Journal of Environmental Management xxx (xxxx) xxx-xxx

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://ees.elsevier.com

Research article

CalcPEFDairy: A Product Environmental Footprint compliant tool for a tailored assessment of raw milk and dairy products

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ARTICLE INFO

Keywords
Life cycle assessment
Data quality requirements
Dry matter balance
Software
Direct dairy farm emissions

ABSTRACT

A compliant tool (CalcPEF$_{Dairy}$) to determine the Product Environmental Footprint (PEF) of Dairy products has been developed following the Product Environmental Footprint Category Rules (PEFCR) v.6.3 guidance and the 2018 approved PEFCR for Dairy products. CalcPEF$_{Dairy}$ is a new tool that simplifies and reduces the work for LCA practitioners when implementing the PEFCR for Dairy products. On contrary to traditional LCA software, CalcPEF$_{Dairy}$ includes all the emission models needed to calculate farm and crop cultivation direct emissions and it also implements the specific calculation formulas stated in the PEFCR such as the Circular Footprint and Data Quality Requirement formulas. Moreover, the PEF compliant datasets provided by the Life Cycle Data Network are incorporated in the tool as source of secondary data. To demonstrate the accuracy of the tool a traditional dairy farm in Catalonia (Northwest of Spain) was assessed and the results compared with the European representative PEF compliant datasets for the production of raw milk, cheese and yoghurt. In addition to the environmental profile, CalcPEF$_{Dairy}$ has determined the case study's environmental single score (ESS) for the production of raw milk (1.0×10^{-4}) cheese (9.7×10^{-6}) and yoghurt (1.4×10^{-5}); these ESS results are within the range of the ESS obtained from the analysed EF-datasets. The data sets' average ESS for raw milk is $9.9 \times 10^{-5} \pm 1.1 \times 10^{-5}$, while for cheese and yoghurt are $1.5 \times 10^{-5} \pm 3.1 \times 10^{-6}$ and $1.9 \times 10^{-5} \pm 3.4 \times 10^{-6}$ respectively. A 78% of the raw milk production ESS is attributed to the dairy farm activities while, the raw milk production stage affects in a 87.4% and 80.1% to the ESS for cheese and yoghurt respectively.

Abbreviations

B_P	Background process
Ca	Activity coefficient corresponding to the livestock feeding situation
CFF	Circular footprint formula
DE	Feed digestibility
DM	Dry Matter (Note: the subscript Ex and i refers to excreted and Intake respectively)
EC	European Commission
EF	Environmental footprint
EF-datasets	Environmental footprint compliant datasets (Note: the subscripts refer to the dairy products cheese, yoghurt, Raw milk or EU average Raw milk)
EF-R$_{milk}$	Environmental footprint compliant Raw milk production results obtained with CalcPEF$_{Dairy}$ tool
EFTA	European free trade association
EI	Environmental impact
EMEP/EEA	The European Monitoring and Evaluation Programme and the European Environmental Agency
EoL	End of Life (life-cycle stage)
ESS	Environmental single score
ESS$_{WO-Toxicity}$	Environmental single score without considering the toxicity-related impacts
EU	European uniron
F_P	Foreground process
FPCM	Fat Protein Corrected Milk
FU	Functional unit
GE	Gross energy
GHG	Greenhouse gas emissions
ILCD	International Life Cycle Data System
IPCC	The Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCDN	The Life Cycle Data Network
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
N_{Ex}	Nitrogen excreted
PEF	Product environmental footprint
PEFCR-D	Product environmental footprint category rules for dairy products

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https://doi.org/10.1016/j.jenvman.2019.110049
Received 24 April 2019; Received in revised form 2 December 2019; Accepted 28 December 2019
Available online xxx
0301-4797/© 2019.

PEFCR	Product environmental footprint category rules
PEF-D	Product environmental footprint of dairy products (Note: the subscripts refer to the dairy products cheese and yoghurt)

1. Introduction

1.1. Dairy and the environment

Dairy products are worldwide consumed due to their importance on the human diet however, the production of milk, its fundamental component, consumes significant natural resources. The high demand of dairy products is estimated to increase milk production up to 1.4 million tonnes per year until 2030 to cover the European and an important share of the global demand (EC, 2017a). The milk's demand growth increases dairy farming activities; which depend on the livestock agricultural sector.

The livestock sector directly influences the water and carbon footprint of dairy products and compromises the environmental quality in terms of water resources depletion, freshwater ecotoxicity, freshwater eutrophication, marine eutrophication, acidification and land use (Leip et al., 2015). According to the Food and Agriculture Organization (FAO, 2010) the dairy sector and the milk production systems are responsible of the 4.0% of the total anthropogenic greenhouse gas (GHG) emissions. Hence, the environmental and sustainable development of the dairy production chain is imperative to satisfy the market demand without affecting and compromising the environmental quality.

Due to the necessity of environmentally assess the dairy production chain and define its sustainable status, the Life Cycle Assessment methodology (LCA) has gained momentum. LCA evaluates the chain's global emissions and impacts in relation to the type and the amount of the supplies (inputs) entering the chain (e.g. dairy and non-dairy ingredients, water, energy, among others). However, the LCA implementation in agricultural related activities, such as the dairy, is not a simple task due to the methodological requirements and the amount of activity data required to generate a robust Life Cycle Inventory (Mourad et al., 2007).

Despite these challenges, several researchers have applied LCA to assess the environmental performance of different dairy products (Dalla Riva et al., 2017; de Léis et al., 2015; Finnegan et al., 2018; Noya et al., 2018; Vasilaki et al., 2016). The reviewed literature identifies the dairy farm activities as the principal source of emissions; this common conclusion has been reached regardless the diverse raw milk production systems (organic, non-organic or mixed), the dairy farm characteristics, the processing facility characteristics and the methodological choices taken by the LCA practitioners. Despite the existence and validity of the ISO 14040 (2006) and the ISO 14044 (2006) standards where the LCA principles, framework, requirements and guidelines are established, the different methodological choices within the existing studies do not allow a direct comparison among the outcomes for similar type of dairy products or for similar dairy farm systems which produce raw milk.

1.2. Ecolabeling, PEF and PEFCR

In addition to the necessity of a clear consensus when implementing LCA, there is also the need to communicate its outcomes in a clear manner to consumers. In the European market, green credentials (ecolabelling) for products have become an issue for stakeholders (business, producers and consumers) since there has been an uncontrolled proliferation of them. In Europe, the overwhelming amount of green credentials is a consequence of the industrial emphasis on reporting the product's levels of sustainability and the European political will of stablish the sustainable production and consumption of goods and services (EC, 2011). Industries mostly use international and corporative product labelling regulations that belong to the same framework of the ISO 14020 & ISO 14025 standards (2000; 2006); while the European political will is supported by European regulations that aim to expand the European green markets and to implement its own green credentials for products (e.g. Eco-design Directive, 2009/125/EC (2009), Labelling Directive, 2010/30/EU (2010), Public Procurement for a Better Environment communication (EC, 2008) and the EU Ecolabel Regulation No 66/2010 (2009). Consequently, there are many choices of methods and initiatives to generate credentials for green products, which confuse stakeholders (Brécard, 2014; EC, 2013).

To create a consensus when implementing the LCA and to control the proliferation of green credentials for products in Europe, on 2013, the Communication "Building the Single Market for Green Products" (EC, 2013) was released. This communication encourages the application of the Product Environmental Footprint (PEF) methods (EU, 2013). The PEF primary goal is to harmonise the LCA methodological choices and to provide objective criteria for comparing the environmental friendliness of products (Manfredi et al., 2012). However, each of the existing products' groups in the market require a bespoke environmental assessment guideline to reach the PEF goals by considering their specific product and production characteristics. This product specific PEF compliant guidelines are known as Product Environmental Footprint Category Rules (PEFCR) which are obtained by following the Guidelines for PEFCR Development (EC, 2017b) and must be used to generate a fully PEF compliant study.

Therefore, during a three-year Environmental Footprint (EF) pilot phase, PEFCR for some representative products' groups were developed and validated. Due to its marked and environmental relevance, the dairy products' group was one of them and the PEFCR for dairy products (PEFCR-D) was approved and issued (EDA, 2018). Additionally, as part of the EF pilot phase, PEF compliant datasets (EF-datasets) were developed and validated. These EF-datasets shall be used together with the also approved EF compliant characterization factors and methods (EC, 2018) when developing an LCA in the PEF framework.

1.3. Why specifically designed software for dairy products?

Implementing the PEFCR-D with the available LCA software (SimaPro, GaBi or Open LCA) to obtain PEF compliant results is not an easy task even for practitioners with a level of LCA expertise. The reason of this challenge is that before running the software, first, it is mandatory to properly determine PEFCR-D compliant inputs (on-farm direct emissions, distribution, use and end of life emissions) and parameters (allocation, product usage and storage utilisation factors). All this information must be obtained as result of applying specific emission models, allocation rules and formulas (Circular Footprint Formula and Data Quality Requirements Formula) that are stated in the PEFCR-D. The determination of this mandatory information cannot be done with commercial LCA software and additionally its adequate calculation demands extra and specific knowledge and expertise to the LCA practitioners.

Therefore, an important step to reach the goals of the EU Single Market for Green Products and a goal of the EF pilot phase was to develop PEF compliant assessment tools (EC, 2013). These tools' aim is to simplify PEFCR application for Small and Medium-sized Enterprises (SMEs) since their staff does not has the required expertise and knowledge to properly perform a PEF assessment; or because, SMEs cannot effort to cover the cost of contracting a third party to do a PEF assessment. Hence, PEF specific tools where developed during the PEF pilot phase for beer, leather, olive oil and T-shirts by following their developed PEFCR guidelines. Therefore, there is the challenge to provide PEF specific tools for the remaining products which have a developed PEFCR such as the case of dairy.

For the particular case of dairy products, currently there are just a few tools assessing the environmental performance of dairy farms and its main product: raw milk. However, they were not developed in agreement with the PEFCR-D making them not PEF compliant and therefore, their outcomes cannot be directly compared. Since they don't follow the PEFCR-D, they do not report the required 16 EI categories (See section 2.2.3); these tools mostly report Global Warming Potential (GWP) because they focus on modelling the farm's GHG emissions. These tools are: AgRE Calc (http://www. agrecalc.com), COMET-Farm (http://cometfarm.nrel.colostate.edu/), Cool Farm Tool (https://www.Coolfarmtool. org/), DairyGem (https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/dairy-gas-emissions-model/), DairyWise (Schils et al., 2007), FarmAC (http://www.farmac.dk/), FASSET (http://www.fasset.dk/), IFSM (https://www.ars. usda. gov/northeast-area/up-pa/pswmru/docs/integrated-farm-system- model/).

To our knowledge there has been only one good attempt to generate a PEFCR-D compliant tool to assess dairy products which is the PMT_01 tool (Famiglietti et al., 2019). However, according to the released information, it was developed following the 2016 PEFCR-D draft for public consultation (Barrucand CNIEL et al., 2016) meaning that it does not considered the changes made until 2018 when the final PEFCR-D was approved and released. For instance, during that two-year span, the International reference Life Cycle Data system (ILCD) format, nomenclature and recommended Life Cycle Impact Assessment (LCIA) models, were adapted to fulfil the requirements of the EF scheme. These adaptations are explained in detail in a Joint Research Centre report (EC, 2018) and incorporated in the approved PEFCR-D version; therefore, the presented PMT_01 tool and its results are not fully PEFCR-D compliant. One relevant example, but not the only one, of these adaptations is that the PMT_01 tool reports Water Resource Depletion impact category according to the Swiss Ecoscarcity model (Frischknecht et al., 2006) instead of the Water Use impact category obtained from the Available WAter REnmaining model (Boulay et al., 2018) as stated in the approved PEFCR-D.

Additionally, the PMT_01 tool excludes the assessment of life cycle stages such as storage at the retail centre, use and end of life. The PMT_01 tool also does not incorporate the official EF-datasets for background processes released by Life Cycle Data Network (LCDN); it uses alternative commercial datasets such as Agribalyse v1.3, Agri-footprint v.4 and Ecoinvent 3.4. Due to these reasons the PMT_01 is not fully PEFCR-D compliant; showing that there is still the need of developing a fully PEF compliant tool.

Consequentially, the aim of this work is to present the $\mathrm{CalcPEF_{Dairy}}$ tool in accordance to the goals of the EU Single Market for Green Products. $\mathrm{CalcPEF_{Dairy}}$ is a specialised PEF compliant tool to assess dairy products (from cradle to grave) that follows the approved PEFCR-D. $\mathrm{CalcPEF_{Dairy}}$ allows an easy implementation of the PEFCR-D for any dairy European production system and overcomes the challenges of using PEFCR-D together with commercial LCA software since it includes emission calculations and considerations that commercially available LCA software does not.

