Measuring Shared Value Creation with Eco-Efficiency: Development of a Multidimensional Value Framework for the Dairy Industry

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Abstract: The concept of creating shared value was first advanced by Harvard Business School and adopted by companies to develop sustainability strategies to maximize their positive impacts on society. Eco-efficiency is a sustainability concept and a prevalent operational decision support tool that assesses the environmental performance of a system as a function of its value. This paper proposes a novel multidimensional value eco-efficiency framework based on a life cycle perspective that broadens the value dimension assessment in keeping with the concept of creating shared value. The framework is tested and implemented in a case study in the Canadian dairy industry. It uses a systemic approach to compare the eco-efficiency performance of 11 multifunctional Greek yogurt systems delivering various co-products with different functions and economic values across the value chain. It makes it possible to identify the trade-offs between the environment and various value dimensions (economic or functional) based on stakeholders' interests. The results show that the scenarios that create the most economic value for the Greek yogurt processors do not perform as well for the other stakeholders along the value chain or in terms of overall environmental performance. By developing a multi-criteria value assessment, this enhanced eco-efficiency framework brings consistency in covering the same scope of analysis between value creation and environmental impacts. More specifically it breaks with the industry's prevailing value creation philosophy and value measurement in eco-efficiency analysis, which is usually based on cost-effectiveness and profit maximization for one stakeholder at the expense of the others in the value chain. Ultimately, it contributes to align companies' efforts in improving their eco-efficiency with sustainability goals and minimize the risk of burden shifting.

Keywords: sustainable value chains, life cycle management tools, eco-efficiency, ISO 14 045, Greek yogurt

1. Introduction

There is a growing awareness of the need to modify production and consumption systems to achieve sustainability and stay within the safe operating space of the earth's system (Steffen et al., 2015). A global shift toward sustainable food systems is particularly needed. Without such a transformation,

the world will not achieve the UN Sustainable Development Goals (SDG's) initiative and the Paris agreement (Rockström et al., 2020).

For many years, academics argued for a paradigm shift in creating and measuring business value to achieve sustainability. In 1997, Elkington, who introduced the concept of the *people, planet, profit* triple bottom line, stated the importance for corporations to break with traditional approaches in business value creation to generate positive impacts on society. An increasing number of companies realize that conventional business models, which place significant pressure on suppliers to improve their cost-effectiveness and own benefits at the expense of the environment and quality delivered to the customer, are neither effective nor sustainable (Porter and Kramer, 2011). These authors introduced the concept of "Creating shared value" for shifting away from individual profit quest toward value generation across the value chain. It implies reconceptualizing the value creation logic and building new systems based on collaboration and sharing rather than aggressive competition to make value chains more eco-efficient and resilient (Bocken et al., 2014). This new value proposal comprising many aspects – customer value, economic value, social value, and environmental value - leads to the co-creation of multiple values by a mix of economic and social actors, including customers and suppliers (Carvalho and Jonker, 2015). However, for the time being, a coherent framework and concrete tailored tools and metrics are still lacking to assess the multidimensional value performance of business units across their value chain (Porter and Kramer, 2011).

This paper suggests using the life cycle assessment (LCA) tools to implement the shared value creation concept. LCA's holistic approach could indeed shift the focus from measuring individual performance to measuring shared value creation across the entire value chain. LCA tools are framed within the international ISO 14000 standard series and are recognized worldwide for their scientific robustness (Guinée et al., 2011). They include environmental life cycle assessment (eLCA), life cycle costing (LCC), and social life cycle assessment (sLCA) tools, which may be used separately or in combination to assess the three dimensions of sustainability (Kloepffer, 2008). Among these standards, ISO 14045 (ISO, 2012) sets out principles and requirements to quantify eco-efficiency (EE). EE is a management concept first introduced in the early 90s by Shaltegger and Strum (Figge and Hahn, 2004) and then popularized by the World Business Council on Sustainable Development (WBCSD). The WBCSD defined it as "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity" (Schmidheiny, 1992) but various definitions and implementations co-exist. For instance, Kicherer et al. (2007) define it as the ratio between economic and environmental impact per functional or unitary unit, and ISO 14045 (ISO, 2012) defines it as a quantitative management tool that enables the study of life cycle environmental impacts of a product system along with its product system value. The standard is expected to expand the scope of EE toward a life cycle perspective (Lorenzo-Toja et al., 2016) and broaden the concept of value creation beyond the economic sphere. Indeed, from the ISO 14045 perspective, value creation may encompass all

aspects of value relevant to the stakeholders affected along the value chain. For instance, consumers seek maximum functionality (e.g., nutritional value, technical performance, experience, aesthetics, hedonism, etc.). In contrast, economic actors seek maximum profits and perhaps an improvement in their positive contribution to society (e.g., social well-being, educational wealth, or even growth and preservation of natural and cultural heritage). The standard recommends using functional value, monetary value (such as cost, price, willingness to pay, value-added, profit, future investment, etc.), other intangible values, or a combination of these depending on the study objectives and intended audience. However, ISO 14045 first harmonization efforts have focused on integrating the environmental life cycle perspective but provide little guidance on incorporating value aspects. It leads to a lack of systemic vision to assess value and creates methodological inconsistencies between the value and environmental aspect assessment.

In practice, the EE concept has been extensively applied in food and other industries using various methodologies, including LCA, data envelopment analysis (DEA), stochastic frontier analysis, and indexes system methods (John et al., 2020). Zielińska-Chmielewska et al. (2021) identified and assessed the relevance of several EE methodologies applied to the food industry. In a literature review on EE, Caiado et al. (2017) emphasize the lack of a specific integrated framework to achieve sustainable development through EE. Similarly, Miah (2017) found a high degree of heterogeneity in the literature in how the economic value was calculated and how the scope of the economic assessment was defined. For instance, some authors consider the investor's perspective, some the manufacturer's perspective, while others integrate the entire value chain. According to these authors, including the consumer's perspective or that of different actors is rarely considered. Only a handful of papers have explored the multidimensional aspects of value in EE. For instance, Catarino et al. (2016), Charmondusit et al. (2014), and Costa et al. (2018) propose to add a social component to the economic and environmental components. D'Anna and Cascini (2016) and Wever and Vogtländer (2013) introduce multiple indicators to measure the functional performance of products related to user interests in EE assessment. John et al. (2020) recommend integrating sector-specific indicators to capture sector-specific added-value, arguing that it would be necessary to include nutritional or product quality indicators in EE analyses for the food industry. Several studies propose to correlate the nutritional attributes of a food or diet with its environmental impacts or resource consumption intensity (Espinoza-Orias et al., 2014; Sturtewagen et al., 2016; Stylianou et al., 2021, 2016) but without introducing the EE concept in their analytical frameworks. Chaudron et al. (2019) seems to be the only ones to carry out a multi-criteria assessment of value (functional nutrient content, taste, and level of abatement of harmful substances) from the consumer's perspective in a comparative EE study on cranberry juices. Still, these authors do not compare the functional scores with other value indicators that could better reflect the different interests of value chain stakeholders.

