Supplementary materials for

Comparative life cycle assessment of five Greek yogurt production systems: A perspective beyond the plant boundaries

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1. Processing options literature overview

At an industrial scale, GY processing options may be classified into two main categories and several alternatives. The protein concentration can be increased either before or after milk fermentation. After fermentation protein concentration can be increased using mechanical separators (i.e. centrifugation (CE)) or a membrane of ultrafiltration (UF). Protein concentration can also be increased before fermentation by fortifying the milk with protein ingredients (FO) or by 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) and has the potential to be used directly as ingredients in other food products (Jørgensen et al., 2019; Shamsia and El-Ghannam, 2012). However, the pre-concentration 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 have been proposed in the literature, using milk protein concentrate (MPC), milk casein concentrate (MCC) or whey protein concentrate (WPC) (Bong & 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 remains 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 the processing yield and cost. Furthermore, the mechanical pressure exerted on the fermented milk during the passage through the UF membrane can damage the gel structure and sensory properties of the finished product. As a matter of fact, there is no simple answer to determine the best approach to produce GY. The processing method influences the volume and composition of by-product generated, as well as the GY composition and its sensorial properties (Desai et al., 2013; Jørgensen et al., 2019; Paredes Valencia et al., 2018; Tamime et al., 2014; Tong, 2013). It could impact also the production yield, resources, utilities consumption such as energy, water, chemicals at the manufacturing plant and the capital 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 based on their strategic positioning and technical constraints.

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Tamime, A.Y., Hickey, M., Muir, D.D., 2014. Strained fermented milks - A review of existing legislative provisions, survey of nutritional labelling of commercial products in selected markets and terminology of products in some selected countries. Int. J. Dairy Technol. 67, 305–333. https://doi.org/10.1111/1471-0307.12147

Tong, P., 2013. Options for making Greek yogurt [WWW Document]. Dairy Foods. URL https://www.dairyfoods.com/articles/89512-options-for-making-greek-yogurt

Uduwerella, G., Chandrapala, J., Vasiljevic, T., 2018. Preconcentration of yoghurt base by ultrafiltration for reduction in acid whey generation during Greek yoghurt manufacturing. Int. J. Dairy Technol. 71, 71–80. https://doi.org/10.1111/1471-0307.12393

Uduwerella, G., Chandrapala, J., Vasiljevic, T., 2017. Minimising generation of acid whey during Greek yoghurt manufacturing. J. Dairy Res. 84, 346–354. https://doi.org/10.1017/S0022029917000279

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

2.1. Centrifugation (CE)

The raw milk is received at the plant and stored at 4^0C in insulated tanks for one hour. The raw milk is then heated at 55^0C 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 at 90⁰C for five minutes then cooled to 42⁰C. This heat treatment has two functions: it destroys the pathogen microorganisms and denatures the whey proteins. The whey protein denaturation is a critical step in the gel formation, as it gives the yogurt its final texture. Optionally, some manufacturers include also a homogenization process at this step to improve the final texture. The milk is then routed to some isothermal fermentation tanks inoculated with a starter culture and maintained between at 40-45⁰C 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 the proteins to 10% by separating the acid whey aqueous part. The concentrated yogurt is then cooled at 15⁰C in thirty seconds with a tubular heat exchanger that stabilizes the pH and finally sent to the packaging area.

2.2. Fortification (FO)

The fortification process includes an additional step between the skimming and the heat treatment operations as compared to the CE option. The solid milk protein concentrate (MPC) powder is first rehydrated with water to reach 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 concentration 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 MPC are transported as is to the dairy plant and mixed directly to 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 also assessed two sourcing alternatives, diafiltered milk from the USA and diafiltered milk from Québec, resulting in three FO alternatives.

2.3. Ultrafiltration (UF)

This option differs from the CE in three main areas: (1) the protein concentration by UF is performed right after the skimming of milk 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 volumic 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 55⁰C. 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 operation. (2) the volume of milk treated during these subsequent operations is reduced 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 pre-concentrated milk, which modifies the fermentation kinetics and increases the buffering capacity.