The tool is capable to assess dairy farm activities and to calculate the direct emissions arising from them. When assessing the raw milk production stage, the tool reports EF compliant raw milk production ($\mathrm{EF\text{-}R_{milk}}$) results. When assessing the whole dairy production system (cradle to grave), the previously obtained $\mathrm{EF\text{-}R_{milk}}$ is used to calculate the PEF of any other processed dairy product (PEF-D) such as cheese, yoghurt or processed milk. The versatility of the tool allows dairy producers to determine the environmental and sustainable status of their production chain, identify environmental hot-spots and environmentally assess the impact of potential changes in their production chain. To our knowledge this is the first fully compliant PEF tool that has been released following the approved PEFCR-D. The $\mathrm{CalcPEF_{Dairy}}$ tool is free-access and can be downloaded by following the instructions presented in the supplementary material. $\mathrm{CalcPEF_{Dairy}}$ aims facilitate and promote the future market uptake of the PEF methodology and ecolabelling criteria among dairy producers towards a single green and sustainable market.

2. Material and methods

2.1. $\mathrm{CalcPEF_{Dairy}}$ tool general information

$\mathrm{CalcPEF_{Dairy}}$ was developed in Microsoft Excel™ together with Microsoft Visual Basic for Applications and it calculates (i) the $\mathrm{EF\text{-}R_{milk}}$ (cradle to farm gate) and (ii) the PEF-D (cradle to grave) for different dairy products (packaged milk, cheese or yoghurt). $\mathrm{CalcPEF_{Dairy}}$, performs three task (i) the collection of buyers and supplier's information, (iii) the collection and modelling of Life Cycle Inventory data and (iii) the Life Cycle Impact Assessment.

The **collection of the buyers and supplier's information** (Fig. 1A) is neither required for the Life Cycle Inventory nor the Life Cycle Impact Assessment. However, this information is used to identify and link cost and revenues with providers and clients since the tool is also capable to perform Life Cycle Cost Analysis. This study focuses only on presenting the $\mathrm{CalcPEF_{Dairy}}$ environmental assessment applications hence, this section will not be further discussed.

The **Life Cycle Inventory (LCI) data collection and modelling** are done separately. First, $\mathrm{CalcPEF_{Dairy}}$ collects activity data (Fig. 1B) regarding the dairy products' characteristics and recipes; and also, regarding the products use and distribution life-cycle stages. Finally, the dairy farm and processing facility Inputs (supplies) and Outputs (products, co-products and wastes) are requested. On a second step (Fig. 1C), the tool models direct farm emissions arising from farm activities such as the livestock's enteric fermentation, manure management and application, among others. Before executing the emission models, the tool requires specific dairy farm activity data such as livestock characteristics, milk characteristics and metrics, manure management systems, etc. Once the models are executed, their results together with all the collected data are included in the LCI.

After completing the LCI, $\mathrm{CalcPEF_{Dairy}}$ manages the different data flows to finally perform the **Life Cycle Impact Assessment (LCIA).** The LCIA results are obtained when $\mathrm{CalcPEF_{Dairy}}$ generates the $\mathrm{EF\text{-}R_{milk}}$ and PEF-D reports (Fig. 1D); which outcomes are presented in a graphical and tabulated manner. The historic LCI data and LCIA results are saved by the tool in different databases so they can be viewed at any time (Fig. 1E).

2.2. Scope

2.2.1. Functional unit and reference flows

The Functional Unit (FU) used to report $\mathrm{EF\text{-}R_{milk}}$ is Raw milk at farm as final product without heating, cooking or further transformation and its reference flow is 1 kg of FPCM. While, the FU used to report the PEF-D results of liquid milk, cheese and yoghurt include packaging and their consumption at home as final product without heating, cooking or further transformation. The reference flow for liquid milk is 1000 ml, for cheese 10 g DM and 125 g for yoghurt or any other fermented product.

2.2.2. System boundary

Fig. 2 shows the $\mathrm{CalcPEF_{Dairy}}$ tool production system boundary with their respective stages and processes. The assessed life cycle stages are (i) raw milk production, (ii) processing, (iii) distribution, (iv) use and (v) the End of Life (EoL). Each of these stages include foreground (core) and/or background (upstream or downstream) processes. A

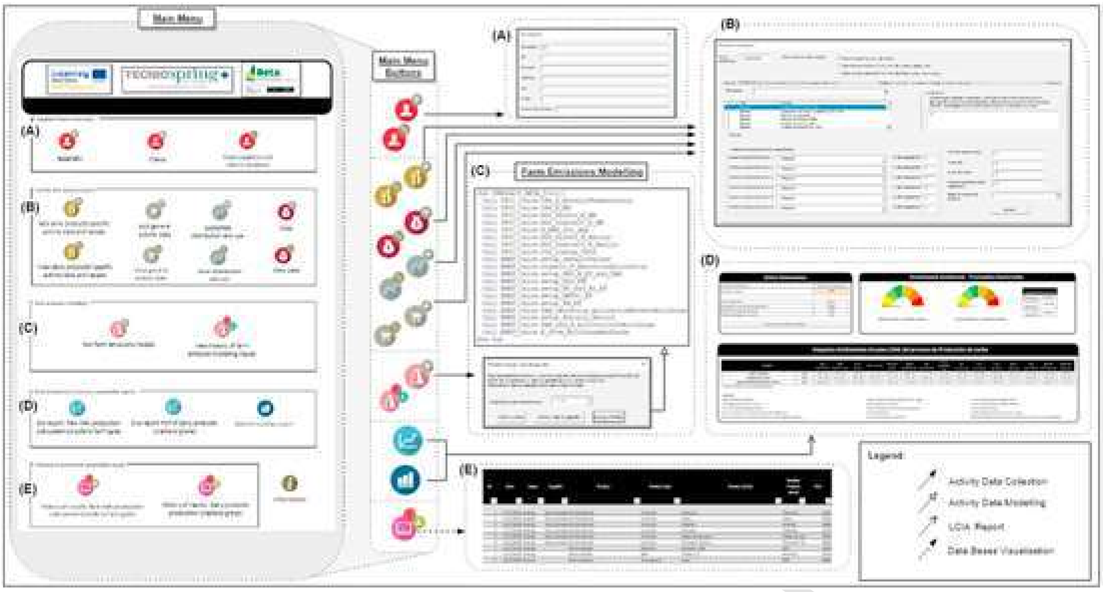

Fig. 1. CalcPEF$_{Dairy}$ Main menu: buttons to (A) collect buyers and suppliers' information, (B) collects activity data, (C) model farm emission (D) generate environmental and economic reports and (E) view data and results.

foreground process (F_P) is a process under the control of the producer or decision maker for which the LCA is carried out; while, a background process (B_P) is a process for which the producer or decision maker has indirect or no control (Life Cycle Initiative, 2018).

The Raw milk production stage includes the processes of raw milk production (F_P) and off-farm feed production (B_P). The raw milk production process includes dairy farm activities and on-farm feed production activities. The dairy processing stage include the processes of (i) dairy processing, (ii) packaging and the (iii) non-dairy ingredients supply. The dairy processing process (F_P) includes activities such as milk processing, container filling, storage, cleaning and maintenance. The packaging process (B_P) involves production and manufacturing activities. While, the non-dairy supply (B_P) process includes non-dairy ingredients production and packaging manufacturing activities. The Distribution stage includes the storage processes (B_P) at the distribution and retail centres and the use stage includes the chilling process (B_P) at the consumer's home. Finally, the EoL stage includes different waste management processes (B_P).

For all the F_P (raw milk production and dairy processing) and their activities (dairy farm activities, on-farm feed production, milk processing, container filling, storage, cleaning and maintenance), primary activity data regarding their inputs (supplies and consumables) and outputs (Products, co-products, emissions and wastes) is collected or modelled by the CalcPEF$_{Dairy}$ to develop a proper LCI.

CalcPEF$_{Dairy}$ is capable to model the entire raw milk production stage as F_P, B_P or as a mixture of both. If fully modelled as a F_P, specific characteristics and data regarding the raw milk production process' activities are needed to create a detailed LCI. The LCIA result of fully modelling this stage as a F_P is a representative EF-R$_{milk}$. On the other hand, if the raw milk production stage is fully modelled as B_P, this stage's LCIA result will be given by the selected EF compliant raw milk production dataset (EF-datasets $_{Rmilk}$). The raw milk productions stage could also be modelled as a F_P and BP mixture for the cases when the dairy processor produces its own milk and also buys milk externally from other producers; or, if it consumes off-farm produced animal feed to produce its own raw milk.

2.2.2.1. Life Cycle Inventory The Life Cycle Inventory (LCI) activity data is collected at the different product's life cycle stages. CalcPEF$_{Dairy}$ collects and manages this LCI activity data to generate a LCIA. The LCI from the raw milk production stage and its LCIA results determine the EF-R$_{milk}$ (cradle to farm gate). While, the LCIA of the whole product's life cycle stages are used to determine the PEF of the assessed dairy products (cradle to grave).Activity data regarding transportation and water consumption is managed by CalcPEF$_{Dairy}$ in a particular way. Therefore, a complete description on how the tool manages the water flows (at the raw milk production and processing stages) and the considerations made regarding transportation are described in the supplementary material.

2.2.2.1.1. Raw milk production stage The collected activity data for this stage's LCI are the supplies consumed during activities in the dairy farm and to produce on-farm animal feeding such as feed seeds, fertilizers, phytosanitary products, animal bedding materials, chemical products, energy consumption and water consumption. The LCI also includes the quantities of the consumed animal feed produced off-farm. Similarly, quantities of the generated wastes from the activities are collected and related to its treatment processes. The total quantities of this stage's products (raw milk) and co-products (meat and manure) shall be also included.To complete the raw milk production stage LCI, the direct farm emissions arising from the farm activities should be calculated. The CalcPEF$_{Dairy}$ tool calculates the farm emissions by executing the suggested PEFCR-D emission models presented in Table 1. For the particular case of N emissions the IPCC and the EMEP/EEA models can be applied through a harmonized mass balance approach proposed by Egas et al. (2019). These models require specific livestock related primary activity data since dairy livestock activities are part of the dairy farm activities; hence, livestock activity data such as herd, feeding, housing and manure management properties and characteristics is collected and included in this stage's LCI.

2.2.2.1.2. Processing stage The required activity data for this stage's LCI are the total supplies consumed during the dairy processing process's activities such as raw milk, chemical products, consumed energy, consumed water, cooling products. The LCI also includes the quantities of packaging and non-dairy ingredients demanded from their respective production and supplies processes. The quantities of the generated wastes during dairy processing are also collected and related to its treatment processes. When organic wastes such as waste-whey or the sewage sludge are applied to the farm's land as natural or organic fertilizers, their nutrients are considered by the CalcPEF$_{Dairy}$ tool when modelling the direct emissions of the dairy farm.To complete the processing stage LCI, the total amount of finished dairy co-products is

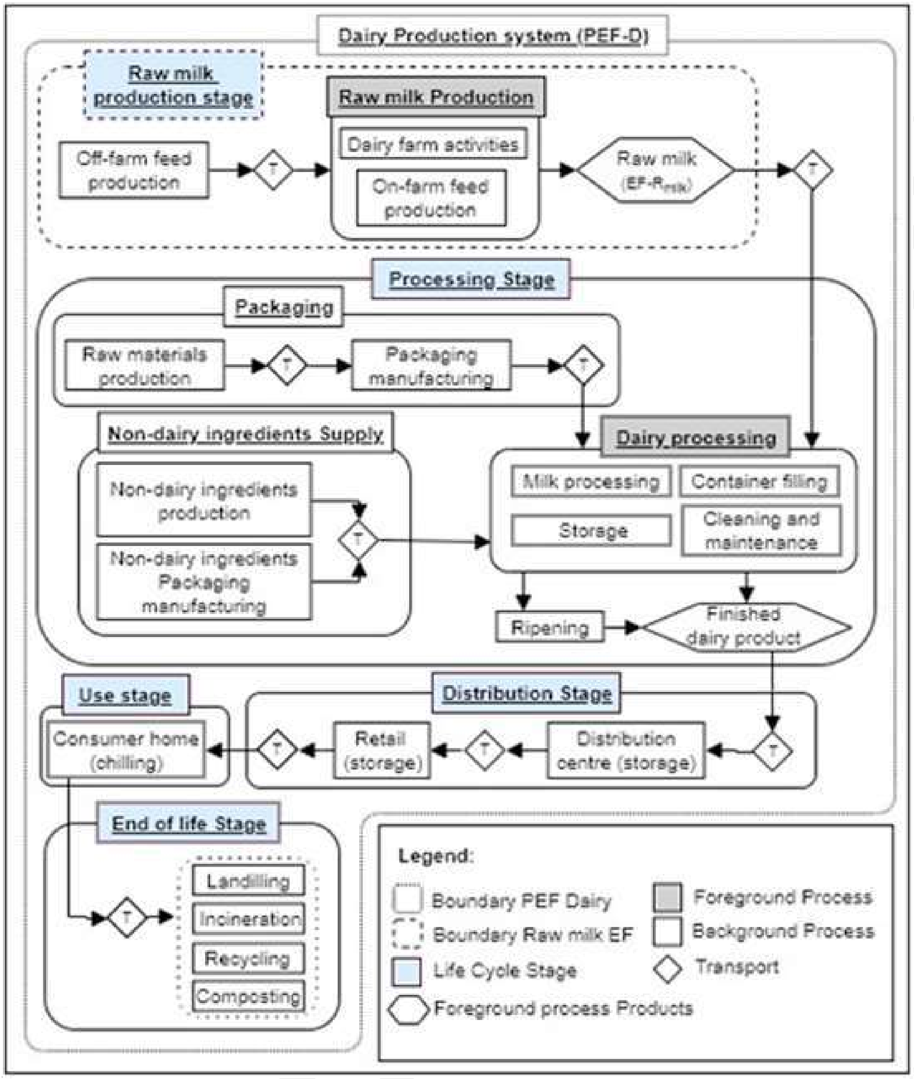

Fig. 2. CalcPEF$_{Dairy}$ tool System boundaries.

collected together with their recipes and properties (Dry mater content). The recipes include all the ingredients (dairy and non-dairy) and supplies that are physically present in 1 kg of finished product; this information is further required to allocate the EI related to this life cycle stage.

