Supplementary information for

Measuring Shared Value Creation with Eco-efficiency:

Development of a Multidimensional Value Framework for the Food Industry

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1. Method

Aggregation of LCA scores in single score

The aggregation of LCA scores in single score usually encompasses two steps: normalization and weighting. However, there is no consensus on how to aggregate category impact scores in LCA, and even the principle of aggregation is controversial since it can introduce interpretation biases and value choices. The ISO 14 044 standard considers this step to be optional and does not recommend it for LCA results to be used for public disclosure. Pizzol et al. (2017) showed that normalization and weighting are perceived as relevant in decision-making, but further development is required to reduce uncertainty and improve robustness. Three different methodologies to aggregate environmental scores into a single value are proposed: two of them measure the externalities related to the environmental impact and one relates the impact scores of the Greek yogurt system to the dairy industry. We tested the three methods on our case study to measure the robustness of our results, as recommended by Pizzol et al. (2017). Comparative results are presented in section 3.1 of this document.

(1) *Stepwise: valuing the Human Health (HH) and Ecosystem Quality (EQ)) damage indicators with the budget constraint method* (Weidema, 2009)

- Use the damage-oriented impact scores on the HH and EQ areas of protection in the IMPACT WORLD+ LCIA method (Bulle et al., 2019) to get the highest level of aggregation based on natural sciences.
- Convert them into a monetary unit using the budget constraints valuation method (Weidema, 2009) developed for Stepwise:
  - 1 DALY (HH) = 74 000 Euros (2003)
  - 1 pdf.m2.year = 0.14 Euros (2003)
- Discount and sum the monetary scores in CAD (2017) to get a single environmental impact score using an inflation rate of 20% from 2003 to 2017 (https://france-inflation.com/calculateur_inflation.php; accessed in July 2019) and an exchange rate of 1.4772 (https://www.poundsterlinglive.com/best-exchange-rates/best-euro-to-canadian-dollar-history-2017; accessed in July 2019)

(2) Stepwise +Ricke: valuing (HH and EQ) + Climate Change (CC): This method, which is presented in the article, is a variation of the previous one. It uses the damage-oriented impact scores for HH and EQ in IMPACT WORLD+, excluding the contribution of CC impacts—a major area of concern for society—that is assessed separately converting midpoint indicators into a monetary unit using the social cost of carbon method in Ricke et al. (2018): 1 ton CO2 eq. = 417 USD (2017).

(3) Normalization to the Canadian dairy industry: First, the damage-oriented impact scores for HH and EQ and CC impact scores are normalized to the estimated annual environmental footprint of the Canadian dairy industry and then equally weighted (weighting factor of 1) as per Eq.1.

(1) $$\mathrm{EI_j} = \sum_{i \in I} \left[\frac{\mathrm{EIj}i\,.\mathrm{p}i}{\mathrm{EID}i} \right]$$

*$\mathbf{EI_j}$: Environmental impact score for scenario j; **EID**, annual environmental impact score for the regional dairy industry; **i**: environmental impact category indicator; **pi**: weighting factor for environmental impact category indicator i with each pi=1.*

The estimated annual environmental footprint of the industry was assessed using the average environmental impacts of 1 kg of Québec milk (Table 1) multiplied by a factor of 20% to account for the average estimated impacts of the dairy industry's other life cycle stages (based on the results of a literature review of about 60 LCA studies on dairy products (Hambly, 2011)). Then, the result was multiplied by the quantity of milk produced in Canada (8.6 billion kg (AAC, 2017)) to reflect the environmental footprint of the Canadian dairy industry.

Table 1: Footprint of the Canadian dairy industry extrapolated from 1 kg of Québec milk average environmental impacts (from the Québec inventory database (Lesage and Samson, 2016) in ecoinvent v3.4)*

	Unit	**Milk**	**Industry**
Quantity	kg	**1**	**8.64E+09**
Climate change	kg CO2 eq.	1.27E+00	1.32E+10
Human Health	DALY	2.00E-06	2.07E+04
Ecosystem quality	pdf*m2*yr	1.48E+00	1.54E+10

Lesage, P.; Samson, R. The Québec Life Cycle Inventory Database Project. Int. J. LIFE CYCLE Assess. **2016, 21, 1282–1289.*

Gross value added (GVA) scores were also normalized for the Canadian dairy industry GVA(19 billion Canadian dollars (AAC, 2017)), as reported in SM Figure 4.3. This method provides a good idea of the order of magnitude of GY system (0% fat) impacts across the industry and facilitates the interpretation to a certain extent.

2. Description of the systems

2.1. The 11 scenarios under study

The three main GY production technologies available in Canada (Centrifugation (CE); Fortification (FO); Ultrafiltration (UF) extensively described in (Houssard et al., 2020) have been associated with five scenarios of whey management, resulting in 11 scenarios:

- **CE-W:** Centrifugation (CE) with whey treated as waste (W)
- **FO-W:** Fortification (FO) with whey treated as waste (W)
- **UF-W:** Ultrafiltration (UF) with whey treated as waste (W)
- **CE-AF:** Centrifugation (CE) with whey used as a complement for animal feed (AF)
- **FO-AF:** Fortification (FO) with whey used as a complement for animal feed (AF)
- **UF-AF:** Ultrafiltration (UF) with whey used as a complement for animal feed (AF)
- **CE-BG:** Centrifugation (CE) with whey used as a substrate for biogas production (BG)
- **FO-AF:** Fortification (FO) with whey used as a substrate for biogas production (BG)
- **UF-AF:** Ultrafiltration (UF) with whey used as a substrate for biogas production (BG)
- **UF-PP:** Ultrafiltration (UF) with whey processed in permeate powder (PP) for the food ingredient or pharmaceutical markets

- **UF-P:** Ultrafiltration (UF) with ultrafiltration permeate (P) concentrated on-site for internal use as an ingredient in other dairy products.

2.2. The five scenarios of whey management (W; AF, BG, PP and P)

This section explains the main assumptions taken for the EE modeling of the whey management systems

(1) *Whey treated as waste by a wastewater treatment plant (CE-W; FO-W and UF-W):* Treatment costs for the GY processor were assumed to be similar to average dairy wastewater treatment costs in Québec.

(2) *Complement for pig feed (CE-AF; FO-AF and UF-AF):* The GY processor assumes the transportation costs to the pig farm. The whey replaces part of the pig feed intake (maize grain) and constitutes a cost reduction for the pig farmer. The pig farmer receives the whey for free, and it was assumed that operating costs for handling the whey or maize grain are similar.

(3) *Substrate for biogas production (CE-BG; FO-BG and UF-BG)*: The GY processor assumes the transportation and treatments costs at a municipal biodigester. The biogas production and purification processes are included. Then, the municipality sells the biogas and sludge on the energy and fertilizer markets to replace natural gas and urea, respectively. The delivery steps up to the end user are excluded.