3. Process simulation data and results

The simulation modeling was based on generic high-capacity lines processing 20 000 $l.h^{-1}$ of raw milk, 16 hours a day with one cycle of clean-in-place (CIP) per day and producing a GY at 10% protein and 0% fat, in the operational conditions specified in tales 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 taking into account the quantity of milk processed between each cycle and number of unit processes (Yee et al., 2013). All materials (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. The packaging, final product cooling and storage operations, general utilities consumption and L&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 S1: 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 to 0.12 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								

3.1. 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

Table S3: Centrifugation simulation results (Benoit and Houssard, 2017) (cont'd)

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%

Thermal treatment								
Milk input flow rate	*m3.h-1*	18.29	Pressure	*Pa*	5.38E+05	Natural gas	*m3.h-1*	99
Milk T°C at discharge	*°C*	90	Power	*W*	2733	Pump power (cal)	*W*	5.04E+03
Heat transfer surface	*m2*	224	pump yield	*%*	95	pump yield	*%*	95
Duration	*s*	67	motor yield	*%*	95	motor yield	*%*	95
Holding time	*s*	300	Consumption per hour	*Wh*	3028	Consumption per hour	*Wh*	5580
Density at 90°C	*kg.m-3*	1008						
Mass flow	*kg.s-1*	5.20						
Cooling								
Milk flow rate	*m3.h-1*	18.56	Pressure	*Pa*	2.59E+05			
Milk av. viscosity	*Pa.s*	0.01	Power	*W*	1335			
Milk T°C at discharge	*°C*	42	pump yield	*%*	95			
Density 42°C	*kg.m-3*	1028	motor yield	*%*	95			
Mass flow	*kg.s-1*	5.20	Consumption per hour	*Wh*	1479			
Heat transfer surface	*m2*	147						
Duration	*s*	42						
Milk flow rate at discharge	*m3.h-1*	18.20						
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			

Table S4: Centrifugation simulation results (Benoit and Houssard, 2017) (cont'd and end)

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 (water	*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)								

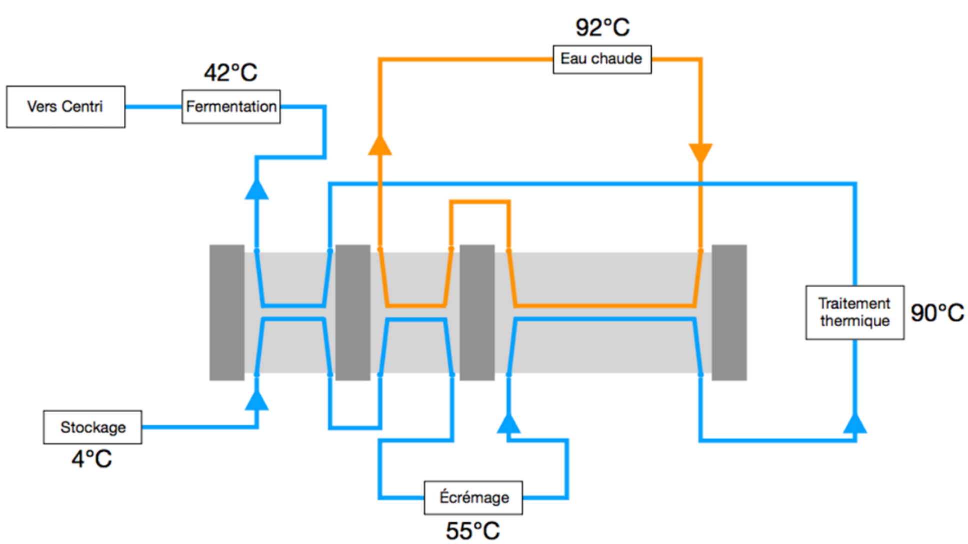

Figure S1: CE, FO and UF Heat exchanger design: cooling and heating regeneration system

3.2. 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 S5: 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%

Table S6: Fortification simulation results (Benoit and Houssard, 2017) (cont'd)

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			

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-chc*
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

Table S7: Fortification simulation results (Benoit and Houssard, 2017) (cont'd and end)

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)								
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 (water	*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)								

3.3. 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 S8: 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%
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						

Table S9: Ultrafiltration simulation results (Benoit and Houssard, 2017) (cont'd and end)

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			
<u>Propylen glycol at 50%</u>				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							
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)									

<u>Note explaining the difference between UF and CE for steam and natural gas consumption</u>

The regenerative design of the heat exchangers (**Figure S1**) uses the hot skimmed-milk circulating in the system after thermal treatment at 90 ^{0}C to pre-heat the raw milk up to 55^{o}C before skimming. The upper flow rate of the hot skimmed milk (18.56 m^3.h^{-1}) for CE as compared to the outgoing hot concentrated skimmed milk (5.90 m^3.h^{-1}) from the thermal treatment section for UF improves heat exchange with the cold raw milk section before skimming.

