | | | **FEU** | Unchanged | CE<FO-L-QC <UF <FO-P-US <FO-L-US | |
| | | R3 1500 km vs national average 1500 km | **CC** | Unchanged | CE<UF<FO-L-QC <FO-P-US<FO-L-US | CE<UF<FO<br>except for FEU<br>FO alternatives vary |
| | | | **HH** | Unchanged | CE<UF<FO-L-QC <FO-L-US<FO-P-US | |
| | | | **EQ** | Unchanged | CE <UF<FO-L-QC <FO-L-US <FO-P-US | |
| | | | **FEU** | Unchanged | CE<FO-L-QC <UF <FO-P-US <FO-L-US | |
| | | R4 3000 km vs national average 1500 km | **CC** | Unchanged | CE < UF < FO-L-QC < FO-P-US < FO-L-US | CE < UF < FO<br>except for FEU<br>FO alternatives vary |
| | | | **HH** | **Changed** | CE < UF < FO-L-QC **< FO-P-US < FO-L-US** | |
| | | | **EQ** | Unchanged | CE < UF < FO-L-QC < FO-L-US < FO-P-US | |
| | | | **FEU** | Unchanged | CE < FO-L-QC < UF < FO-P-US < FO-L-US | |

**Table 16.** (continued and end).

| - | OBJECT | CHANGE | IMPACT CATEGORY | CONCLUSION VS REFERENCE | LCA RESULTS | GENERAL CLASSIFICATION |
|---|---|---|---|---|---|---|
| | | R5 5000 km vs national average 1500 km | **CC** | Unchanged | CE<UF<FO-L-QC <FO-P-US<FO-L-US | FO-L-QC<FO-P-US <FO-L-US |
| | | | **HH** | **Changed** | CE<UF<FO-L-QC **<FO-P-US<FO-L-US** | |
| | | | **EQ** | **Changed** | CE <UF<FO-L-QC **<FO-P-US <FO-L-US** | |
| | | | **FEU** | Unchanged | CE<FO-L-QC <UF <FO-P-US <FO-L-US | |

### *S8.3. Influence of the MPC Drying Process and Transportation Distances*

The transportation of 1 ton of liquid MPC over 1500 km corresponds to 20 420 MJ deprived as compared to 75 600 MJ deprived for equivalent MPC drying. These results are consistent with the previous study by Depping et al., (2017) showing that liquid concentrates have a lower cumulative energy demand than powders for distances ≤ 1 000 km due to the high energy intensity of the spray drying operation. Focusing on CC impacts, the powder scenario (MPC-P-US-A) becomes more favorable than liquid MPC (MPC-L-US-A) for distances over 750 km (red dot in Figure S3) but with four times less kg transported (0.03 kg MPC powder versus 0.12 kg MPC liquid per kg of functional unit).

The milk sourcing region and type of MPC (powder versus liquid) are more sensitive parameters than the transportation distances. Indeed, MPC-L-US is still more impactful for a transportation distance reduced to 250 km than MPC-L-QC transported over 3 250 km. Selecting MPC with milk sourced from less impactful regions in the USA such as New York State in North East (R1) significantly reduces the gap with MPC-L-QC. In contrast, MPC (powder or liquid) from South West USA (R4) would be the worst scenario. Finally, producing liquid MPC at the GY plant in Québec (0 km transportation) decreases the MPC-L-QC system impact by 2% but has a very limited influence on the total life cycle environmental performance of the FO-L-QC scenario. **Table S17** provides the numerical gaps for each scenario.

**Table 17.** Numerical impact variation as a function of scenario; CE: centrifugation; UF: ultrafiltration; FO-L-QC: fortification with liquid MPC from Québec. FO-P-US-AV: fortification with MPC 80 powder from USA with USA raw milk average; FO-L-US-AV: fortification liquid MPC from USA with USA raw milk average; FO-P-US -R1: fortification with MPC 80 powder from north east USA; FO-L-US -R1: fortification with liquid MPC from north east USA (R2: southeast; R3: upper Midwest; R4: southwest plus high plains; R5: west coast).