2.2.2.1.3. Distribution and use stages Activity data and calculation parameters are part of these stages' LCI. Activity data such as (i) the quantities of the energy consumed for storage (at the distribution and retail centre) and for chilling (at the consumers house) are needed together with (ii) the transport type and distances (among the different facilities until reach the consumers home). Some parameters needed to have a robust LCI at these stages are (i) the transport utilisation ratios, (ii) the product's storage duration times and, (iii) the storage product's volume at the distribution centre, retail and consumer's home.Since this activity data and parameters are related to background processes for which the producer has no control, the PEFCR-D provides European representative LCI activity data and parameters. This European representative information is included in CalcPEF$_{Dairy}$ and set up as default. However, if more accurate information is available, the default values can be modified.

2.2.2.1.4. End of life stage To assess this stage as required by the PEFCR-D, the Circular Footprint Formula (CFF) must be applied. Therefore, the LCI of this stage must include the CFF formula variables which mainly are packaging's related processes' emissions and other country and non-country dependent parameters. The CFF is presented in Equation (1) and fully detailed in the PEFCR guide (EC, 2017b).

$$\left(1 - R_1\right) E_v + R_1 \times \left(AE_{recicled} + (1 - A)\, E_v \times \frac{Q_{Sin}}{Q_P}\right) + (1 - A)\, R_2 \left(E_{recyclingEoL} \cdot \right.$$
$$+ \; (1 - B)\, R_3 \times \left(E_{ER} - LHV \times X_{ER,\, heat} \times E_{SE,\, heat} - LHV \times X_{ER,\, elect} \times E\right.$$
$$+ \; \left(1 - R_2 - R_3\right) \times E_D$$

Production (cradle to gate), energy recovery, landfilling and recycling are the packaging related processes from which the emissions (E) are required. The country dependent parameters are: the allocation factor for burdens and credits (A), the allocation factor for energy recovery process (B), the product's material proportion that will be recycled (R_2) and the product's material proportion that is used for energy recovery (R_3). While the non-country dependent parameters are: the quality proportion between secondary and primary materials (Q_S/Q_P), the material's low heating value (LHV), the efficiency of electric and heat recovery processes ($X_{ER,heat}$ and $X_{ER,elec}$ respectively) and the material's proportion input recycled from a previous system (R_1).Since the producers has no control on any of this LCI activity data and for the correct application of the CFF, the PEFCR guideline provides European representative information which should be used together with the respective EF-datasets. CalcPEF$_{Dairy}$ simplifies this stage's assessment since it

Table 1
Farm activities and emissions.

Activity data Source	Substance	Methodology
Included		
Enteric Fermentation Manure storage (and pre-treatment)	Methane (CH_4), emitted to air	IPCC – Tier 2
Manure storage (and pre-treatment) Manure excretion on the pasture Manure application Nitrogen fertilizer application Crop residues Organic soils Mineral soils	Direct nitrous oxide (N_2O), emitted to air	IPCC – Tier 1
Manure storage (and pre-treatment) Manure excretion on the pasture Manure application Nitrogen fertilizer application	Indirect nitrous oxide (N_2O) due to N volatilization (ammonia and nitric oxides), emitted to air	IPCC – Tier 1
Manure storage (and pre-treatment) Manure excretion on the pasture Manure application Nitrogen fertilizer application	Ammonia (NH_3) and nitric oxides (NO_X), emitted to air	EMEP/EEA – Tier 2
Manure excretion on the pasture Manure application Artificial fertilizer application	Phosphate (PO_4^{-}) emitted to ground and surface water	SALCA – Phosphorus
Manure excretion on the pasture Manure application Artificial fertilizer application	Phosphorus (P) emitted to surface water	SALCA – Phosphorus
Animal Housing	Particulate matter (PM2.5), emitted to air	EMEP/EEA – Tier 2
Silage feeding	Non-methane volatile solids (NMVOC), emitted to air	EMEP/EEA – Tier 2
Housing Grazing Manure excretion on the pasture Manure application Artificial fertilizer application Crop residues	Nitrate (NO_3), emitted to ground water	IPCC – Tier 1
Application of lime Application of urea Peat drainage	Carbon dioxide (CO_2), emitted to air	IPCC – Tier 1
Manure application	Heavy metals emitted to groundwater and soil	SALCA-Heavy metals
Application of pesticides	Pesticides emitted to soil	PEFCR V6.3: Active component applied 90% to agricultural soil, 9% to air and 1% to water.
Excluded		
Milk cooling	Refrigerants emitted to air	–
Carbon sequestration	Carbon dioxide (CO_2), emitted to air	–

incorporates the CFF formula, the EF-datasets for packaging related processes and the default European and country representative parameters provided in the PEFCR guide which can be modified by the user if required.

2.2.3. Life Cycle Impact Assessment

A PEF compliant LCIA assessment includes 16 different EI categories (Table 2). CalcPEF$_{Dairy}$ calculates these EI categories by using the characterization factors from the recommended EF-LCIA methods (EC, 2018) released by the LCDN in the EF dataset package v2.0 as xml files (Table 3). The EF-LCIA methods are used together with the emissions (elementary flows) arising from the different system's stages. These elementary flows are obtained by the CalcPEF$_{Dairy}$ as result of the emissions models at the farm or from the EF-datasets implemented in the tool for different processes (Table 3). The EF-datasets were also released as xml files and contain information such as the process's elementary flows, reference flow's unit, location, modelling criteria, among others.

Once the LCIA results, for the 16 EI categories, are obtained, they are normalized and weighted to obtain the product's Environmental Single Score (EC, 2017b). Normalization factors per person and weighting factors (i) with Toxicity-related impacts and (ii) without Toxicity-related impacts were used to calculate and report the Environmental Single Score (ESS) in this study.

2.2.4. Allocation rules

The dairy production system is a multifunctional system which outputs have economic value (products and co-products) and non-economic value (wastes). For the outputs with economic value

Table 2
Environmental Category Impacts of the PEF profile.

Impact category	Unit	LCIA method
Climate change (GWP)	kg CO_2 eq	Baseline model of 100 years of the IPCC (Stocker et al., 2013)
Ozone Depletion Potential (ODP)	kg CFC-11$_{eq}$	Steady-state ODPs 1999 as in WMO assessment (WMO, 1999)
Human toxicity, cancer (HTP-C)	CTUh	USEtox model (Rosenbaum et al., 2008)
Human toxicity, non-cancer (HTP-NC)	CTUh	USEtox model (Rosenbaum et al., 2008)
Particulate matter formation (PMF)	DI *	UNEP recommended model (Fantke et al., 2016)
Ionizing radiation, human health (IRP)	kg U235 eq	Human health effect model (Frischknecht et al., 2000)
Photochemical ozone formation, human health (POCP)	kg NMVOC eq	LOTOS-EUROS model as implemented in ReCiPe (van Zelm et al., 2008)
Acidification (AP)	mol H+ eq	Accumulated Exceedance (Posch et al., 2008; Seppälä et al., 2006)
Eutrophication, terrestrial (T-EP)	mol N eq	Accumulated Exceedance (Posch et al., 2008; Seppälä et al., 2006)
Eutrophication, freshwater (F-EP)	kg P eq	EUTREND model as implemented in ReCiPe (Struijs et al., 2009)
Eutrophication, marine (M-EP)	kg N eq	EUTREND model as implemented in ReCiPe (Struijs et al., 2009)
Ecotoxicity, freshwater (FETP)	CTUe	USEtox model (Rosenbaum et al., 2008)
Land use (LOP)	SQi *	Soil quality index based on LANCA (Bos et al., 2016)
Water scarcity (W-RD)	m3 world eq	Available WAter REmaining (AWARE) Boulay et al. (2018)
Resource use, minerals and metals (M-RD)	kg Sb eq	CML 2002 (Guinée, 2002; Van Oers et al., 2002)
Resource use, fossils (F-RD)	MJ	CML 2002 (Guiné;e, 2002; Van Oers et al., 2002)

* DI = Disease incidence, SQi = Soil quality index

CalcPEF$_{Dairy}$ follows two allocation rules to assign EI: (i) at the dairy farm among the farm's co-products (raw milk and meat) and (ii) at the processing facility among the final dairy products (processed milk, cheese and yoghurt) and coproducts sold (cheese whey and cream).

The first **allocation rule, at the dairy farm**, follows a biophysical allocation criterion. A share of the total raw milk production stage EI is assigned to the produced raw milk by an allocation factor (AF) obtained from Equation (2). Where M_{meat} is the mass (kg) of livestock sold per year and M_{milk} is the mass (kg) of the fat and protein corrected milk (FPCM) sold per year. The FPCM is calculate with Equation (3), correcting the produced farm's milk to 4% of fat and 3.3% of protein. EDA, 2018

.

$$AF_{RAW\ MILK} = 1 - 6.04 \times \frac{M_{meat}}{M_{milk}} \tag{2}$$

$$FPCM\left(\frac{kg}{year}\right) = Production\left(\frac{kg}{year}\right) \times (0.1226 \times True\ fat\% + 0.0776 \times Ture\ protein\% + 0.2534) \tag{3}$$

The second **allocation rule at the processing facility** assigns a share of the total processing stage EI to the different outputs with economic value on two different ways depending if the supplies consumed at this stage are (i) physically or (ii) not physically present in the final dairy co-products.

For the first case, since CalcPEF$_{Dairy}$ collects the recipes of the different dairy products, it knows the quantity of ingredients (dairy and non-dairy) and packaging materials that are physically present in 1 kg of final product. Hence, the EI regarding the production of those processing supplies (raw milk, salt, sugar, fruit, salt, plastics, paper, etc) are directly related to the respective product's FU.

Besides the ingredients, the production stage consumes other supplies such as chemical products, water, energy and it also manages the generated wastes, such as waste water, outside of the farm. These production, consumption and management activities are not physically present in the final product but are directly related and needed to produce it. Therefore, the total EI arising from them are allocated to each of the final sold products (cheese, yoghurt, processed milk, cream, etc) by using a dry matter criteria (DM) presented in Equation (4). Where AF_i is the allocation factor of the co-product *i*, DM_i is the dry matter content (g/kg) and Q_i is total quantity produced (kg) of the co-product *i*.

$$AF_i = \frac{DM_i \times Q_i}{\sum_{i=1}^{n}\left(DM_i \times Q_i\right)} \tag{4}$$

2.2.5. Assumptions and limitations

CalcPEF$_{Dairy}$ tool follows the latest PEFCR-D and the PEFCR v.6.3 guidance to obtain PEF compliant results for raw milk, cheese and yoghurt; however, some assumptions are still needed. The tool limitations are mainly related to the available EF-datasets found in the PEF databases.

- Due to the EF-datasets availability the tool results are representative in a European context.
- The EI related to the supplies (production/consumption) that are not physically present in the final product are allocated following a DM based allocation criteria to the sold products and coproducts.
- Since CaclPEFDairy only incorporates the official EF-datasets, the lack of EF-dataset variety for some inputs, production

Table 3
Life Cycle Data Network PEF official datasets.