4. Life cycle inventory: key parameters and reference flows

Table S10: LCA key parameters and reference flows

<table>
<tr><td colspan="13">CRADLE TO GRAVE INVENTORY - INTERMEDIATE FLOWS for a line treating 20,000 l.h-1 of raw milk</td></tr>
<tr><td colspan="13">Functional unit : 1 kg of yogurt consumed</td></tr>
<tr><td colspan="13">(Flows are calculated before losses and watage and co-products allocation)</td></tr>
<tr><th rowspan="2">Life cycle steps</th><th rowspan="2">Operation</th><th colspan="5">Key parameters and data sources</th><th colspan="5">Reference flows per funtional unit</th><th rowspan="2">Comments</th></tr>
<tr><th>Data</th><th>Quantity</th><th>Unit</th><th>Source</th><th>Data used from ecoinvent 3.4</th><th>Flow</th><th>Quantity (CE)</th><th>Quantity (FO)</th><th>Quantity (UF)</th><th>Unit</th></tr>
<tr><td colspan="13">Supply chain ingredients</td></tr>
<tr><td rowspan="19">Supply chain ingredients</td><td rowspan="2">Raw Milk production in Quebec</td><td>Cow milk production in Quebec</td><td>1.00</td><td>kg</td><td>_</td><td>ecoinvent 3.4 : Cow milk {CA-QC}| milk production, from cow | Alloc Rec, U</td><td rowspan="2">Raw milk Qc</td><td rowspan="2">3.59E+00</td><td rowspan="2">2.83E+00</td><td rowspan="2">3.50E+00</td><td rowspan="2">kg</td><td rowspan="3">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.</td></tr>
<tr><td>Losses & wastage at farm</td><td>3.50</td><td>%</td><td>Average of FAO (2011), Gunders (2012), Bareille (2015)</td><td>_</td></tr>
<tr><td>Raw milk (Qc) transportation to plant</td><td>Average distrance of transport from farm to plant in Qc</td><td>182.00</td><td>km</td><td>PLQ (2016) : Annual report</td><td>Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| | Cut-off, U</td><td>Transport</td><td>6.54E-01</td><td>5.16E-01</td><td>6.37E-01</td><td>t.km</td></tr>
<tr><td rowspan="2">MPC production</td><td>Cow milk production in USA or Qc for 1 Kg MPC 80 in powder</td><td>16.50</td><td>kg</td><td>Thoma (2013)</td><td>Dataset, Thoma (2007-2008) Milk, at farm, national average/US U System or : Cow milk {CA-QC}| milk production, from cow | Alloc Rec, U</td><td>MPC Powder</td><td rowspan="2">_</td><td>2.92E-02</td><td rowspan="2">_</td><td rowspan="2">kg</td><td rowspan="2">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)</td></tr>
<tr><td>Raw milk Losses & wastage at farm</td><td>3.50</td><td>%</td><td>Average of FAO (2011), Gunders (2012), Bareille</td><td>_</td><td>Liquid MPC</td><td>1.19E-01</td></tr>
<tr><td></td><td>Paking material (for 1 kg MPC 80)</td><td>0.01</td><td>kg</td><td>Internal calculation</td><td>Kraft paper, unbleached {GLO}| market for | Cut-off, U</td><td>Kraft paper (for MPC powder)</td><td>_</td><td>2.92E-04</td><td>_</td><td>Kg</td><td></td></tr>
<tr><td></td><td>Electricity processing (for 1 kg MPC 80)</td><td>0.30</td><td>Kwh</td><td rowspan="9">Simulation, Benoit & Houssard (2017) + Yee (2013) + Prasad (2005)</td><td>Electricity, medium voltage {US}| market group for | Cut-off, U or</td><td>Electricity (for MPC powder)</td><td>_</td><td>8.87E-03</td><td>_</td><td>kWh</td><td></td></tr>
<tr><td></td><td>Natural gas (for 1 kg MPC 80)</td><td>19.51</td><td>MJ</td><td>Heat, district or industrial, natural gas {WECC, US only}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U</td><td>Natural gas (for MPC powder)</td><td>_</td><td>2.32E+00</td><td>_</td><td>MJ</td><td></td></tr>
<tr><td></td><td>Tap water (for 1 kg MPC 80)</td><td>0.68</td><td>kg</td><td>Tap water {RoW}| tap water production, direct filtration treatment | Cut-off, U</td><td>Tap water(for MPC powder)</td><td>_</td><td>1.99E-04</td><td>_</td><td>Kg</td><td></td></tr>
<tr><td></td><td>Water deionised</td><td>7.40</td><td>kg</td><td>Water, deionised, from tap water, at user {RoW}| production | Cut-off, U</td><td>Water deionised (for MPC powder)</td><td></td><td>6.57E-02</td><td>_</td><td>Kg</td><td></td></tr>
<tr><td></td><td>Nitric acid</td><td>4.12E-04</td><td>kg</td><td>Nitric acid, without water, in 50% solution state {GLO}| market for | Cut-off, U</td><td>Nitric Acid (for MPC powder)</td><td>_</td><td>9.56E-04</td><td>_</td><td>Kg</td><td></td></tr>
<tr><td></td><td>Sodium hydroxide</td><td>1.07E-03</td><td>kg</td><td>Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U</td><td>Sodium hydroxide (for MPC powder)</td><td>_</td><td>2.13E-07</td><td>_</td><td>Kg</td><td></td></tr>
<tr><td></td><td>Other chemicals</td><td>1.81E-11</td><td>kg</td><td>Chemical factory, organics {GLO}| market for | Cut-off, U</td><td>Other chemicals (for MPC powder)</td><td></td><td>1.19E-12</td><td>_</td><td>Kg</td><td></td></tr>
<tr><td></td><td>Wastewater treatment</td><td>1.10E-03</td><td>m3</td><td>Modified to USA_Wastewater from potato starch production {CA-QC}| treatment of, capacity 1.1E10l/year | Alloc Rec, U</td><td>Watewater treatment</td><td>_</td><td>3.22E-05</td><td>_</td><td>m3</td><td></td></tr>
<tr><td>Raw milk or diafiltered milk regional transportation (USA-USA or Qc-Qc)</td><td>Average distrance of transport from farm to plant (Qc or USA)</td><td>182.00</td><td>km</td><td>Estimate based on Qc</td><td>Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| | Cut-off, U</td><td>Transport</td><td>_</td><td>8.77E-02</td><td>_</td><td>t.km</td><td></td></tr>
<tr><td>MPC transportation from USA to Qc Manufacturing plant</td><td>MPC powder</td><td>1500.00</td><td>km</td><td>Estimate based on av. distance from Wisconsin state (US) to Montreal (Qc)</td><td>Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| | Cut-off, U</td><td>Transport</td><td>_</td><td>4.38E-02</td><td>_</td><td>t.km</td><td></td></tr>
<tr><td>MPC transportation from USA to Qc Manufacturing plant</td><td>MPC liquid</td><td>1500.00</td><td>km</td><td>Estimae based on av. distance from Wisconsin state (US) to Montreal (Qc)</td><td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, cooling {GLO}| | Cut-off, U</td><td>Transport</td><td>_</td><td>1.78E-01</td><td>_</td><td>t.km</td><td></td></tr>
</table>