Many EE studies have been published in the dairy industry using different approaches. Most of them combine LCA and DEA (Rebolledo-Leiva et al., 2022). For instance, Cortés et al. (2021) assessed the

EE of dairy farms in Spain, Soteriades et al. did the same for French (2016) and UK dairy farms (2020), and Streimikien et al. (2022) conducted an EE assessment of 317 farms in Lithuania focusing on GHG emissions. These authors also identified in the literature several other EE frameworks for dairy farms applied in various countries, such as Cecchini et al. (2018) in Italy, Le et al. (2020) in Canada, Martinsson and Hansson (2021) in Sweden. However, all these studies are limited to a cradle to farm gate scope. They focus on the value creation of one specific actor of the value chain, and the value dimension of EE is limited to a few economic indicators. Benoit et al. (2019) developed an operational tool to assess EE in dairy processing that considers the profit generated by the dairy processors. Nevertheless, the focus is still on the economic value generated by one specific value chain actor. Grassauer et al. (2022) introduced a novel EE approach using DEA to assess the functional value of various dairy farm models fulfilling several functions of agriculture. Rebolledo-Leiva et al. (2022) developed separate indexes on two life cycle stages of dairy production (feed and milk production) for assessing the eco-efficiency and the value created by the feed farmers and the dairy farmers. They demonstrated that the efforts should be placed on the feed stage, which presents the lowest eco-efficient indexes. Lindgaard-Jørgensen et al. (2015) have also adopted this broader perspective by measuring the economic value generated by each economic actor included in the boundaries of their study. Still, the consumers were out of the scope.

None of the various EE studies in the food sector adopt a multidimensional approach to assess the value created across the whole value chain and at different levels, to consider individual, territorial, or societal interests. The literature review also highlighted a lack of consistency in the scope of analysis between the assessment of shared value creation and environmental impacts. This paper aims to fill this gap by developing a consistent multidimensional value framework for EE measurement in the dairy industry. The framework is applied to a case study on Greek yogurt (GY) in Canada for assessing the EE of 11 scenarios combining different GY processing technologies, supply chains, and co-product valorization pathways.

The specific objectives are to:

(1) Develop a multidimensional value assessment framework to support shared value creation in EE approaches.
(2) Implement this framework in a case study to illustrate the potential environmental and value trade-offs among the value chain actors.
(3) Discuss the relevance and limitations of the framework and its potential for other applications or enhancement.

The paper is structured in five sections. Section 2 describes the novel EE assessment framework and the case study. Results are presented in section 3, followed by a discussion (section 4) and a conclusion (section 5).

2. Method:

2.1 Development of the novel EE framework

The general methodology follows the five steps of ISO 14 045 guidelines (Figure 1): (1) definition of the scope of work (2) and (3) assessment of the environmental and value scores of the studied systems separately (4) quantification of EE by combining the environmental and value dimensions into EE metrics and (5) interpretation of the EE results.

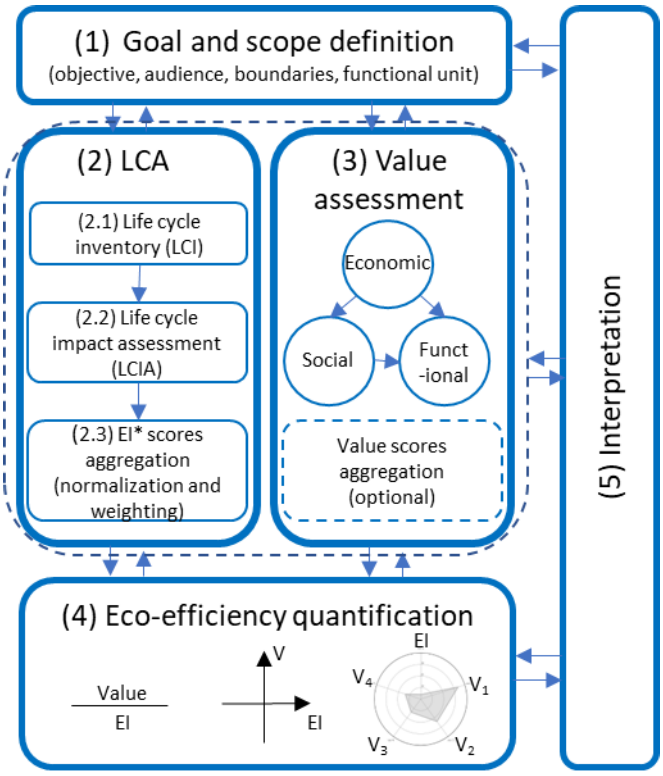

Figure 1. Eco-efficiency assessment steps adapted from ISO 14 045; *EI scores: environmental impact scores

2.1.1 Multidimensional value assessment model

The value assessment model adopts a life cycle perspective, as recommended in Hunkeler et al. (2008) life cycle costing textbook. It also addresses a multilevel assessment in line with the recommendations of Huppes and Ishikawa (2005) and multidimensional assessment to guide EE actions toward sustainability. Figure 2 illustrates the general framework to assess the financial, socio-economic, and functional components of value typically created by a food value chain. These components are meant to reflect stakeholders' multiple and possibly divergent interests at different levels in the chain (individual, territorial, societal). The monetary indicators represent the interests of the economic actors across the value chain and wealth creation for the society, whereas the functional indicators are representative of product nutritional, health and sensory attributes. The next section describes the monetary and functional indicators considered in this study.

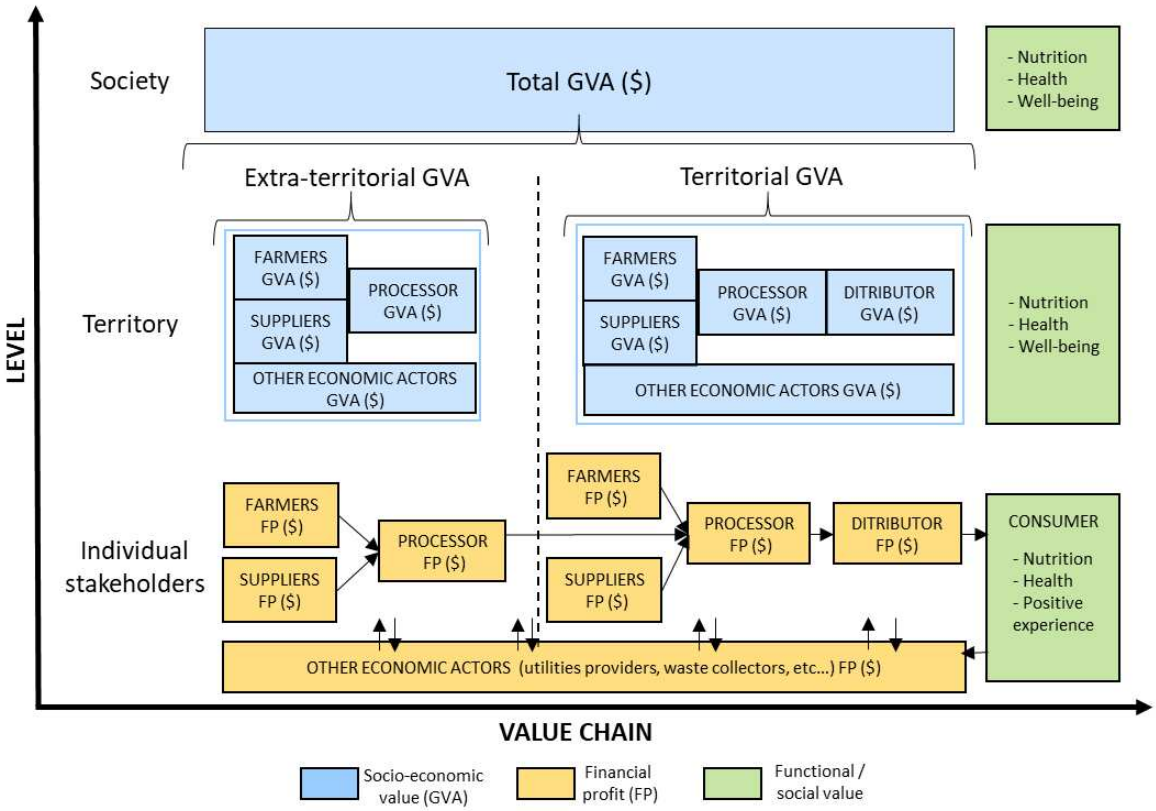

Figure 2. Eco-efficiency multidimensional and multilevel assessment framework adapted from ISO 14 045; *EI scores: environmental impact scores