| Climate change | | | Human health | | | Ecosystem quality | | | Fossil and nuclear energy use | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | kg CO2 eq | Delta with CE | | DALY | Delta with CE | | PDF.m2.yr | Delta with CE | | MJ deprived | Delta with CE |
| CE | 2.51E+00 | 0.0% | CE | 3.74E-06 | 0.0% | CE | 2.93E+00 | 0.0% | CE | 12.00496 | 0.0% |
| UF | 2.56E+00 | 2.1% | UF | 3.77E-06 | 0.6% | UF | 2.95E+00 | 0.7% | FO_L_QC | 12.426219 | 3.5% |
| FO_L_QC | 2.70E+00 | 7.8% | FO_L_QC | 4.04E-06 | 7.9% | FO_L_QC | 3.15E+00 | 7.5% | UF | 12.718108 | 5.9% |
| FO_L_US R1 | 2.72E+00 | 8.5% | FO_L_US AV | 4.12E-06 | 10.1% | FO_L_US R3 | 3.26E+00 | 11.1% | FO_L_US R1 | 13.378094 | 11.4% |
| FO_P_US R1 | 2.73E+00 | 8.9% | FO_P_US AV | 4.13E-06 | 10.2% | FO_P_US R3 | 3.28E+00 | 11.7% | FO_P_US R1 | 13.515249 | 12.6% |
| FO_P_US R3 | 2.79E+00 | 11.1% | FO_L_US R3 | 5.57E-06 | 48.9% | FO_L_US R1 | 3.32E+00 | 13.1% | FO_P_US R3 | 13.769422 | 14.7% |
| FO_L_US R3 | 2.81E+00 | 12.0% | FO_P_US R3 | 5.58E-06 | 49.0% | FO_P_US R1 | 3.35E+00 | 14.1% | FO_P_US AV | 13.988385 | 16.5% |
| FO_P_US AV | 2.86E+00 | 14.0% | FO_L_US R1 | 5.98E-06 | 59.6% | FO_L_US R2 | 3.39E+00 | 15.4% | FO_L_US R3 | 14.048611 | 17.0% |
| FO_L_US AV | 2.88E+00 | 14.9% | FO_P_US R1 | 6.00E-06 | 60.1% | FO-P_US R2 | 3.40E+00 | 15.9% | FO_P_US R4 | 14.156732 | 17.9% |
| FO-P_US R2 | 2.93E+00 | 16.8% | FO-P_US R2 | 8.90E-06 | 137.6% | FO_L_US AV | 3.71E+00 | 26.5% | FO_L_US AV | 14.267574 | 18.8% |
| FO_P_US R5 | 2.93E+00 | 16.8% | FO_L_US R2 | 8.90E-06 | 137.7% | FO_P_US R5 | 3.73E+00 | 27.1% | FO_P_US R5 | 14.534375 | 21.1% |
| FO_L_US R2 | 2.97E+00 | 18.2% | FO_P_US R4 | 9.85E-06 | 162.9% | FO_P_US AV | 3.73E+00 | 27.1% | FO-P_US R2 | 14.655493 | 22.1% |
| FO_P_US R4 | 2.97E+00 | 18.4% | FO_L_US R4 | 9.86E-06 | 163.4% | FO_L_US R5 | 3.74E+00 | 27.4% | FO_L_US R4 | 14.978978 | 24.8% |
| FO_L_US R4 | 3.03E+00 | 21.0% | FO_P_US R5 | 1.69E-05 | 352.3% | FO_L_US R4 | 4.67E+00 | 59.3% | FO_L_US R2 | 15.115701 | 25.9% |
| FO_L_US R5 | 3.05E+00 | 21.5% | FO_L_US R5 | 1.70E-05 | 353.5% | FO_P_US R4 | 4.68E+00 | 59.5% | FO_L_US R5 | 16.080697 | 34.0% |