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 1	158.00	g	Keoleian (2004)							
	Wood pallet	Weight	18.14	Kg	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 reused	300.00	times								
		Number of 500 g countainer per	780.00	u								
		Number of 100 g container per p	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	Data	Quantity	Unit	Source	Data used from ecoinvent 3.4	Flow	Quantity (CE)	Quantity (FO)	Quantity (UF)	Unit	Comments
GY plant processing												
Plant processing	Milk filling & storage at 4^0C	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 4^0C. 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 4^0C	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 55^0C
		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 ^0C & 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 water flows are supposed to be recirculated).
		FO : electricy consumption	1865	Wh								
		UF : electricy consumption	270	Wh								
	Centrifugation at 35 - 40^0C	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 | Alloc Rec, 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 4^0C	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 energy cost. 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 water usage	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	Data	Quantity	Unit	Source	Data used from ecoinvent 3.4	Flow	Quantity (CE)	Quantity (FO)	Quantity (UF)	Unit	Comments
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
	Refrigeration, 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							
		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)	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	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). (*) 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
	Refrigeration + 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	

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5. MPC allocation factors

Table S11: 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 base on milk components prices in 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 make the comparison easier, results with economic allocations were based on USA prices for MPC from USA and Québec or on Québec but not a mix of USA prices for MPC USA and Québec prices for MPC Québec.