Financial profit of individual economic actors: The financial profit is the net income from sales after deduction of all costs related to production, including materials costs, capital costs, labor costs, and taxes (Piper, 2012). It is typically the value captured by private actors (the company and its shareholders). It is measured as presented in Equation (1):

$$\mathrm{FP_{aj}} = R_a - IC_{aj} - \sum_i OC_{iaj} \qquad \forall \ a \in A, j \in J \ and \ i \in I, \tag{1}$$

FP_{aj}: Financial Profit of actor a for scenario j; Ra: Revenue of actor a; IC_{aj}: Indirect Costs, depreciation and taxes of actor a for scenario j; OC_{iaj}: Operational Cost i (raw material, energy, transportation, utilities costs) of actor a for scenario j; with A: set of the economic stakeholders, J: set of the technical scenarios, and I: set of the operational costs for each scenario under study.

Socio-economic value measured by gross value added (GVA) at the territory level: The GVA is a socio-economic indicator that measures the creation of value for society at the company level. It is the sum of indirect costs (labour costs and capital costs)including depreciation, profits and taxes (David Hunkeler et al., 2008). It is also defined by the value of output (revenue) less the value of intermediate consumption (operational costs) (United Nations, 2009) as per Equation (2).

$$\mathrm{GVA_{aj}} = R_a - \sum_i OC_{iaj} \qquad \forall \ a \in A, j \in J \ and \ i \in I \tag{2}$$

OC_{iaj}: Operational Cost i (raw material, energy, transportation, utilities costs) of actor a for scenario j; GVA_{aj} : Gross Value Added of actor a for scenario j;

The GVA generated by the actors in the value chain on the territory are added to assess the creation of value within a given territory.

$$\mathrm{GVA_{tj}} = \sum_a (R_a - OC_{atj}) \ = \ \sum_a \mathrm{GVA_{aj}} \qquad \forall \ t \in T, j \in J \ and \ a \in A* \qquad (3)$$

GVAtj: Gross value added created inside the territory t for scenario j; A: set of the economic actors a from the value chain inside the territory t; T set of territories t included in the value chain.*

Socio-economic value measured by total gross value added (Total GVA) at the society level: The GVAs generated by each territory are added to assess the creation of value across the value chain, as per Equation (4).

$$\mathrm{TGVA_j} = \sum_t GVA_{tj} \qquad \forall \ j \in J \ and \ t \in T \qquad (4)$$

TGVAj: Total Gross Value Added created along the value chain for scenario j.

Functional value: The functional value of food products refers to their nutritional attributes, health benefits, and sensory characteristics (e.g., texture, taste, flavor, etc.) (Ebringer et al., 2008). It could also encompass packaging functionalities (e.g., shelf life, practicality, lightness, robustness, aesthetics, etc.) that are more generally presented as attributes of a positive consumer perception (Pinya, 2007; Venter et al., 2011). Functional value indicators may be kept separate or aggregated into a single score. Aggregation may be achieved with various multicriteria decision analysis (MCDA) techniques (Cinelli et al., 2014). However, this ultimate step goes beyond the scope of this study since the objective is to discuss the trade-offs between the various value dimensions in the decision process.

2.1.2 Expression of EE indicators in relative unit

The expression of the value and environmental indicators in relative unit is another specificity of this framework. While the EE concept is a relative concept, a reference situation *r* is compared to different alternatives *j* (ISO, 2012). Thus, the value dimension is expressed in terms of value improvement by a differential between the value (V) of the reference *r* and alternative *j* (Vj-Vr). The environmental dimension is expressed by a differential in terms of environmental performance between the environmental impact (EI) of reference r and alternative j (EIr-EIj). From a life cycle perspective, this method simplifies the data collection since the values and impacts that are similar from one operator to another or from one life cycle stage to another do not need to be included in the analysis (Mami et al., 2017).

2.1.3 Graphical representation in EE profiles

A graphical representation in XY profiles (Figure 3) combines the environmental and the value dimensions of EE. The (X,Y) graph represents the value created versus the environmental

performance relative to a reference scenario. The four quadrants identify win-win, trade-off, and lose-lose solutions. The reference scenario R is at the center of the graph. EE scores are based on the difference between the reference R scenario and alternatives. Couples (X,Y) are the dots from which X is the difference of environmental performance (EP) and Y is the difference of value performance (V). A more efficient alternative than the system of reference shows an improvement in one of the two dimensions. For instance, alternatives A, C and D are more efficient than the reference R, but alternative B is less efficient than R. The model is inspired by the model in Mami (2017) and the incremental approach in Huppes and Ishikawa (2005). It makes it possible to seek optimal situations that maximize value creation and environmental performance consistent with accepted societal trade-offs for both dimensions. A trade-off of 1 (V/EP = 1:1) means that society places the same importance on an improvement in value creation and in environmental performance. The theoretical optimum would be the dot O and dots A and C or any dot placed on the same perpendicular to the trade-off line will all have the same eco-efficiency (Figure 1a). For a trade-off of 0.5 (V/EP = 1:2 = 0.5), the theoretical optimum would be the dot O* (Figure 1b), meaning that society places twice the importance on improving a unit of environmental performance than on a unit of additional value. In this situation, dots A and D have the same eco-efficiency but are less eco-efficient than C. The perpendicular lines to the trade-off lines are the isolines.