(4) *Permeate powder for the food industry (UF-PP)*: If the market conditions are favorable, the UF permeate, which is rich in lactose, may be valorized in human nutrition or the pharmaceutical industry (Vuillemard, 2018). This prospective scenario includes maintaining the permeate at 4^0C and transporting it to an ingredient plant in Québec over 150 km. After reception and storage at 4^0C, the permeate is concentrated by evaporation to reach 62% total solids concentration and spray-dried to achieve 4% humidity, as reported by Schuck et al. (Schuck et al., 2015). The powder is then packed in 25 kg kraft paper bags. The production of permeate powder (PP) is included up to plant gate. Further downstream processes and end use are excluded.

(5) *Concentrated permeate for on-site valorization (UF-P)*: The milk solids from the UF permeate (mostly lactose) may also be concentrated at the GY plant and used to produce other dairy products such as drinkable yogurts. A process of concentration by evaporation at 50% of total solids is included in this scenario. Further downstream processes and end use are not.

2.3. Other co-products from GY systems production

The FO technology required permeate powder (MPC 80) that is supplied from the USA. The milk production systems in Canada or the USA that produce respectively GY or MPC 80 also produce cream. Cream is a high-value co-product of these dairy production systems included in the EE system modeling.

Permeate powder produced in USA: The permeate powder in the USA results from the ultrafiltration of skimmed milk solids. It is a co-product of the MPC powder used for the FO technology, like cream. It follows the same processing steps as the permeate powder produced in Canada (UF-PP) described in section 2.2 (4).

Cream (Canada or USA): All the steps from raw milk production to skimming are included in the system modeling. Further downstream processes are excluded. In Canada, the cream co-produced with the GY is used on site to respond to internal demand for milk fats in other dairy products at the same yogurt plant. The revenue from this cream is therefore based on Class 2a milk for yogurt.

3. Life cycle inventory

3.1. Environmental life cycle inventory

Table 2: Detailed life cycle inventory including data sources for 1 kg of GY produced before losses and wastage. CE: centrifugation; FO: fortification with MPC 80 powder from the USA; UF: ultrafiltration. See Houssard et al. (2019) for more information on key parameters.

	Unit	CE	FO	UF	Data sources	ecoinvent 3.4 processes
Inputs from technosphere						
Raw material procurement						
Raw milk	kg	3.47	2.73	3.38	Houssard et al. (2019)	Cow milk {CA-QC}| milk production, from cow | Cut-off, U
MPC powder	kg	_	0.03	_		*Not in ecoinvent: MPC 80 manufactured in US created by Houssard (2018); milk, at farm, national average/US U System created by Thoma (2006).*
Raw milk transportation to yogurt plant	t.km	0.65	0.52	0.64		Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| Cut-off, U
MPC transportation to GY plant	t.km	_	0.04	_		
Primary packaging						
PP containers (50% of FU) - polypropylene	g	17.67	17.67	17.67	Houssard et al. (2019)	Polypropylene granulate {GLO}| market for | Cut-off, U; injection moulding {CA-QC} | injection moulding | Cut-off, U; modified from {FR} thermoforming of plastic sheets {CA-QC} | processing | Cut-off, U
PS containers (50% of FU) - polystyrene	g	20.45	20.45	20.45		polystyrene, general purpose {GLO}| market for | Cut-off, U; modified from {FR} thermoforming of plastic sheets {CA-QC} | processing | Cut-off, U
PET seal for PP containers	g	0.51	0.51	0.51		Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U; extrusion, plastic film {CA-QC}| production | Cut-off, U
Laminated paper seal for PS containers	g	1.20	1.20	1.20		Proxy: paper, melamine impregnated {GLO}| market for | Cut-off, U
HDPE lid for PP containers	g	7.17	7.17	7.17		polyethylene, high density, granulate {GLO}| market for | Cut-off, U; extrusion, plastic film {CA-QC}| production | Cut-off, U

Bleached cardboard for PS containers	g	5.73	5.73	5.73		solid bleached board {CA-QC}| production | Cut-off, U
Secondary packaging						
Corrugated board	g	48.86	48.86	48.86		Corrugated board box {CA-QC}| production | Cut-off, U
LLDPE stretchwrap film	g	0.79	0.79	0.79	Houssard et al. (2019)	Polyethylene, linear low density, granulate {GLO}| market for | Cut-off, U; Extrusion, plastic film {CA-QC}| production | Cut-off, U
Wood pallet	g	0.14	0.14	0.14		Proxy: EUR-flat pallet {GLO}| market for | Cut-off, U
GY processing at plant						
Electricity	Wh	47.93	44.99	32.99		Electricity, medium voltage {CA-QC} | market for | Cut-off, U
Natural gas	MJ	0.70	0.58	0.82		Heat, district or industrial, natural gas {CA-QC} | market for | Cut-off, U
Sodium hydroxide in 50% solution state	g	0.36	0.36	0.35		Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U
Nitric acid in 50% solution state	g	0.14	0.14	0.14	Houssard et al. (2019)	Nitric acid, without water, in 50% solution state {GLO}| market for | Cut-off, U
Deionised water	kg	0.26	0.34	0.25		Modified from {CH}|-water, deionised, from tap water, at user {CA-Qc} | production | Cut-off, U, U
Tap water	kg	2.94	2.31	2.87		Tap water {CA-QC} | market for | Cut-off, U (water flows corrected)
Inputs from technosphere						
Distribution						
Electricity	Wh	186.1	186.1	186.1		Electricity, medium voltage {CA-QC} | market for | Cut-off, U
Transportation	t.km	0.15	0.15	0.15	Houssard et al. (2019)	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO5, R134a refrigerant, cooling {GLO}| market for | Cut-off, U;
Consumption						
Plastic bag	g	2	2	2	Houssard et al. (2019)	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U and extrusion, plastic film {CA-QC} | production | Cut-off, U

Transportation	km	0.15	0.15	0.15		Transport, passenger car, medium size, petrol, EURO 5 {RoW}| transport, passenger car, medium size, petrol, EURO 5 | Cut-off, U
Electricity (refrigeration)	Wh	54.7	54.7	54.7		Electricity, low voltage {CA-QC} | market for | Cut-off, U
Tap water	kg	0.8	0.8	0.8		Tap water {CA-QC} | market for | Cut-off, U (water flows corrected)
Output to technosphere						
Wastes to treatment (plant, distribution, consumption, end of life)						
White water (plant)	m3	3.20E-03	2.65E-03	3.12E-03		Proxy: Wastewater from potato starch production {CA-QC} | treatment of, capacity 1.1E10l/year | alloc Rec, U
Wastewater treatment (consumption)	m3	8.000E-07	8.000E-04	8.000E-04		wastewater, average {CA-QC} | treatment of wastewater, average, capacity 4.7E10l/year | Cut-off, U
Cardboard and corrugated board	g	71.160	71.160	71.160		Waste paperboard {RoW}| treatment of, sanitary landfill | Cut-off, U
Plastic mixture landfill	g	49.178	49.178	49.178	Houssard et al. (2019)	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | Cut-off, U
Municipal waste collection (transportation)	t.km	0.012	0.012	0.012		Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Cut-off, U
Products and co-products						
Cream	kg	0.34	0.27	0.33		
Greek yogurt (GY)	**kg**	**1.00**	**1.00**	**1.00**	Houssard et al. (2019)	
Whey	kg	2.13	1.56	2.05		

More details on GY manufacturing processes and key parameters are available in Houssard et al. (2019).