Dataset	Developer	Source
Energy	Thinkstep	http://lcdn.thinkstep.com/Node/
Transport	Thinkstep	http://lcdn.thinkstep.com/Node/
Packaging	Thinkstep	http://lcdn.thinkstep.com/Node/
End of life	Thinkstep	http://lcdn.thinkstep.com/Node/
Incineration	Thinkstep	http://lcdn.thinkstep.com/Node/
Plastics	Thinkstep	http://lcdn.thinkstep.com/Node/
Agrofood	Quantis	https://lcdn.quantis-software.com/PEF/
Feed crops and compounds	Fefac	http://lcdn.blonkconsultants.nl/Node/
Chemicals	Ecoinvent	http://ecoinvent.lca-data.com/
Glass recycling	RDC	http://soda.rdc.yp5.be/login.xhtml?stock = FEVE_EF_comp
EF 2.0	LCDN	http://eplca.jrc.ec.europa.eu/permalink/EF_2.0_Complete.zip

processes, waste management and recycling processes does not allow the tool to properly assess some of the life-cycle stages.
- The water scarcity modelling is affected by the lack of location specific taped water datasets; there is only one average European representative dataset included in the official EF-datasets. This affects the water scarcity modelling results since the methodology's (AWARE) characterization factors vary according to the process location. Therefore, instead of location specific water production datasets, the tool can use location specific water elementary flows to properly model the water scarcity potential. However, if modelled in this way, the rest of impacts related to the tap water production are not considered.
- Another tool limitation is that it cannot assess dairy farms with mixed types of livestock; the raw milk production of each livestock (e.g. bovine, ovine and caprine) must be assessed separately.
- The tool assumes that all the on-farm produced crops are used animal feed and consumed by the farm's livestock. If there is the case that the farm sells a share of the total crop production, an external allocation outside of the tool should be done.

2.2.6. Data quality requirements

As stablished by the PEFCR-D, $\text{CalcPEF}_{\text{Dairy}}$ determines the data quality requirements (DQR) for raw milk production and the dairy products. The DQR calculation is based on Equation (5); where $\overline{TeR}$ is the weighted average of the Technological-Representativeness, $\overline{GR}$ is the weighted average of the Geographical-Representativeness, $\overline{TiR}$ is the Time-Representativeness, and $\overline{P}$ is the weighted average of the Precision/uncertainty. The application of the DQR formula is explained in detail in the PEFCR-D (EDA, 2018) and the PEFCR guidelines (EC, 2017b).

$$DQR = \frac{\text{EQ \textbackslash x \textbackslash to (TeR)} + \text{EQ \textbackslash x \textbackslash to (GR)} + \text{EQ \textbackslash x \textbackslash to (TiR)} + \text{EQ \textbackslash x \textbackslash to (P}}{4}$$

2.3. Case study

The $\text{CalcPEF}_{\text{Dairy}}$ tool validation is carried out by assessing the environmental performance of a traditional dairy production system in Catalonia (Northwest of Spain) which produces cow's raw milk and then process it into cheese and yoghurt. The system has a total of 84 livestock heads from which 50 are productive. The productive livestock annual raw milk production is 407.76 tons (12.3%DM, 3.4% fat and 4% protein); from which 283.35 tons are sold before processing. At processing a 77.3% of the raw milk is used to produce 16.02 tons of cheese (70.86% DM). From the cheese production process, 6.89 tons of cheese whey (6.8%DM) are generated as coproduct and used as animal feeding. The remaining 22.7% of the raw milk is processed to produce a total of 32.9 tonnes of yoghurt (10.57%DM).

The case study's livestock diet is mixed; it is fed under grazing conditions and with crops produced inside and outside the farm. The livestock spends 70% of the year grazing in open spaces and the remaining time it is kept in a stall where the produced manure is manged as deep bedding. The total of the livestock's managed manure (47.46 tons DM) is applied to the farm's land as natural fertilizer to produce alfalfa and barley. The alfalfa and the barley grain are fed to the livestock while the barley straw is used as animal bedding. The distribution, use and EoL stages of the case study production system and the transportation characteristics were modelled as stated in the PEFCR-D and the PEFCR guidelines.

As presented, the system's F_P are raw milk production and dairy processing for which general and specific LCI were developed. The F_P available bills and stock inventories were used to determine their yearly consumption of ingredients and supplies (Table 4). Staff interviews and site visits were carried out to estimate the

Table 4
Case study's general Life Cycle Inventory.

Item	Stage	Quantity (Unit)	Transport	
			Type	Distanc (km) [a]
Inputs				
Animal feeding				
Alfalfa (produced at farm)	Rm	17267.5 (kg/ year)	–	–
Barley grain (produced at farm)	Rm	23435.1 (kg/ year)	–	–
Maize (corn grain) production;, technology mix, production mix, at farm, EU + 28 (1e3ab044-c0c1-4a1c-9a0d-7a9135851ae6)	Rm	15056.3 (kg/ year)	T	203.1
Wheat grain, technology mix, production mix, at farm, EU + 28 (797 b63d1-100e-44a7-bf06-62ee8f216b32)	Rm	45168.8 (kg/ year)	T	203.1
Soy powder (purchased)	Rm	4758.9 (kg/ year)	T	203.1
Fertilizers				
Managed manure (produced at farm)	Rm	47464.6 (kg DM/ year)	–	–
Animal bedding				
Barley Straw (produced at farm)	Rm	60791.7 (kg/ year)	–	–
Packing materials				
Plastic can, body PP, raw material production, blow moulding, production mix, at plant,0.91 g/cm3, 42.08 g/mol per repeating unit, EU-28 + EFTA (446b8c18-677a-453e-a905-360796366951)	P	963.3 (kg/ year)	V	10
Plastic Film, PP, raw material production, plastic extrusion, production mix, at plant, grammage: 0.0458 kg/m2, thickness 50 μm, EU-28 + EFTA (3f9f3fb2-1aad-4cdf-a419-928c9818d62 d)	P	216.6 (m2/ year)	V	10
Screw cap, PP, raw material production, plastic injection moulding, production mix, at plant,0.91 g/cm3, 42.08 g/mol per repeating unit, EU-28 + EFTA (05a26a08-1ab5-4523-b25f-41b9be0ffc76)	P	65.8 (kg/ year)	V	10
Chemical products				
Nitric acid production, technology mix, production mix, at plant,100% active substance, RER (153d694 d-6e48-47c4-9797-ff4bb6678612)	–	71.4 (kg/ year)	V	10
Consumed at farm	Rm	14.3 (kg/ year)	–	–
Consumed at processing facility	P	57.12 (kg/ year)	–	–
Sodium hydroxide production, technology mix, production mix, at plant,100% active substance, RER (2ba49ead-4683-4671-bded-d52b80215e9e)	–	47.6 (kg/ year)	V	10
Consumed at farm	Rm	9.5 (kg/ year)	–	–
Consumed at processing facility	P	38.1 (kg/ year)	–	–
Energy consumed				

Table 4 (*Continued*)

Item	Stage	Quantity (Unit)	Transport	
			Type	Distance (km) [a]
Electricity grid mix 1kV–60kV,AC, technology mix, consumption mix, to consumer, 1 kV–60 kV, ES (b8d76497-d392-4d90-a2ac-4ee3e2df2946)		11712.1 (kWh/year)	–	–
Consumed at farm	Rm	2576.7 (kWh/year)	–	–
Consumed at processing facility	P	9135.4 (kWh/year)	–	–
Diesel mix at refinery, from crude oil, production mix, at refinery, 10 ppm sulphur, 7.23 wt% bio components, EU-28 + 3 (da248653-790 b-44bf-9e43-d4ae66cafbe1) Diesel combustion in construction machine, diesel driven, GLO (dae81b4f-688f-44cd-906 b-9435d3843e65)	–	12408.8 (kg/year)	T	203.1
Consumed at farm	Rm	9803.0 (kg/year)	–	–
Consumed at processing facility	P	2605.9 (kg/year)	–	–
Water consumed				
Tap water, technology mix, at user, per m3 water, EU-28 + 3 (212b8494-a769-4c2e-8d82-9a6ef61baad7)	–	1209.1 (m3/year)	–	–
For irrigation (consumed at farm)	Rm	290.2 (m3/year)	–	–
For animal trough (consumed at farm)	Rm	677.10 (m3/year)		
For dairy processing cleaning (consumed at processing facility)	P	241.8 (m3/year)	–	–
Total quantity of ingredients				
Dairy ferments	P	0.6 (kg/year)	V	10
Rennet	P	8.9 (kg/year)	V	10
Sodium chloride powder production, technology mix, production mix, at plant,100% active substance, RER (bd92e590-afa8-430c-8089-6491c32163fb)	P	76.2 (kg/year)	V	10
Total processed raw milk	P	124399.6 (kg/year)	–	–
Outputs				
Economic value outputs				
Raw milk (DM = 12.3%, 3.4% fat and 4% protein)	Rm	283352.0 (kg/year)	–	–
Cheese (DM = 70.86%)	P	16019.9 (kg/year)	–	–
Yoghurt (DM = 10.57%)	P	32901.3 (kg/year)	–	–
Mature livestock to slaughter house	Rm	8081.1 (kg/year)	–	–
Young livestock to slaughter house	Rm	1631.8 (kg/year)	–	–
Non-economic value outputs				
Treatment of effluents from potato starch production, waste water treatment including sludge treatment, production mix, at plant, 1m3 of waste water treated, EU-28+EFTA (2c42b213-0e00-4d8f-8a02-bda8c3f9b652) COD: 11.5 g/l	P	241.8 (m3/year)	–	–
Cheese whey for animal feeding (DM = 6.8%, 1039.79 kg/m3)	P	6.6 (m3/year)	–	–

T = Articulated lorry transport, Euro 5, Total weight >32 t (without fuel), diesel driven, Euro 5, cargo, consumption mix, to consumer, more than 32t gross weight/24,7t payload capacity, EU-28 + 3 (42e1c0c4-2d0d-4ae8-9cb4-5ea5a91bc41a).
V= Articulated lorry transport, Euro 3, Total weight <7.5 t (without fuel), diesel driven, Euro 3, cargo, consumption mix, to consumer, up to 7,5t gross weight/3,3t payload capacity, EU-28 + 3 (aea613ae- 573 b-443a-aba2-6a69900ca2ff).
[a] Distances after applying respective utilisation ratios (T = 64% and V = 20%).

consumption share of chemical products, energy and water between the dairy farm and the processing facility; and also, to collect specific data regarding the farm and processing facility (Table 5 and Table 6).

The case study $\text{CalcPEF}_{\text{Dairy}}$ LCIA outcomes for raw milk ($\text{EF-R}_{\text{milk}}$), cheese ($\text{PEF-D}_{\text{Cheese}}$) and yoghurt ($\text{PEF-D}_{\text{yoghurt}}$) are presented and discussed. The tool's $\text{EF-R}_{\text{milk}}$ result is compared among the average European EF-dataset ($\text{EF-datasets}_{\text{Rmilk,EU}}$) and country specific EF-datasets for France, Great Britain, Poland, Ireland, Belgium, Germany and Italy. For the case of dairy products, the $\text{CalcPEF}_{\text{Dairy}}$ tool together with the default parameters and LCI provided by the PEFCR-D were used to calculate the PEF for additional virtual cheese types (fresh, soft, semi-hard and hard) and spoonable virtual yoghurts (plain, flavoured and fruited). Therefore, these additional virtual PEF results and the case study $\text{PEF-D}_{\text{Cheese}}$ and $\text{PEF-D}_{\text{yoghurt}}$ results are compared among each other and between respective average European EF-dataset for cheese ($\text{EF-dataset}_{\text{Cheese}}$) and yoghurt ($\text{EF-dataset}_{\text{yoghurt}}$) respectively. The $\text{EF-datasets}_{\text{cheese}}$ and $\text{EF-datasets}_{\text{yoghurt}}$ reproduce the PEF benchmark outcomes presented in the PEFCR-D. The comparison between the $\text{CalcPEF}_{\text{Dairy}}$ results (case study, the virtual products) and the PEFCR-

Table 5
Specific raw milk production stage LCI: Dairy farm and livestock activity data.

Item	Quantity	Units
Productive livestock	50	heads
Weight	600	kg
Time in farm	365	days
Non-productive livestock	34	heads
Weight	500	kg
Time in farm	365	days
Young livestock sold	13	cabezas
Weight	125	kg
Time in farm	30	day
Raw milk properties		
Raw milk production rate	22.34	Litters/head/day
Fat content	3.4	%
Protein content	4	%
Annually based livestock feeding conditions		
Grazing - significant energy expend	70	% year
Stall. housing or buildings - very little or no energy expend	30	% year
Manure management		
Pasture/Range/Paddock	70	% of excreted manure
Deep bedding	30	% of excreted manure
Temperature	20	Degrees Celsius
Grazing/pasture area	50	ha
Managed manure/fertilizers application area	7	ha
Feed digestibility (DE)	72.5	%

Table 6
Specific processing stage LCI: product's properties and recipes.