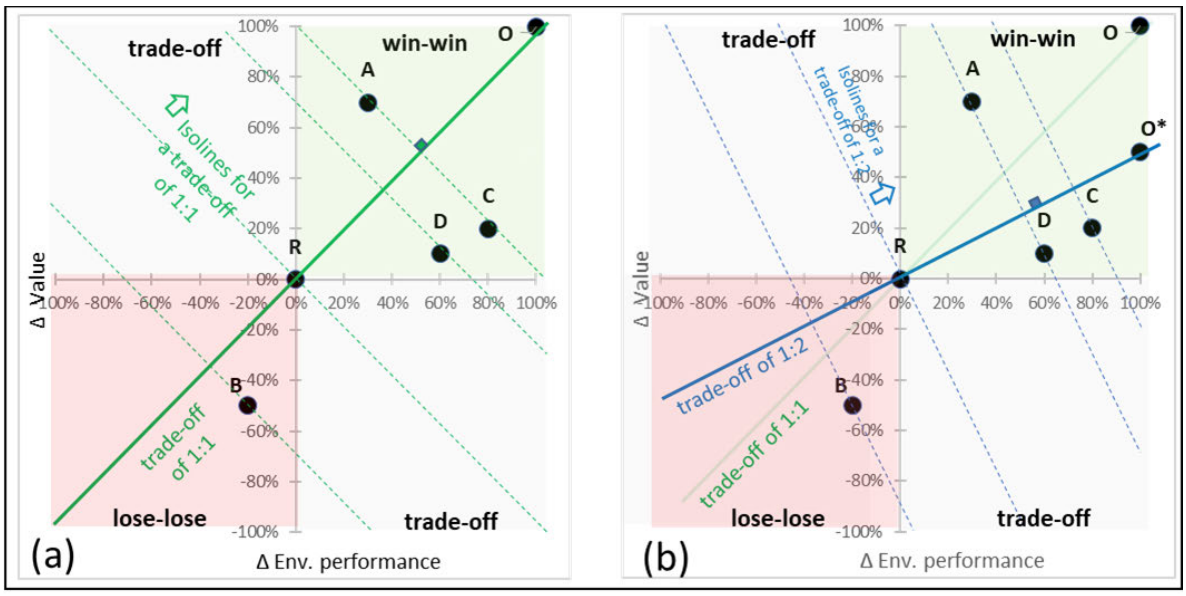

Figure 3 (a,b): EE (X,Y) graph profile with two types of trade-off

2.1.4 Combining the multidimensional value and environmental scores in a spider graph

One could generate as many EE (X,Y) graph profiles as there are value dimension components. However, multiplying the graphs could create confusion and reduce the effectiveness of the decision-making process. Alternatively, one could aggregate the multifunctional values into a single score through a weighting scheme application, but this will require the acceptance of universal value

choices and result in a loss of information. Therefore, to meet the objectives of this study, it is suggested to consolidate the value and environmental dimensions in a spider graph to compare the scenarios and identify trade-offs between the various dimensions (Figure 4). Despite the interpretation bias that spider graphs can generate (Dias and Domingues, 2014), they prove to be an appropriate form of illustration in the context of this study. Each dimension is reported in percentage (%) of the difference with the scenario of reference. The area represents the scenario's EE performance. The reference (R) corresponds to 100%. Areas smaller than the reference represent a decrease in EE and larger areas represent an improvement in EE.

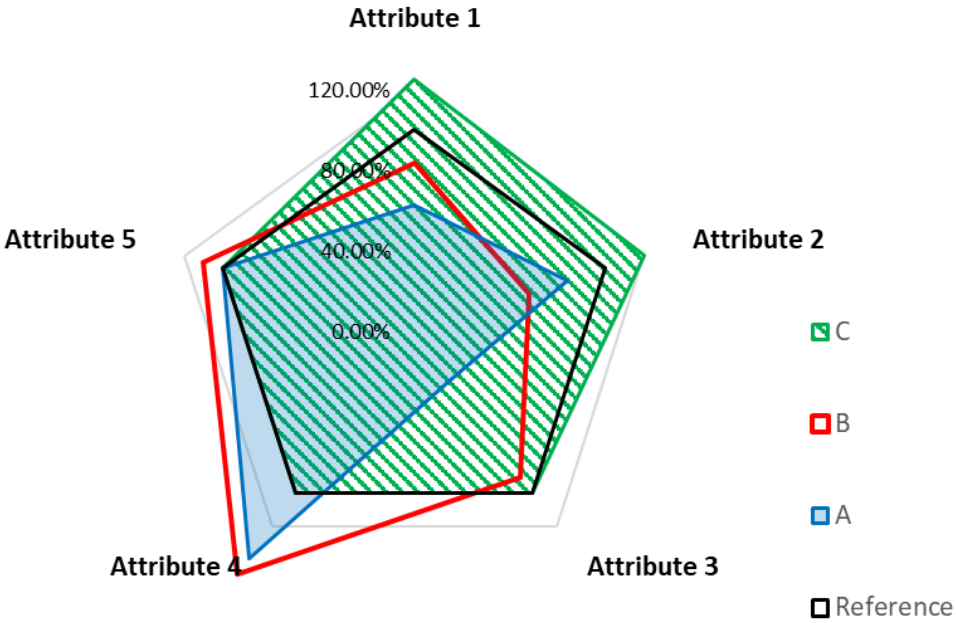

Figure 4: Representation of EE profile spider graph

2.2. Goal and scope definition of the case study

The EE framework is applied to a case study comparing 11 Greek yogurt (GY) production systems in the province of Québec, Canada, in 2017. GY production has grown exponentially in North America over the last decade, bringing new environmental challenges to the industry due to the large amount of whey by-products generated (Erickson, 2017). This case study is based on previous LCA results from Houssard et al. (2020, 2021). It also includes additional co-products valorization scenarios and multidimensional value indicators to compare the GY systems' EE performance. GY systems are briefly described hereafter, but more details are available in Houssard and al. (2020, 2021). The objective was to determine which GY system is the most eco-efficient based on the value generated per environmental impact unit. The primary function of all the production systems is to meet the demand for GY at 10% protein and 0 % fat in Canada. The systems also deliver different quantities and types of co-products (cream and permeate powder from milk filtration in the USA or Canada and various types of whey-based products) depending on the GY processing technology and whey

valorization pathway (Figure 5). The co-products were considered an integral part of the systems' value, and the partition of impacts between co-products is not required.

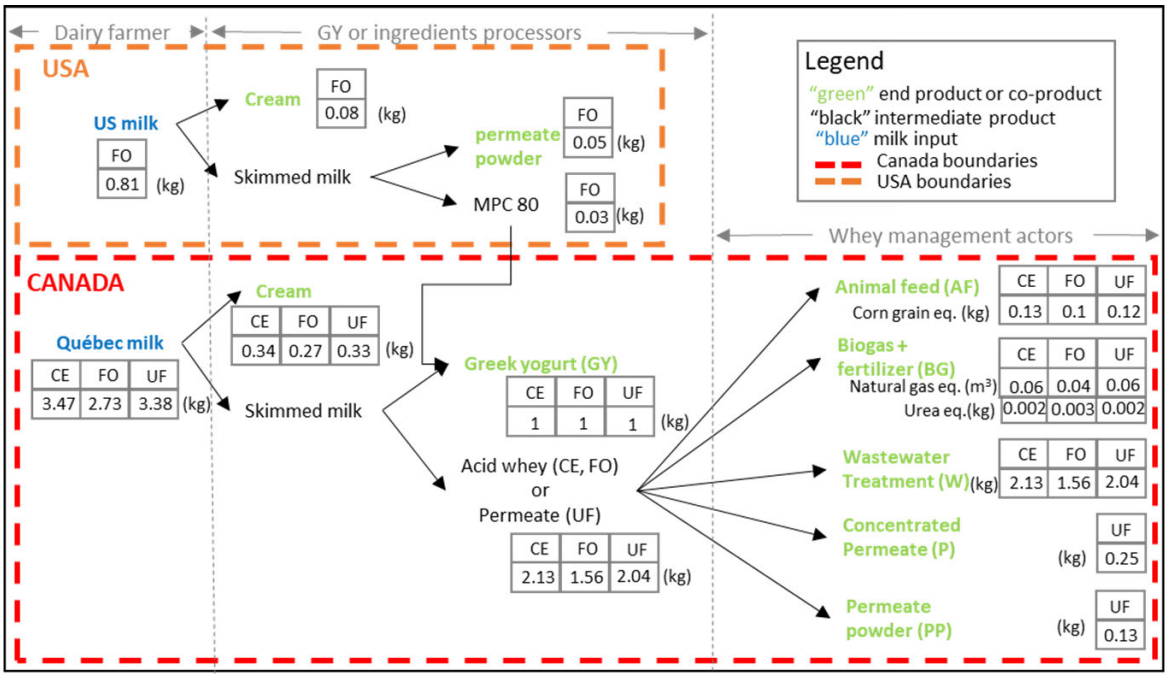

Figure 5. GY system inputs and outputs per technology and territory (CE: centrifugation, FO: fortification, UF: ultrafiltration) before losses and wastage. Numbers in the CE, FO, and UF boxes refer to the input or output quantities of co-products or intermediate products per 1 kg of GY produced

The functional unit was defined as 1 kg of GY, at 10% protein and 0 % fat, consumed in Québec, Canada in 2017. The EE results of each scenario are compared to the reference (CE-AF), which was the most common scenario in Canada in 2017. Then, the EE results were linearly scaled up to the quantity of GY consumed in Canada in 2017 to assess the magnitude of the results at the territory level. This proxy is justified by the fact that Québec produces 75% of all yogurts manufactured and consumed in Canada (Roy, 2021).