3.2. Life cycle cost inventory

3.2.1. GVA assessment for the economic actors

The revenues and operational costs considered to calculate the GVA of each economic agent are detailed in tables 3 and 4:

- Raw material and services provider costs (e.g., electricity, natural gas, waste water treatment, chemicals, etc.) are included based on the inventory consumption (Table 2) and 2017 unit prices. Data sources are referred in Table 5. Losses and wastage across the life cycle stages are considered in the operational costs.

- Background service providers' gross value-added (GVA) was added using Exiobase, as detailed in section 2.2.2.
- Costs and revenues that are equivalent for all scenarios were not considered. They refer to the packaging, distribution, use and end of life stages of GY that are all the same for the functional unit.
- The GY processor's GVA is based on the difference between the average GY selling price (after a 50% deduction as a gross estimate for the distributor revenue) and GY manufacturer operating costs.
- All the co-products' operational costs and revenues fall within the system boundaries with the following assumptions:
    - Cream from GY production is reused in other dairy products that are manufactured in the same yogurt plant. Therefore, cream price is based on Canadian Class 2b.
    - Liquid permeate from GY production is reused in other dairy products that are manufactured in the same yogurt plant. Therefore, lactose price is based on Canadian Class 2b.
    - Pig farmers' operating costs are beyond the system boundaries. They are assumed to be equivalent to corn grain operating costs and are therefore included in the corn grain costs external system.
    - Biogas end user and permeate powder end users are not included in the system boundaries.

Table 3: GY value chain actor revenues and costs based on inventory flows for 1 kg of GY consumed; L&W included across the value chain

Economic actor	Costs and revenues types		Unit price (CAD)	Value in CAD			Unit	inventory (with L&W)			L&W rate (%)
				CE	FO	UF		CE	FO	UF	
QC farmer	operating costs	raw milk production (including transportation)	0.42	1.44	1.13	1.40	kg	4.60	3.62	4.48	32.5
		transportation	*0.05*	included	included	included	*kg*	3.47	2.73	3.38	29.0
	revenues	raw milk Class 2a	0.83	3.72	2.93	3.62		4.48	3.52	4.36	29.0
	GVA			2.28	1.79	2.22					
QC yogurt processor	operating costs	raw milk transported	0.83	3.72	2.93	3.62	kg	4.48	3.52	4.36	29.0
		MPC 80 transported	6.92	_	0.26	_	kg	_	0.04	_	29.0
		GY packaging	NI	NI	NI	NI	NI	NI	NI	NI	
		eletrical energy	0.04	3.62E-03	2.49E-03	1.83E-03	kwh	0.08	0.06	0.04	29.0
		natural gas	0.12	3.04E-03	2.48E-03	3.54E-03	m3	0.02	0.02	0.03	29.0
		water	0.45	1.86E-03	1.55E-03	1.81E-03	m3	4.12E-03	3.43E-03	4.02E-03	29.0
		wastewater cost	0.34	1.40E-03	1.12E-03	1.36E-03	m3	4.12E-03	3.31E-03	4.02E-03	29.0
		acid cleaner	3.72	6.67E-04	6.57E-04	6.48E-04	kg	1.79E-04	1.77E-04	1.74E-04	29.0
		alkalin cleaner	3.56	1.66E-03	1.63E-03	1.61E-03	kg	4.66E-04	4.59E-04	4.53E-04	29.0
		UF membran cost	0.001	_	_	2.54E-04	u/ kg SM	_	_	3.93	29.0
		whey transportation	0.05	1.39E-01	1.01E-01	1.33E-01	kg	2.75E+00	2.01E+00	2.63E+00	29.0
		whey treatment	0.34	9.33E-04	6.83E-04	8.93E-04	m3	2.75E-03	2.01E-03	2.63E-03	29.0
	revenues	cream	3.77	1.61	1.28	1.57	kg	0.43	0.34	0.42	26.0
		Greek yogurt price estimate (*)	5.08	6.40	6.40	6.40	kg	1.26	1.26	1.26	26.0
		whey or permeate	0	0.00	0.00	0.00	kg	2.68	1.97	2.57	26.0
	GVA			4.14	4.38	4.20					
QC GY distributor	operating costs	Greek yogurt	5.08	6.10E+00	6.10E+00	6.10E+00	kg	1.20E+00	1.20E+00	1.20E+00	20.0
		eletrical energy	0.04	9.58E-03	9.58E-03	9.58E-03	kwh	2.23E-01	2.23E-01	2.23E-01	20.0
		natural gas	0.12	NI	NI	NI	m3	NI	NI	NI	20.0
		transportation	0.05	6.05E-02	6.05E-02	6.05E-02	kg	1.20E+00	1.20E+00	1.20E+00	20.0
		other operating costs	NI	NI	NI	NI	u	NI	NI	NI	20.0
	revenues	Greek yogurt selling price (*)	10.159	12.19	12.19	12.19	kg	1.20	1.20	1.20	20.0
	GVA			NI	NI	NI					
QC waste collector	operating costs	solid waste landfill average	0.216	NI	NI	NI	kg	NI	NI	NI	
		wastewater treatment	0.3395	NI	NI	NI	kg	NI	NI	NI	
	revenues		NI	NI	NI	NI	NI	NI	NI	NI	
		VA solid waste	0.3258792	5.06E-02	5.00E-02	5.00E-02	kg	1.55E-01	1.53E-01	1.53E-01	29.0
		VA wastewater treatment	0.3982968	2.06E-03	1.73E-03	2.02E-03	m3	5.17E-03	4.35E-03	5.06E-03	29.0
		VA whey treatment	0.3982968	6.94E-03	4.98E-03	6.68E-03	m3	1.74E-02	1.25E-02	1.68E-02	29.0
	GVA			0.05	0.05	0.05					
USA farmer	operating costs	Raw milk production	0.35	_	0.29	_	kg	_	1.09	_	32.5
		transportation	0.05		0.05		kg	_	1.07	_	29.0
	revenues	Raw milk Class IV	0.48		0.52			_	1.07	_	29.0
	GVA				0.17				1.07		
USA ingredient manufacturer	operating costs	raw milk transported	0.48	_	0.52	_	kg	_	1.07	_	29.0
		electrical energy	0.07	_	8.14E-04	_	kwh	_	0.01	_	29.0
		Natural gas	0.19	_	1.54E-03	_	m3	_	0.01	_	29.0
		water	0.94	_	2.76E-04	_	m3	_	2.94E-04	_	29.0
		wastewater cost	1.39		4.68E-05		m3		3.37E-05		29.0
		acid cleaner	3.72	_	4.70E-05	_	kg	_	1.26E-05	_	29.0
		alkalin cleaner	3.56		1.17E-04		kg		3.29E-05		29.0
		UF membran cost	0.000		2.54E-04		u/ kg SM		0.96		29.0
		kraft paper bag	0.013		1.94E-05		u/25 kg		0.04		29.0
		MPC 80 transportation	0.19		0.007		kg		0.04		29.0
	revenues	Cream	7.68	_	0.80	_	kg	_	0.10	_	29.0
		MPC 80 transported	6.92	_	0.26	_	kg	_	0.04	_	29.0
		Permeate powder	0.48	_	0.49	_	kg	_	1.02	_	29.0
	GVA				1.03						