Ingredient	Unit (/kg dairy product)	Dairy Product		Transport	
		Cheese (DM = 70.86%)	Yoghurt (DM = 10.57%)	Type	Distance [a] (km)
Dairy ferments	kg	3.8E-05	–	V	10
Rennet	kg	5.6E-04	–	V	10
Sodium chloride powder production, technology mix, production mix, at plant,100% active substance, RER (bd92e590-afa8-430c-8089-6491c32163fb)	kg	4.8E-03	–	V	10
Case study's Raw milk (DM = 12.3%, 3.4% fat and 4% protein)	kg	6.00 E+00	8.6E-01	–	–
Plastic can, body PP, raw material production, blow moulding, production mix, at plant,0.91 g/cm3, 42.08 g/mol per repeating unit, EU-28+EFTA (446b8c18-677a-453e-a905-360796366951)	kg	–	2.9E-02	V	10
Plastic Film, PP, raw material production, plastic extrusion, production mix, at plant, grammage: 0.0458 kg/m2, thickness 50 µm, EU-28+EFTA (3f9f3fb2-1aad-4cdf-a419-928c9818d62 d)	m2	1.4E-02	–	V	10
Screw cap, PP, raw material production, plastic injection moulding, production mix, at plant,0.91 g/cm3, 42.08 g/mol per repeating unit, EU-28+EFTA (05a26a08-1ab5-4523-b25f-41b9be0ffc76	kg	–	2.00E-03	V	10

V= Articulated lorry transport, Euro 3, Total weight <7.5 t (without fuel), diesel driven, Euro 3, cargo, consumption mix, to consumer, up to 7,5t gross weight/3,3t payload capacity, EU-28 + 3 (aea613ae- 573 b-443a-aba2-6a69900ca2ff).
DM = Dry matter content.
[a] Distances after applying respective utilisation ratios.

D benchmark datasets aim to demonstrate that the tools performance with different input and show that the obtained outcomes are in the range of the benchmark PEFCR-D results. This comparison does not aims to lead a real environmental performance assessment and discussion among the virtual products, the case study results and the benchmark results since the virtual products were modelled with the default PEFCR-D data which is an average of different product types and therefore the conclusions obtained from comparing the products may be misleading.

Finally, to present the tool's versatility and to demonstrate the relevance of a correct assessment of the raw milk production stage, the outcomes of a scenario and sensitivity analysis are presented. From the case study, a total of six parameters were modified for this analysis (livestock feeding location, feed digestibility, activity coefficient, manure management conditions and heavy metals concentration).

3. Results and discussion

3.1. Environmental impacts

The case study EF-R_{milk}, PEF-D_{Cheese} and PEF-$D_{yoghurt}$ results are presented in Table 7. The discussion of the results in the following sections focus on the most relevant impact categories for dairy products (GWP, PMF, AP, F-EP, M-EP, T-EP, LOP, W-RD and F-RD) as stated in the PEFCR-D. Additionally the discussion of this research will focus on the ESS ($ESS_{WO\text{-}Toxicity}$) since the PEFCR-D only reports them as benchmark values.

3.1.1. Raw milk production environmental footprint

The EF-R_{milk} weighting results confirm that most of the 16 characterized EI are related to dairy farm activities such as irrigation, livestock drinking water, enteric fermentation, manure management, among others. The $ESS_{WO\text{-}Toxicity}$ for EF-R_{milk} is 1.0×10^{-4}; over it, the direct dairy farm emissions have an impact 78%; while, the production and/or consumption of energy, chemicals, water and others have an overall impact of 22%. The calculated DQR for EF-R_{milk} is 1.5 (the parameters' values used to determine the DQR are presented the supplementary material).

As shown in Fig. 3, a 67.6% of GWP is caused by CH_4 emissions arising from the livestock's enteric fermentation and a 15.6% by N_2O emissions from manure management (74.8% of them arise from the excretion of manure during grazing). PMFP is mainly caused by NH_3 emissions from the farm's manure management activities (64.4%), from which 44.4% are emitted during the storage of manure. A 68.3% of the F-RD is accredited to the consumption of energy and a 31% to the production of livestock feed. AP and T-EP are associated to the farm's NH_3 and NO_2 emissions; these emissions contribute an 84.7% to AP and 83.9% to T-EP. A 50.9% of the F-EP and a 37.1% of the M-EP are associated to the production of livestock feed.

Another important compartment related to F-EP is the phosphorus emitted to waterbodies from the applied manure; its share on F-EP is 47.6%. LOP is attributed to the agricultural activities related to the farm such as livestock feed production (16.3%) and usage of manure as fertilizer on the land (73.6%). W-RD is associated to the feed production process (64.7%) and to the tap water consumed in the farm to fill the animals' drinking thoughts and for irrigation of the land (33.6%). The presented information has great value to the raw milk or dairy producer since it will allow the identification of environmental hot-spots, simulate the impact of possible solutions and then execute the best one to improve the activities from which most of the emissions arise.

3.1.2. Product Environmental Footprint of dairy products

As expected the raw milk production stage have the greatest influence in the case study's PEF-D_{cheese} and PEF-$D_{yoghurt}$ results. The $ESS_{WO\text{-}Toxicity}$ for PEF-D_{cheese} is 9.7×10^{-6} and the raw milk production stage has an overall influence of 87.4% (Fig. 4). Regarding PEF-$D_{yoghurt}$ the influence of the raw milk production stage over its $ESS_{WO\text{-}Toxicity}$ (1.4×10^{-5}) is 80.1% (Fig. 5). The calculated DQR for PEF-D_{cheese} is 1.5 while for PEF-$D_{yoghurt}$ is 1.4 (the parameters' values used to determine the DQR are presented the supplementary material).

More specifically, the PEF-D_{cheese} and PEF-$D_{yoghurt}$ results show that EI categories such as GWP, PMFP, AP, T-EP, F-EP, M-EP, LOP and W-RD are mostly affected by the raw milk production stage (in ranges from 55% to 99%). For the PEF-D_{cheese}, a 95% of the F-RD is attributed to the processing facility and to the raw milk production stages due to the consumption of electricity and diesel; while for PEF-$D_{yoghurt}$, the main F-RD is the production of the packaging materials (37%).

Table 7
Impact assessment and environmental single score results for case study's dairy products: raw milk (FU: 1 kg FPCM), cheese (FU: 10 g DM) and yoghurt (FU: 125 g).

Dairy product	Detail	Environmental category impacts (Unit [a])																Single Score (Points)
		GWP (kg CO_{2e0q})	ODP (kg CFC-11_{eq})	FETP (CTUe)	HTP-C (CTUh)	HTP-NC (CTUh)	PMFP (DI)	IRP (kg $U235_{eq}$)	POCP (kg $NMVOC_{eq}$)	AP (mol $H+_{eq}$)	T-EP (mol N_{eq})	F-EP (kg P_{eq})	M-EP (kg N_{eq})	LOP (SQi)	W-RD (m^3 $world_{eq}$)	MM-RD (kg Sb_{eq})	F-RD (MJ)	
Raw milk	Characterization	1.0 E+00	6.2E-11	3.0 E+00	2.0E-08	1.8E-06	1.2E-07	3.1E-03	4.4E-03	1.4E-02	6.4E-02	3.1E-05	2.9E-03	1.4 E+02	2.6E-01	2.7E-08	1.5 E+00	–
	Normalization [b]	1.3E-04	2.6E-09	2.5E-04	5.3E-04	3.9E-03	1.9E-04	7.2E-07	1.1E-04	2.5E-04	3.6E-04	1.2E-05	1.0E-04	1.0E-04	2.3E-05	4.7E-07	2.3E-05	–
	Weighted [c] ($W_{Toxicity}$)	2.8E-05	1.7E-10	4.8E-06	1.1E-05	7.2E-05	1.7E-05	3.6E-08	5.2E-06	1.6E-05	1.3E-05	3.5E-07	3.0E-06	8.3E-06	1.9E-06	3.5E-08	1.9E-06	1.8E-04
	Weighted [c] ($WO_{Toxicity}$)	3.0E-05	1.8E-10	0.0 E+00	0.0 E+00	0.0 E+00	1.8E-05	3.9E-08	5.6E-06	1.7E-05	1.4E-05	3.6E-07	3.2E-06	8.8E-06	2.0E-06	3.8E-08	2.1E-06	1.0E-04
Cheese	Characterization	9.9E-02	2.5E-11	7.6E-01	1.8E-09	1.7E-07	1.2E-08	1.1E-03	4.9E-04	1.3E-03	5.9E-03	3.3E-06	2.8E-04	1.2 E+01	3.0E-02	4.8E-09	2.7E-01	–
	Normalization [b]	1.3E-05	1.1E-09	6.5E-05	4.6E-05	3.7E-04	1.8E-05	2.5E-07	1.2E-05	2.3E-05	3.3E-05	1.3E-06	1.0E-05	8.9E-06	2.6E-06	8.3E-08	4.2E-06	–
	Weighted [c] ($W_{Toxicity}$)	2.7E-06	6.8E-11	1.2E-06	9.9E-07	6.8E-06	1.7E-06	1.3E-08	5.8E-07	1.4E-06	1.2E-06	3.7E-08	3.0E-07	7.1E-07	2.2E-07	6.2E-09	3.5E-07	1.8E-05
	Weighted [c] ($WO_{Toxicity}$)	2.8E-06	7.3E-11	0.0 E+00	0.0 E+00	0.0 E+00	1.8E-06	1.4E-08	6.1E-07	1.5E-06	1.3E-06	3.9E-08	3.1E-07	7.5E-07	2.3E-07	6.7E-09	3.7E-07	9.7E-06
Yoghurt	Characterization	1.4E-01	3.7E-11	9.7E-01	2.5E-09	2.2E-07	1.5E-08	2.3E-03	6.6E-04	1.7E-03	7.5E-03	6.2E-06	3.7E-04	1.5 E+01	4.1E-02	7.5E-09	7.8E-01	–
	Normalization [b]	1.8E-05	1.6E-09	8.3E-05	6.4E-05	4.7E-04	2.4E-05	5.5E-07	1.6E-05	3.0E-05	4.3E-05	2.4E-06	1.3E-05	1.1E-05	3.5E-06	1.3E-07	1.2E-05	–
	Weighted [c] ($W_{Toxicity}$)	3.8E-06	9.9E-11	1.6E-06	1.4E-06	8.7E-06	2.2E-06	2.8E-08	7.7E-07	1.8E-06	1.6E-06	6.8E-08	3.9E-07	9.0E-07	3.0E-07	9.7E-09	9.9E-07	2.5E-05
	Weighted [c] ($WO_{Toxicity}$)	4.0E-06	1.1E-10	0.0 E+00	0.0 E+00	0.0 E+00	2.3E-06	3.0E-08	8.2E-07	2.0E-06	1.7E-06	7.2E-08	4.1E-07	9.5E-07	3.2E-07	1.0E-08	1.1E-06	1.4E-05

DI = Disease incidence.
SQi = Soil quality index.
$W_{Toxicity}$ = whit toxicity-related impact categories.
$WO_{Toxicity}$ = without toxicity-related impact categories.
[a] Units for characterization results only.
[b] Unit less.
[c] Points.

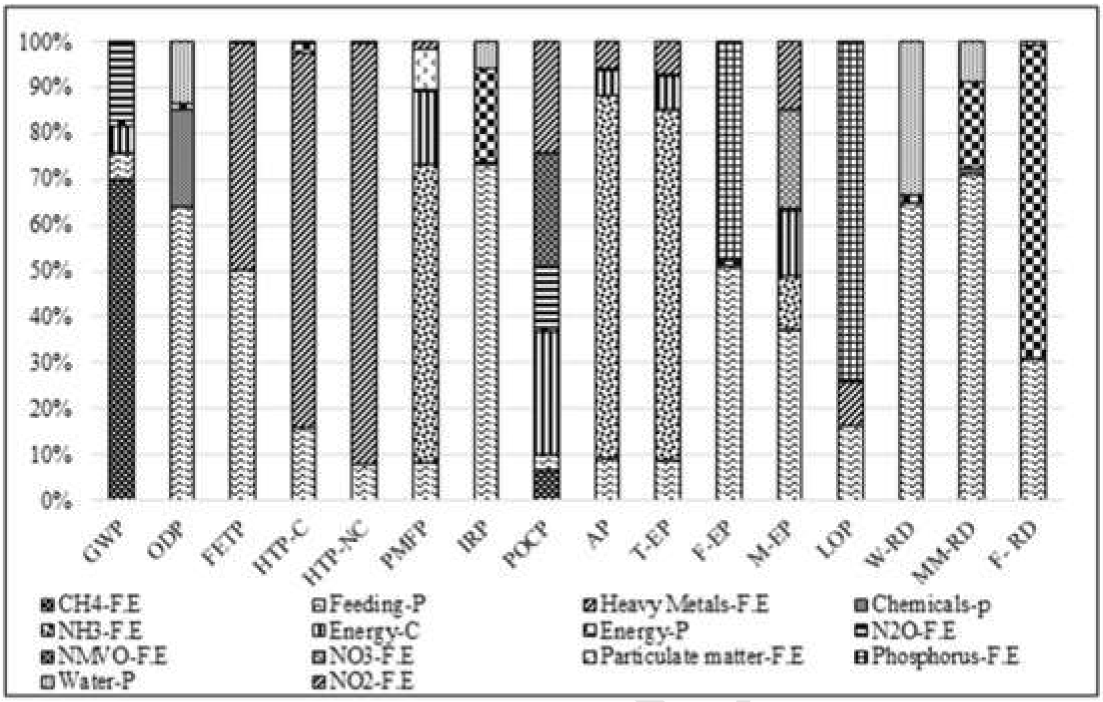

Fig. 3. Characterization results for the different compartments per 1 kg FPCM of raw milk (F. E = Farm emissions, C = Consumption, P = Production, T = Transport).