2.2.1 System boundaries

The approach is based on a value chain perspective. It includes all the processes involved in the production of GY systems, from milk production at the farm to waste disposal. From an environmental perspective, it includes all the raw materials and utilities supply flows for milk production, product and co-products manufacturing, distribution, consumption, and waste treatment. From a value perspective, it considers all the value generated by the actors of the value chain, including the dairy farmer, packaging manufacturer, utilities supplier, GY processor, distributor, consumer, waste collector, and co-products valorization actors (Figure 2). To be consistent with the scope of the LCA, the background value procured by indirect actors such as water, energy, or animal feed suppliers was also considered using generic input/output databases.

Product losses and wastage during milk production, GY manufacturing, distribution, and consumption stages are included, as described in Houssard et al. (2020).

2.2.2 System description

Standard Greek yogurt production consists in concentrating the proteins of regular yogurt through centrifugation before packing. This operation, which separates the liquid phase (whey) from the yogurt gel, entails new environmental challenges for the dairy industry. Every kg of GY produced generates around 2 kg of acid whey, a by-product that is difficult to valorize (Erickson, 2017). GY processors, therefore, developed several alternative production approaches to reduce the large volumes of acid whey and different pathways to valorize the acid whey (Jørgensen et al., 2019). For instance, fortification (FO) and ultrafiltration (UF) technologies reduce the acid whey volume by pre-concentrating the milk proteins before fermentation. FO consists of adding milk protein concentrate (MPC) powder sourced from the USA to the milk. UF consists in concentrating the proteins using a membrane filtration process. While it does not reduce whey volume, UF produces a sweet whey permeate, which is easier to valorize than acid whey (Houssard et al., 2020).

In this study, the centrifugation technology (CE), which is the market reference, was compared to fortification (FO) and ultrafiltration (UF). Five whey management processes were also investigated (treatment by a wastewater treatment plant (W), animal feed (AF), anaerobic digestion with biogas and digestate coproduction (BG), permeate powder (PP), and on-site valorization of permeate (P)). Accordingly, 11 scenarios are modeled as depicted in Figure 5 (CE-W; FO-W; UF-W; CE-AF; FO-AF; UF-AF; CE-BG; FO-BG; UF-BG; UF-PP, and UF-P). The milk protein concentrate (MPC 80) manufactured in the USA is used in the FO process only. The three technologies (CE, FO, and UF) and technical processes of whey management are extensively described in (Houssard et al., 2021, 2020) and summarized in SI 2.

2.2.3 Environmental life cycle assessment

The environmental LCA was conducted in accordance with ISO 14 040 and ISO 14 044 standards (ISO, 2006a, 2006b). The LCA model was designed using SimaPro v8.5.2.2 software (Pré Consultants, 2018), and the environmental impacts were assessed using IMPACT World+ (Bulle et al., 2019). As recommended by ISO 14 045, the environmental impact scores are presented separately in an environmental profile. They were then aggregated into a single score, using normalization and weighting methods based on SETAC recommendations (Kägi et al., 2016),.before being integrated into the EE profiles.

Life cycle inventory (LCI)*:* The LCI accounts for all the material and energy flows included in the system's boundaries. Table A1 in Appendix summarizes the main inputs and outputs for each scenario. A complete LCI is available in SI 3.1. Foreground data were collected from a technical survey conducted with three of Canada's leading GY processors and completed with modeling results from a dairy process simulation software developed at Université Laval (Benoit et al., 2019).

The background data are from the Québec inventory database (Lesage and Samson, 2016) as available from ecoinvent v3.4 LCI database and targeted US datasets were extracted from Thoma et al. (2013). The detailed processes included in each scenario are described in Houssard et al.(2021, 2020).

Environmental impact scores: To provide a comprehensive approach, the two main areas of protection human health (HH) and ecosystem quality (EQ) impact scores are assessed using IMPACT WORLD+ at the damage level (excluding climate change (CC)), which provides the highest level of aggregation based on natural sciences. Climate change impacts (CC), a major area of concern for society, are assessed separately as a midpoint indicator. The impact category scores are first presented in an environmental profile to highlight the environmental hotspots and raise the potential trade-offs between the various impact categories. Then, scores are aggregated into a single score.

Aggregation into single score: Due to the possible methodological biases and value choices introduced by the weighting factors, it is recommended to test different aggregation methods to assess the robustness of the results (Pizzol et al., 2017). Therefore, the three impact categories were converted into a monetary unit using the data from the budget constraints valuation method (Weidema, 2009) and the carbon social cost method (Ricke et al., 2018), which enables the implicit normalization and weighting of the importance of each impact category. Then, two other methods were tested: (a) valuation of the two damage indicators (HH and EQ) using the Stepwise valuation method (Weidema, 2009) and (b) normalization and weighting of the environmental footprint of the Canadian dairy industry. The three methods are detailed in the supplementary information (SI 1.).

2.2.4 Multidimensional value assessment

The value indicators were selected to represent the different perspectives of GY value chain stakeholders, while focusing on the Québec dairy farmer, GY processor, consumer, Canadian territory, and society. The analysis encompasses socio-economic indicators for the economic actors and three functional value indicators for the consumer.

Socio-economic indicators: The revenues and operational costs considered to calculate the socio-economic indicators are detailed in SI 3.2. The operational costs include all the direct costs that are supposed to vary from one technology to another, such as milk, transportation, energy, water, wastewater, chemicals, UF membrane, whey treatment, and valorization pathways. The revenues include product and co-product outputs. Costs and revenues are calculated for each economic actor in the value chain: dairy farmers (Canada or USA), yogurt processors, distributors, waste collectors, ingredient suppliers, whey valorization economic actors. Furthermore, to be consistent with the environmental LCA scope, the GVAs of background suppliers (e.g., energy producers, chemical ingredients suppliers, etc.), namely other economic actors, were also estimated. The GVAs of background economic actors (e.g., local and global energy and chemical suppliers) were estimated

to be 48% of the Canadian or USA GY economic actors' GVAs. These figures were calculated using the EXIOBASE database model with economic factors, version 3.4, considering the Canadian dairy industry as a proxy for all foreground actors (SI 3.2.2).

Functional value indicators: The functional value indicators (see SI 4.3 for a detailed description) originate from recent studies (Uduwerella et al. (2018) and Moineau-Jean et al., (2019, 2020)) comparing GY (at 10% protein and 0% fat) processed with CE or UF technologies (no data was available for UF). Three functional indicators representative of the main functions seek by GY consumers (Fisberg and Machado, 2015) were selected: calcium content, probiotic concentration, and typical flavor. They do not provide a complete profile of GY functional attributes, but they are sufficient to meet the objectives of this research. They illustrate the trade-offs between different attributes of value depending on the technology.