Table 4: Whey valorization actor revenues and costs based on inventory flows for 1 kg of GY consumed; L&W included across the value chain

Economic actor	Costs and revenues types			CAD				Quantity (with L&W)			
			Unit price (CAD)	CE	FO	UF	Unit	CE	FO	UF	L&W rate (%)
Pig farmer	operating costs	TBD	NI	NI	NI	NI	NI	NI	NI	NI	26.00
	revenues	Corn grain substitution	0.258	4.23E-02	3.25E-02	3.90E-02	kg	1.64E-01	1.26E-01	1.51E-01	26.00
	GVA			0.04	0.03	0.04					
Biodigestion	operating costs	digestate valorization	0.05	2.15E-05	1.57E-05	2.06E-05	kg	4.29E-04	3.14E-04	4.11E-04	26.0
		electricity	0.04	2.33E-03	1.71E-03	2.24E-03	kwh	5.44E-02	3.98E-02	5.23E-02	26.0
		natural gas	0.12	2.18E-03	1.60E-03	2.10E-03	m3	1.77E-02	1.29E-02	1.70E-02	27.0
		tap water	0.00	0.00E+00	0.00E+00	0.00E+00	m3	4.28E-04	3.14E-04	4.13E-04	26.0
		waste water treatment	0.34	1.46E-04	1.07E-04	1.40E-04	m3	4.29E-04	3.14E-04	4.13E-04	26.0
		transportation	0.05	8.39E-05	1.34E-04	5.81E-05	kg	1.66E-03	2.65E-03	1.15E-03	26.0
	revenues	biogas	0.12	8.84E-03	6.47E-03	8.46E-03	m3	7.36E-02	5.39E-02	7.05E-02	26.00
		fertilizer	0	0.00E+00	0.00E+00	0.00E+00	kg	1.66E-03	2.65E-03	1.15E-03	26.00
		GVA waste water treatment	0.40	1.71E-04	1.25E-04	1.65E-04	m3	4.29E-04	3.14E-04	4.13E-04	26.00
	GVA			4.24E-03	3.04E-03	4.06E-03					
GY processor	operating costs	eletrical energy	0.04	_	_	5.40E-04	kwh	_	_	1.26E-02	26.00
		natural gas	0.12	_	_	1.17E-01	m3	_	_	9.49E-01	27.00
		water	0.45	_	_	1.45E-01	m3	_	_	3.22E-01	28.00
	revenues	permeate price class 2a	0.37	_	_	0.95	kg	_	_	2.57	26.0
	GVA					0.68					
Ingredient manufacturer	operating costs	eletrical energy	0.04	0.00E+00	0.00E+00	3.87E-03	kwh	0.00E+00	0.00E+00	9.03E-02	26.00
		natural gas	0.12	0.00E+00	0.00E+00	7.11E-01	m3	0.00E+00	0.00E+00	5.75E+00	26.00
		water	0.45	0.00E+00	0.00E+00	2.36E-01	m3	0.00E+00	0.00E+00	5.22E-01	26.00
		wastewater cost	0.34	0.00E+00	0.00E+00	3.31E-05	m3	0.00E+00	0.00E+00	9.75E-05	26.00
		acid cleaner	3.72	0.00E+00	0.00E+00	1.95E-04	kg	0.00E+00	0.00E+00	5.24E-05	26.00
		alkalin cleaner	3.72	0.00E+00	0.00E+00	5.13E-04	kg	0.00E+00	0.00E+00	1.38E-04	26.00
		packaging	0.01	0.00E+00	1.79E-06	0.00E+00	kg	0.00E+00	0.00E+00	1.26E-02	26.00
	revenues	permeate powder market price	1.29	0.00E+00	0.00E+00	2.13E-01	kg	0.00E+00	0.00E+00	1.65E-01	26.00
		GVA waste water treatment	0.40	0.00E+00	0.00E+00	3.88E-05	m3	0.00E+00	0.00E+00	9.75E-05	26.00
	GVA			_	_	-0.74		_	_		

Note that the UF-PP scenario has a negative GVA in 2017 due to unfavourable market price conditions for milk ingredients.