6. Losses and wastage (L&W) literature overview

Table S12: Dairy products losses and wastage (L&W) compiled data

Source	Region	Product	Units	Value chain stage: 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 is not included in the compilation. (*) includes only data from yogurt.

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7. LCA detailed results

7.1. 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 is removed purposely 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 S13: 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		**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**
Quality	**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		**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**
nuclear energy		**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**
use	**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 S14: 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		**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**
Quality	**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		**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**
nuclear energy		**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**
use	**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 S15: US raw milk versus Québec cow milk; FU: 1kg 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.

7.2. Midpoint indicators contributing to the impacts on human health and ecosystem quality

Table S16: Cradle to grave impacts 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 S13a: 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 S17b: 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 S18a: 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 S14b: 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

7.3. Other factors influencing the five GY systems performance

UF has a 6% and 2% higher impact than CE in the FEU and CC impact categories, respectively from cradle to grave (Table S9). This is partially attributable to the higher natural gas consumption by the heat exchangers at the plant (Table S10).

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 S9). 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 S11, S14 and S15) reveals twice 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 on 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 FEU discrepancy (56%) between the USA and Québec may be explained by higher nitrous oxide emissions caused by the more humid climate in Québec. A sensitivity analysis, based on data collected by Thoma at farms and regional level in USA (Thoma et al., 2013b) reveals notable gaps between regions, resulting in significant CC scores variations (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 USA region concerned.

8. Complementary sensitivity analyses

8.1. 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 S5. Sensitive parameters are consistent across categories. It shows that the LCA results for each scenario are sensitive to parameters linked to the yield of the separation processes. Such parameters (skimmed milk output, GY protein content, skimmed milk protein content, protein retention coefficient…) influence the quantity of raw milk required at the input. Furthermore, the allocation factors attributed to co-products significantly influence the magnitude of the impacts attributed to GY. Results are also sensitive to L&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.