3. Results

3.1 Environmental LCA profile results

Figure 6a illustrates the environmental profile of three technologies: centrifugation (CE), fortification (FO), and ultrafiltration (UF) with whey valorization as pig feedstuff (AF). Figure 6b illustrates five different whey management scenarios for the ultrafiltration (UF) technology.

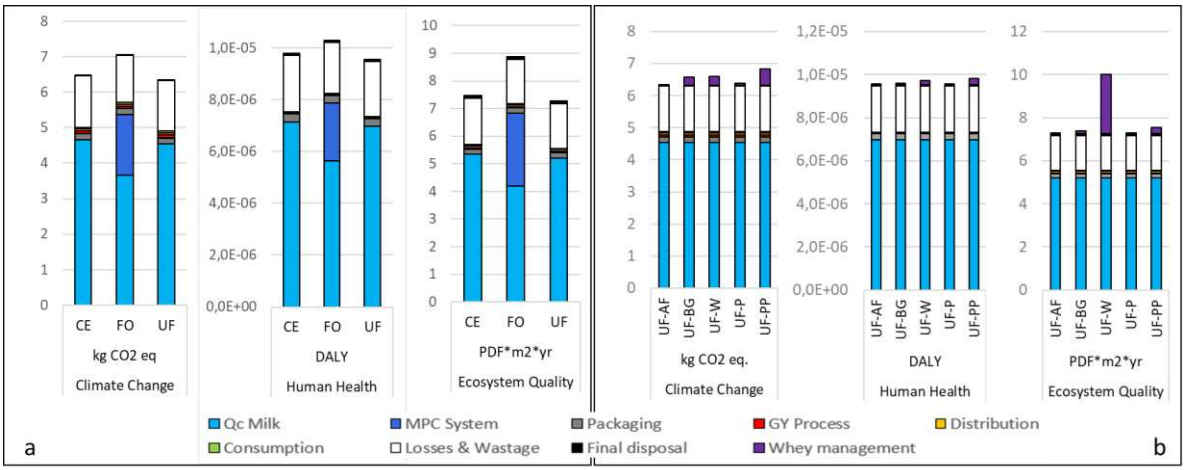

Figure 6. (a) LCA results for the three technologies: centrifugation (CE), fortification (FO) and ultrafiltration (UF) with whey valorization as pig feedstuff (AF); **(b)** LCA results for ultrafiltration (UF) with five different whey management scenarios: animal feed (AF), biogas (BG); permeate on-site valorization (P); permeate powder (PP), and treatment at wastewater plant (W)

The major contributors to all the impacts categories are milk production and milk ingredients supply, followed by losses and wastage. For the FO technology, the significant contribution of the MPC supply system from the USA is explained by two key factors: (1) milk production in the USA has, on average, 20% more impacts on climate change (CC), 4% more on human health (HH) and 82% more on ecosystem quality (EQ) than Québec milk production (Houssard et al., 2020) and (2) the MPC

system produces MPC powder and permeate powder, two processes that required large amounts of natural gas (as shown in Appendix Table A1) and thus significantly contribute to climate change.

Whey management is generally not a major contributor to the systems' environmental impacts. It contributes to 0.1 to 27% of the impacts over all the categories, with significant differences from one whey management scenario to another. Whereas the contributions of animal feed (AF), biogas (BG), and permeate on-site valorization (P) are less than 5% of all impact categories, PP contributes to 8.5% of the CC impacts due to the energy-intensive processes of evaporation and spray-drying for powder making. Treatment at wastewater plant (W) contributes to 27% of the EQ impacts. Since the quantity of whey to be managed depends on the GY technology (CE, FO, UF) (Appendix Table A1 and Figure 5), whey management impacts vary accordingly (see Figure 4 in SI 4.1). Still, they do not significantly change the results due to whey management's relatively low contribution to the total life cycle impacts.

As the GY systems deliver 1 kg of GY and other functions that differ from one system to another (i.e., different types and quantities of co-products (cream and whey)), they are not functionally equivalent. The environmental profiles cannot be used to make any comparative claims about the superiority of one system over another. They are to be considered as intermediary results only. Product systems may only be compared by considering the value created (e.g., function delivered, GVA generated, etc.) by each single system through the EE profile.

3.2 Multidimensional value profile results

Table 1 summarizes the difference in GVA between the reference and alternative scenarios for the main individual actors (dairy farmer, GY processor), Canadian territory, USA territory, and total value chain (TGVA). Distributors/retailers, waste collectors, ingredient suppliers, whey valorization, and other economic actors are included at the territory level and TGVA. Detailed results are available in SI 4.2. Due to the sensitivity of individual financial profit information, the GVA was used as a proxy to assess the difference in the financial profits of the economic actors in the value chain for each alternative compared to the reference scenario (CE-AF). This assumption implies that the indirect costs are similar for all scenarios. It is a limitation of the study because it is unlikely that the capital costs of the equipment at the GY processor plant are the same for the CE, UF, and FO technologies.

The GVA generated on the Canadian territory is the sum of the GVAs generated by each actor in the value chain within the Canadian territory (i.e., dairy farmer, GY processor, local suppliers, waste collectors, whey valorization actors, and other background actors). In contrast, the USA GVA is the GVA generated in the USA for the FO scenarios. It includes MPC ingredient suppliers from the USA and the US dairy farmers who supplied them with raw milk. The Total GVA (TGVA) includes the GVAs of all the economic actors in the value chain within and beyond the Canadian territory.

The FO and UF scenarios all reduce the GVA of dairy farmers. The only scenario that creates more value in Canada than the reference scenario is UF-P. Following the three FO scenarios, the UF-P

scenario also creates the most overall value (TGVA). These differences are explained in the next section on EE profile results.

Table 1. *The difference in GVA (ΔGVA) of alternative scenarios relative to the reference scenario (CE-AF) in Canadian dollars (CAD) for the main economic actors in the value chain in 2017 at the individual, territorial and societal levels.*

	ΔGVA (CAD 2017)				
Scenario	**Dairy farmer**	**GY processor**	**Canada (*)**	**USA (*)**	**ΔTGVA**
CE-AF (reference)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
FO-AF	-1.71E+07	6.90E+06	-2.04E+07	8.45E+07	6.42E+07
UF-AF	-2.08E+06	1.98E+06	-4.69E+05	0.00E+00	-4.69E+05
CE-W	0.00E+00	-3.29E+04	-2.46E+06	0.00E+00	-2.46E+06
FO-W	-1.71E+07	6.88E+06	-2.23E+07	8.45E+07	6.22E+07
UF-W	-2.08E+06	1.94E+06	-2.72E+06	0.00E+00	-2.72E+06
CE-BG	0.00E+00	0.00E+00	-2.59E+06	0.00E+00	-2.59E+06
FO-BG	-1.71E+07	6.90E+06	-2.24E+07	8.45E+07	6.21E+07
UF-BG	-2.08E+06	1.98E+06	-2.85E+06	0.00E+00	-2.85E+06
UF-P	-2.08E+06	3.08E+07	5.23E+07	0.00E+00	5.23E+07
UF-PP	-2.08E+06	1.98E+06	-5.32E+07	0.00E+00	-5.32E+07

3.3 Socio-economic EE profile results

The reference scenario (CE-AF) is set at the graph origin in Figure 7 (a,b,c,d). The same importance is given to the environment and the value components. Environmental LCA results are expressed as a single score on the X-axis. They represent the difference in environmental externalities in million Canadian dollars (CAD) between CE-AF and the ten alternative product systems, referring to the total consumption of GY (10% protein, 0% fat) in Canada in 2017. A positive difference (right quadrant on the X-axis) indicates a reduction in environmental externalities. In contrast, a negative difference (left quadrant on the X-axis) indicates an increase in environmental externalities. These environmental externalities are based on the social cost of carbon and budget constraints valuation method described in the SI (SI1.). Still, the two other tested aggregation methods show similar results (see Figure 5 in SI 4.4) and could also be used. Socio-economic values are plotted on the Y-axis in million CAD for the total GY production in Canada. They represent the difference in GVA between the alternative scenarios and CE-AF. A positive difference (top quadrants on the Y-axis) indicates an increase in GVA, and a negative difference (bottom quadrants on the Y-axis) indicates a decrease in GVA as compared to CE-AF.