Table 5: Data sources for Canadian and USA costs and revenues

Economic actor	Costs and revenues types		Unit price	unit	Data for calculation	Source	URL	Access date
QC farmer	operating costs	raw milk production (including transportation)	43.09	CAD/hl	d = 1037 kg.l^{-1}	CCL (2018)	http://www.cdc-ccl.gc.ca/CDC/index-fra.php?id=3941	Sep-19
		transportation	2.43	CAD/hl	d = 1037 kg.l^{-2}	PLQ (2017)	http://lait.org/fichiers/RapportAnnuel/FPLQ-2017/transport.pdf	Sep-19
	revenues	raw milk Class 2a	0.83	CAD/kg	P = 3.27 w/w; F = 3.97 w/w; OS = 5.56 w/w Av. 2017 Cost for class 2 a P, F and OS (confidential)	PLQ (2017)	Personal communication with Folence Bouchard-Santerre	Jul-18
QC yogurt processor	operating costs	raw milk transported	0.83	CAD/kg	P = 3.27 w/w; F = 3.97 w/w; OS = 5.56 w/w Av. 2017 Cost for class 2 a P, F and OS (confidential)	PLQ (2017)	Personal communication with Folence Bouchard-Santerre	Jul-18
		MPC 80 transported	8.14	CAD/kg	Transportation = 1500 km; Av. MPC price = 6.17 USD/kg; Exchange rate: 1.2969 CAD/USD	Ingredient digest (2017)	https://www.dairy.com/docs/sample-publications/ingredient-digest.pdf https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/	Sep-19
		GY packaging	NI					
		eletrical energy	0.04	CAD/kwh		Énergie et ressource naturelles Qc (2014)	https://mern.gouv.qc.ca/energie/statistiques/statistiques-energie-prix-electricite.jsp	Sep-19
		natural gas	3.26	CAD/GJ		Energir (2018)	https://www.energir.com/fr/grandes-entreprises/prix-du-gaz-naturel/prix-et-historique/	Sep-19
		water	0.45	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
		wastewater cost	0.34	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
		acid cleaner	3.72	CAD/kg		CYNDAN(2018)	CYNDAN, 2018, Food and Beverages CIP Cleaners, Ressource en ligne - URL : https://cyndan.com.au/en/24-cip-cleaners - consulté en mars 2018.	Mar-18
		alkalin cleaner	3.56	CAD/kg		CYNDAN(2018)	CYNDAN, 2018, Food and Beverages CIP Cleaners, Ressource en ligne - URL : https://cyndan.com.au/en/24-cip-cleaners - consulté en mars 2018.	Mar-18
		UF membrane cost	0.001	u/ kg SM	Shelf life : 3 years; Size 1007 m2; Cost for 10KPA : 82.36 CAD/m2; capacity in kg of SM treated (SM= Skimmed milk)	Alfa Laval (2015); Simulation Benoit and Houssard (2017)		
		whey transportation	0.05	CAD/kg	asssumed to be twice the milk transportation cost	assumption		
		whey treatment	0.34	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
	revenues	cream	3.77	CAD/kg	P = 2.04 w/w; F = 40 w/w; OS = 3.48 w/w Av. 2017 Cost for class 2 a P, F and OS (confidential)	PLQ (2017)	Personal communication with Folence Bouchard-Santerre	Jul-18
		Greek yogurt price estimate (*)	5.08	CAD/kg	Av. Grocery price : 10.159 CAD Revenue assumed to be half the price of grocery	Market survey Montréal (2017)		
		whey or permeate	0	CAD/kg	No value			
QC GY distributor	operating costs	Greek yogurt	5.08	CAD/kg	See Qc yogurt processor price estimate			
		eletrical energy	0.04	CAD/kwh		Énergie et ressource naturelles Qc (2014)	https://mern.gouv.qc.ca/energie/statistiques/statistiques-energie-prix-electricite.jsp	Sep-19
		natural gas	0.12	CAD/GJ		Energir (2018)	https://www.energir.com/fr/grandes-entreprises/prix-du-gaz-naturel/prix-et-historique/	Sep-19
		transportation	0.05	CAD/kg	assumed to be twice the price of Qc milk transportation			
		other operating costs	NI					
	revenues	Greek yogurt selling price (*)	10.159		Av. Grocery price : 10.159 CAD	Market survey Montréal (2017)		
QC waste collector	operating costs	solid waste landfill average	216	CAD/ton		Ville de Montréal (2017)	http://ville.montreal.qc.ca/vuesurlesindicateurs/index.php?kpi=2441	Sep-19
		wastewater treatment	0.3395	CAD/m3		MAMROT(2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
	revenues		NI					
		VA solid waste	0.3258792	CAD/kg	1.5087 CAD/EURO; inflation rate: 4.8%; 216 CAD/ton (cf solid waste landfill); 0.64 Euro (2011)/Euro (2011)			
		VA wastewater treatment	0.40	CAD/kg	1.5087 CAD/EURO; inflation rate: 4.8%; 216 CAD/ton (cf solid waste landfill); 0.88 Euro (2011)/Euro (2011)	EXIOBASE Consortium. (2017). EXIOBASE (Version 3) [product-by-product industry-technology-assumption coefficients, for year 2011]. Retrieved from EXIOBASE. Retrieved March 14, 2019, from https://www.exiobase.eu/index.php/data-download/exiobase3mon?limit=20&limitstart=20		
		VA whey treatment	0.40	CAD/kg	assumed to be the same than wastewater			

Economic actor	Costs and revenues types		Unit price	unit	Data for calculation	Source	URL	Access date
USA farmer	operating costs	Raw milk production	12.29	USD/cwt	1 cwt = 45.35 kg; exchange rate : 1.29 CAD/USD	USDA ERS (2017)	https://www.ers.usda.gov/data-products/milk-cost-of-production-estimates/milk-cost-of-production-estimates/#Milk%20Cost-of-Production%20Estimates-2016%20Base	
		transportation	0.05	CSD/kg	assumed to be twice the price of Qc milk transportation			
	revenues	Raw milk Class IV	16.90	USD/cwt	1 cwt = 45.35 kg; exchange rate : 1.29 CAD/USD	USDA ERS (2017)	https://www.ams.usda.gov/mnreports/dymclassprices.pdf	Sep-19
USA ingredient manufacturer	operating costs	raw milk transported	16.90	USD/cwt	1 cwt = 45.35 kg; exchange rate : 1.29 CAD/USD	USDA ERS (2017)	https://www.ams.usda.gov/mnreports/dymclassprices.pdf	Sep-19
		electrical energy	6.88	USC/kwh	US industrial average electrical cost; exchange rate : 1.29 CAD/USD	EIA (2017)	https://www.eia.gov/electricity/annual/html/epa_02_04.html	Sep-19
		Natural gas	4.1	USD/1000cubic feet	US industrial average Natural gas cost; exchange rate : 1.29 CAD/USD; 35.3147 cubic foot/m3	EIA (2017)	https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm	Sep-19
		water	3.55E-03	USD/gallon	exchange rate : 1.29 CAD/USD;	Statista (2013)	https://www.statista.com/statistics/754676/average-us-industrial-water-and-sewage-costs/	Sep-19
		wastewater cost	5.25E-03	USD/gallon	exchange rate : 1.29 CAD/USD;	Statista (2013)	https://www.statista.com/statistics/754676/average-us-industrial-water-and-sewage-costs/	Sep-19
		acid cleaner	3.72	CAD/kg		CYNDAN(2018)	CYNDAN, 2018, Food and Beverages CIP Cleaners, Ressource en ligne - URL : https://cyndan.com.au/en/24-cip-cleaners	Mar-18
		alkalin cleaner	3.56	CAD/kg		CYNDAN(2018)	CYNDAN, 2018, Food and Beverages CIP Cleaners, Ressource en ligne - URL : https://cyndan.com.au/en/24-cip-cleaners	Mar-18
		UF membran cost	2.65E-04	u/ kg SM	Shelf life : 3 years; Size 1007 m2; Cost for 10KPA : 82.36 CAD/m2; capacity in kg of SM treated (SM= Skimmed milk)	Alfa Laval (2015); Simulation Benoit and Houssard (2017)		
		kraft paper bag (25 kg)	0.25	USD/u	exchange rate : 1.29 CAD/USD;	Alibaba (2019)	https://www.alibaba.com/showroom/25kg+kraft+paper+bag.html?fsb=y&IndexArea=product_en&CatId=23190205&SearchText=25kg+kraft+paper+bag&isGalleryList=G	Sep-19
		MPC 80 transportation	0.19	CAD/kg	Based on PLC transportation : 1500 km; 2.42 CAD/hl milk (over 182 km)			
	revenues	Cream	2.69	USD/pound	US butterfat class IV price (Butter and powders); 1.29 CAD/USD;	USDA ERS (2019)	https://www.ams.usda.gov/mnreports/dymclassprices.pdf	Sep-19
		MPC 80	2.78	USD/lb	Exchange rate: 1.2969 CAD/USD	*Ingredient Digest (2017)*	https://www.dairy.com/docs/sample-publications/ingredient-digest.pdf	Sep-19
		Permeate powder	0.17	USD/pound	US OS class IV price (Butter and powders); Exchange rate: 1.2969 CAD/USD; 0.4536 kg/pound	USDA ERS (2019)	https://www.ams.usda.gov/mnreports/dymclassprices.pdf	Sep-19