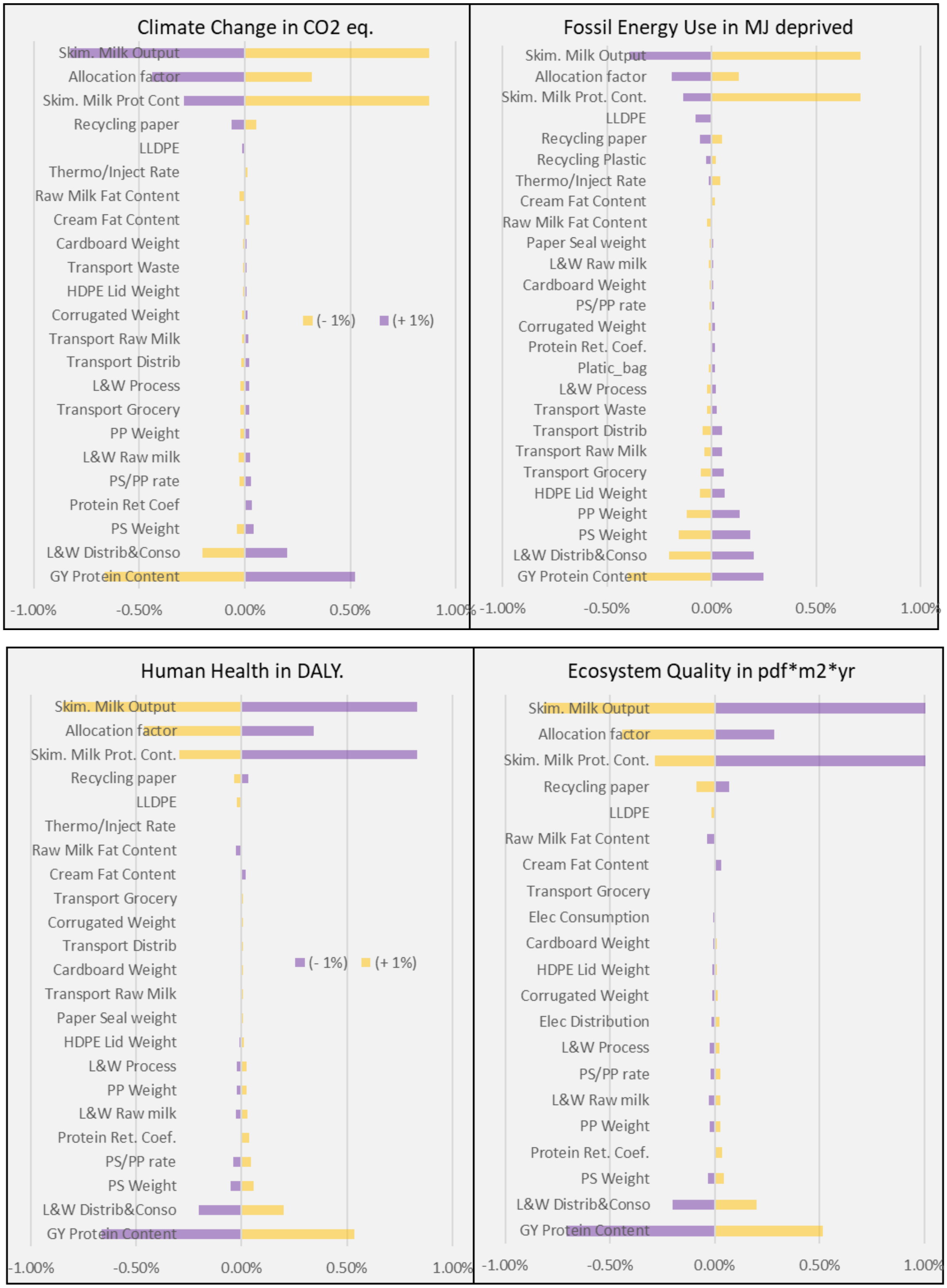

Figure S2: Change in CC, FEU, HH and EQ impacts for (+/- 1%) change on input parameters by for CE option. Parameters causing less than 0.01% change on the four impact categories (CC, HH, EQ or FEU) are not represented in the figure.

8.2. Modeling and methodological choices detailed sensitivity analysis

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

- Impact method: Impact World+ results are compared with Recipe (E) results
- Functional unit: 1kg of GY consumed is compared with 1 kg of milk treated in input
- The allocation rule: mass allocation on dry matter is compared with economic allocation
- The allocation factor: permeate from UF treated as waste (0% allocation) is compared with the valorization of milk components from UF permeate based on average Québec class VII prices in 2017
- The 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 selected (IMPACT World+ versus ReCiPe (E)), nor to the technology yield (illustrated by the variation in the protein retention coefficient), nor to the functional unit selected (1 kg of yogurt consumed versus 1 kg of milk treated). However, as summarized in Table S4, conclusions change with respect to the allocation rule (mass versus economic), allocation factor (value attributed to the whey) and region of milk sourcing.

Table S15: 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-L-QC except for FEU 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-L-QC except for FEU 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	

Table S15: Change in scenario classification according to sensitivity analyses (cont'd)

-	OBJECT	CHANGE	IMPACT CATEGORY	CONCLUSION VS REFERENCE	LCA RESULTS	GENERAL CLASSIFICATION
SENSIBILITY TO KEY PARAMETERS	**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-L-US<FO-P-US	CE<UF<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<UF<FO-L-QC** <FO-L-US<FO-P-US	
	Allocation	Economic instead of mass allocation	**CC**	**Changed**	**FO-L-QC**< UF <FO-P-US<FO-L-US < CE	**Lowest: FO-L-QC** others vary
			HH	**Changed**	**FO-L-QC** <FO-L-US<FO-P-US=UF<CE	
			EQ	**Changed**	**FO-L-QC<** UF<CE <FO-L-US <FO-P-US	
			FEU	**Changed**	**FO-L-QC**<CE<UF< <FO-L-US <FO-P-US	
		Economic allocation with whey UF at 17.5 % instead of 0 %	**CC**	**Changed**	**UF< FO-L-QC** < FO-L-US<FO-P-US< CE	**Lowest: UF<FO-L-QC** Except for FEU others vary
			HH	**Changed**	**UF< FO-L-QC** <CE <FO-L-US<FO-P-US	
			EQ	**Changed**	**UF <FO-L-QC**<CE <FO-L-US <FO-P-US	
			FEU	**Changed**	FO-L-QC<UF<CE <FO-L-US <FO-P-US	
	Protein retention coefficient	Variation ± 0.01	**CC**	**Unchanged**	**CE<UF<FO-L-QC** <FO-P-US<FO-L-US	CE<UF<FO-LQC Except for FEU 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	

Table S15: Change in scenario classification according to sensitivity analyses (cont'd and end)