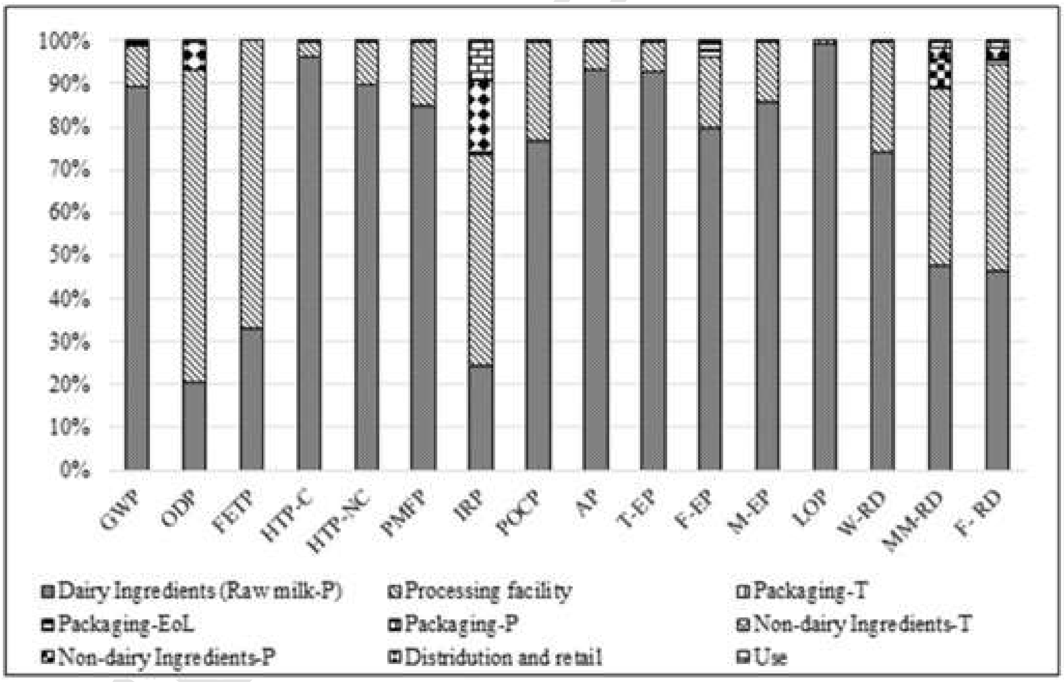

Fig. 4. Characterization results for the different compartments per 10 g DM of Cheese (C = Consumption, P = Production, T = Transport, EoL = End of life).

3.2. CalcPEF$_{Dairy}$ results against Environmental Footprint compliant datasets

The lack of detailed information regarding the dairy farms used to develop the EF-datasets $_{Rmilk}$ and the EU average representative EF-datasets$_{cheese}$ and EF-datasets$_{yoghurt}$ have made unfeasible to replicate their results whit the tool. However, since the tool's case study outcomes (EF-R$_{milk}$, PEF-D$_{cheese}$ and PEF-D$_{yoghurt)}$ have been obtained following the PEFCR-D, they can be directly compared with their respective EF-datasets outcomes evidencing the tool's versatility and accuracy.

For the case of raw milk, the EF-R$_{milk}$ result is compared with the average European EF-dataset (EF-datasets$_{Rmilk,EU}$, Cow milk production mix at farm per kg FPCM, EU-28 + 3) which represent 72% of the European production. The EF-datasets$_{Rmilk,EU}$ is the weighted average of different country specific and representative raw cow milk production systems (Table 8) which have their own EF-datasets. Therefore,

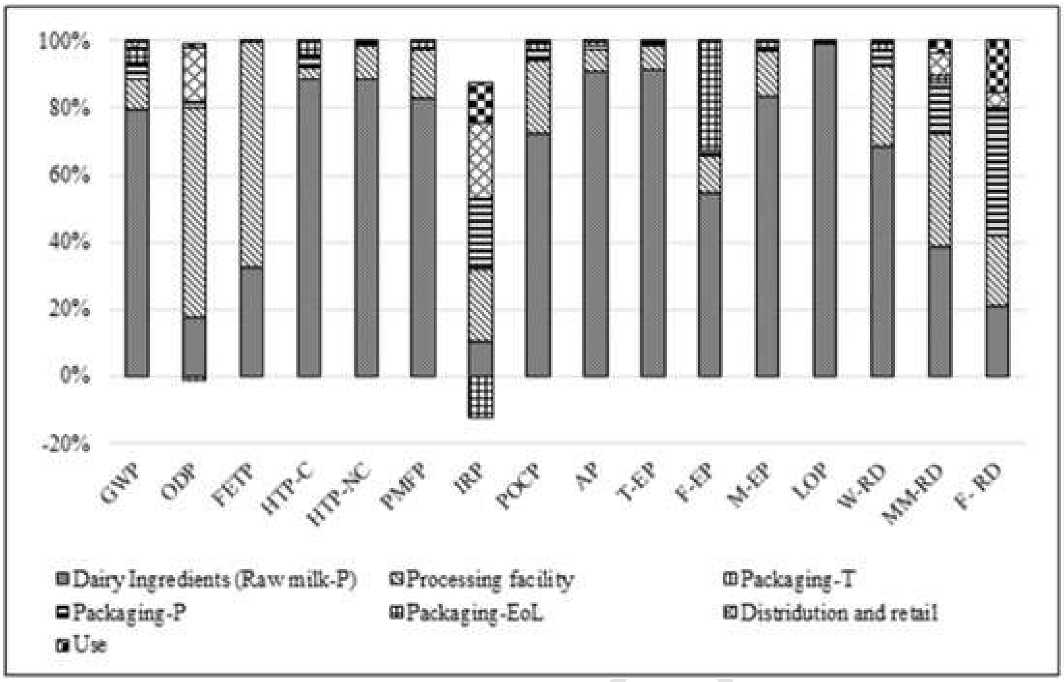

Fig. 5. Characterization results for the different compartments per 125 g of Yoghurt (C = Consumption, P = Production, T = Transport, EoL = End of life).

the outcomes of these country specific raw milk production EF-datasets are also compared with the case study EF-R_{milk} results.

For the case of dairy products, the PEF of specific cheese and spoonable yoghurt types were also modelled and calculated with $CalcPEF_{Dairy}$. The modelling followed the PEFCR-D; hence, it includes the stated parameters, processing LCI for each product and uses the EF-$datasets_{Rmilk,EU}$ to include the raw milk production stage (the detailed PEFCR-D parameters and LCI used for modelling are presented in the supplementary material). These additional PEF results and the case study PEF-D_{Cheese} and PEF-$D_{yoghurt}$ results are compared among each other and between respective EF-$dataset_{Cheese}$ and EF-dataset $_{yoghurt}$.

3.2.1. Raw milk comparative

The EF-$datasets_{Rmilk,EU}$ results and the results from representative EF-$datasets_{Rmilk}$ for production systems from France, Great Britain, Poland, Ireland, Belgium, Germany and Italy (Table 8) are compared with the case study EF-R_{milk}. The EI characterization results reported by the EF-R_{milk} and the raw milk production EF-datasets are similar among them for most of the 16 assessed EI categories and in all cases similar in order of magnitude (Fig. 6A). The case study's $ESS_{WO\text{-}Toxicity}$ for raw milk is 1.01×10^{-4}; this value is in the range of the assessed EF-datasets ESS (from 8.4×10^{-5} to 1.1×10^{-4}) presented in Fig. 6B. The case study's similar single score outcome shows the tool's reliability when assessing the study's dairy farm since it correctly applies the PEFCR-D, the EF-datasets for background processes and it can accurately determine direct farm emissions through the correct application of the required models.

As evidenced in Fig. 6A, the EF-R_{milk} and the assessed raw milk production EF-datasets present differences among each other regarding their EI categories results. Therefore, the possible sources of these differences are discussed based on the available general information of the dairy farms used to develop the EF-datasets (Table 8). As presented in Section 3.1.1 most of the N and P emissions affecting the EF-R_{milk} in terms of GWP, PMFP, AP, F-ET, T-EP and M-EP arise during the manure management and manure application farm activities.

Therefore, these EI are nutrient manure related and their differences might relay on details regarding the execution of those specific dairy farm activities (manure management and manure application). However, since those farming details are not stated in the dataset's information, a detailed assessment of differences on the emission sources between the EF-R_{milk} and the assessed raw milk production EF-datasets is not possible.

3.2.2. Dairy products comparative

Following the PEFCR-D default parameters, recipes and consumed supplies, the $CalcPEF_{Dairy}$ tool was used to determine the PEF of: (i) fresh (PEF-$D_{Ch,fresh}$), soft (PEF-$D_{Ch,soft}$), semi-hard (PEF-$D_{Ch,semi\text{-}h}$) and hard (PEF-$D_{Ch,hard}$) virtual cheeses; and (ii) plain (PEF-$D_{Y,plain}$), flavoured (PEF-$D_{Y,flav}$) and fruited (PEF-$D_{Y,fruit}$) virtual spoonable yoghurts. This comparison only aims to show the user that $CalcPEF_{Dairy}$ results are in the range of the PEFCR-D representative products benchmark results. Conclusion obtained from comparing the PEF of the products may generate mislead conclusions since the compared virtual products where modelled with the PEFCR-D default parameters, recipes and consumed supplies. In reality, these default values might not be representative for each of the compared virtual products.

These additional PEF cheese and yoghurt outcomes are presented and compared with their respective case study (PEF-D_{cheese} and PEF-$D_{yoghurt}$) and datasets results (EF-$datasets_{cheese}$ and the EF-$datasets_{yoghurt}$) as presented in Fig. 7 and Fig. 8 respectively. The EF-$datasets_{cheese}$ and the EF-$datasets_{yoghurt}$ EI characterization results and the single environmental scores represent the European benchmark values reported in the PEFCR-D.

The European benchmark $ESS_{WO\text{-}Toxicity}$ for cheese is 9.5×10^{-6}; while for yoghurt is 1.6×10^{-5}. The average ESS for the assessed cheeses is $1.5 \times 10^{-5} \pm 3.0 \times 10^{-6}$ (Fig. 7B) and for yoghurt $1.9 \times 10^{-5} \pm 3.4 \times 10^{-6}$ (Fig. 8B). The tool's EI characterization results for cheese (PEF-D_{cheese}, PEF-$D_{Ch,fresh}$, PEF-$D_{Ch,soft}$, PEF-$D_{Ch,semi\text{-}h}$ and PEF-$D_{Ch,hard}$) in and yoghurt (PEF-$D_{yoghurt}$ PEF-$D_{Y,plain}$, PEF-$D_{Y,flav}$ and PEF-$D_{Y,fruit}$) have similar order of magnitude as their respective benchmarks; hence, the tool's performance is reliable to calculate the PEF of dairy products. The differences among the single score results are a consequence of the variations on the different EI categories results for each product. The EI categories are mainly affected by the

Table 8

Dairy farms' characteristics used to assess the raw milk production life-cycle stage (FU: 1 kg FPCM) in the case study (EF-R_{milk}) and the EF-datasets (EU = European average, FR = France, GB = Great Britain, PL = Poland, IE = Ireland, BE = Belgium, DE = Germany and IT = Italy) and dairy farm activities ("✓" = considered for assessment, "-" = not considered for assessment).