Figure 7. (a,b,c,d) Socio-economic EE profiles of the GY systems in Québec, Canada. GY production technologies assessed are centrifugation (CE), fortification (FO) and ultrafiltration (UF) combined with five whey valorization or management scenarios: animal feed (AF), biogas + fertilizer (BG), waste treatment (W), concentrated permeate for on-site valorization (P), permeate powder (PP); GVA = gross value added; TGVA = total gross value added by the value chain; GVA Canada: GVA generated on the Canadian territory.

Figures 7 (a,b,c,d) shows that FO-W, CE-W and UF-W increase the environmental externalities caused by GY system production in Canada by 44, 27 and 20 million CAD, respectively, as compared to CE-AF. FO-BG, FO-AF and CE-BG also cause more environmental damages than CE-AF, increasing the environmental externalities by 29, 25 and 1 million CAD, respectively. Other scenarios have an environmental performance almost equivalent to CE-AF.

FO scenarios generate around 7 million CAD more GVA for the GY processor than CE-AF (Figure 7a) and 17 million CAD less for the dairy farmer in Québec (Figure 7b), resulting in around 22 million CAD decrease on the entire value chain for the Canadian territory GVA (Figure 7c). This decrease in Canada is offset by an increase in the US territory (Figure 7d). Indeed, the MPC and other co-products (cream and permeate powder) manufactured in the USA generate around 62 million CAD

additional TGVA. UF-P is the only scenario that presents a GVA almost equivalent to the reference for the Québec dairy farmer (-2 million CAD; Figure 7b), with an increase in GVA for the GY processor (31 million CAD; Figure 7a), Canadian territory (52 million CAD; Figure 7c) and global value chain (52 million CAD; Figure 7d) simultaneously. UF-P is the most eco-efficient scenario since it decreases also the environmental externalities. An uncertainty analysis would be required to confirm the robustness of these results, but it remains beyond the scope of this study.

3.4 Multidimensional eco-efficiency profile results for the CE and UF scenarios

Figure 8 compares GY produced with CE and UF technologies according to their environmental, socio-economic, and functional values (Functional value data was not available for FO technology making impossible the comparison with CE and UF technologies). Furthermore, since GY's functional attributes are independent of whey management pathways (W, AF, BG), the analysis compares only the reference CE-AF (black line; at 100% on all dimensions) to UF-AF, UF-P, and UF-PP. This simplification makes Figure 8 more readable, and Figure 7 is enough to compare the other scenarios. For each dimension, a score above 100% indicates a better performance than CE-AF. UF-PP has an equal or lower performance than CE-AF in all dimensions, except for calcium concentration. UF-P has a better GVA for the GY processor and Canadian territory with an environmental impact equivalent to CE-AF but at the expense of the probiotic content and typical flavor sought by the consumer. UF-AF yields results similar to UF-P on environmental and functional dimensions but, UF-P creates more GVA.

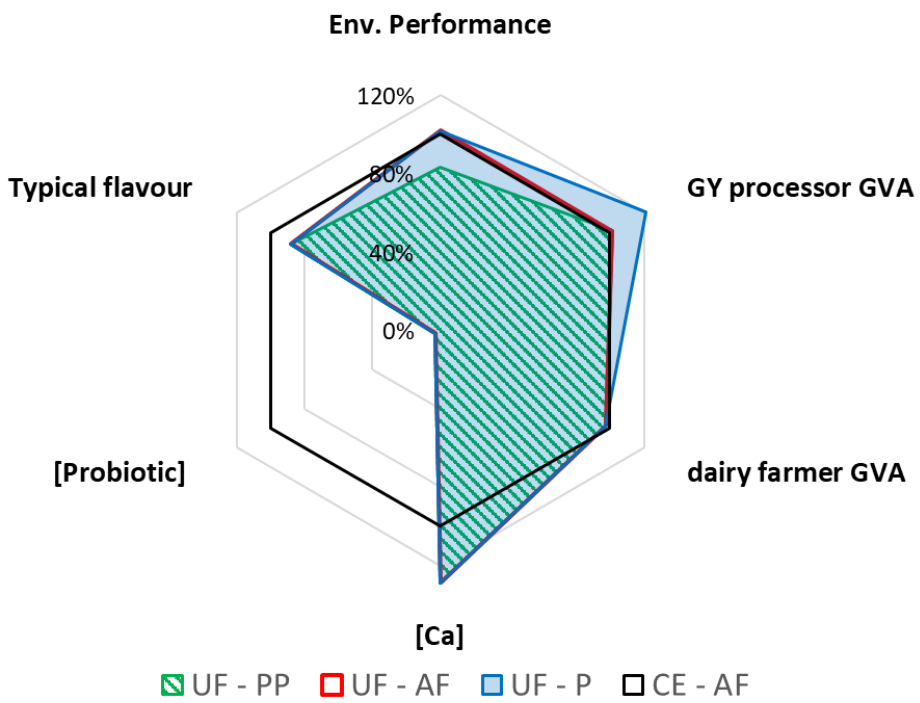

Figure 8. Multidimensional EE profile for CE and UF technologies with several whey management alternatives: animal feed (AF), concentrated permeate for on-site valorization (P), and permeate powder (PP)

From a global EE perspective, Figures 7 and 8 show that the processing technology (CE, FO and UF) has more influence on EE performance than whey management, even if some whey management pathways perform better than others. Figure 7a shows that, except UF-P, the best scenarios (FO scenarios) to create value for the GY processor are at the expense of the environmental performance. Furthermore, Results show that a value improvement for the GY processor, such as FO scenarios, is not always good for the other economic actors. In this case study, fortifying GY with MPC from the USA (Figure 7a) decreases the Canadian dairy farmer's GVA (Figure 7b) and the overall GVA generated within the Canadian territory (Figure 7c). Finally, when considering consumer interests (Figure 8), there are also trade-offs between the functional value (i.e., nutritional, health, and sensory attributes) and socio-economic value performance. Indeed, the most eco-efficient scenario (UF-P) from a socio-economic perspective underperforms on two (probiotic and typical flavor) of the three functional dimensions as compared to the reference scenario.

4. Discussion

4.1 A comprehensive and consistent framework to better assess dairy systems sustainability across the value chain

By using a life cycle perspective for both, the environment and value dimensions - encompassing various value indicators to reflect the different stakeholders' interests and accounting for the value generated by all the background economic actors included in the LCA boundaries - this novel EE framework provides a more comprehensive and consistent way to assess EE than the current dairy industry practice. Its holistic approach makes it possible to identify the trade-offs between the different functions/value components and the environmental performance, as well as between various stakeholders of the value chain at different levels (i.e., individual, territorial, societal) to support more informed decisions. This novel EE framework enables GY processors to seek win-win-win trade-offs for themselves, local dairy farmers, and consumers, intending to generate greater equity between stakeholders and more positive impacts on society. The approach is a new mindset compared to the traditional concept of EE presented in the literature review, which usually seeks the cost effectiveness of a product per unit of environmental impact and individual financial performance. This novel framework pushes the boundaries of EE to account for the functions delivered to society: more valuable co-products, more revenues for economic actors, more functional benefits for consumers, and better environmental performance. In this sense, it shifts the focus away from individual performance and embraces the concept of creating shared value by Porter and Kramer (2011). More broadly, in line with the ideas put forward by Schaltegger (2012), it may contribute to changing corporate governance strategies toward a more systemic inclusion of internal and external stakeholders' views. As such, it provides an enhanced sustainability measurement tool to guide corporate social responsibility (CSR) decisions in the private sector.