Economic actor	Costs and revenues types		Unit price (CAD)	unit	Data for calculation	Source	URL	Access date
Pig farmer	operating costs	NI	NI		Supposed to be included in Corn grain system			
	revenues	Corn grain substitution	258	CAD/ton	Calculation based on eq. energy content between corn grain and whey	AAFC (2019)	http://www.agr.gc.ca/resources/prod/doc/misb/mag-gam/fgf-cdp/fgf_taba_20190826-eng.pdf	Sep-19
Biodigestion		digestate valorization	50	CAD/ton		HEC (2019)	Personal communication with Remy Nicolai	Jul-19
	operating costs	electricity	0.04	CAD/kwh		Énergie et ressource naturelles Qc (2014)	https://mern.gouv.qc.ca/energie/statistiques/statistiques-energie-prix-electricite.jsp	Sep-19
		natural gas	0.12	CAD/GJ		Energir (2018)	https://www.energir.com/fr/grandes-entreprises/prix-du-gaz-naturel/prix-et-historique/	Sep-19
		tap water	0.45	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
		waste water treatment	0.34	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
		transportation	5.23	CAD/hl	Assumed to be twice the distance of Qc milk			
	revenues	biogas	0.12	CAD/Nm3		HEC (2019)	Personal communication with Remy Nicolai	Jul-19
		fertilizer	0		No revenue			
		GVA waste water treatment	0.40	CAD/kg	1.5087 CAD/EURO; inflation rate: 4.8%; 216 CAD/ton (cf solid waste landfill); 0.88 Euro (2011)/Euro (2011)	EXIOBASE Consortium. (2017). EXIOBASE (Version 3) [product-by-product industry-technology-assumption coefficients, for year 2011]. Retrieved from EXIOBASE. Retrieved March 14, 2019, from https://www.exiobase.eu/index.php/data-download/exiobase3mon?limit=20&limitstart=20		
GY processor	operating costs	eletrical energy	0.04	CAD/kwh		Énergie et ressource naturelles Qc (2014)	https://mern.gouv.qc.ca/energie/statistiques/statistiques-energie-prix-electricite.jsp	Sep-19
		natural gas	0.12	CAD/GJ		Energir (2018)	https://www.energir.com/fr/grandes-entreprises/prix-du-gaz-naturel/prix-et-historique/	Sep-19
		water	0.45	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
	revenues	UF permeate price class 2a	0.37	CAD/kg	P = 0.18 w/w; F = 0 w/w; OS = 5.99 w/w Av. 2017 Cost for class 2 a P, F and OS (confidential)	PLQ (2017)	Personal communication with Folence Bouchard-Santerre	Jul-18
Ingredient manufacturer	operating costs	eletrical energy	0.04	CAD/kwh		Énergie et ressource naturelles Qc (2014)	https://mern.gouv.qc.ca/energie/statistiques/statistiques-energie-prix-electricite.jsp	Sep-19
		natural gas	3.26	CAD/GJ		Energir (2018)	https://www.energir.com/fr/grandes-entreprises/prix-du-gaz-naturel/prix-et-historique/	Sep-19
		water	0.45	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
		wastewater cost	0.34	CAD/m3		Mamrot (2015)	MAMROT, 2015, Rapport sur le coût et les sources de revenus des services d'eau, Ministère Québécois des Affaires municipales et de l'Occupation du territoire.	Sep-19
		acid cleaner	3.72	CAD/kg		CYNDAN(2018)	CYNDAN, 2018, Food and Beverages CIP Cleaners, Ressource en ligne - URL : https://cyndan.com.au/en/24-cip-cleaners - consulté en mars 2018.	Mar-18
		alkalin cleaner	3.56	CAD/kg		CYNDAN(2018)	CYNDAN, 2018, Food and Beverages CIP Cleaners, Ressource en ligne - URL : https://cyndan.com.au/en/24-cip-cleaners - consulté en mars 2018.	Mar-18
		kraft paper bag (25 kg)	0.25	USD/u	exchange rate : 1.29 CAD/USD;	Alibaba (2019)	https://www.alibaba.com/showroom/25kg+kraft+paper+bag.html?fsb=y&IndexArea=product_en&CatId=23190205&SearchText=25kg+kraft+paper+bag&isGalleryList=G	Sep-19
	revenues	permeate powder market price	0.87	Euro/kg	exchange rate : 1.4772 CAD/USD;	CLAL (2017)	https://www.clal.it/en/?section=grafici_siero	Sep-19
		GVA waste water treatment	0.40	CAD/kg	1.5087 CAD/EURO; inflation rate: 4.8%; 216 CAD/ton (cf solid waste landfill); 0.88 Euro (2011)/Euro (2011)	EXIOBASE Consortium. (2017). EXIOBASE (Version 3) [product-by-product industry-technology-assumption coefficients, for year 2011]. Retrieved from EXIOBASE. Retrieved March 14, 2019, from https://www.exiobase.eu/index.php/data-download/exiobase3mon?limit=20&limitstart=20		

3.2.2. Other economic actors' VA estimation with Exiobase

The direct value added associated with the foreground system stages (i.e. milk production, transportation, yogurt manufacturing and associated waste treatment) was estimated to be between 48% and 50% of the life cycle value added of the yogurt. Modelling was performed with the Exiobase EEIO database (v3.4, as available in openLCA) for a national scope (Canada) considering the dairy product manufacturing sector as a proxy for yogurt manufacturing. Value-added components considered are i) consumption of fixed capital, ii) remaining net operating surplus, iii) other net taxes on production, and iv) total taxes less subsidies on products purchased. Due to uncertainties regarding which transportation inputs in the Exiobase model had to be related to the actual milk transportation, a sensitivity analysis was carried out and confirmed that the foreground system's contribution to life cycle value-added remains in the 48-50% range (Figure 3).