-	OBJECT	CHANGE	IMPACT CATEGORY	CONCLUSION VS REFERENCE	LCA RESULTS	GENERAL CLASSIFICATION
	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 except for FEU
			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	CE<UF<FO-L-QC except for FEU
			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 except for FEU 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 except for FEU 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	
		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	

8.3. Influence of the MPC drying process and transportation distances

The transportation of 1 tonne of liquid MPC over 1 500 km would correspond to 20 420 MJ deprived compared to 75 600 MJ deprived for equivalent MPC drying. These results are consistent with the previous study from 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 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**) 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 the type of MPC (powder versus liquid) are more sensitive parameters than the distances of transportation. 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), reduces significantly the gap with MPC-L-QC. At the opposite, MPC (powder or liquid) from South West USA (R4) would be the worst scenarios. Finally, producing liquid MPC at the GY plant in Quebec (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 FO-L-QC scenario. **Table S16** provides the numerical gaps for each scenario.

Table S16: 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%

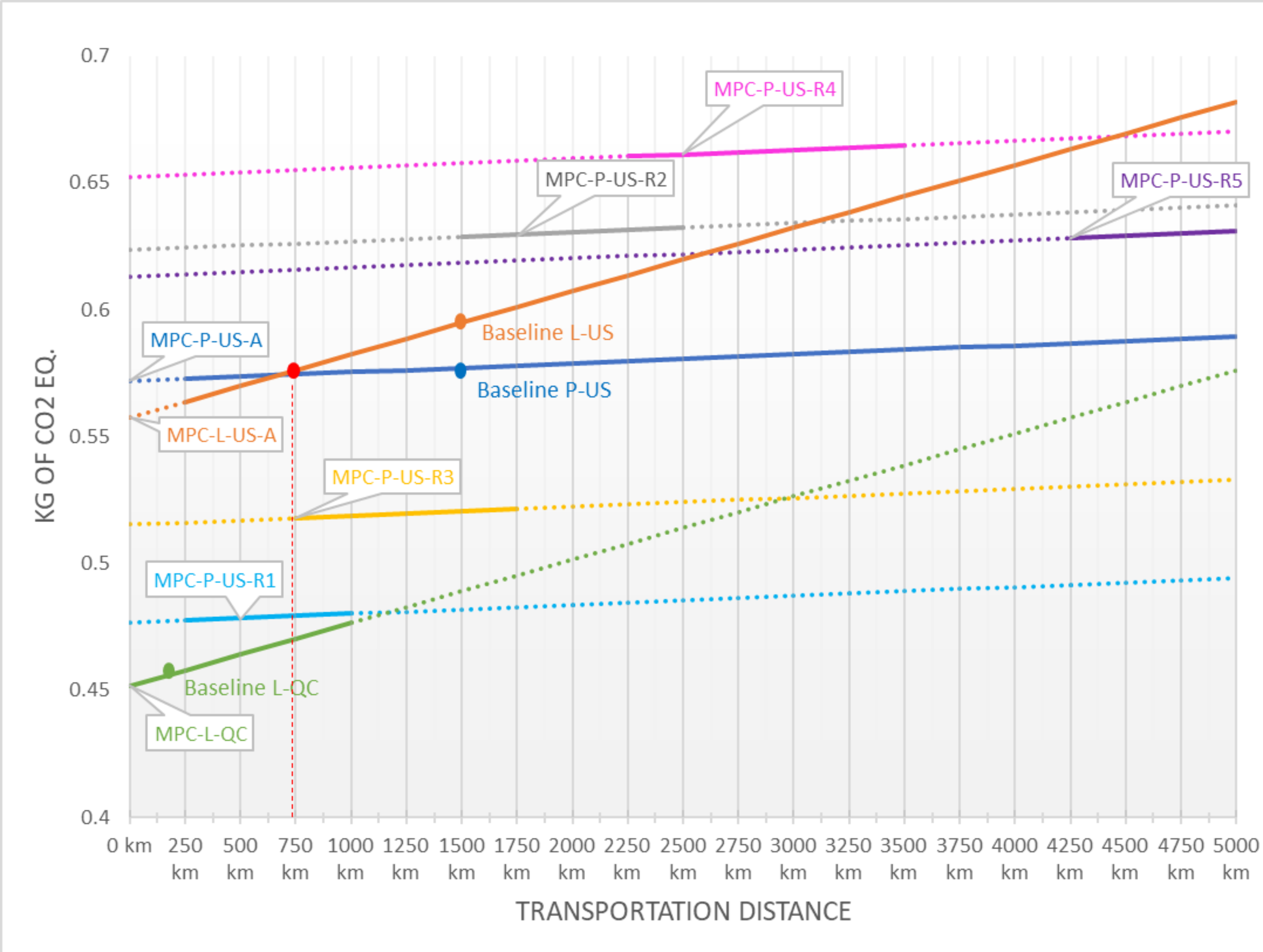