4.1. Limitations

This EE framework has some limitations that leave space for additional research and stir reflection.

First, the environmental and socio-economic scores reported at the Canadian GY industry scale assume that all GY business units on the Canadian territory rely on the same technology and whey management pathways. It is not realistic since more than one technology usually operates on the same territory. Therefore, the results should not be interpreted as absolute performance gains or losses at the territory scale. They are valid for scenario comparison only.

Furthermore, the GVA used as a proxy to measure the financial profit could be seen as a significant limitation of GY processor's results. Indeed, the capital investment costs that are lower for FO and higher for UF than CE (Jørgensen et al., 2019; Nsabimana et al., 2005) may change the findings if the aim is to pursue short-term profit. However, this research focuses on the method rather than the results. Besides, from a sustainability perspective, the essence of this work is to look at long-term value creation rather than short-term profit.

The spider graph representation could be subject to criticism. Dias and Domingues (2014) have highlighted the limitations of spider graphs. Indeed, the arbitrary order of the dimensions, which are depicted as all equally important, can bias the final weighting process which is left to the decision-maker. Several aggregations methods may be applied to reduce the number of dimensions and facilitate the decision-making process. However, the objective was to show the potential trade-offs between the various dimensions and the interest in integrating functional value dimensions in EE to support decisions rather than providing a specific aggregation scheme. Finally, there is always a tension between the desire to reduce complexity to ease interpretation for facilitating decision-making and the risk of losing relevant information. As recommended by the life cycle management standards (ISO, 2012, 2006b), providing disaggregated environmental and multidimensional value scores before the final aggregation will improve transparency and reduce misinterpretation of results.

More broadly, the framework could not be considered as a comprehensive sustainability measurement tool since it does not encompass all the components of value creation. GVA is a widely used proxy to measure the creation of value for society at the company level since the sum of GVA at the country level is the gross domestic product (GDP). However, GDP is an increasingly controversial development indicator that does not capture social inequalities or employment rates. Furthermore, some experts in environmental economics advocate that financial profit should not be measured in well-being indicators because generating private profit constitutes a market loophole (Bernard, 2011; Greenlaw and Shapiro, 2017). The complex relationship between the socio-economic performance measured by GVA and social well-being has yet to be established. Therefore, additional semi-qualitative indicators currently assessed in social LCA are required to conduct a sustainability life cycle assessment. The value dimensions suggested in this study are not

exhaustive. Though, they are considered sufficient to illustrate the relevance of such a multidimensional framework that measures shared value creation throughout the value chain.

5. **Conclusion:**

The EE multidimensional value framework developed in this paper is unique. It makes it possible to compare the EE of different dairy production systems, considering the interests and perspectives of various stakeholders in the value chain and to identify trade-offs at different levels (i.e., individual, territorial, societal) and across multiple dimensions of value creation. In doing so, this EE framework allows shifting beyond the traditional value creation logic, which focuses sole maximization of cost-effectiveness and profit of a single stakeholder toward the creation of shared value among the society. Its implementation on Canadian GY value chains shows that the scenarios that create the most economic value for the Canadian Greek yogurt processors reduce the benefits for other stakeholders such as the dairy farmers or face a trade-off with the environmental dimension. It identifies and fosters collaboration opportunities between the actors of the GY value chain to maximize societal and environmental benefits rather than prioritize individual economic gain.

This novel EE framework could be a useful sustainability measurement tool to support the implementation of corporate social responsibility (CSR) strategies. It has been applied to a case study in the Canadian dairy industry, but it might be easily adapted to other activity sectors. In the short term, it is recommended to complete this research with data on the GY FO technology's nutritional, health, and sensory attributes in order to provide a more comprehensive comparative assessment of the functional value of the three technologies. It could also be interesting to test this EE framework on other food systems to assess its relevance to other applications.

Appendix:

Table A1. *Main input and output flows for 1 kg of GY consumed (including life cycle losses and wastage).*

	Input	Unit	CE-AF	CE-BG	CE-W	FO-AF	FO-BG	FO-W	UF-AF	UF-BG	UF-W	UF-P	UF-PP
Québec	Raw milk	kg	4.60	4.60	4.60	3.62	3.62	3.62	4.48	4.48	4.48	4.48	4.48
	Electricity	kwh	3.08E-01	3.62E-01	3.08E-01	2.81E-01	3.21E-01	2.81E-01	2.66E-01	3.18E-01	2.66E-01	2.78E-01	3.56E-01
	Natural gas	m3	2.46E-02	4.22E-02	2.46E-02	2.00E-02	3.30E-02	2.00E-02	2.87E-02	4.57E-02	2.87E-02	9.78E-01	5.78E+00
	Water	m3	4.12E-03	4.55E-03	4.12E-03	3.43E-03	3.74E-03	3.43E-03	4.02E-03	4.43E-03	4.02E-03	3.26E-01	5.26E-01

USA	Raw milk	kg	_	_	_	1.09	1.09	1.09	_	_	_	_	_
	Electricity	kwh	_	_	_	1.18E-02	1.18E-02	1.18E-02	_	_	_	_	_
	Heat	m3	_	_	_	8.22E-03	8.22E-03	8.22E-03	_	_	_	_	_
	Water	m3	_	_	_	2.94E-04	2.94E-04	2.94E-04	_	_	_	_	_
	Output												
Québec	Cream	kg	0.43	0.43	0.43	0.34	0.34	0.34	0.42	0.42	0.42	0.42	0.42
	Greek yogurt	kg	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Whey for AF	kg	2.68	_	_	1.97	_	_	2.57	_	_	_	_
	Treated waste water	m3	4.12E-03	4.55E-03	6.87E-03	3.31E-03	3.31E-03	5.32E-03	4.02E-03	4.43E-03	6.65E-03	4.02E-03	4.12E-03
	Biogas	m3	_	7.36E-02	_	_	5.39E-02	_	_	7.05E-02	_	_	_
	Fetilizer	kg	_	1.66E-03	_	_	_	_	_	1.15E-03	_	_	_
	Concentrated permeate	kg	_	_	_	_	_	_	_	_	_	6.47E-01	_
	Permeate Powder	kg	_	_	_	_	_	_	_	_	_	_	1.31E-01
USA	Cream	kg	_	_	_	0.10	0.10	0.10	_	_	_	_	_
	MPC 80	kg	_	_	_	0.04	0.04	0.04	_	_	_	_	_
	Permeate Powder	kg	_	_	_	1.02	1.02	1.02	_	_	_	_	1.65E-01
	Treated waste water	m3	_	_	_	3.37E-05	3.37E-05	3.37E-05	_	_	_	_	_

Centrifugation (CE), fortification (FO) and ultrafiltration (UF) combined with five whey valorization or management scenarios: animal feed (AF), biogas + fertilizer, waste treatment (W), concentrated permeate for on-site valorization (P) and permeate powder (PP).

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