ID		Cow milk production System, at farm per kg FPCM	Operation area (ha)	Milk yield (kg/cow/year)	Milk AF	Dairy cows (heads)	Heifers (avg heads)	Included activities at farm					Excluded activities at farm		
								All feeding inputs	Emissions		Milking and farm infrastructure	Energy and water consumption	Cooling agents	Packaging	Transport raw milk collection
									Pasture and peat degradation	Enteric and manure management					
EF-R_{milk}		Case study	57	8155	0.86	50	34	✓	✓	✓	✓	✓	✓	✓	✓
EF-$datasets_{Rmilk}$	EU	Production mix	–	–	–	–	–	–	–	–	–	–	–	–	–
	FR	Production mix	–	7426	–	–	–	✓	✓[a]	✓	✓	✓	✓	✓	✓
	GB	Mixed system	130	7780	0.85	149	114	✓	✓	✓	✓	✓	✓	✓	✓
	PL	Mixed system	32	6830	0.83	15	11	✓	✓	✓	✓	✓	✓	✓	✓
	IE	Grazing system	44	6998	0.84	48	37	✓	✓	✓	✓	✓	✓	✓	✓
	BE	Non-grazing system	40	7660	0.85	45	34	✓	–	✓	✓	✓	✓	✓	✓
	DE	Non-grazing system	97	8165	0.82	90	69	✓	–	✓	✓	✓	✓	✓	✓
	IT	Non-grazing system	72	8810	0.88	154	118	✓	–	✓	✓	✓	✓	✓	✓

[a] Only pasture related emissions, AF = Allocation factor.

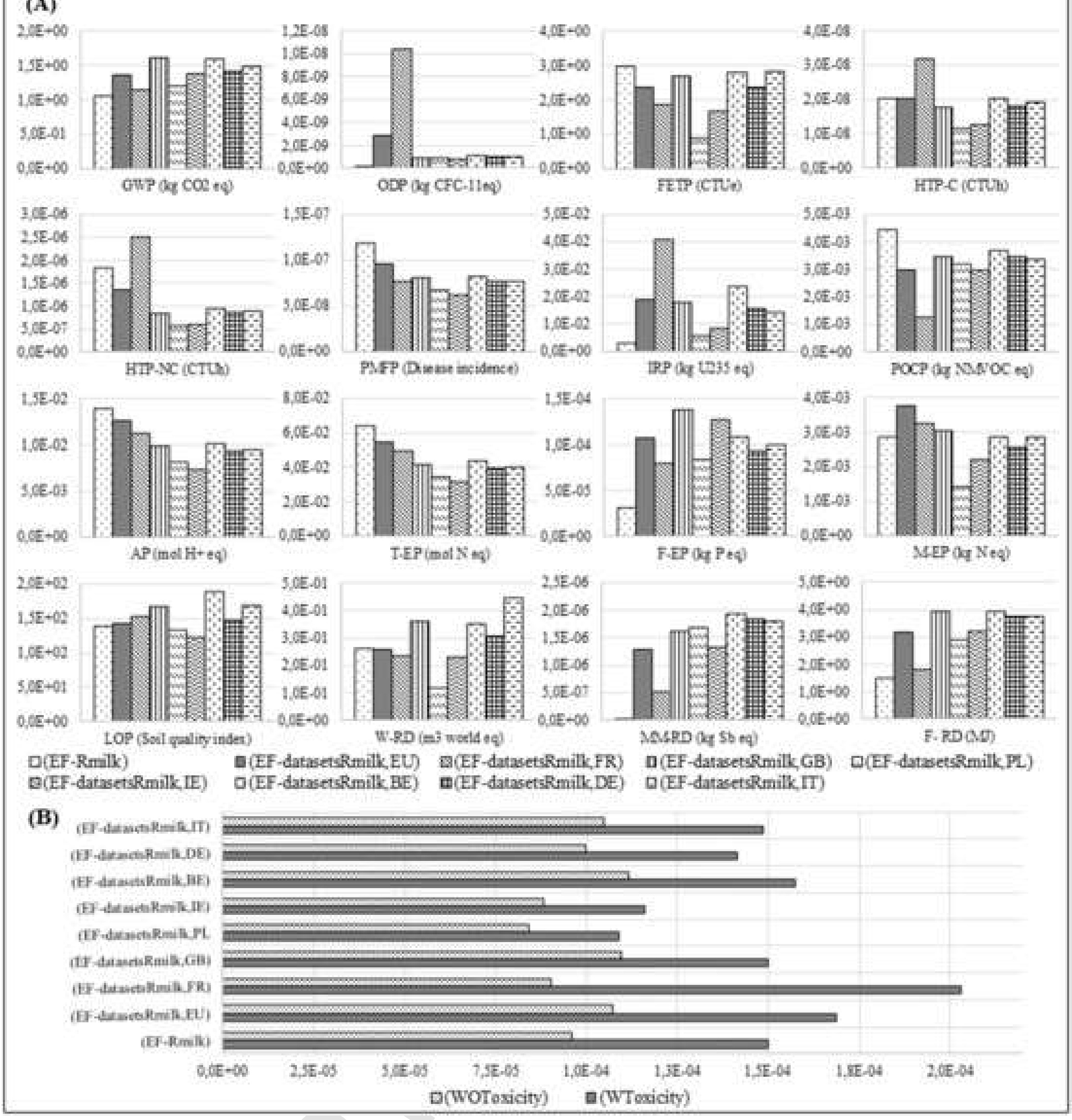

Fig. 6. Raw milk (FU: 1 kg FPCM) production comparative results: (A) characterization and (B) environmental single scores with and without toxicity-related impacts ($W_{Toxicity}$ and $WO_{Toxicity}$). Among the Case study (EF-Rmilk) and EF-datasets (EU = European average, FR = France, GB = Great Britain, PL = Poland, IE = Ireland, BE = Belgium, DE = Germany and IT = Italy).

raw milk source and specific parameters and supplies that each product uses during its life-time.

For the assessed cheeses and yoghurts, the raw milk production stage is the main contributor for GWP, PMFP, AP, T-EP, F-EP, M-EP, LOP and W-RD. Hence, the differences among the results of these EI categories have the tendency to follow a similar trend as the results obtained from their respective raw milk production stages as presented in Section 3.1.1 (EF-R_{milk} for PEF-D_{cheese} and PEF-$D_{yoghurt}$; and EF-$datasets_{Rmilk,EU}$ for PEF-$D_{Ch,fresh}$, PEF-$D_{Ch,soft}$, sPEF-$D_{Ch,semi\text{-}h}$, PEF-$D_{Ch,hard}$, PEF-$D_{Y,plain}$, PEF-$D_{Y,flav}$ and PEF-$D_{Y,fruit}$).

For the case of cheeses, the raw milk production trend on their final EI characterization results (Fig. 7A) is more stressed due to the amount of raw milk required for production. Excluding the EF-$dataset_{Cheese}$, they use an average of 6.9 kg of FPCM per kg produced. While, for yoghurts (Fig. 8A), and also excluding the EF-$dataset_{yoghurt}$, the influence of the raw milk production stage over the EI categories is weaker since yoghurts require less milk than cheese to be produced (0.9 kg FPCM per kg in average). The raw milk production stage is not the only parameter influencing the EI characterization results for cheese and yoghurts; there are other product's characteristics (kg FPCM/kg and DM content) and processing supplies (e.g. energy and water consumption, chemicals, non-dairy ingredients, etc) that play an important role in the final EI category results.

For the case of the case study outocmes, PEF-D_{cheese} and PEF-$D_{yoghurt}$, the processing energy consumed per kilogram of finieshed product influences the F-RD outcomes; making them the lowest among the assessed PEF results. While the F-RD outcomes for the PEF-$D_{Y,fruit}$, PEF-$D_{Y,plain}$ and PEF-$D_{Y,flav}$ are similar since they were modelled similarlly with the PEFCR-D default parameters of energy consumptin and type and amount of packaging materials per kilogram of finished product.

Since PEF-$D_{Ch,fresh}$, PEF-$D_{Ch,soft}$, PEF-$D_{Ch,semi\text{-}h}$ and PEF-$D_{Ch,hard}$ use the same raw milk source and where modelled using the PEFCR-D default processing consumables, they are also expected to report similar F-RD results among each other; however, this does not occur. The PEF-$D_{Ch,fresh}$ reports the highest F-RD outcomes. These differences are caused by the PEF-$D_{Ch,fresh}$ specific DM content (23%) which is the

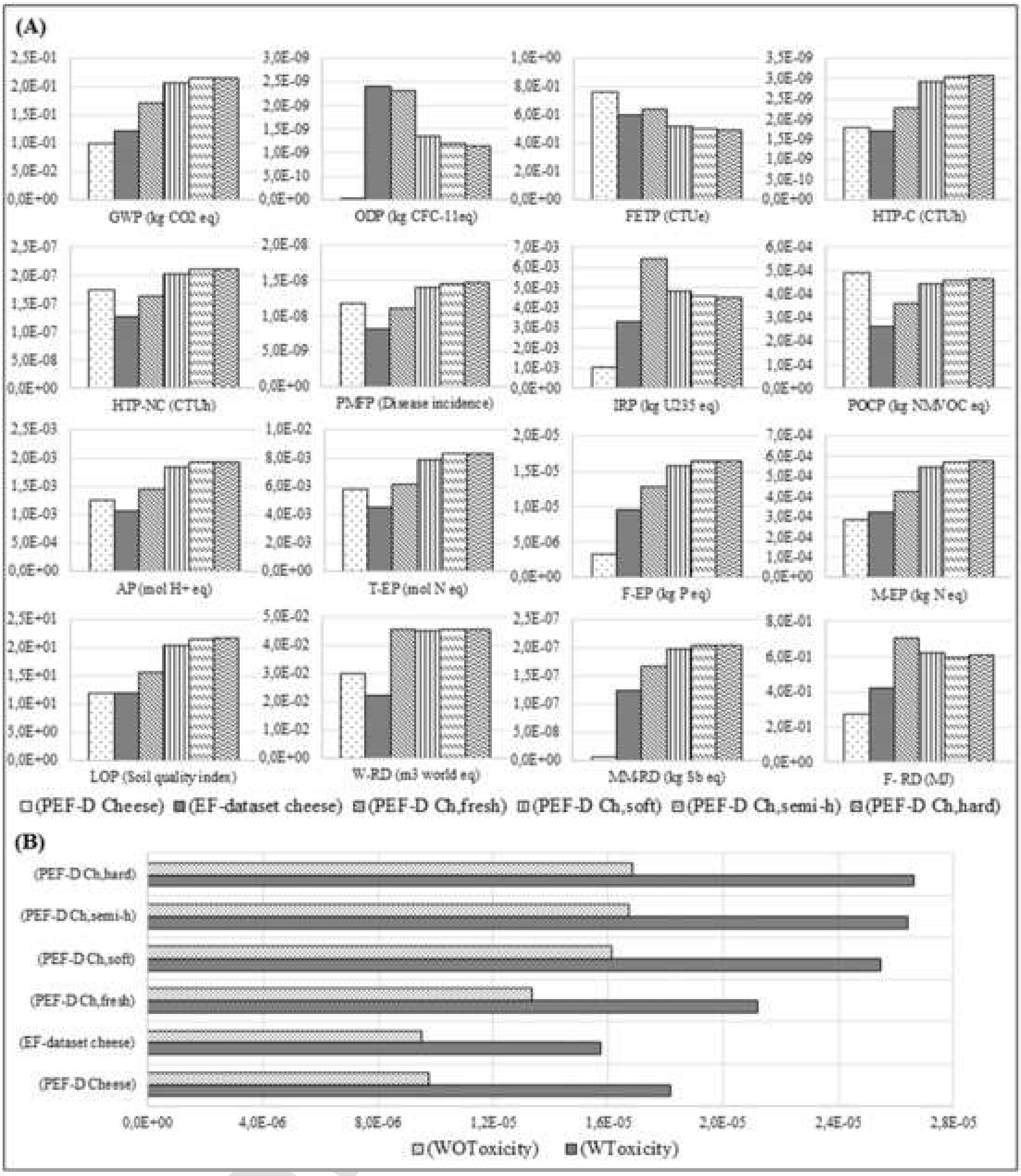

Fig. 7. PEF results comparative for cheese (FU: 10 g DM): (A) environmental profile and (B) environmental single scores with and without toxicity-related impacts ($W_{Toxicity}$ and $WO_{Toxicity}$). Among the case study (PEF-D_{cheese}), EU representative dataset (EF-$datasets_{cheese}$) and other assessed cheese types (PEF-$D_{Ch,fresh}$, PEF-$D_{Ch,soft}$, PEF-$D_{Ch,semi-h}$ and PEF-$D_{Ch,hard}$).

lowest DM content among the products and therefore more no-physycally related EI are atributed per cheese FU (10 g DM). This increases the processing facility incluence in the final F-RD results of this cheese type.