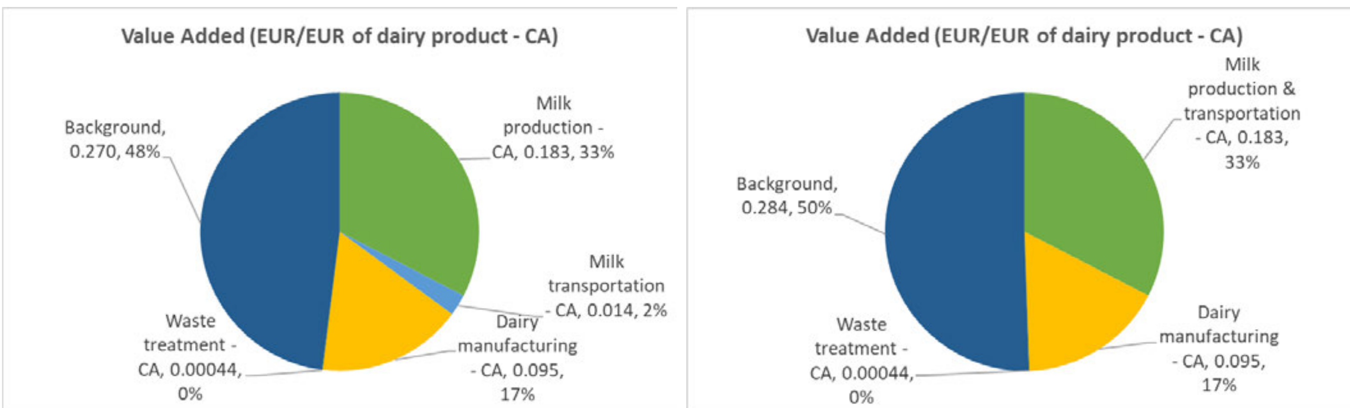

Figure 3: *Sensitivity analysis on value-added distribution between the foreground and background system stages of dairy product in Canada.*

4. Additional results

4.1. Whey management impacts on climate change for each GY technology

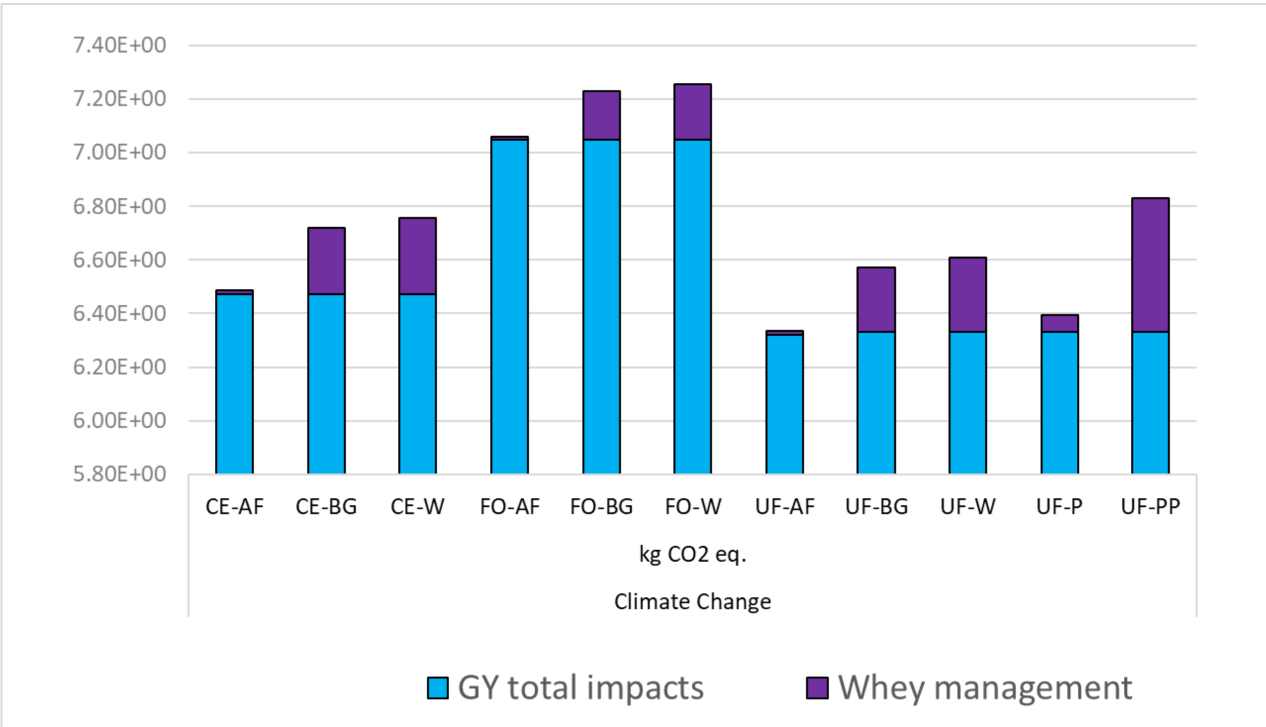

Figure 4: *Comparison of whey management impacts on climate change for CE: centrifugation; FO: fortification; UF: ultrafiltration; animal feed (AF), biogas (BG); permeate on-site valorization (P); permeate powder (PP); treatment at wastewater plant (W).*

4.2. Socio-economic value indicators

Table 6 provides the gross value added (GVA) results of each scenario for the main individual actors (dairy farmer, GY processor), Canadian territory, USA territory and total value chain (TGVA) based on sections 3.2.1 and 3.2.2 data and reported for the estimated Canadian GY (at 0% fat) annual production in 2017 (≈35 265 000 kg)[1]. These results are used to calculate the difference of GVA between the alternative scenarios and the reference scenario (CE-AF) in the manuscript (Table 2).

[1] Internal calculation based on : ACF Canada, l'industrie laitière en chiffre – édition 2017; PLQ and Nielsen personal interviews.