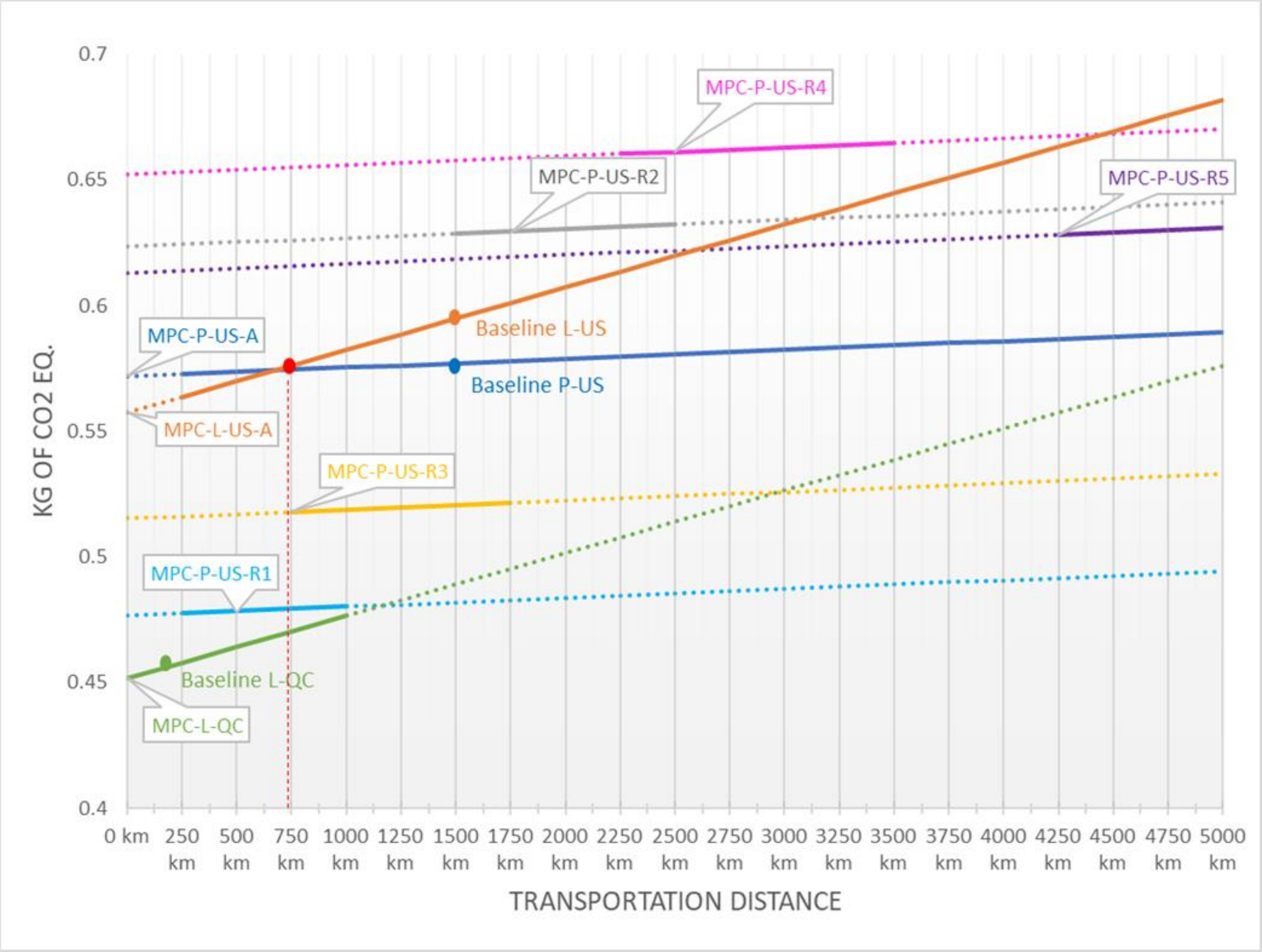


**Figure 3.** CC impacts variation as a function of transportation distance from MPC plant to GY plant for the three MPC sourcing alternatives scaled-up to the FU (1 kg of GY): MPC-P-US-A: 0.03 kg MPC 80 powder from USA with USA raw milk average; 0.12 kg MPC-L-US -A: liquid MPC from USA with

USA raw milk average; 0.03 kg MPC-PUS -R1: MPC 80 powder from north east USA (R2: southeast; R3: upper Midwest; R4: southwest plus high plains; R5: west coast); 0.12 kg MPC-L-QC: liquid MPC from Québec.