Regarding W-RD, PEF-$D_{Y,fruit}$, PEF-$D_{Y,plain}$ and PEF-$D_{Y,flav}$ consume same amount of water durin the processing stage. However, PEF-$D_{Y,fruit}$ reports twice W-RD than PEF-$D_{Y,plain}$ and PEF-$D_{Y,flav}$ because it is the only type of yoghurt that includes fruits (non-dairy ingredient) in its recipe. Therefre, the W-RD results for PEF-$D_{Y,fruit}$ is highly affected by the fruit trees' water consumption until harvesting. The case study's PEF-$D_{yoghurt}$ reports the smallest W-RD among the assessed yoghurts due to the less amount of water consumed in the processing stage and because it does not incorporate sugar nor fruit. The W-RD results for PEF-$D_{Ch,fresh}$, PEF-$D_{Ch,soft}$, PEF-$D_{Ch,semi-h}$ and PEF-$D_{Ch,hard}$ are almost equal since they use the same raw milk source and consume the same water during processing.

3.3. Scenario and sensitivity analysis

From the case study, a total of six dairy farm activities and characteristics were modified for this scenario and sensitivity analysis (SS) which are (i) the livestock feeding location, (ii) solid manure management conditions, (iii) liquid manure management conditions, (iv) the feed digestibility, (v) the livestock activity coefficient and (vi) the manure heavy metals concentration. These changes on the case study characteristics affect its PEF-D_{cheese} and PEF-$D_{yoghurt}$ base line results. The variations for the six assessed scenarios are presented in Table 9.

- **SS1**, the livestock location shares were swap. Meaning that livestock spends 30% of the year in grazing conditions and 70% in the stall; the excreted manure managed conditions (Deep bedding) have not change. This scenario outcomes show that locating the

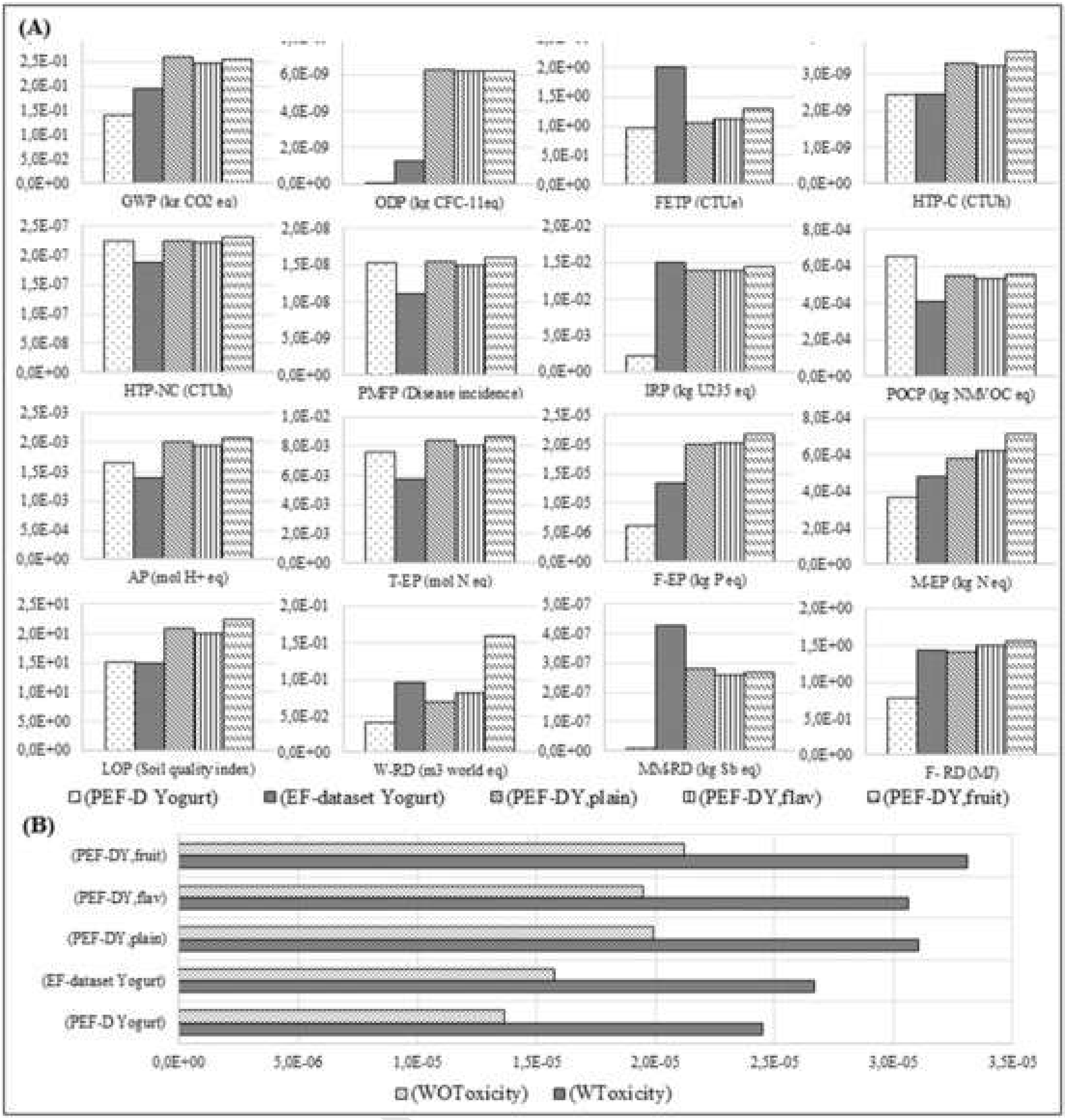

Fig. 8. PEF results comparative for yoghurt (FU:125 g): (A) environmental profile and (B) environmental single scores with and without toxicity-related impacts ($W_{Toxicity}$ and $WO_{Toxicity}$). Among the case study (PEF-$D_{yoghurt}$), EU representative dataset (EF-$datasets_{yoghurt}$) other assessed yoghurt types (PEF-$D_{Y,plain}$, PEF-$D_{Y,flav}$ and PEF-$D_{Y,fruit}$).

livestock more time in the stall increases in more than a 10% to GWP, PMFP, AP and T-EP. There is a reduction on the toxicity-related impact categories and a significant increment (over 60%) for impact categories that highly depend on N emissions (PMFP, AP and T-EP) through the whole farm's manure management chain. This scenario evidences the influence of the livestock's feeding location on different raw milk production systems.

- **SS2**, the manure collected at the stall changed; from being fully managed as deep bedding to be managed as liquid. The changes on manure management techniques only reduced GWP (1.9%). While, AP, PMFP T-EP and F-EP increased more than 5%. M-EP also increased but in less than 5%. The increment on these EI categories could be explained by the higher leakage impact that has the application of liquid manure on the field; which could affect in a higher-level ground water reservoirs and deeper amounts of agricultural soil.
- **SS3**, the management of the manure collected at the stall changed; from being fully managed as deep bedding to be managed as solid. The implementation of this manure management technique decreased GWP by a 14.0% and presented increments of less than 1% for PMPF, AP, T-EP and M-EP. The toxicity related EI categories did not present any variations since the tool uses the same heavy metals emission factors for a deep bedding and solid manure management systems.
- **SS4**, the feed digestibility (DE) has been reduced to the minimum percentage for pasture fed animals (55%) according to the IPCC (2006). This change increased GWP in a 49.2% due to the increment of methane (CH_4) emissions from enteric fermentation and during manure management. As a consequence of the DE reduction, the excreted dry mater (DM_{Ex}) increased; increasing the outcomes for the toxicity-related EI categories too.
- **SS5**, the activity coefficient corresponding to the livestock feeding situation (Ca) was modified from significant (0.36) to modest (0.17) energy expense to acquire feed (IPCC, 2006). The Ca reduction decreased GWP in a 4.8% however, it also had positive influence on the ecotoxicity related EI categories and POCP whit reductions between 2% and 6%. These impact reductions are attributed to the decrement of CH_4 emissions and DM_{Ex}.

As a consequence of the to the IPCC Tier 1 approach used to determine the amount of nitrogen excreted (N_{ex}), SS4 and SS5 do not

Table 9
Variation of the environmental impacts for 1 kg of FPCM at farm for scenarios: (SS1) modification of livestock location, (SS2) use of solid manure management, (SS3) use of liquid manure management, (SS4) modification of Feed digestibility, (SS5) modification of activity coefficient correspondent to feeding situation, (SS6) modification of heavy metals concentration.

Scenario	Environmental category impacts															
	GWP	ODP	FETP	HTP-C	HTP-NC	PMFP	IRP	POCP	AP	T-EP	F-EP	M-EP	LOP	W-RD	MM-RD	F- RD
Base	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
SS1	11.3%	0.0%	−2.9%	−3.7%	−7.5%	66.2%	0.0%	23.4%	65.6%	63.6%	0.0%	4.2%	0.0%	0.0%	0.0%	0.0%
SS2	−1.9%	0.0%	4.5%	0.0%	10.0%	6.4%	0.0%	−0.2%	7.8%	7.6%	4.1%	2.7%	0.0%	0.0%	0.0%	0.0%
SS3	−14.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	−1.7%	0.3%	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
SS4	49.4%	0.0%	17.3%	18.1%	48.0%	0.0%	0.0%	16.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SS5	−4.8%	0.0%	−2.3%	−2.6%	−6.2%	0.0%	0.0%	−2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SS6	0.0%	0.0%	5.9%	−36.6%	−15.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

present variations on their N related EI categories. However, in reality, variations on DE and Ca do affect N_{ex}. This is the reason because, the IPCC Tier 2 approach to determine N_{ex} involves the livestock gross energy (GE) demand as a function of the DE and Ca. Therefore, the modification of these two parameters will have an influence on the N related EI categories. $CalcPEF_{Dairy}$ uses the Tier 1 methodology since the PEFCR-D allows it.

- **SS6**, the concentration of heavy metals applied to agricultural soils from cattle manure (mg/kg DM) was modified. The values given by the EC "Survey of wastes spread on land" (EC, 2001) were used instead of the values suggested by the SALCA-Heavy metals documentation (Freiermuth, 2006). The manure heavy metals concentration only affects the toxicity-related EI. A decrement on HTP-C (36.6%) and HTP-NC (15.1%) were registered while FETP increased a 5.9%. This scenario shows the relevance of having an accurate concentration of heavy metals by location and type of excreted manure (solid or slurry). The concentrations used in this scenario are European representative values; therefore, if more location accurate values are used, the final environmental performance of the raw milk production could affected positively or negatively depending on the real spatial location of the dairy farm

4. Conclusions

The $CalcPEF_{Dairy}$ tool presented in this work is able to perform a fully compliant PEF analysis and report PEF compliant results for raw milk and processed dairy products (packaged milk, cheese and yoghurt). The case study's raw milk production stage results obtained with $CalcPEF_{Dairy}$ are coherent and in line with previous studies; where, the dairy farm activities, at the raw milk production stage, are the main source of emissions that affect most of evaluated impact categories. Moreover, the $CalcPEF_{Dairy}$ outcomes are consistent with the results given by the assessed EF-datasets for raw milk, cheese and yoghurt.

$CalcPEF_{Dairy}$ has shown its accuracy to estimate farm emissions as stated in the PEFCR-D. Hence, it allows users to accurately assess the dairy farm, reflect the particularities of the farm activities and consequently a bespoke EI assessment of the raw milk production stage. Hence, the raw milk production stage $CalcPEF_{Dairy}$ results could avoid the use of proxy datasets when assessing the dairy products' production system. The importance of accurately assessing the farm emissions and the CalcPEFDairy versatility, when assessing them, was demonstrated through 6 scenario and sensitivity assessments were important dairy farm variables were modified.

When comparing the case study results ($EF\text{-}R_{milk}$) among the EF-datasets for different raw milk production systems ($EF\text{-}datasets_{Rmilk}$), it was possible to observe differences in several impact categories among them. This despite generally having similar farm characteristics and activities. Since currently there is not clear and detailed information about the farm characteristics used to generate the raw milk production EF-datasets, an assessment and more specific hot-spot identification among the used EF-datasets the case study's dairy farm was not possible. Better information regarding the raw milk EF-datasets is needed due to the relevant influence this production stage in the PEF of dairy products. Moreover, this information would help to select the most appropriate raw milk production system proxy when the raw milk production stage cannot be assessed.

Author contribution section

Daniel Egas: Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Sergio Ponsá:** Resources, Writing - Review & Editing, Funding acquisition. **Joan Colon:** Conceptualization, Software, Formal analysis , Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Acknowledgements

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 712949 (TECNIOspring PLUS) and from the Agency for Business Competitiveness of the Government of Catalonia. Also, this work was developed with the support of a PhD scholarship from the University of Vic – Central University of Catalonia call 2017–18 in the framework of the Experimental Sciences and Technology PhD program. This study was carried out within the framework of the "INNOTRANSLACT" project (EFA005/15 INNOTRANSLACT) under the program INTERREG POCTEFA co-financed by the European Regional Development Fund.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.110049.

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