Table 6: Gross value added from GY (10% protein and 0% fat) processed in Canada for the value chain actors (by individuals (farmers and processors), territory (Canada, USA) and global (TGVA))

	GVA (CAD 2017)				
Scenario	**Dairy farmer**	**GY processor**	**Canada (*)**	**USA (*)**	**TGVA**
CE-AF (reference)	8,03E+07	1,46E+08	4,42E+08	0,00E+00	4,42E+08
FO-AF	6,32E+07	1,55E+08	4,25E+08	8,14E+07	5,06E+08
UF-AF	7,83E+07	1,48E+08	4,41E+08	0,00E+00	4,41E+08
CE-W	8,03E+07	1,46E+08	4,39E+08	0,00E+00	4,39E+08
FO-W	6,32E+07	1,55E+08	4,23E+08	8,14E+07	5,04E+08
UF-W	7,83E+07	1,48E+08	4,39E+08	0,00E+00	4,39E+08
CE-BG	8,03E+07	1,46E+08	4,39E+08	0,00E+00	4,39E+08
FO-BG	6,32E+07	1,55E+08	4,23E+08	8,14E+07	5,04E+08
UF-BG	7,83E+07	1,48E+08	4,39E+08	0,00E+00	4,39E+08
UF-P	7,83E+07	1,72E+08	4,85E+08	0,00E+00	4,85E+08
UF-PP	7,83E+07	1,48E+08	3,89E+08	0,00E+00	3,89E+08

4.3. Functional value indicators

The functional value indicators selected (Table 7) originate from recent studies (from Uduwerella et al. (2018) and Moineau-Jean et al. (2019)) comparing GY (at 10% protein and 0% fat) processed using CE or UF technologies. The attributes from theses previous studies which turned out to be similar for CE and UF (e.g. protein content, syneresis, …) were not considered in our analysis.

Table 7: Functional value indicators selected for GY (10% protein and 0% fat) processed by UF or CE technologies

Functional value attributes	Indicator	Unit	CE	UF	Reference
Nutritional	Calcium content	mg/100 g	170	219	Uduwerella et al. (2018)
Health	Probiotic concentration (40 days storage)	log cfu.g^{-1}	7.27	5.77	Moineau-Jean et al. (2019)
Sensory	Typical flavour (40 days storage)	points	34	30	Moineau-Jean et al. (2020)

Remark: The probiotic concentration reflects *Lactobacillus Heleveticus* viability after 40 days of storage. Because the difference was not significant at 3 days, it seems there is a loss of viability of UF GY probiotic during storage. However, this effect is not currently well understood [65]. As demonstrated by Moineau-Jean et al. [66], the perception of typical flavour is highly correlated to several other sensory attributes, such as of texture (smoothness), acidity (perception of acidity) or taste (aftertaste) and was selected to reflect the sensory profile of GY. To be consistent with the probiotic concentration attribute, the typical flavour score that was selected is also after 40 days of storage. The perceived typical flavour difference is not significant at 40 days (12%) but is at 3 days (34%), meaning that consumers may perceive a difference if they consume the product at the beginning of its shelf life [66].

4.4. Comparison of normalization and weighting method results

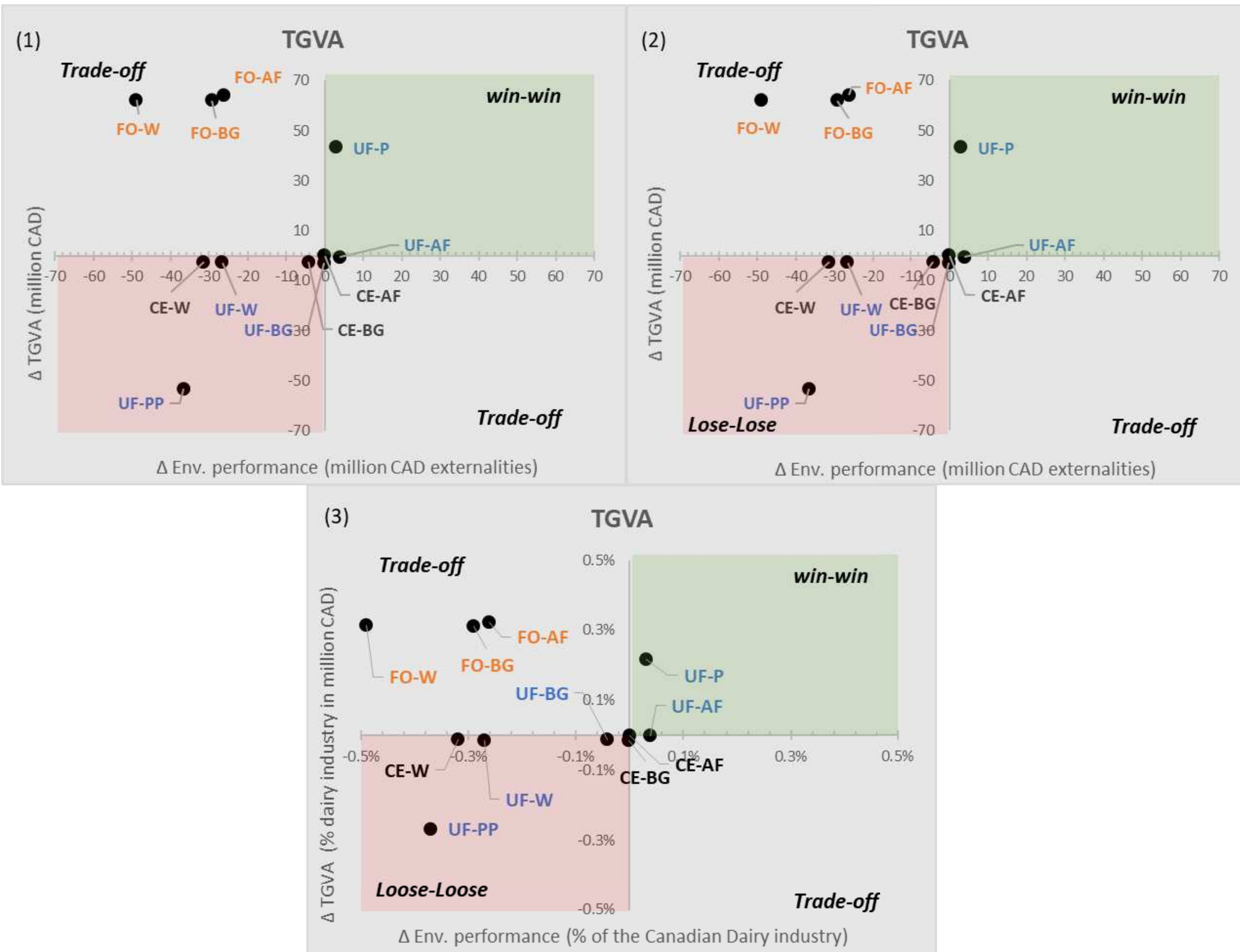

Figure 5: *Comparison of normalization and weighting method on TGVA EE profile results: (1) Stepwise; (2) Stepwise+Ricke; (3) % of the Canadian dairy industry*

Note: The results only consider 0% fat GY, which is estimated to make up 50% of the Canadian GY market (personal communication with Nielsen and GY manufacturers). Since the impacts of GY increase with yogurt fat content (Houssard et al., 2019), the environmental impacts of the total GY market in Canada are at least twice the ones presented in these figures.