### *S8.4. Potential CC Impact Reduction as a Function of Losses and Wastage (L and W), Energy Consumption at Plant and Packaging Parameters*

A 1% reduction in L and W would decrease the CC impacts by 1.84E-2 eq. $CO_2$, whereas a 1% reduction in energy consumption (electricity and natural gas) would decrease CC impacts by only 0.03E-2 eq. $CO_2$ at the manufacturing plant. To reduce CC impacts, a 1% L and W reduction at the GY plant (yellow dot) is more effective than a 10% reduction in energy consumption (Figure S4). Even higher impact mitigation potential may be explored by reducing L and W in distribution and consumption, which represent 20% of the life cycle impacts.

Reducing the weight of single-serving PS containers or encouraging multi-serving PP containers could have a greater benefit on CC than efforts to reduce plant energy consumption. As highlighted in the dairy LCA literature, this finding confirms that manufacturers' efforts to reduce weight or losses and improve the design or material selection of primary packaging components could reduce the product's environmental impact.

Simultaneously reducing PS weight and PS rate by 10% is only as effective as reducing the L and W by 1% at the plant. Therefore, efforts spent on reducing packaging environmental impacts must be qualified by the potential collateral effects on L and W. Indeed, switching to multi-serve PP containers instead of single serve PS containers may increase L and W in the household stage, resulting in a potential increase in the environmental burden. Packaging improvements may reduce the impacts of the GY system, especially in the CC and FEU categories, but packaging eco-design efforts must integrate the potential risk of additional product L and W in the value chain because any additional L and W offset the gains from packaging and are more damaging to the environment (Wikstrom et al., 2014). The further research required in this area is beyond the scope of this study.

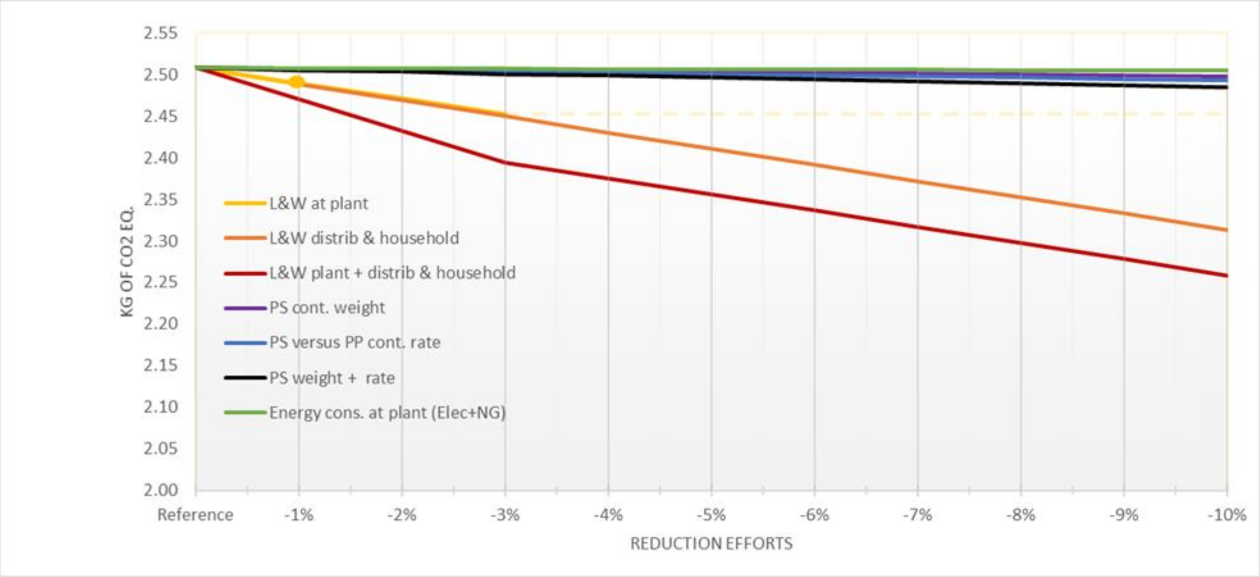


**Figure 4.** Potential CC impacts reduction as a function of key parameter reduction efforts (reduction of energy consumption at the plant (electricity and natural gas), L and W reduction at plant, at home and in the distribution stage, packaging improvement (PS weight reduction and PS versus PP rate reduction) for 1 kg of GY consumed based on the CE technology scenario.

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