Figure S3: CC impacts variation as a function of transportation distance from MPC plant to GY plant for the three MPC sourcing alternatives scaled-up to the FU (1 kg of GY): MPC-P-US-A: 0.03 kg MPC 80 powder from USA with USA raw milk average; 0.12 kg MPC-L-US -A : liquid MPC from USA with USA raw milk average; 0.03 kg MPC-P-US -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.

8.4. Potential CC impacts reduction as a function of losses and wastage (L&W), energy consumption at plant and packaging parameters

A 1% reduction in L&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 by only 0.03E-2 eq. CO_2 impacts at the manufacturing plant. A 1% L&W reduction at the GY plant (yellow dot) is more effective than a 10% reduction in energy consumption to reduce CC impacts (Figure). Even higher impact mitigation potential may be explored by reducing L&W at distribution and consumption, which represents 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 confirms that manufacturers' efforts to reduce weight or losses or improve the design or material selection of primary packaging components could reduce the environmental impact of the product.

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

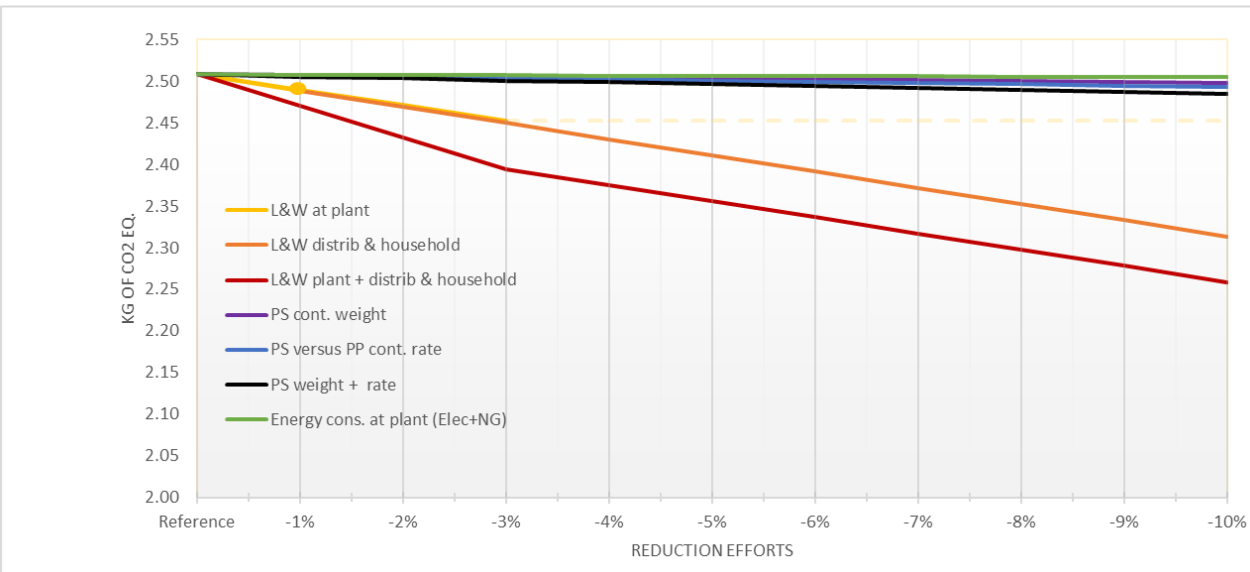

Figure S4: Potential CC impacts reduction as a function of key parameter reduction efforts (reduction of energy consumption at the plant (electricity and natural gas), L&W reduction at plant, at home and distribution stage, packaging improvement (PS weight reduction & PS versus PP rate reduction) for 1 kg of GY consumed based on the CE technology scenario.

Wikstrom, F., Williams, H., Verghese, K., Clune, S., 2014. The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies - A neglected topic. J. Clean. Prod. 73, 100–108. https://doi.org/10.1016/j.jclepro.2013.10.042